Developing Infrastructure-Relevant Guidelines for Preliminary Conceptual Planning of a New Light Rail Transit System

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ABSTRACT

Increasingly, local planners, transit agency personnel, other professionals, and civic and community leaders have need of comprehensive, readily accessible guidelines to provide a resource for developing conceptual design and evaluation plans, particularly involving infrastructure and fleet requirements, for new light rail transit (LRT) systems in their communities.

This paper addresses this need and seeks to initiate the development of such a resource by presenting a sampling compilation of Best Practices and design recommendations for conceptual planning of LRT alignments and associated infrastructure. This discussion lays out preliminary criteria for such a more comprehensive and inclusive guideline document, as well as providing design information based on common practice. The paper hopefully will both serve as a resource to the intended audience and stimulate further development and elaboration of a comprehensive guidelines document. It is intended to have applicability and transferability for a broad range of North American communities in the early stages of considering and evaluating new LRT systems.

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BACKGROUND

In communities across North America, the possible mobility, economic, and environmental benefits of installing new light rail transit (LRT) systems (both "full-size" and "streetcar" implementations) have continued to generate interest. Striving to realistically envision this public transport technology and assess its physical requirements, impacts, and costs, local planners, transit agency personnel, other professionals, and civic leaders, and community stakeholders increasingly have need of generically applicable, comprehensive, compiled, readily accessible guidelines as a resource for developing preliminary, conceptual design and evaluation plans, particularly with respect to infrastructure and rolling stock fleet requirements.

Towards the development of such a resource, this paper discusses a sampling or compilation of selected best practices and design recommendations — preliminary information that perhaps could provide the basis of a more robust manual for conceptual planning. In the following sections, fundamental components of an LRT system will be summarized. Specific information, based on Best Practices drawn from professional sources within the transit industry, and relevant to the conceptual planning process, is presented as an illustration of what information might be useful and how it might be included in such a manual for conceptually planning an LRT project.

While costs in some cases are discussed generally, it is important to note that costs are "time-sensitive" and constantly mutable. Any cost guidelines are relevant to the current year, 2015.

As these topics are discussed here, the intent of this paper is to provide a summary overview that hopefully will inspire the development of a far more comprehensive, thorough, and detailed guide to these issues. The proposed conceptual design manual could elaborate more fully on these topics, but it is recommended that information be provided only as detailed as needed for systems-level conceptual evaluation and design (sometimes described as a "view from 30,000 feet"), and presented in a style appropriate for civic leaders and officials, urban planners, and the general public. An effort has been made to implement such a style in this illustrative presentation.

TRACKWAY ROUTE AND INFRASTRUCTURE

Certainly, the most prominent feature of any rail transit line (except perhaps for a subway) is the running way or trackway itself and its associated infrastructure (stations are discussed in another section, below). Identifying a viable route is critical.

Route Selection

Most LRT routes are typically selected on the basis of existing travel corridors, with specific alignments utilizing "opportunity assets" — existing infrastructural assets (such as existing roadways, lightly used or abandoned railway corridors, etc.) which provide an opportunity for enhanced or re-purposed use by the rail project. In selecting a potential rail transit route, the existence of one or more "opportunity assets" is an important factor along with travel patterns and density, locations of activity centers and residential areas, residential and employment density, etc. A half-mile (800-m) walking-access radius or "watershed" around stations is usually assumed.

The *Guidebook for Transportation Corridor Studies* of the National Cooperative Highway Research Program (NCHRP)/ Transportation Research Board (TRB) (*1*), published in 1999, provides a quite useful definition of a corridor:

> Broadly defined, a corridor generally refers to a geographic area that accommodates travel or potential travel. Normally, a corridor is considered to be a "travel shed," an area where trips tend to cluster in a general linear pattern, with feeder routes (highway, transit, or non-motorized) linking to trunk lines that carry longer distance trips in a metropolitan area.

Alignments that can minimize costs (especially by facilitating surface construction) within a corridor serving clear travel patterns and mobility needs are desirable. The experience of many new North American LRT systems suggests that local arterials, or available railway corridors, are ideal in this regard. Arterial alignments often follow busy inner-city corridors, facilitate lower-cost surface construction, and offer relatively close surface access to activity points. Railway alignments typically offer opportunities for the lowest surface construction costs together with rapid connections to outlying suburban and regional stations.

Sharing of tracks by LRT and "heavy" railroad operations is technically possible, but involves special authorization and oversight by the Federal Railroad Administration (FRA). Where this has been permitted, the FRA has required temporal separation (i.e., operating times of use by each type of rolling stock, LRT or "heavy", must be kept strictly exclusive).

In contrast to these common types of surface alignments, freeway alignments, while occasionally necessary, often present serious challenges, most of which impose substantially higher investment costs. Subway and elevated alignments usually are also significantly more expensive than surface (at-grade) construction, but also are sometimes an unavoidable or preferable option.

Local urban area travel corridors often have already been well identified and studied by a community's official transportation planning agencies and perhaps the state transportation or highway agency, particularly through trip generation, trip distribution, and traffic assignment procedures. Development of the conceptual design manual proposed here could elaborate discussion of the corridor selection process by relying in part on considerable resources available online that can provide guidance in corridor selection. In addition to the NCHRP/TRB *Guidebook* cited above, several representative examples are included in the References to this paper. (Although some are mode-specific, information about corridor selection can be utilized more generically.) (*2,3,4,5,6,7,8,9,10*)

Types of Trackway Infrastructure

LRT is a quite flexible rail transit mode, able to operate within the urban street system, or on exclusive right-of-way (ROW) such as in an abandoned railroad alignment (somewhat like commuter/regional rail service), or in rapid transit-style grade-separated service in elevated or subway alignments. In most cases, LRT is typically envisioned as a predominantly surface-running mode, and this is recommended as the primary focus of the proposed conceptual design manual.

However, a typical route often includes a mix of different types of trackway infrastructure. Some of the most prevalent categories are discussed further below.

Alignments and Clearance Profiles

Critical to conceptual planning of a transit mode such as LRT is an understanding of clearance profiles/ envelopes for alternative alignment configurations, and providing such information would be one of the most valuable functions of the kind of manual being proposed. To simplify the presentation, characteristics of a "standard" lowfloor LRT car are assumed (see Rolling Stock Assumptions section, further below). Technical information on these issues has been assembled from various resources providing design recommendations and transit agency Best Practices. (*10,11,12,13,14, 15,16,17,18,19,20,21,22,23,24,34,35*)

Also, the infrastructure of the traction electrification system (TES), and methods of suspending the overhead contact system (OCS) delivering power to trains, can influence clearance profiles. The Traction Electric Power Infrastructure section, further below, can help with clarifying some of these elements and their influences.

Minimum vertical clearance for an LRT system is generally determined by the minimum height of the rolling stock. The pantograph (current-collecting device atop the car) can continue to function in a lowered position, making the minimum total height 12 feet (about 3600 mm); recommended minimum height of overhead contact wire is 13'10" (4192 mm). Standard wire height is recommended in the range of 16-18 feet (4850-5450 mm). Where LRT tracks cross or share use of active heavy railroad trackage, recommended contact wire height is 22 feet (6670 mm).

For most modern LRT systems, a minimum curve radius of 82 ft. (25 m) is standard (although rolling stock with sharper turning capability can be procured). However, it's advisable, as much as possible, to avoid plotting tortuous alignments with tight curves, since this kind of route design can limit train speed, cause "wheel squeal" as trains pass, and impose excessive wear on both wheels and rails. (Where sharp curves pose noise and wear problems, track-based lubrication systems are commonly used.) Recommended curve radii range from 100 feet (30 m) in streets to at least 300 feet (91 m) or more in exclusive alignments.

It's also desirable to keep gradients (and vertical curvature) as minimal as possible, mainly because heftier, more specialized motors and gearing may be required, and sharp vertical curves may need to be eliminated with additional infrastructure — all adding expense. Also, sharp grades tend to impose limits on speed and wheel-rail traction problems in some conditions. A 6% gradient is generally accepted as a desired maximum, but grades of 9% and even greater are possible with appropriately configured rolling stock.

Trackway alignments with double track (one track in each direction) are preferred, although ROW constraints or other factors (such as projected light traffic) occasionally make a single track or other routing alternatives a desired option. For a constrained, narrow surface ROW situation, several common alternatives are available:

- **Single tracks for each direction on parallel streets** — In this case, Best Practice suggests that distance between the paired single tracks should generally be kept no greater than about two blocks, or perhaps a quarter-mile. Examples include full-performance LRT in San Diego, Portland, Dallas, Houston, and Phoenix. Some circulator streetcar loops are designed to provide bidirectional service in this way (e.g., Portland, Kenosha, Little Rock).

- **Bi-directional single track** — In this configuration, LRT traffic for each direction is funneled from a double-track alignment into a single track accessed by a switch at each end, with permission to enter the single-track section controlled by a signal system, often automated. One train must wait until a train occupying the section clears it. Obviously, this can become a bottleneck, but if the section can be quickly cleared, and headways are not extremely short, this solution to the ROW problem can work efficiently and safely.

- **Interlaced (gauntlet) track** — This configuration effectively works like a single-track section, but there are no switches and the rails are crossed and then laid side-by-side (interlaced). This has the advantage of eliminating the capital and maintenance expense of movable switches. For more explanation, see the article "Amsterdam’s Leidsestraat shows how interlaced (gauntlet) track can help squeeze light rail into a narrow alignment". (*25*)

It's also worth noting that some systems planned for initially lighter traffic volumes, with headways between trains in the range of 15-20 minutes, have intentionally installed single-track sections, with passing sidings (typically several hundred feet/meters or more in length) to permit opposing trains to pass. Sometimes these sidings are located at stations to minimize running delays. However, this system requires competent design together with precise scheduling. LRT systems in San Diego, Sacramento, and San Jose are examples where single-track sections were part of the initial system design.

As discussed previously, LRT is a versatile rail mode able to operate in a variety of alignments. From the perspective of the needs of conceptual planning, the most common of these are considered in the following discussion.

It should be emphasized that ROW and utility impacts tend to be major cost and schedule drivers for LRT projects, particularly those using roadway alignments. Utility relocations for an in-street alignment can amount to as much as 20% of construction costs; ROW, depending on street configuration (e.g., appropriating vs..retaining all traffic lanes) can also represent as much as 30% of a project cost. Environmental factors can also significantly drive design and costs (for example, in some situations, archeological finds can be expensive).

Cost figures cited below are derived from 2007 median total system costs presented in a study of 24 LRT projects described a 2008 TRB paper by Alan Hoback (*26*); these unit costs have been roughly escalated to 2015 dollars for this conceptual planning paper, and are presented here as "median" costs. On the basis of the author's experience, they seem plausible for comparative purposes and "horseback" conceptual approximation of system-level investments.

• **Surface railway in exclusive alignment** — Typically this is installed with ballasted track, i.e. rails fastened to crossties (most commonly, either timber or concrete), laid on rock ballast. Especially when abandoned or lightly used railway corridors are used for such alignments, aside from right-of-way (ROW) acquisition, the installation cost is usually the lowest of all alternative types of trackway, mainly because some major construction tasks are minimized or avoided, such as structural civil works, pavement removal, utility relocation, streetscape renovation, etc. Examples: Major segments of LRT lines in San Diego, Los Angeles, Denver, St. Louis, Baltimore, Charlotte, Norfolk, Dallas, Minneapolis, Pittsburgh, Edmonton, Calgary.

Median cost of an exclusive alignment on an abandoned railway ROW is \$24 million/mile (\$15 million/km). For shared use of an active ROW, the cost is \$35 million/mile (\$22 million/km).

Recommended width of exclusive alignments with center-mounted TES poles between tracks ranges between 28-50 feet (8.5-15.1 m), typically including provision for adequate drainage, and possible allowance for safety fencing and measures to facilitate maintenance access to the trackway. (Sometimes this may mean an access road or path, but usually the urban-suburban street system is sufficient.) If the LRT alignment uses or parallels heavy railroad ROW, 20-25 feet (6-8 m) of separation from the railroad is typically recommended.

Fencing or other measures (such as shrubbery) might be necessary to discourage trespassers and unsafe crossing of the tracks. Specially designed pedestrian crossings can optimize safety. Roadway crossings are typically protected by automatic crossing gates activated by train movement.

• **Surface railway in roadway** — Common alternatives are to install paved track in a roadway (in either dedicated transit lanes or mixed-traffic lanes), or in a center median reservation (which can typically consist of ballasted track, paved track, or track embedded in turf (grass, also called lawn track). Examples include major segments of full-performance LRT in Portland (MAX), Dallas (Lancaster Road), Houston, Phoenix, San Jose (North Main St.), Boston, San Francisco. This is certainly the most common alignment for streetcar-type systems, e.g., New Orleans, San Francisco (F-Line), Portland, Kenosha, Tacoma, Little Rock, Tampa, Tucson, Philadelphia, Toronto.

Particularly for full-performance LRT, design should aim for dedicated (reserved) lanes in roadways, with mixed-traffic operation tolerated only in exceptionally difficult circumstances. In contrast, modern-era North American streetcar systems predominantly are designed for mixed-traffic running, although more consideration of lane dedication for this sub-mode should be given.

The trackway can be separated from traffic lanes by any number of common methods, such as curbs, traffic buttons, raised but mountable center reservation, tapered traffic barriers, and others. Including any separation elements, recommended alignment widths for double-track with center

TES poles between tracks range from 28 to 35 feet (8.5-10.5 m). Widths for similar alignments with side poles and span-wire suspension of the OCS range from 22 to 29 feet (7-9 m).

Construction cost is relatively high due to such factors as pavement removal, relocation of underground utilities, and urban renovation of the adjacent streetscape. Median cost for a street/arterial lane alignment is $63 million/mile ($39 million/km). For insertion of LRT into an existing roadway median, the median cost is $32 million/mile ($20 million/km).

• **Surface railway in pedestrian-transit mall** — Commonplace in many European cities, this type of alignment typically consists of paved track running through an area shared with pedestrians and in some cases bus operations. In North America, Memphis offers an example with a heritage-type streetcar service operated through the Main St. pedestrian mall. Portland operates both LRT trains and buses in dedicated lanes over the city's downtown transit mall on 5th and 6th Avenues, but a lane is shared with private motor vehicles, and the streets do not function as pedestrian malls.

• **Elevated alignment** —Elevated structures may be necessary to avoid major obstacles (e.g., highways, heavy railroads, rough terrain). Modern elevated railway construction typically uses direct fixation track installation, whereby the rails are anchored directly with fasteners to concrete plinths that are attached to the elevated support deck. Bridges and viaducts likewise use this type of track installation. Examples of LRT systems with significant elevated segments include Los Angeles (Green Line and Gold Line serving Union Station and Chinatown), Dallas DART (especially the Trinity viaduct and northern portions of the Red Line), St. Louis Metrolink (particularly leading to the Lambert Field airport), and Seattle Link.

Median cost of an elevated alignment runs $61 million/mile ($38 million/km). This also suggests that the median cost of new bridge construction is about $11,550/lineal foot ($3500/m). However, experience indicates that the cost of modifying an existing bridge over a significant waterway may be lower.

The footprint of elevated trackway structure is somewhat less than that of surface alignments. Typical pier width is about 8 feet (2380 mm), height 23 feet (7000 mm); deck width is about 25.5 feet (7700 mm). A minimum height for the base of the deck is 16-17 feet (4850-5150 mm). However, in urban areas there are problems of shadow, visual obtrusion, and noise. Furthermore, elevated stations expand the footprint substantially, with vast overhanging structure and access facilities at surface level.

• **Subway (tunnel) alignment** — Tunnels and subways may be justified by the same kinds of criteria as elevated alignments, but in situations where an underground routing may be preferable, perhaps for environmental or even cost reasons. Examples of LRT systems with a subway or tunnel include those in Buffalo, Los Angeles, St. Louis, Dallas, Portland, Minneapolis, Seattle, Pittsburgh, Boston, Philadelphia, Newark, San Francisco, Cleveland, Edmonton, Toronto.

Subway LRT system costs are high. Median cost of a conventional cut-and-cover tunnel is $134 million/mile ($83 million/km), and for a tunnel bored with a tunnel boring machine (TBM), $279 million/mile ($173 million/km). It should be noted that costs of rehabilitating a preexisting tunnel appear considerably lower.

Subway tubes may be about 25 feet (7-8 m) in width/diameter. Stations, of course, are much larger, and require access with stairs, elevators, and often escalators. Other than the high cost of subway construction, for conceptual planning, there is little surface physical impact except for features such as:

  • **Entrances to subway stations** — These often take the form of kiosk-like stairways leading downward from sidewalks or other public spaces. Access to subway stations can also be integrated with other major structures, such as office or retail buildings.

• **Tunnel Portals** — Where there is a transition between surface and subway alignments, structures are necessary to form a secure opening. Typical modern portals assume about as much space as dual traffic lanes. However, provisions must be made to ensure that intrusion by trespassers (or stray motor vehicles) into the portal does not occur.

FARE COLLECTION SYSTEM

In preliminary conceptual planning, thought needs to be given to the method of fare collection, because this can significantly impact some aspects of infrastructure (stations, communications) and vehicle equipment (fareboxes or onboard ticketing devices). Typically (on the basis of author's experience) there are four major fare collection options for modern LRT systems:

• **Onboard fare collection by operator** — Boarding passengers pay by cash or passcard at a farebox next to the train operator, as on most buses. Slow, usually requiring all passengers to board through front door.

• **Station-based ticket vending machines and Proof of Purchase —** Most widely used for LRT systems, the Proof-of-Purchase (POP) system involves passengers purchasing tickets from station-based ticket vending machines (TVMs). Boarding is fast, as passengers may board through all doors of trains. Roving inspectors aboard trains randomly check that passengers have valid tickets.

The use of station-based TVMs improves efficiency and convenience to passengers, but it imposes extra expense and ongoing security considerations. TVMs typically are integrated into an automated fare collection system and linked to the central operations facility via the communications network.

• **Onboard ticket vending machines and Proof of Purchase** — POP system for lighter-traffic services, such as streetcar lines. Passengers purchase tickets from onboard TVMs rather than at stations.

• **Station-based ticket vending machines and turnstile access** — Passengers use TVMs in the station to purchase tickets, then must insert tickets in automatic turnstiles to access platforms. (Turnstile facilities may increase the footprint of stations.)

STATION/PLATFORM DESIGN AND CLEARANCES

In addition to the trackway itself, stations are probably the most visible features of an LRT system. For the discussion in this section, resources that have been particularly helpful are specified in the References. (*12,13,14,15,16,17,21,22,23,35*)

Modern LRT (including streetcar-type) stations have platforms for easy, fast, and safe passenger boardings. To conform with requirements of the Americans With Disabilities (ADA) Act (and Canadian equivalent), platforms designed for level boarding must extend approximately 14 inches (330-356 mm) above the top of rail, or 8-10 inches (203-254 mm) when bridgeplates are used (i.e., mini-ramps that extend at stops and then retract under the railcar floor). In addition, typical full-performance LRT stations have amenities, equipment, and facilities that may include a canopy or shelter; one or more benches; information kiosk; TVM; surveillance cameras.

With rare exceptions, stations are constructed along tangent (straight) track so that car doors and floors align safely with the platform. It's recommended that tangent track extend at least 50 feet (15 m) from each end of platforms. Platform length is usually determined by planned train length — i.e., the length of a car times projected peak number of cars in a train. There are several common configurations for LRT stations:

• **Curbside** — Sidewalk and curb are used as boarding platform. Examples: San Diego Trolley, Portland MAX, Denver LRT. Particularly for some streetcar systems, this may involve a "bulgeout" 8-10 foot extension of the sidewalk+curb into a curbside parking or traffic lane.

• **Side platforms** — In this common configuration, station platforms are located on each side of the trackway, one per track direction. Often they are staggered on each side of intersections, to minimize ROW requirements and maintain traffic lane capacity. Recommended platform widths vary from 10 feet to 16 feet (3-5 m). However, actual width should be calculated on the basis of projected demand (peak passenger volumes).

• **Center island platforms** — The station is positioned as a single platform between both tracks, saving cost by eliminating the need for duplicate station amenities. Typically recommended platform widths range from 15 to 20 feet (4.5-6.0 m).

LRT stations may need other facilities, such as interfaces with buses, bicycle racks, and especially park & ride facilities (and other provision for motor vehicle access). According to a study by the Victoria Transport Policy Institute, appropriate parking typically "requires 300-350 square feet per space, including access lanes and landscaping, allowing 100-150 spaces per acre (250-370 per hectare), depending on design." (*27*)

A 2009 report by the Ventura County Planning Division cited cost figures per parking space. (*28*) Roughly escalating the report's figure for surface parking to 2015 dollars results in an estimation of $3500 per space.

TRACTION ELECTRIC POWER INFRASTRUCTURE

Electric power is a crucial advantage of LRT operation, producing benefits in performance, environmental effects, and ongoing cost. For the discussion in this section, resources that have been particularly helpful are specified in the References. (*11*,*12*,*13*,*14*,*15*,*16*,*17*,*18*,*19*,*20*,*23*,*29*,*31*,*32*,*35*)

Providing power to LRT cars and trains typically requires system infrastructure in the form of an traction electrification system (TES) and particularly an overhead contact system (OCS) that supplies direct current (DC) power via an overhead wire to the LRT trains. (Some “wireless” power options are available, and have been deployed in several applications. While these alternatives may offer a potential of minimizing much TES infrastructure, they tend to be proprietary and somewhat experimental technologies, with expense and performance characteristics currently undergoing further evaluation.)

The circuit of direct current is completed by returning the electric current to its source via the steel running rails. Because the rails handle the negative side of the circuit, they pose no danger. Competent bonding and other measures in the installation of track and TES are designed to ensure an efficient traction power circuit.

TES infrastructure affects the overall profile (and environmental impact) of an LRT alignment, including clearances. Thus, some rudimentary understanding of this would be essential to the conceptual planning process, and worthy of inclusion in the proposed manual.

Substations

A conceptual planning manual should perhaps first explain that electric power needs to be delivered to the OCS by means of power substations, relatively small facilities that take the very high-voltage AC power from the public utility grid and convert it into the nominal 750 volts direct current (VDC) used for LRT train propulsion. While 750 VDC is the industry standard, the actual OCS voltage may vary between as little as 600 VDC to as much as 900 VDC in actual operation. Also, occasionally a different standard voltage may be implemented in response to specific needs; for example, Seattle's Link LRT system uses a nominal 1500 VDC standard.

Those involved in planning and designing LRT systems may find it helpful to know that, while LRT railcars formerly used DC motors, almost all modern vehicles now use alternating current (AC) motors (they're more powerful, cooler, and easier and cheaper to maintain). The external TES and OCS, however, continue to rely on DC rather than AC because DC has better distribution characteristics, and modern car-borne solid-state control technology is designed to process DC, providing much finer and more efficient control of AC motor speed. Use of an AC rather than DC distribution system would require much higher voltage (e.g. grid voltages of 11 KV or higher) to compensate for voltage drop, and this could be a problem in urban areas with a contact wire just 16 to 20 feet (5-6 m) high.

Substations can vary in size from small units (often cylindrical, about the size of a garbage can) attached to utility poles, to small surface cabinets, to small buildings about the size of a storage shed, in the range of 100-200 square feet (SF) (roughly 9-20 sq. m), and possibly larger in some cases. Depending on the size and configuration of the system (streetcar operation being on the lower end), LRT substation power ratings typically range between as little as 0.5 megawatts (MW) to as much as 3.0 MW. Also depending on specific configuration, substations are typically spaced at intervals ranging from about 0.5 mile to approximately 1.5-2.0 miles (800-3200 m). Full-performance LRT, which generally operates larger cars with heavier passenger loads at higher speeds, tends to require substation characteristics at the higher ends of these ranges.

A phenomenon involved in the interface between substations and the OCS is voltage drop. Every electrical wire has inherent resistance to the flow of electric current, and this produces a drop in voltage which gets greater over distance. The longer the wire extends from the original electric source, the greater the voltage drop. Thus, the further a train is from the nearest substation, the lower the voltage and the electric power available from the OCS.

Types of OCS

Electric power is most commonly delivered to an LRT railcar via a trolley (contact) wire above the track. A device atop the railcar contacts the trolley wire and conveys power to the car.

The device on the car roof contacting the trolley wire usually is a pole or a pantograph. The pole (with either a wheel or a shoe at the contact end) was widespread in the historical era of street and interurban railways, and is still used on a few legacy and heritage streetcar systems. The much more common device is the pantograph, which folds down on the roof when not in use and extends upward to put a horizontal component, a carbon shoe, in contact with the trolley wire. Pantographs (manipulated by electro-hydraulic mechanisms) are easily controlled by the car operator inside the cab, and are widely recommended as the preferred collection device.

Of particular interest in conceptual planning is the physical design of the TES and the OCS. It's useful to understand that there are two common configurations of OCS:

- **Simple trolley wire** — A single wire is suspended from various types of hangers above the track. This is often preferred in downtown areas, street alignments, and neighborhoods because it has a very unobtrusive visual profile. However, because of voltage drop, the trolley wire often must be supplemented with additional (usually thicker) feeder cables, in most cases buried underground parallel to the LRT line. Also, all such wires sag between attachment points, and some method of tensioning is needed in the OCS to keep the trolley wire as straight as possible, especially during seasonal temperature changes which can cause the wire to expand or contract.

• **Catenary** — This is a specific type of OCS (although the term is erroneously used to refer to any overhead power system in general). In this configuration, a top wire (called the messenger) is suspended by hangers from horizontal arms or span wires attached to the TES poles, and the trolley wire is hung from the messenger (usually with vertical spacers). The messenger is intentionally allowed to sag, forming a long, extended upside-down arc known as a catenary curve — hence the name. (This catenary curve can be seen in any hanging wire, such as a utility or power line wire or even a clothesline, and a simple trolley wire also hangs in such a geometric curve.) But due to the spacers, the trolley/contact wire is kept straight. To prevent excessive sag in the messenger wire, a tensioning system is also used with catenary suspension.

A straighter contact wire under the catenary (messenger) works particularly better for higher-speed operation, since the sags in a simple trolley wire OCS at faster LRT speeds tend to cause the pantograph (or pole) to bounce, producing burns and chips in both wires and shoes. Another major advantage of catenary is that the thicker messenger wire serves additionally as a feeder to the contact wire, usually eliminating or minimizing the need for extra parallel feeders — a major cost saving.

Methods of OCS Suspension Over Trackway

To suspend the OCS over the trackway alignment, two methods are commonly used:

• **Cantilever suspension** — The OCS is held by a horizontal bracket, rod, or other solid structural member attached at the opposite end to a vertical TES pole. Most commonly, cantilever brackets are fastened back-to-back on single poles in the middle of the trackway, centered between the two tracks of a double-track alignment. However, in a less common configuration, cantilever brackets or rods can extend up to 18’ (5.5 m) from poles at the side of the alignment, often at the side or in the easement of a roadway.

• **Side-attached span wires** — The OCS can be suspended from transverse span wires, or cross-spans, attached to poles (or other supports, such as the facades of buildings) at each side of the alignment. This method is frequently useful for supporting the OCS where poles are difficult to place in the center, such as in a narrow arterial, and at intersections. Cross-span suspension can also be used in multi-track situations, such as storage sidings. However, for double-track alignments, it is somewhat more expensive than using center poles with double bracket arms, since approximately twice as many poles are required.

Stray Current Control

As explained earlier, the traction direct current is returned to the power source (e.g., nearest substation) via the trackway rails themselves. However, there always is a relatively tiny amount of stray current loss due to the effects of ambient moisture, rain, insulation imperfections, and other factors.

Poorly installed or maintained rails, insulators, and other hardware, or poor-quality materials, sometimes can result in sufficient stray current over a prolonged period to corrode metallic materials, including underground utilities. Electric railway engineers have methods to deal with this problem, providing ongoing corrosion control and conducting periodic inspections to ensure that stray currents remain within acceptable limits.

SIGNALIZATION AND COMMUNICATION INFRASTRUCTURE

Signal and communications systems have long been essential to efficient and safe train operation, and some rudimentary, simple understanding of how these systems function in a railway setting would be highly useful in conceptual LRT planning. For the discussion in this section, resources that have been particularly helpful are specified in the References. (*11*,*14*,*15*,*16*,*17*,*18*,*19*,*35*)

Signalization

A key element of signalization is train-to-wayside communication (TWC), a variety of means (radio, induction, electric signals, etc.) by which trains communicate with the fixed system. A central operations and dispatching command center usually oversees and controls train traffic. Signal systems can be complex, but typical LRT systems use:

- **Railway-type systems** — These include automatic block signals (ABS), whereby tracks are segregated into fixed blocks, and train occupancy and movement are detected and managed from hard-wired block to block. Train operators follow the guidance of wayside visual signals (typically colored lights). Detection systems for crossing gates at level road crossings are integrated into the signal system.

  For larger, more complex LRT operations, signalization can involve more sophisticated features, such as cab signals, automatic train stop (ATS), automatic speed control, and even automatic train operation (ATO). For such systems, variable blocks, with wireless communications-based train control (CBTC), replace fixed blocks. Also, on most railway lines under FRA jurisdiction, a high-tech positive train control (PTC) system, monitoring and controlling train movement via GPS, is mandatory.

- **Street operation systems** — Operating in public streets, as with buses, typically relies on line-of-sight control by operators, plus the traffic signal system. In some cases, operators just obey the same signal lights as motor vehicle drivers, but most LRT systems integrate train operation with the traffic signal system, with special signals controlling train movements. Prioritization, allowing trains to move ahead of other traffic, is often included.

Communications

Besides signalization, many other functions rely on a competent, secure communications system. This system may be hard-wired, wireless, or (most often) a combination of both. Some of the most important typical communications functions include:

- **Radio communications** — Facilitating communication among operators, supervisors, central control, maintenance workers, security personnel, etc.

- **Public address system** — Helping keep passengers informed of special situations.

- **Variable message board (VMB) communications** — Also called passenger information displays (PIDs), VMBs provide information on next-train arrival times, delays, emergency situations, etc.

- **CCTV surveillance** — A closed-circuit television (CCTV) system observing station platforms and other public areas plays a crucial role in ensuring security.

- **Automated fare collection** — Handling the essential data flow of fare transactions.

• **Automatic vehicle location (AVL)** — GPS-based system that tracks and reports train locations. This interfaces with both the central operations/dispatching center and the VMB system to inform passengers of train schedule issues.

• **Supervisory Control and Data Acquisition (SCADA) system** — A basic data communications system that monitors, acquires, and transmits data and control instructions to the LRT system's master central control system.

Any cabling necessary for both signalization and communication is typically included in or alongside the trackway.

ROLLING STOCK FLEET AND FACILITIES REQUIREMENTS

Selection of the type and configuration of an LRT railcar is an important consideration in conceptual planning, with implications for infrastructure design. An excellent overview of such issues, applicable to full-performance as well as streetcar-type LRT, is presented in the *Modern Streetcar Vehicle Guideline* prepared by APTA's Streetcar Subcommittee. (*23*) In addition to this resource, others that have been particularly helpful for the discussion in this section are specified in the References. (*14,15,16,17,18,19,35*)

Rolling Stock Assumptions

It is recommended that the proposed planning manual assume rolling stock configurations that conform to the widespread lowfloor standard, i.e., a floor height approximately 14 inches (356 mm) above top of rail. With very rare exceptions, modern cars in North America are double-ended, i.e., with cabs at each end and doors on both sides. Thus they are capable of reversing direction at the end of lines (without the need for turning loops), and can board passengers from platforms on either side.

As noted earlier, on modern cars pantographs (rather than poles or other devices) are recommended for current collection from the OCS. Likewise AC rather than DC motors have become standard and are widely recommended.

Another consideration is railcar wheel profile (this particularly involves the wheel contours and flange sizes). If track-sharing with heavy railroad operation is planned, or even contemplated for the future, LRT car wheels compatible in profile with heavy railroad-type wheels should be considered.

Most modern LRT rolling stock have articulated carbodies, i.e., segmented into sections that allow a longer car to "bend" around curves. As a result, the length of LRT railcars has gradually been increasing. Full-performance cars today range in length from 81 to 96 feet (24.8 m to 29.4 m), and a width of 8 ft. 8 in. (2650 mm). European practice has widely transitioned to the use of longer cars with more articulations (rather than coupling cars to form trains), and U.S. practice may eventually follow.

Streetcar-type cars also typically double-ended, with articulated but shorter carbodies, generally ranging from 66 ft. (20.0 m) to 79 ft. (24.1 m). However, longer streetcars are available in lengths of as much as 98 ft (30.0 m) and even longer. These vehicles may be as wide as a full-performance LRT car, or somewhat narrower, with 8 ft (2400 mm) being a common size.

It should be noted that heritage-type streetcars (either renovated historic cars or modern replicas) remain a popular choice for new systems in some communities. Physical and operational characteristics of such cars are obviously very different from those of modern cars, and system design should consider whether eventual conversion to a modern-type system, or sharing of infrastructure, is a future possibility.

Estimating Fleet Size

Estimating rolling stock fleet size involves assumptions of passenger capacity per car and average speed. The following are roughly plausible peak passenger capacity assumptions for typical modern U.S. articulated cars:

- Full-performance LRT car, 90-96 ft. (27.3-29.4 m) — 150
- Full-performance LRT car, 81 ft. (24.8 m) — 125
- Streetcar, 66 ft. (20.0 m) — 110

Average schedule speed depends on numerous variables, particularly the number of station-stops and their spacing. The following are roughly plausible assumptions for different configurations and conditions:

- Full-performance LRT, predominantly urban arterial alignment — 15 mph (24 km/h)
- Full-performance LRT, predominantly exclusive railway alignment — 20 mph (32 km/h)
- Streetcar, predominantly urban arterial alignment — 12 mph (19 km/h)
- Streetcar, downtown urban circulator — 9 mph (14 km/h)

For conceptual planning, fleet size can be roughly calculated on the basis of necessary capacity for assumed peak-hour/peak-direction loads, which can be approximated in most cases as 10% of projected target weekday ridership. The throughput of cars (and capacity) can be calculated by end-to-end trip time based on assumed schedule speed. If it takes about a half-hour to travel end-to-end, then a car can make only one peak-direction trip per hour. Vehicle spares (to handle contingencies such as vehicles out of service) can be assumed at a ratio of 15-20% of projected peak requirements.

For example, assume an 8-mile route in a predominantly arterial-type alignment, with projected target ridership of 25,000. Peak-hour/peak-direction ridership can be assumed at 2,500. At an average speed of 15 mph, trip time is more than a half-hour end-to-end, and 20 "short" (81-ft/25-m) full-performance cars would be needed to supply adequate capacity. By using a spare-ratio assumption of 15% (3 cars), a fleet size of 23 railcars would be calculated for this example.

Storage and Maintenance Facility

A facility for storage and maintenance of rolling stock is essential. Cars must be stored when not in use, and structures and equipment are needed for maintaining and repairing cars, servicing and cleaning them, and coordinating maintenance of way operations.

Often called a "carbarn", this facility typically is laid out with a throat track leading to a "fan" of multiple tracks accessed via switches from the throat track, a series of parallel tracks for outdoor storage, and the maintenance building or shed, also with multiple parallel tracks. Inside the maintenance structure is usually a wide array of both conventional and specialized equipment, inspection pits for accessing the underside of cars, storage for parts for cars and infrastructure maintenance, employee facilities, and perhaps other areas, such as administrative and operations offices.

In addition to maintenance, other major functions, including operations and administration, can also be housed at such a facility. Alternatively, these activities could be located at the general transit office or in a separate building.

Identifying workable sites for the storage and maintenance facility is critical in the conceptual planning of a minimal operable system (MOS). Ideally, it should be as close as possible to the revenue-service route itself. Lengthy access trackage to a remotely located storage-maintenance site would result in lots of extra car mileage and time deadheading back and forth, and clearly should be avoided.

Information on site requirements and costs may be helpful in conceptual planning. In a 2002 report, Dallas Area Rapid Transit (DART) presented results of a "survey of transit systems and their light rail maintenance facilities nationwide" that indicated "a ratio of 0.2 acres per light rail vehicle." DART cited a ratio of 0.3 acres per vehicle from their own experience. (*33*)

To assess size and cost relationships of such a facility, this author examined data for similar facilities in Houston, Portland (Elmonica), Dallas (Northwest Operations Facility), Salt Lake City (Jordan River), Denver (Elati), and Norfolk. Based on railcar capacity, space per railcar ranged from 770 to 2760 sq.ft. (71-253 sq.m). Facility cost per car-space, in 2015 dollars, ranged from $416,000 to $1,546,000.

SUMMATION

This paper has been intended to have applicability and transferability for a broad range of North American communities in the early stages of considering, evaluating, and conceptualizing new LRT systems. Even at a conceptual and envisioning level, it's often useful for planners, political and civic leaders, decisionmakers, and community stakeholders to have a general understanding of details of LRT design and technical issues.

A more comprehensive manual could include graphics and summary tables, and elaborate and expand on many of the topics discussed, providing a solid and thorough resource. Hopefully this paper will both serve as a useful resource to the intended audience and stimulate further development and elaboration of a comprehensive guidelines document.

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