TRANSIT COOPERATIVE RESEARCH PROGRAM

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TCRP Report 7

Reducing the Visual Impact of Overhead Contact Systems

Transportation Research Board

National Research Council

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Reducing the Visual Impact of Overhead Contact Systems

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TRANSIT COOPERATIVE RESEARCH PROGRAM

The nation's growth and the need to meet mobility, environmental, and energy objectives place demands on public transit systems. Current systems, some of which are old and in need of upgrading, must expand service area, increase service frequency, and improve efficiency to serve these demands. Research is necessary to solve operating problems, to adapt appropriate new technologies from other industries, and to introduce innovations into the transit industry. The Transit Cooperative Research Program (TCRP) serves as one of the principal means by which the transit industry can develop innovative near-term solutions to meet demands placed on it.

The need for TCRP was originally identified in *TRB Special Report 213—Research for Public Transit: New Directions,* published in 1987 and based on a study sponsored by the Urban Mass Transportation Administration—now the Federal Transit Administration (FTA). A report by the American Public Transit Association (APTA), *Transportation 2000,* also recognized the need for local, problem-solving research. TCRP, modeled after the longstanding and successful National Cooperative Highway Research Program, undertakes research and other technical activities in response to the needs of transit service providers. The scope of TCRP includes a variety of transit research fields including planning, service configuration, equipment, facilities, operations, human resources, maintenance, policy, and administrative practices.

TCRP was established under FTA sponsorship in July 1992. Proposed by the U.S. Department of Transportation, TCRP was authorized as part of the Intermodal Surface Transportation Efficiency Act of 1991 (ISTEA). On May 13, 1992, a memorandum agreement outlining TCRP operating procedures was executed by the three cooperating organizations: FTA, the National Academy of Sciences, acting through the Transportation Research Board (TRB), and the Transit Development Corporation, Inc. (TDC), a nonprofit educational and research organization established by APTA. TDC is responsible for forming the independent governing board, designated as the TCRP Oversight and Project Selection (TOPS) Committee.

Research problem statements for TCRP are solicited periodically but may be submitted to TRB by anyone at any time. It is the responsibility of the TOPS Committee to formulate the research program by identifying the highest priority projects. As part of the evaluation, the TOPS Committee defines funding levels and expected products.

Once selected, each project is assigned to an expert panel, appointed by the Transportation Research Board. The panels prepare project statements (requests for proposals), select contractors, and provide technical guidance and counsel throughout the life of the project. The process for developing research problem statements and selecting research agencies has been used by TRB in managing cooperative research programs since 1962. As in other TRB activities, TCRP project panels serve voluntarily without compensation.

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The TCRP provides a forum where transit agencies can cooperatively address common operational problems. The TCRP results support and complement other ongoing transit research and training programs.

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Each report is reviewed and accepted for publication by the technical panel according to procedures established and monitored by the Transportation Research Board Executive Committee and the Governing Board of the National Research Council.

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FOREWORD

By Staff
Transportation Research Board

This report will be of interest to planners, designers, engineers, transit professionals, hardware suppliers, and others interested in light rail and trolley bus systems. It describes ways to minimize the visual impact of overhead contact systems (OCS) using various types of hardware, support structures, construction techniques, and streetscape treatments. This report provides good and bad examples of OCS in the United States and abroad and contains a comprehensive review—compiled from OCS manufacturers—of OCS hardware and design techniques currently in use in North America and Europe. The report focuses on trolleybus and light rail systems in the street environment.

Electric transit vehicle applications will make positive contributions to reducing mobile source air-quality problems in most urban areas in this country. Additionally, the noise level associated with these electric vehicles is significantly lower than with diesel buses. A major obstacle to electric transit vehicle applications is the need for an overhead contact wire system. The concept of OCS is unfamiliar to much of the U.S. population and is perceived as visually obtrusive.

As plans emerge to upgrade existing OCS, reinstall older systems, and prepare for new ones, information on how to minimize visual impact is needed. For example, during the rehabilitation and expansion of the Seattle system, certain communities initially did not endorse the reinstitution of trolleybus service because of the "visual pollution" problem. One community that had installed all its utilities underground refused to accept trolleybus service.

Under TCRP Project D-4, research was undertaken by Urbitran Associates, Inc., Arthur Schwartz Associates, and Skidmore, Owings and Merrill to produce a report that investigates methods to reduce the visual impact of OCS installations. The methods studied included improved design techniques which, when coupled with streetscape treatments, make the OCS less visible and more acceptable.

To produce the report, a comprehensive review of OCS hardware and design techniques was conducted, and the operational needs of transit systems that affect OCS and its visual impact were identified. The research identified good examples of OCS, design techniques, and streetscape improvements. This information formed the basis of the report, which should aid transit professionals, urban planners, and component suppliers in minimizing the visual impact of OCS in urban environments.

The unpublished final report, as submitted by Urbitran Associates, summarizes the research effort and findings. Copies of the report are available on a loan basis or for purchase ($10.00) on request to TCRP, Transportation Research Board, Box 289, Washington, D.C. 20055.

CONTENTS

ACKNOWLEDGMENTS

Arthur D. Schwartz of Arthur Schwartz Associates was the prinicpal investigator for this project. John S. Kulpa of Urbitran Associates, Inc., was the project manager and a major contributor to the report. The TCRP Project D-4 panel provided useful input and review for the report.

Also, the contribution of numerous transit agencies and suppliers in providing information and assistance must be gratefully acknowledged. Special thanks must be given to transit agency staff who took time to provide guided tours.

REDUCING THE VISUAL IMPACT OF OVERHEAD CONTACT SYSTEMS

SUMMARY

There is widespread agreement that electric transit vehicle applications will make positive contributions to reducing mobile source air-quality problems in most urban areas in this country. Additionally, the noise level associated with these electric vehicles is significantly lower than with diesel buses. However, a major obstacle to electric transit vehicle applications is the need for an overhead contact wire system. The concept of an overhead contact system (OCS) is unfamiliar to much of the U.S. population and is perceived as visually obtrusive.

As plans emerge to upgrade existing OCS, reinstall older systems, and prepare for new ones, useful information on how to minimize visual impact is needed. For example, during the rehabilitation and expansion of the Seattle system, certain communities initially did not endorse the reinstitution of trolleybus service because of the "visual pollution" problem. One community that had installed all its utilities underground refused to accept trolleybus service.

This research effort identified good examples of OCS, design techniques, and street-scape improvements and formed the basis of the report.

This report is intended to provide information that will aid designers of overhead contact systems (OCS), urban planners, engineers, transit professionals, hardware suppliers, and others in minimizing the visual impact of these systems, whether trolleybus or light rail, in an urban environment.

Chapter 1 provides an introduction and describes the function of OCS for trolleybus and light rail systems. In a trolleybus system, the OCS must deliver positive and negative current as well as provide a guideway for the trolley poles. In a light rail system, the OCS must deliver positive current as well as be positioned over the track to maintain pantograph contact. The negative circuit path is completed through the rails.

Chapter 2 describes nonintrusive and intrusive designs. The key consideration is what the overall visual impact of the design is on the intersection or street segment. Individual details, although important, are less critical than the complete effect that the hardware has in any given location.

Chapter 3 discusses the influence system design has on visual impact including the need for emergency wire and the use of one-way operation to minimize visual impact in trolleybus systems, the provision of turning capability in trolleybus and light rail OCS design, and the effect of curve design and the design of the electrical distribution system on the appearance of light rail OCS. An approach to evaluating the visual impact of trolleybus intersections is presented.

Chapter 4 describes the types of suspension used in trolleybus and light rail OCS, including direct suspension, pendulum suspension, and fixed- and constant-tension catenary.

Chapter 5 identifies the type and amount of hardware required for various trolleybus curves. It also describes approaches to light rail curve design that differ in the amount of supporting structure used.

The discussion of intersections in Chapter 3 is expanded in Chapter 6. This chapter addresses specific intersection hardware and support structures.

The visual impact of OCS elements including poles, building eyebolts and structural attachments, span wire and mast-arm support, catenary systems, and such components as feed taps and switch control are described in Chapter 7.

A series of artist's renderings and descriptions illustrate the ways in which streetscape improvements can be used to enhance the visual quality of OCS through design, landscaping, and the consolidation of street-furniture elements. Included in this chapter is a quick-reference matrix that allows the reader to look up an OCS element to find its general suitability in terms of location and design considerations.

Chapter 9 discusses the advantages and limitations of presenting OCS designs using photographs, technical plans, architectural renderings, and reproductions of computer-generated images.

The complexity of the regulatory environment for transit projects using OCS is described in Chapter 10, including such issues as safety codes, land use and environmental regulation, and regulations for the use of public streets.

Chapter 11 contains the conclusions of this research effort of which the primary conclusion is that the visual impact of OCS can only be reduced if such reduction is made a specific goal throughout the design process.

Appendix A is a glossary of terms, and Appendix B is a list of trolleybus and light rail systems in the United States and Canada.

CHAPTER 1

INTRODUCTION

PURPOSE

This report provides information that will aid designers of overhead contact systems (OCS), urban planners, public advocacy groups, and component suppliers in minimizing the visual impact of these systems, whether trolleybus or light rail, in an urban environment.

The report takes into account the inherent differences and similarities between trolleybus and light rail systems. The material in this report will also be useful to people involved with other types of systems although these are not directly addressed. These include light rail systems using trolley-pole current collection and trolleybus and light rail systems operating on exclusive rights of way.

This report is not a detailed design manual. OCS design issues are too specific to local situations and to transit agency preferences to permit textbook solutions. The report is intended to help planners and designers anticipate visual impact problems and suggest possible solutions.

FUNCTION OF OCS

Trolleybus and light rail OCS designs are based on street railway OCS initially developed in the late 19th century. The pantograph current collector and the use of catenary overhead was introduced early in the 20th century for railroad electrification. Although sometimes used on interurban electric railways, the widespread use of these elements in urban transit in North America is relatively recent. Trolleybus OCS was initially that of a street railway system with two contact wires; however, subsequent changes made as a result of the maneuverability of the bus simplified such areas as curve construction.

The function of OCS is somewhat different for trolleybus and light rail systems. In a trolleybus system, the OCS must deliver positive and negative current at a nominal 600-700 volts direct current (VDC) as well as provide a guideway for the trolley poles. In a light rail system, the OCS must deliver positive current at a nominal 600-1500 VDC as well as be positioned over the track to maintain pantograph contact. The negative circuit path is completed through the rails.

In trolleybus system design, the most important goal is to provide OCS that is appropriately located for bus movement. To minimize wear and prevent dewirements, the optimum position of the OCS is (1) centered over the bus path in tangent sections and gentle curves or (2) with the wire over the inside rear corner of the bus on sharp turns.

Wire height must be high to clear other traffic yet low enough to give maximum maneuverability. The most common specification for wire height is a minimum at the lowest point of 5.5 m (18 ft), which requires support heights of 5.6 m (18 ft 6 in.) to 5.8 m (19 ft). The 18-ft wire height is specified in the National Electrical Safety Code (NESC), which most state electrical codes follow. California requires a minimum height of 5.8 m (19 ft). At the 5.5 m (18 ft) height, the bus can maneuver 3.7 m (12 ft) to 4.6 m (15 ft) from the wire centerline. Lower wire height is used in some older systems but is unlikely to apply to any new system.

Crossings with railroads require that wire height be raised to 6.7 m (22 ft) or 7.0 m (23 ft). At these heights, buses must be almost directly under the wires because maneuverability is limited to approximately 1 m (2 to 4 ft). Lower wire can be used when necessary to pass under low structures. Although a wire height of 3.7 m (12 ft) is sufficient for bus operation, heights of less than 4.9 m (16 ft) should be used over a public roadway only when absolutely necessary. Exemptions to state codes can usually be obtained for such situations.

Insulation is required between polarities as well as between sections, which means that switches and crossovers will have dead sections that buses must coast through. Locating these dead sections to minimize their effect on bus movement is an important consideration in intersection design.

OCS for light rail systems must be located so that the pantograph shoe always remains in contact with the wire. This requires considering both track location and superelevation to determine the actual position of the pantograph. Allowance must be made for tilt and sway of a moving vehicle, wind, and the position of the pantograph relative to the truck center of the car.

The same constraints on minimum wire height in streets and areas accessible to the public as described for trolleybuses apply to light rail systems; however, use of a power supply greater than 750 volts places the system in the high-voltage category, which has higher clearance requirements (6.1 m [20 ft]) in the NESC. Minimum and maximum working wire heights are functions of vehicle and pantograph design, and they vary substantially among transit agencies.

Insulation in the contact wire is only needed between electrical sections of the OCS. Because the wire is not a guideway, air gaps may be used for insulation. Also, commutating insulation is often used, where the pantograph shoe is in momentary contact with both sections, which eliminates arcing at the insulator.

CHAPTER **2**

NONINTRUSIVE AND INTRUSIVE DESIGN EXAMPLES

Throughout existing electric transit systems, examples of nonintrusive and intrusive OCS treatments abound. The definitions of nonintrusive and intrusive designs are not always obvious and include such issues as the background and character of the neighborhood in which the OCS is located, the operational constraints affecting the design, and the hardware components selected for use on the system as a whole. What looks good and functions well in one setting may be completely inappropriate in another.

The overall visual impact of the design on the intersection or street segment is the key consideration. Individual details, although important, are less critical than the complete effect the hardware has in any given location.

In general, a nonintrusive OCS design will have the following characteristics:

1. It will appear to be well integrated with the streetscape. That is, it will appear to have been designed as part of the street taking into account such matters as neighborhood context, building scale, materials, and historic character. It will not appear to be added as an afterthought. In responding to the streetscape, it may change in different parts of a route. Different pole types and OCS designs can often be used effectively in various situations.
2. It will not add to the clutter of poles and wires any more than necessary. This means that care will be taken in locating poles and securing joint use of poles wherever possible. Opportunities to attach support spans onto building eyebolts will also be taken at every turn to eliminate poles wherever possible. In addition, curves and turns will have been designed to reduce their profiles and avoid complex wiring arrangements through bus-route adjustments and appropriate design.
3. It will minimize visual mass by using materials lighter in texture and form whenever possible. Examples of this include painting poles and mast arms in colors that blend well into the background; avoiding certain materials such as concrete poles that are larger in diameter than steel ones; and designing fewer curves, switches, and crossing elements wherever physically and operationally possible.
4. It will integrate street furniture into the design. Items such as street lighting, traffic signals, bus shelters, decorative banners and other elements should be designed as part of the OCS to minimize duplication and turn the overall OCS into an urban amenity.
5. Only necessary elements will be designed into the system. For instance, overhead support systems for switches and crossovers not yet operational but planned at some future date should not be built until they are necessary. Poles should be only as high and only as massive as necessary to support the weight of the OCS within reasonable tolerances.
6. It will respond to the environments and neighborhoods through which it passes and will alter form appropriately—which could mean different poles, eyebolts, and other hardware all on the same system.

On the other hand, intrusive OCS design will probably exhibit one or more of the following characteristics:

1. It will create a forest of poles by ignoring the need for joint-use agreements, avoiding eyebolt-suspension opportunities, and placing individual poles at regular intervals regardless of the poles that already exist in the streetscape.
2. Switches and crossovers will be designed without any attempt to reduce their incidence by using route adjustment. Curve segments may also be designed for a far higher operational speed than is ever practically attainable, which will require more frequent pulloffs and support systems.
3. Much of the system will anticipate future service additions and every possible configuration to avoid the need to make significant physical changes. Although this may appear to be a prudent approach, the result is the installation of hardware that (1) does not have any immediate functional use and (2) adds to maintenance requirements.
4. The overhead wiring will not match the operational context of the roadway underneath. An example of this is installing wiring for advance turn lanes on a narrow, one-lane street where trolleybuses could not position themselves to take advantage of the wired turn lane. (See Figure 3-11.)
5. Finally, the OCS will likely have been installed in an isolated fashion without the benefit of consultation and coordination with local planners, urban designers, utilities, and other interested parties. Although such consultation adds to the time required to implement any given project, in the long run, it serves to improve the system by integrating ancillary functions, minimizing clutter, and being sensitive to local urban design and planning concerns.

Figures 2-1 through 2-7 illustrate various nonintrusive and intrusive OCS treatments.

Figure 2-1. Nonintrusive trolleybus OCS in a residential area—Seattle. The appropriate use of wood poles in a heavily wooded area almost conceals the wire.

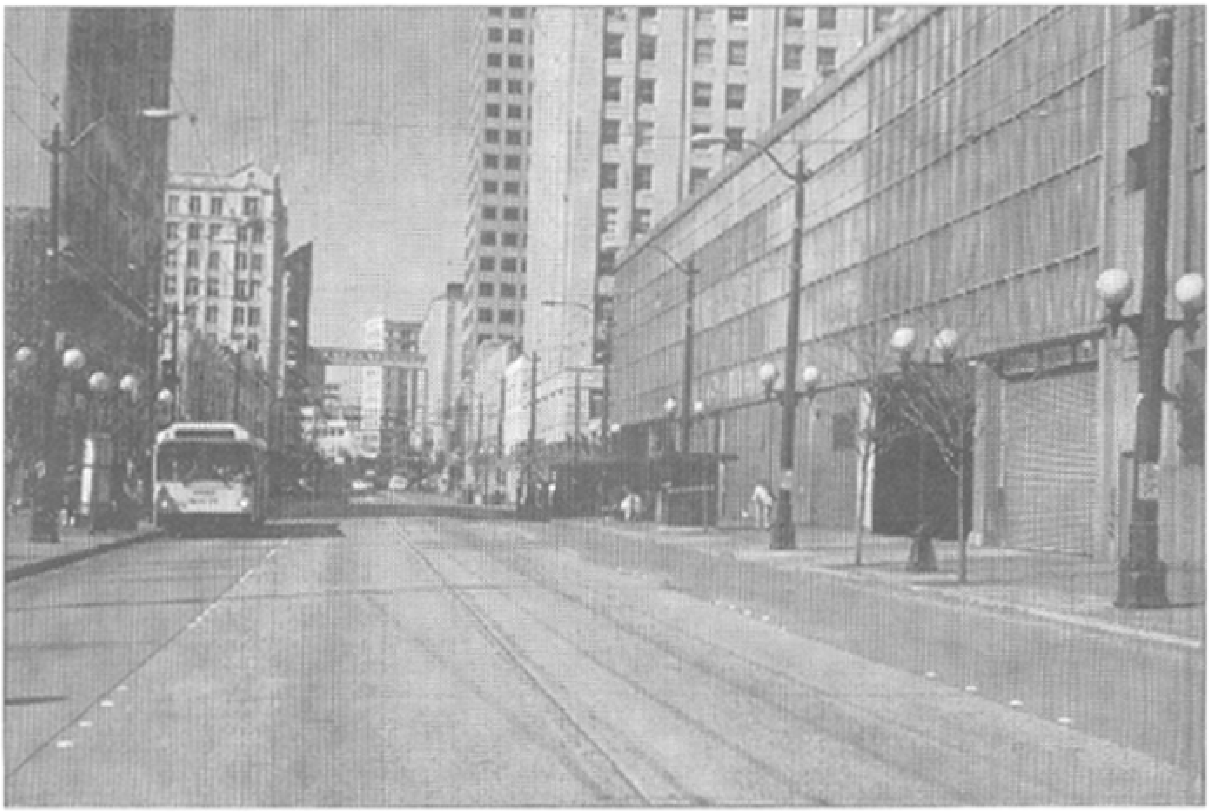

Figure 2-2. Nonintrusive trolleybus OCS in a downtown area—Seattle. Joint-use poles with decorative features work well in this design.

Figure 2-3. Intrusive trolleybus OCS—Philadelphia. The assortment of OCS, utility, and traffic-signal poles of different styles and colors is unfortunately all too common.

Figure 2-4. Nonintrusive LRT direct-suspension OCS—Sacramento. The OCS in this pedestrian mall is effectively camouflaged by the buildings, trees, and street furniture.

Figure 2-5. Intrusive LRT direct suspension—Pittsburgh. The use of tall, bulky poles; three-level spans; and an excessive number of feed taps and insulators produces a very cluttered appearance.

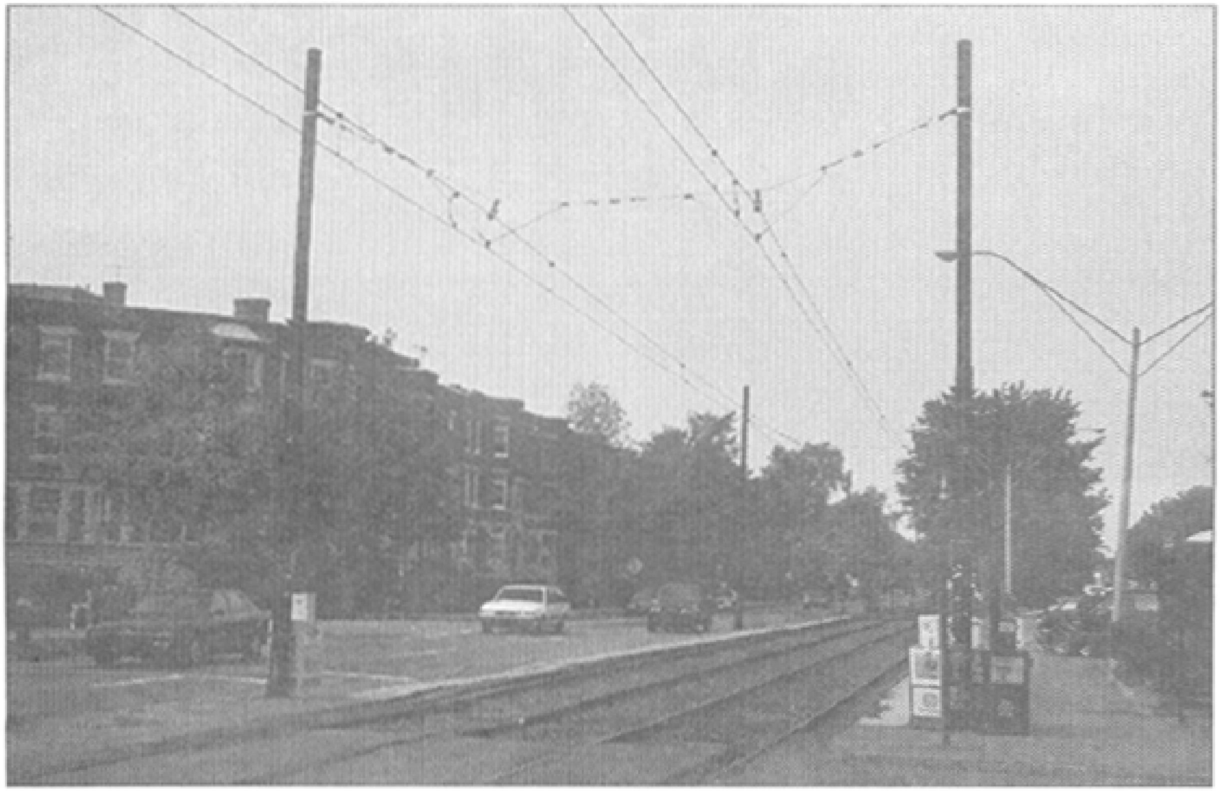

Figure 2-6. Nonintrusive catenary—Boston. The slender poles, light messenger wire, and single-span support produce a very clean design.

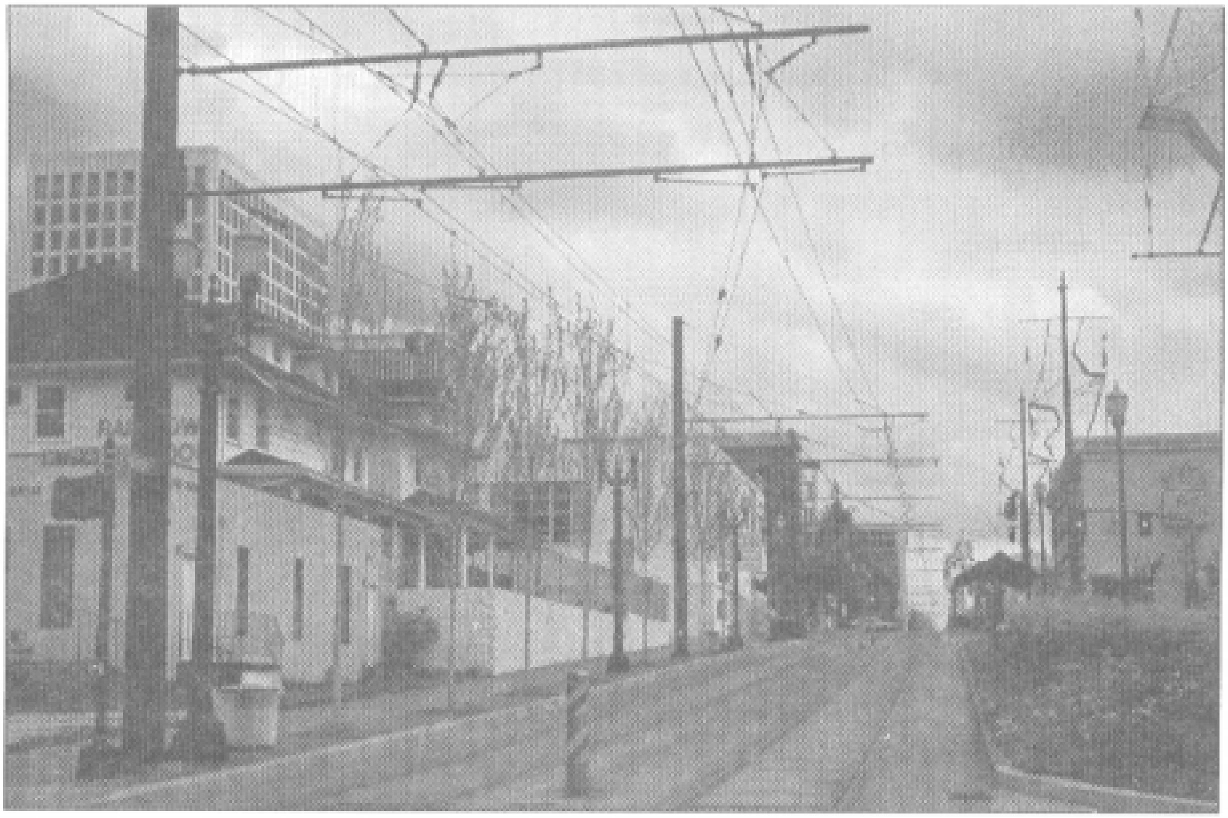

Figure 2-7. Intrusive catenary—Portland. A cluttered streetscape is produced by the use of (1) double-deck mast arms and catenary in an area where direct suspension is appropriate and (2) an excessive number of poles.

CHAPTER 3

SYSTEM DESIGN CONSIDERATIONS

TROLLEYBUS OPERATIONS AND SYSTEM DESIGN

The goal in trolleybus-system design should be to minimize, where appropriate, the use of system elements that are visually obtrusive. In general, special work (e.g., switches, crossovers, and curve segments) is more obtrusive than straight trolley wire. Use of these components should be avoided or minimized where it is feasible to do so without significantly affecting operations.

The first step in designing an OCS for trolleybuses is to determine the wire and special work actually needed. This requires the preparation of a system wire map showing revenue routes with scheduled turnbacks as well as garage access routes. Garage access routes must take into account minimizing running time and the amount of nonrevenue wire.

Any new system is likely to use vehicles with auxiliary power units (APUs) installed on board. Powered by batteries, the simplest APU can eliminate the need for most of the wire installed but not regularly used on existing systems. This includes wire and special work used only in emergencies and wire used infrequently on a scheduled basis. The use of an APU will require additional stops for removing and replacing trolley poles, which will expose drivers to traffic hazards and increase travel time. Thus, use of the APU in revenue service should be limited to a few early morning or late evening trips when passenger usage and vehicle traffic are at a minimum.

Emergency wire is most often provided in downtown areas, where a street closure will affect multiple routes. Most transit systems that use trolleybuses have enough spare diesel buses to substitute for trolleybuses on one route; however, they can only schedule multiple route substitutions on weekends or late evenings.

Figure 3-1 shows a diagram of an OCS design in an area of downtown Seattle. The wire used for scheduled service, including garage movements, is differentiated from the wire needed only in emergencies. It can be seen that the intersection at First Avenue and Stewart Street and the two blocks of wire on Stewart Street could be eliminated with APU availibility, and that the two most complex intersections on Third Avenue would each require less than half the special work used in the current design.

Another means of reducing the wire and special work is to review the regular route operation to determine if there are any route variations that operate infrequently and could be handled by rescheduling buses or by using the APU. For example, two short turn locations used at different times of day perhaps could be combined into a single location. Another example is a situation where a few late evening trips operate over both branches of a route that is otherwise scheduled with alternate trips on each branch. Here, the APU could be used for the turn connecting the branches.

Although the appearance of an intersection is influenced by several factors, including street width and the placement of special work within the intersection, the most important factor is the amount of special work in the design. Figure 3-2 presents plans for the following types of intersections:

1. Diverging route
2. Half wye
3. Crossing with one pair of turns
4. Full wye
5. Crossing with two pairs of turns (½ grand union)
6. Crossing with all possible turns (grand union)

Photographs of the first five types are shown in Figures 3-3 through 3-7. No complete grand union exists in the United States or Canada; it is included only as a theoretical worst case.

Table 1 lists special work elements used in each type of intersection and gives a visual impact rating for each type. The rating is based on switches and crossovers having a weight of one and curve segments having a weight of one-half.

Simple intersections, with visual impact ratings of less than six, are not included in this discussion. Simple intersections include such types as a right-turn switch with a rating of two, a left-turn switch with a rating of four, and a two-way crossing without turns with a rating of four.

Intersections similar to the first two types—visual impact ratings in the range of six through eight—appear to be suitable for use at any location. Intersections similar to the second two types—visual impact ratings in the range of 9 through 15—may be used in most locations but should be avoided in the most visually sensitive areas if feasible. Intersections with visual impact ratings of greater than 15 should be avoided unless there is no feasible alternative.

One approach to reducing special-work concentration is to use one-way operation for route location in dense areas and for garage access. The use of separate streets for garage entry and exit will result in two intersections, each with approximately half the visual impact of a single intersection used for both entrance and exit routes.

One-way operation on parallel streets is often feasible in downtown areas, even though the streets are used for two-way traffic. Even where a single "Main Street" is used by many transit routes, the intersecting streets are often appropriate for one-way operation.

For example, an intersection of two streets with one-way operation—with both turns as shown in Figure 3-8—has a visual impact rating of seven. Four such intersections replace the grand union of Figure 3-2, which has an impact rating of 40. Even where bus movement is concentrated on two intersecting streets, the use of a parallel street and dispersal of turn movements will reduce the impact of special work substantially. The layout shown in Figure 3-9 uses four intersections with impact ratings between five and seven to provide for all possible movements.

On streets with two-way operation, right turns produce less visual impact than left turns because crossovers are not needed and the special work is kept out of the center of the intersection. Thus, where feasible, a right turn should be used rather than a left turn to provide the same movement capability.

Street width will also affect the visual impact of intersections. Straight wire is usually designed with the negative (curb side) wire between 2.7 m (9 ft) and 4.2 m (14 ft) from the curb, depending on parking regulations and system preference. This distance establishes the location of intersection approaches. Thus, the spacing of special-work elements will vary depending on street width. Figure 3-10 shows a diverging route on a narrow street. The same configuration on a much wider street is shown in Figure 3-3.

Advance turn wire can have either a positive or a negative impact on the appearance of an intersection. When used on a narrow street, advance turn wire can produce a cluttered look as shown in Figure 3-11; however, advance wires do serve to move switches out of the intersection, which reduces the impact of concentrated special work. Generally, advance turn wire should be used for all left turns where there are two or more lanes of moving traffic in the direction of the turn approach. An exception may be made where the turn is not regularly used. Advance right-turn wires are appropriate only where there are two or more lanes of moving traffic and where high levels of pedestrian movement commonly delay right-turn movements.

Finally, although garage OCS design is not part of this report, it should be noted that garage OCS sometimes overflows into an adjacent street. The use of street access to individual garage tracks should be avoided, if at all possible, because the concentration of special work and poles will be much greater than in any other design situation.

LIGHT RAIL OPERATIONS AND SYSTEM DESIGN

The goal in light rail OCS design is similar to trolleybus OCS design, i.e., to reduce the system complexity and the size and quantity of OCS components; however, light rail OCS differs from trolleybus OCS in that there are generally fewer routes in a system. Thus, there are fewer junctions and crossings where complex OCS is required. Because there are more constraints in route location, opportunities to reduce complexity by changing movement paths are relatively uncommon; however, there are many more variables in system design that can influence the appearance of the light rail OCS.

Intersections in rail systems do not generally require the concentration of OCS components found in trolleybus OCSs. The use of single wire eliminates the need for insulation between polarities. Because the OCS does not function as a guideway, crossing and switch hardware are much less complex. Also, the OCS is limited in complexity by track design. Complex intersections are minimized in rail system design because of the high initial and maintenance costs of the special track work. A full-wye intersection (Figure 3-12) is the most complex design commonly used in North American light rail systems.

The choice of single-end or double-end cars will affect the overall design of the physical plant, including the appearance of the OCS. With double-end cars, loops are only needed where service frequency requires a high-capacity turn capability. The complexity of the OCS needed for a small radius loop is shown in Figure 3-13; however, this figure represents a worst case because of the inside pole placement required by the small site. Use of larger loops, such as a loop around a city block, will significantly reduce intrusiveness, as would more sensitive site design and choice of poles and hardware. Also, wye turnarounds can be fitted into a small area more easily than loops and are particularly appropriate for infrequently used turnback points.

Right-of-way width and location will influence OCS design. Adequate width for center poles can cut pole requirements and the attendant clutter in half. Figures 3-14 and 3-15 show the difference in appearance between center- and side-pole construction. An alternative to poles on both sides of double track is the use of two-track mast arms; however, it is difficult to design unobtrusive two-track arms.

Curves are a significant problem with regard to a complex OCS. In particular, sharp curves in catenary systems are very obtrusive and should be avoided. It is often desirable to transition from catenary to direct suspension at the approach to a sharp turn or complex intersection as shown in Figure 3-12. In recent designs, one tendency has been to use poles for every pulloff location. Using backbone wires for pulloffs can substantially reduce pole requirements; however, sufficient right-of-way width must be available to avoid shallow angle backbones because such shallow angles require extremely high tension in the backbone wire.

Electrical distribution system design can strongly influence OCS appearance in light rail systems. Several systems have adopted catenary for track in city streets to avoid the use of underground feeders. Substation spacing also affects OCS design. Where large, widely spaced substations are used, the distribution system—usually the contact wire and messenger in the catenary—has to be sized to handle the higher power load between substations. An example of the result of this design approach is shown in Figure 3-16. The usual justification for such construction is the high cost of underground feeders; however, much of this cost is for street excavation and restoration, which must be done to install track in any case.

Finally, light rail systems usually include stations that can act as focal points for overhead clutter and visual elements. In addition to the overhead wire, station and platform lighting as well as other furniture such as kiosks and shelters will be present. Figure 3-17 illustrates a reasonably well-designed station that is sensitive to the general reduction of visual clutter and integration of station elements into a unified design; however, a clear oversight is the lack of integration of the platform lighting into the station elements to reduce the number of poles. Working the lighting into the station design would have been a significant improvement.

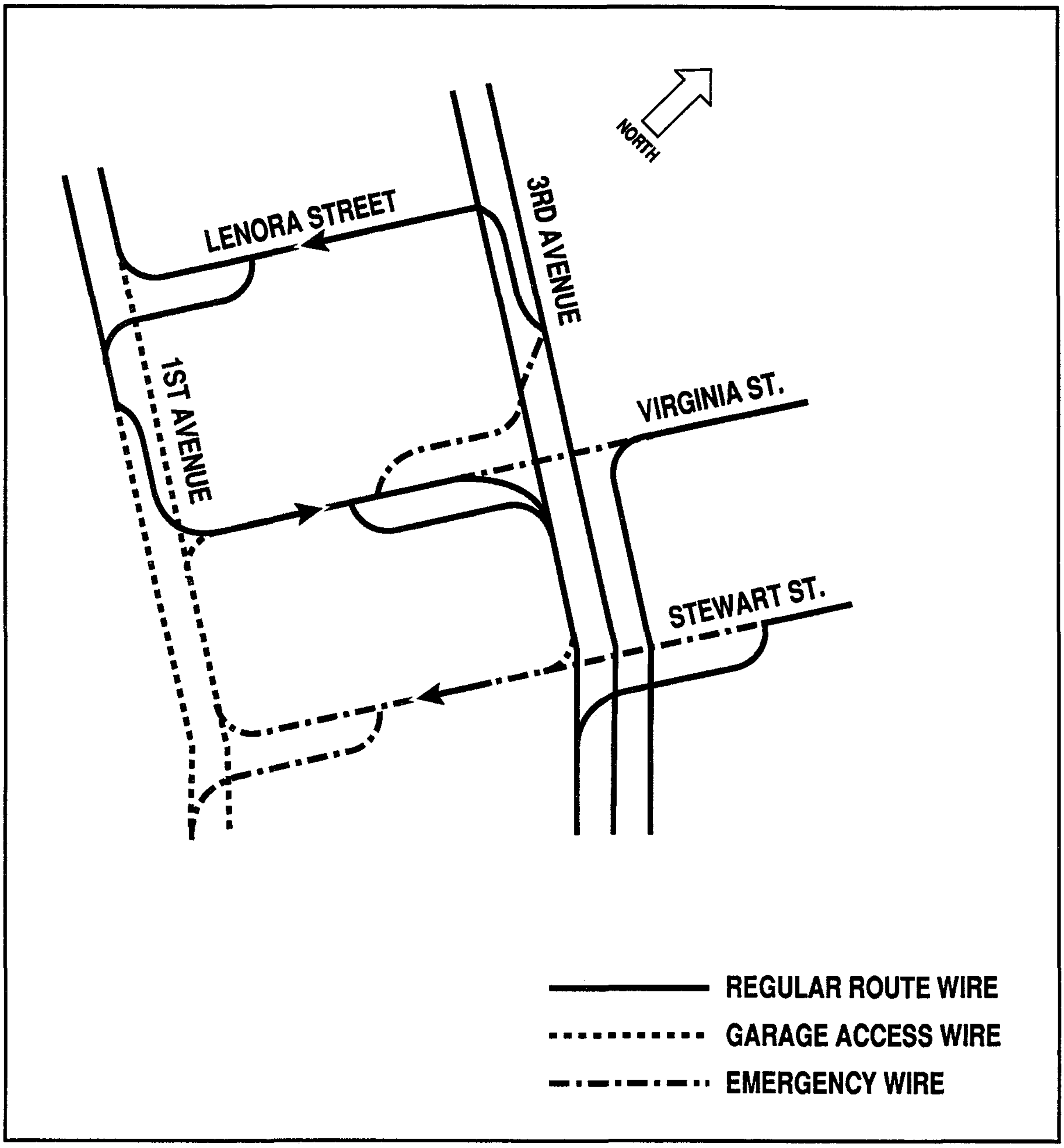

Figure 3-1. Regular route, garage access, and emergency wire—north end of Seattle CBD.

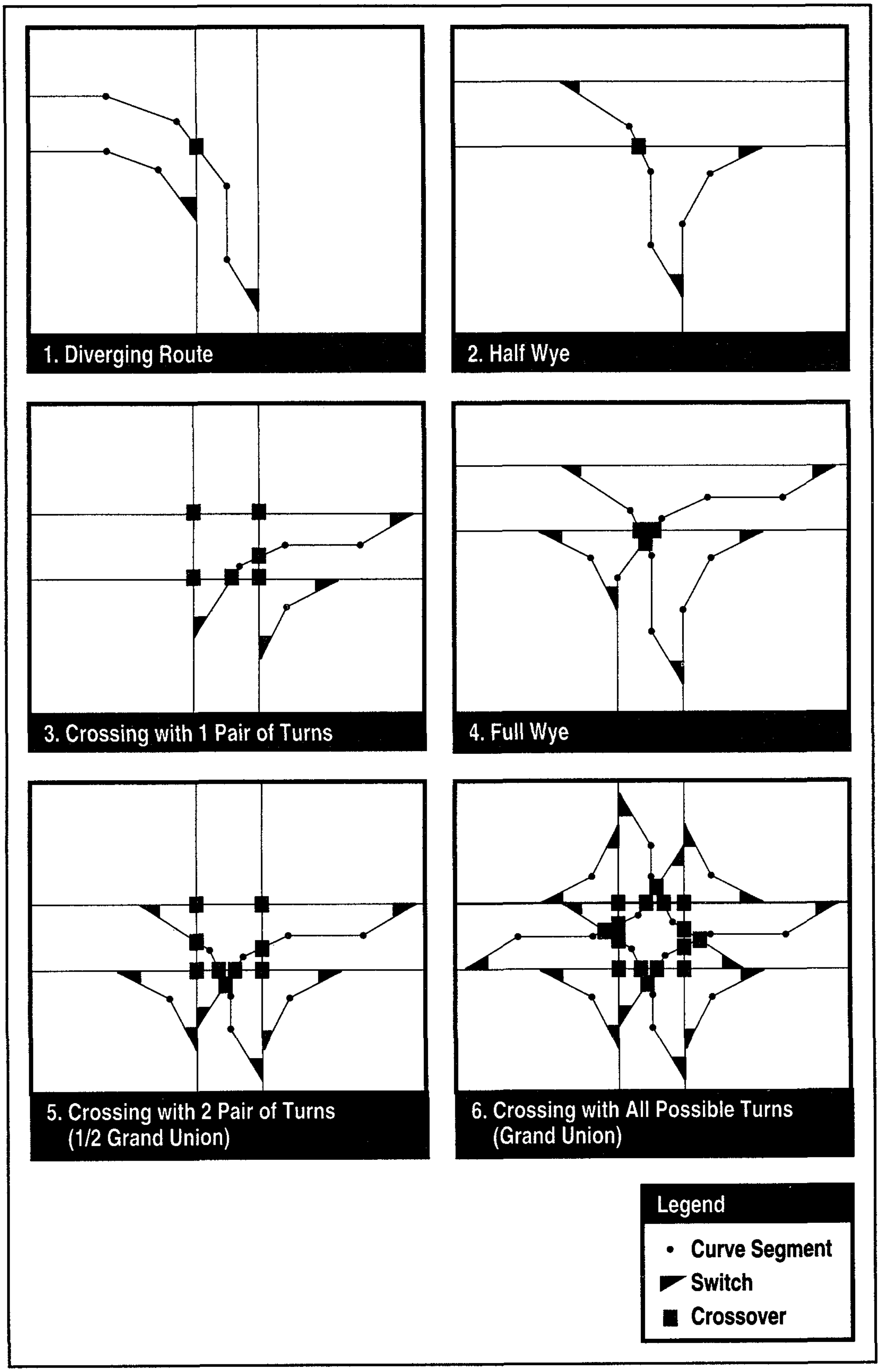

Figure 3-2. Intersections types.

Figure 3-3. Diverging route at Third Ave. and Cedar St.—Seattle (Type 1—visual impact rating: 6). Note directional control contractors ahead of facing switch.

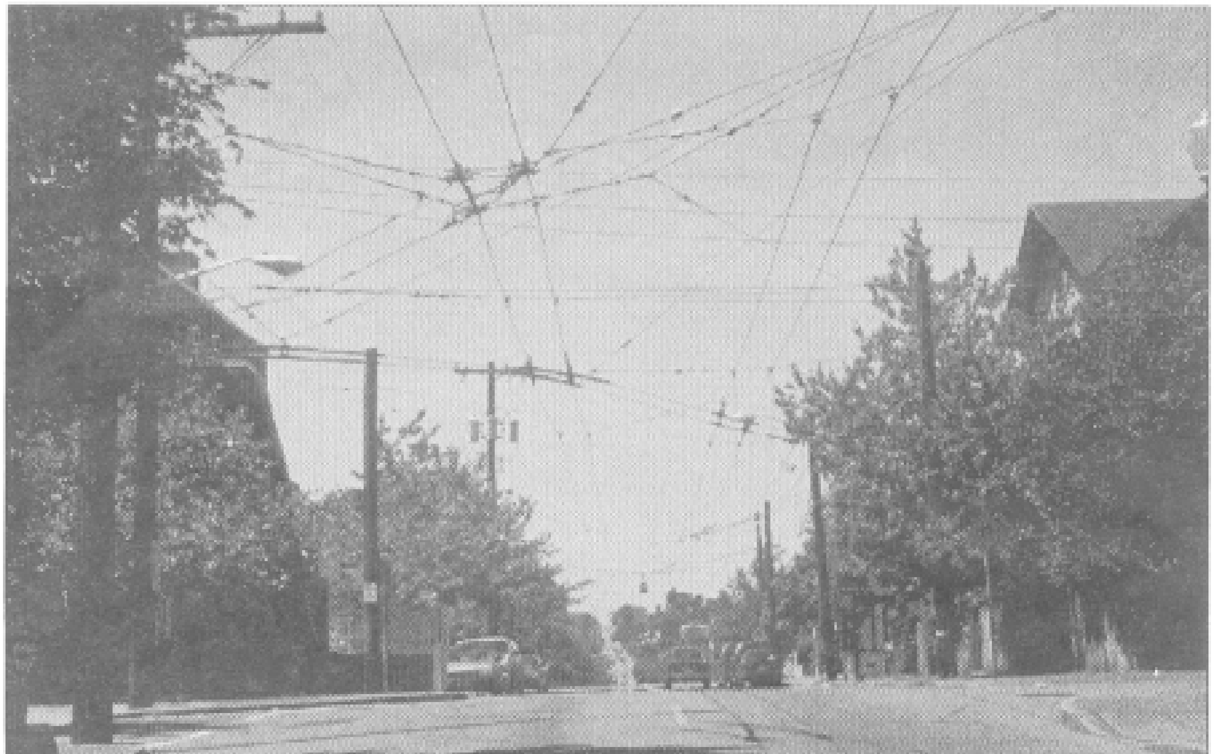

Figure 3-4. Half wye at 33rd Ave. and E. Union St.—Seattle (Type 2—visual impact rating: 6.5).

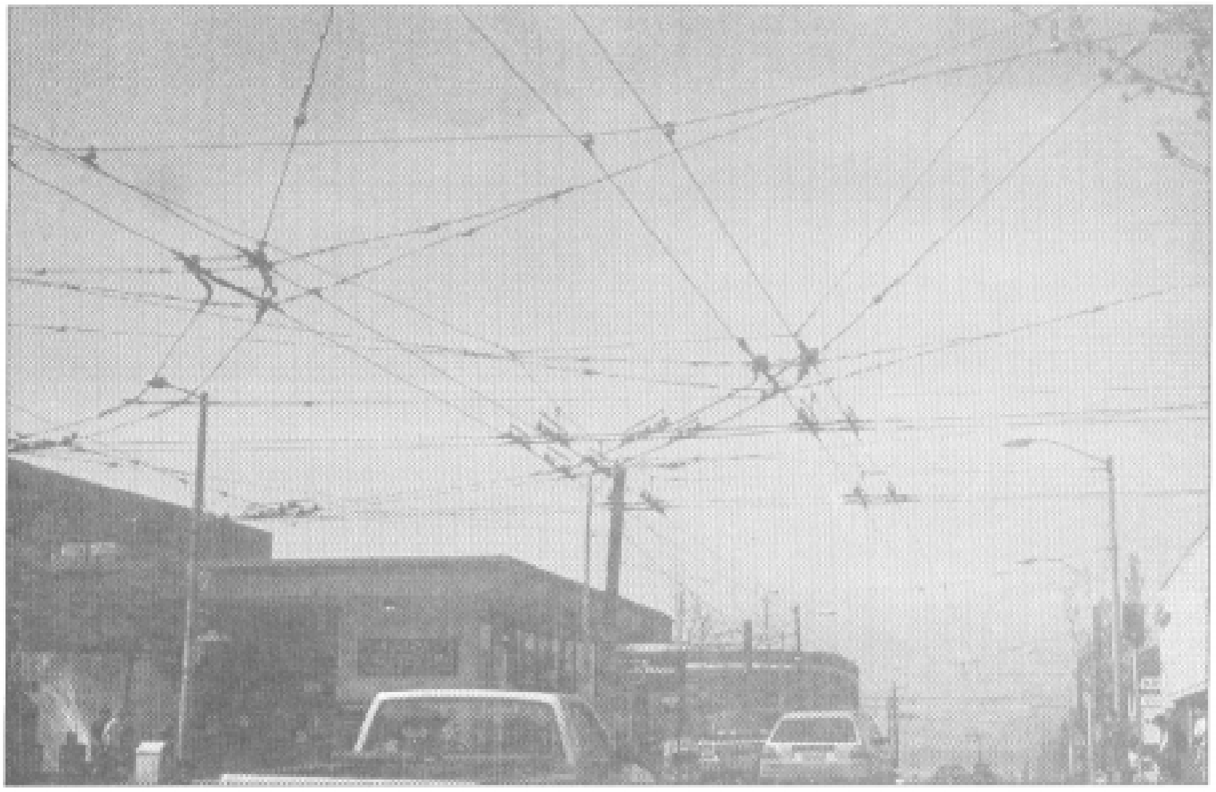

Figure 3-5. Crossing with one pair of turns at Broadway and John St.—Seattle (Type 3—visual impact rating: 12).

Figure 3-6. Full wye at Queen Anne Ave. and Boston St.—Seattle (Type 4—visual impact rating: 14). Note inductive antenna and the control cable and box on the pole at the right.

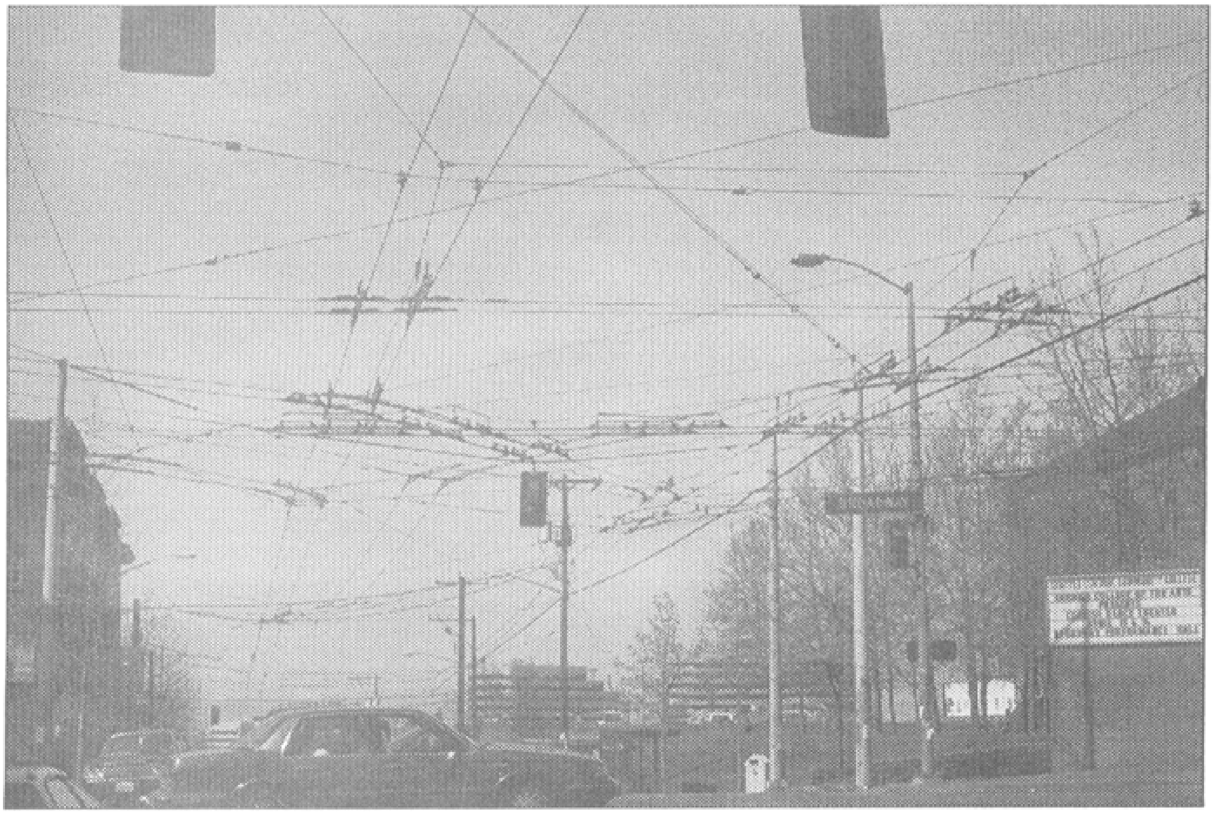

Figure 3-7. Crossing with two pairs of turns (½ grand union) at Broadway and Pine St.—Seattle (Type 5—visual impact rating: 21).

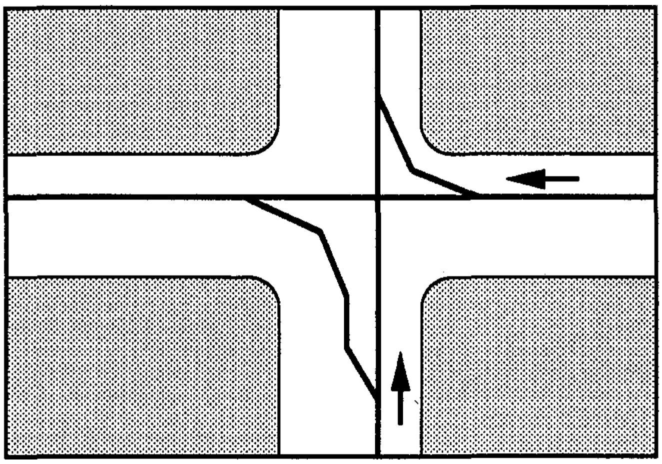

Figure 3-8. Intersection of two streets with one-way operation and both turns.

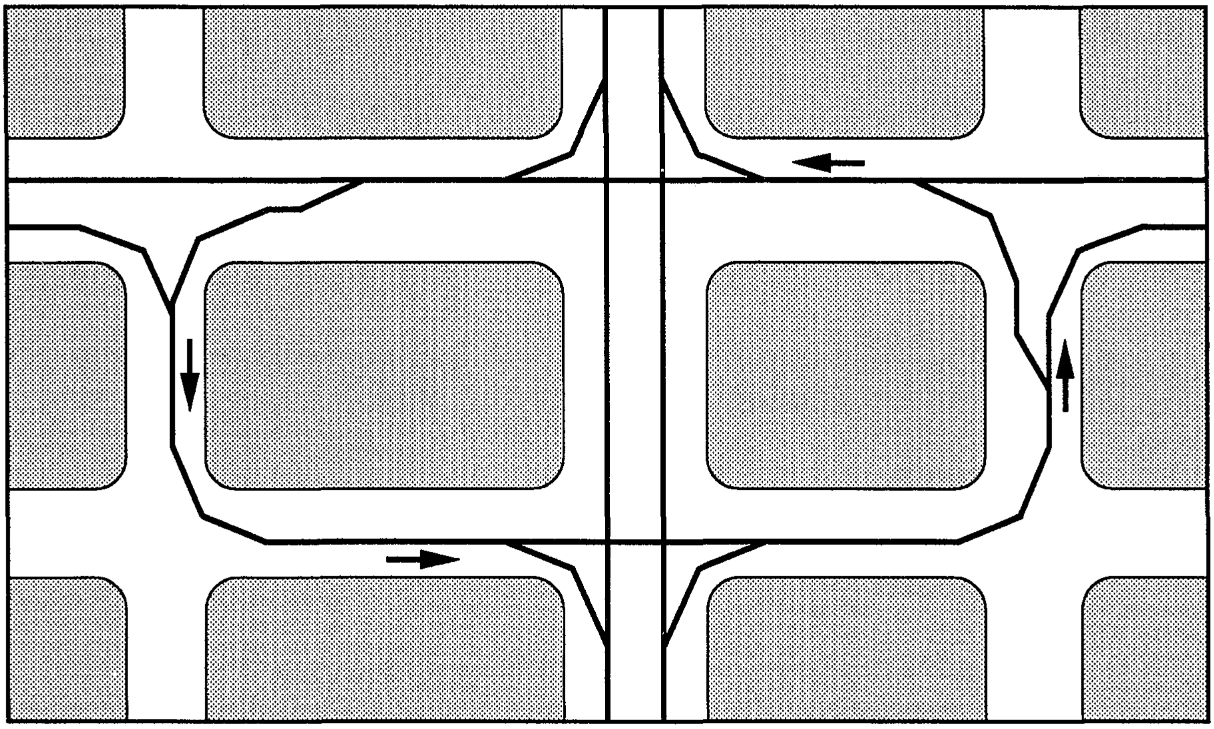

Figure 3-9. Use of one-way operation on parallel streets to provide all possible turns without complex intersections.

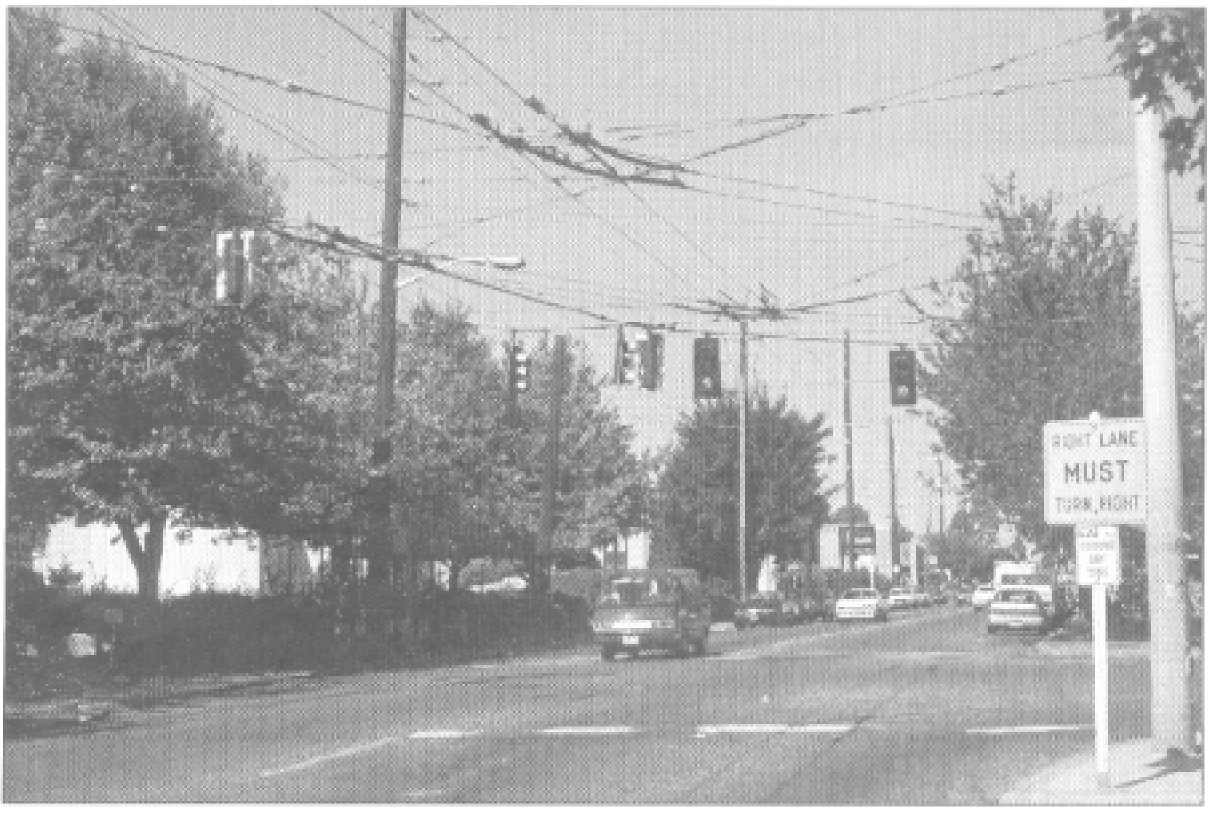

Figure 3-10. Diverging route on narrow street at 15th Ave. E and E. Thomas St.—Seattle. Compare this figure with Figure 3-3 to observe the effect of street width on appearance.

Figure 3-11. Advance turn wire on narrow street at Divisadero and Jackson Sts.—San Francisco. Note that the advance turn wire can only be used by moving into the opposite direction through lane.

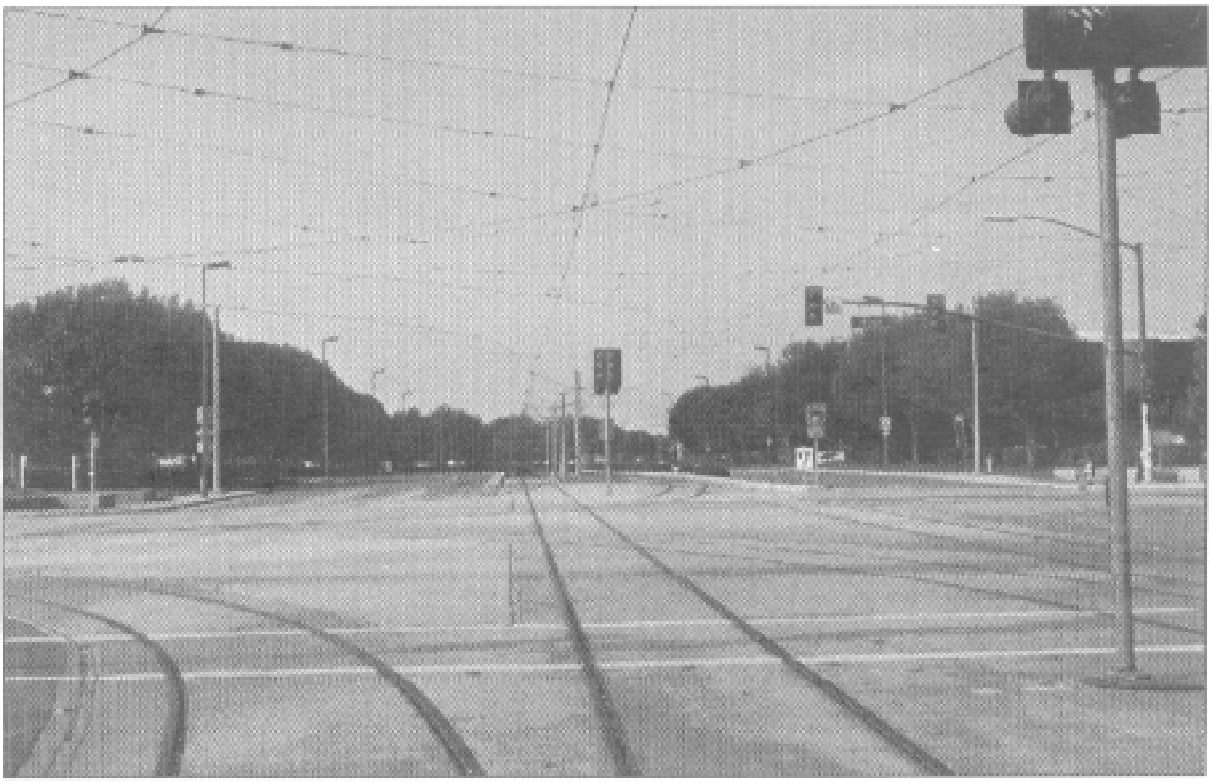

Figure 3-12. Full wye on LRT route—San Jose. Note the minimal appearance of the OCS as compared to a trolleybus intersection, and the use of only small hardware components in the design.

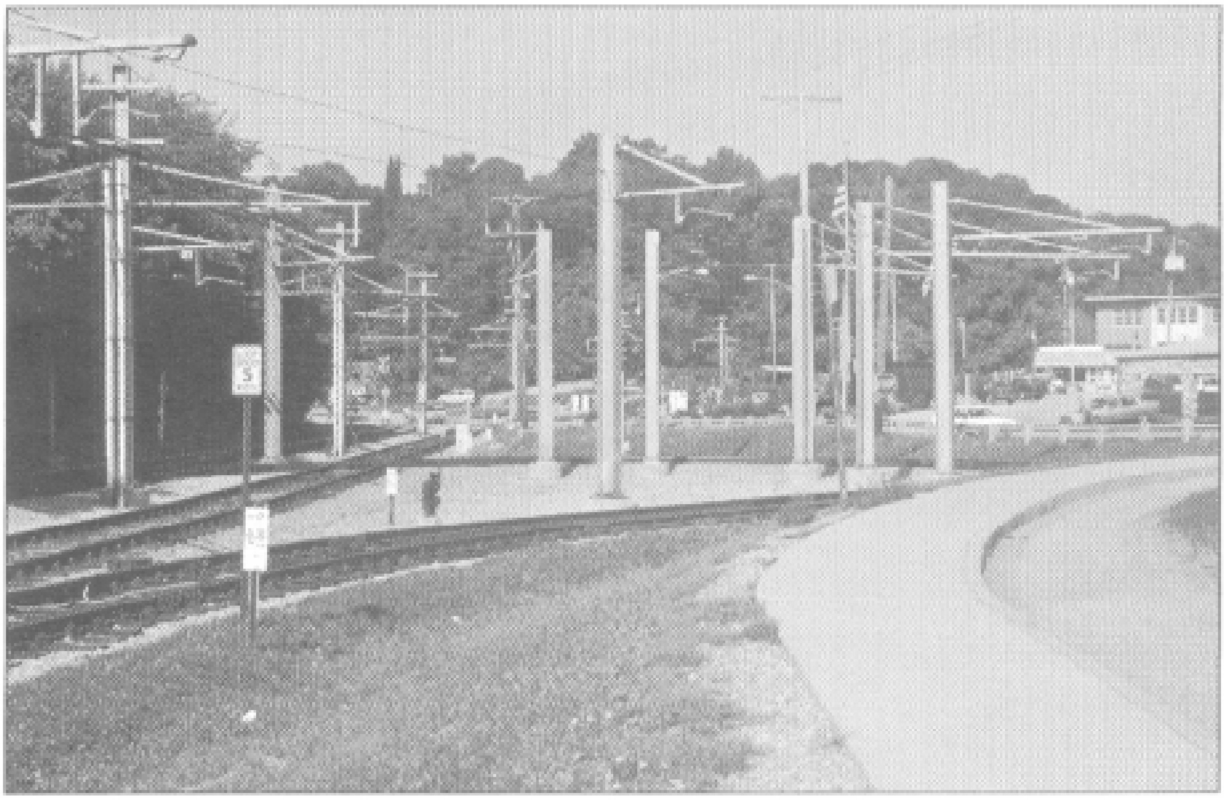

Figure 3-13. Loop—Pittsburgh. Note that the small space forced the use of inside poles. This increased the concentration of poles to an even greater level than would otherwise be needed.

Figure 3-14. Center pole construction—Sacramento. This is an example of the use of a design intended for right of way in a street environment.

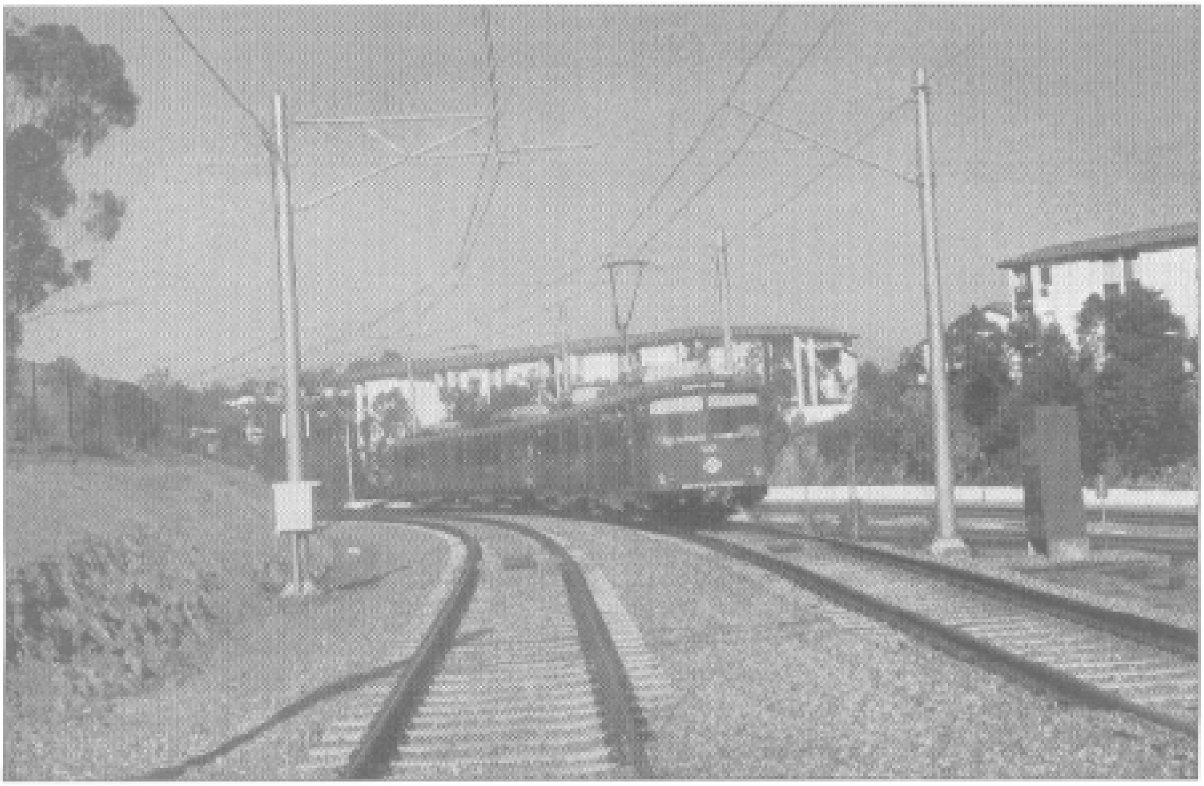

Figure 3-15. Side pole construction with mast arms—San Diego. Note the "finger pointing" effect of the mast arms is minimized by the diagonal arm.

Figure 3-16. Catenary—Pittsburgh. Note that the need for electrical capacity has forced the use of a very heavy (1 million MCM) messenger and parallel feeders. Also note the external conduits on the pole in the foreground.

Figure 3-17. Light rail station—Sacramento. A clean, simple station design could be substantially improved by consolidating station lighting and OCS poles.

TABLE 1 Number of special-work components for each intersection type

TYPE	SWITCHES	CROSSOVERS	CURVE SEGMENTS	VISUAL IMPACT RATING
1	2	1	6	6
2	3	1	5	6.5
3	4	6	4	12
4	6	3	10	14
5	8	9	8	21
6	16	16	16	40

CHAPTER **4**

OCS DESIGN

The basic requirements for any OCS are (1) that it meet the positioning requirements described in Chapter 1 and (2) that it be stable in the horizontal plane while providing a certain amount of vertical resilience. An OCS that does not meet these requirements will produce frequent loss of contact between the current collector and the wire, resulting in dewirements on trolley-pole systems and damage to current collectors, OCS, and propulsion equipment of pantograph systems. The vertical resilience of the OCS must be matched to the current-collection system. Problems can occur if the OCS is either too stiff or too soft.

Trolleybus systems are usually designed using either direct suspension or pendulum suspension. In North America, direct suspension is more common. Only San Francisco, Edmonton, and Vancouver use pendulum suspension and only Edmonton has used it extensively. Pendulum suspension has performance advantages and is better able to handle temperature extremes, while direct suspension is less costly and more durable. Pendulum suspension has somewhat more visual impact because of the additional hardware, although there is not a large difference. Illustrations of both systems are shown in Figures 4-1 and 4-2.

One possible visual problem with pendulum suspension is it requires span wires to cross the contact wire at nearly a right angle. In areas where there are numerous obstacles, such as driveways, to pole placement, Y-shaped spans would be needed for pendulum suspension where an angled span could be used for direct suspension. For the most part, Edmonton uses bracket arm support with pendulum suspension to avoid this problem.

Light rail systems may use either direct suspension or catenary. In catenary systems, the contact wire is suspended from a messenger wire. The primary advantage of catenary is that it provides a more level contact wire, which improves contact at high speeds. Catenary has most often been used with pantograph current collectors because these have higher mass than trolley poles and do not vary as readily in wire height. Pantograph operation on direct suspension wire is limited to about 55 kph (35 mph). As mentioned previously, catenary also provides additional electrical capacity.

The visual impact of catenary is substantially higher than that of direct suspension as a result of (1) the mass of the messenger wire, (2) the frequent contact wire hangers, and (3) the need to provide a primary support at the messenger wire and a steady arm at the contact wire for horizontal rigidity. However, using catenary permits greater distance between support points, which reduces the number of poles needed. Pole spacing with direct suspension is limited to approximately 30 m to 37 m (100 ft to 120 ft) for both rail and trolleybus systems. Use of direct suspension with contact wire larger than 4/0 AWG requires either a constant-tension system or closer support spacing. Pole spacing with simple catenary can be on the order of 60 m (200 ft). Longer pole spacing may be used with compound catenary, commonly used only in railroad applications. The visual impact of catenary is even greater when it is used in a visually confined area such as a downtown street. Figures 4-3, 4-4, and 4-5 show direct-suspension light rail OCS and catenary in confined and open settings.

In recent years, constant-tension catenary has largely replaced fixed-tension catenary in new installations. Constant-tension catenary uses counterweights to produce a constant wire tension, which eliminates the variation in wire profile as a result of temperature changes. The visual impact of constant-tension systems is generally less than fixed-tension systems because components need not be sized to handle extremely high tensions during cold weather conditions; however, the counterweight assemblies and associated hardware, as well as the overlap sections required for constant tension systems, periodically produce a greater visual impact at relatively infrequent locations, as shown in Figure 4-6. Constant-tension sections are typically approximately 1 mile in length.

Constant tension can also be used with direct-suspension contact wire. Although common in Europe, this system has been used in Portland and to a limited extent in Boston. An example is shown in Figure 4-7. The same advantages and disadvantages listed for constant-tension catenary also apply to constant-tension direct suspension. In addition, the spacing of support points can be somewhat longer than for fixed-tension direct suspension.

Constant-tension systems require that sections of the contact wire be able to move longitudinally in relation to each other. This has resulted in constant tension being used mostly for rail systems that have pantograph current collectors. A means of guiding a pole between sections is required for constant-tension wire to be used with trolley poles. Although a European manufacturer has developed such a device, it has had very limited application.

Using spring or gas-filled tension control devices can be a less complex means of controlling tension than using counterweights. Some systems that use weight tensioning on mainline runs use such tensioners for crossovers, terminal sidings, and other short sections of wire. Boston has used this type of tension control for several sections of direct-suspension mainline OCS.

All OCS designs require adequate electrical capacity to operate the desired level of service. The following variables can influence the design:

- Substation spacing,
- The use of parallel feeder cables,

- The electrical capacity of the contact wire, and
- Electrical demand for the system.

As mentioned previously, the messenger wire in catenary systems serves as a feeder cable. Although older systems have many miles of overhead feeder, underground feeder cable is almost universal in new construction. Except in the downtown area, Seattle uses a feederless system where small substations are directly connected to the contact wire. Such a system is not feasible for rail or trolleybus systems with frequent headways because the number of substations required would be excessive. For most rail systems, the power demand of a single train is greater than the electrical capacity of the contact wire.

Electrical capacity affects the visual impact of OCS when—to avoid more frequent substations or underground feeders—the OCS is designed to be heavier than otherwise necessary. This occurs almost exclusively on rail systems. The use of catenary in low-speed street sections can be described as a poorly disguised form of overhead feeder in areas where feeder cables hung on poles would be visually unacceptable, as shown in Figure 4-4.

One feature of OCS for systems that use pantographs is that the wire cannot be centered precisely over the track. The wire must make contact with the pantograph shoe over a large part of its width to avoid wearing a groove in the shoe, which would shorten its life and damage the wire hangers. On curves, the staggered wire position is provided by reducing the number of pulloff points. For tangent wire, the attachment points must be staggered in relation to the track centerline to meet this requirement. It has been common practice to stagger the wire at about every other attachment point. This results in "wiggly" wire which is particularly noticeable from directly under the wire.

The wiggly wire effect could readily be reduced without affecting the function of the stagger by increasing the stagger distance to every fourth or sixth attachment point. This design is recommended for locations such as street track in downtown areas where the wire is readily visible from a position on or near the track.

Figure 4-1. Direct-suspension trolleybus span—San Francisco. Note the porcelain insulators including the mid-span insulators, a California requirement rarely used elsewhere.

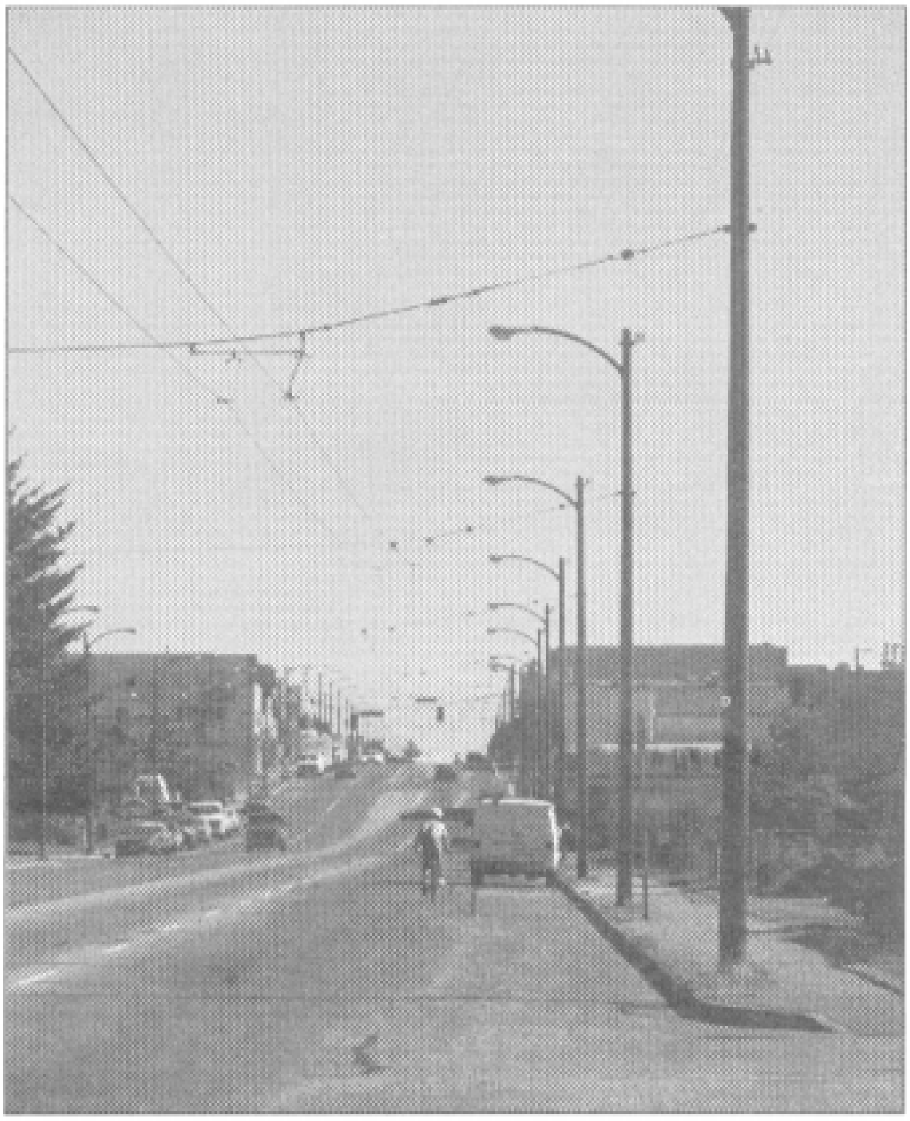

Figure 4-2. Pendulum-suspension trolleybus span—Vancouver. Note that the nearest span is a feed span that uses a combination of hardware.

Figure 4-3. Direct-suspension LRT span—Pittsburgh. This unmodernized section shows the simplicity of nearly century-old street railway OCS technology.

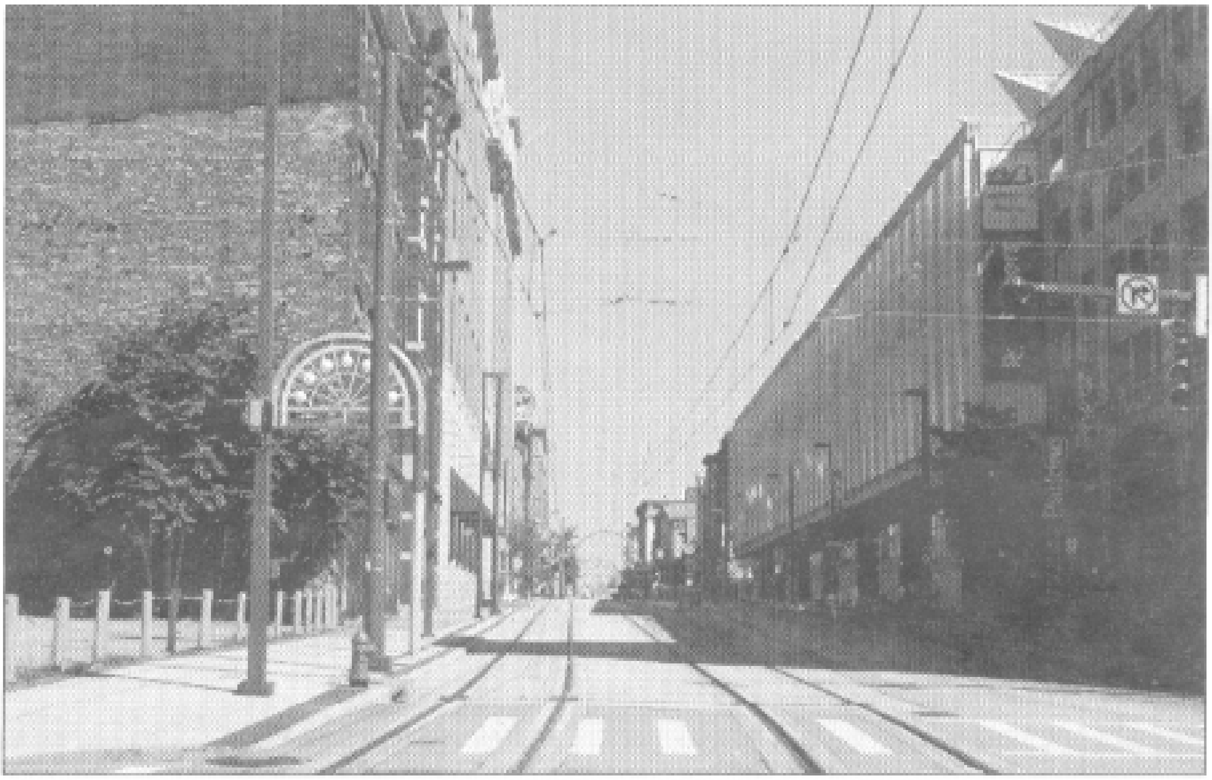

Figure 4-4. Catenary in street—Baltimore. Although a fairly neat catenary design, this amount of wire is out of scale for a narrow street in a downtown area.

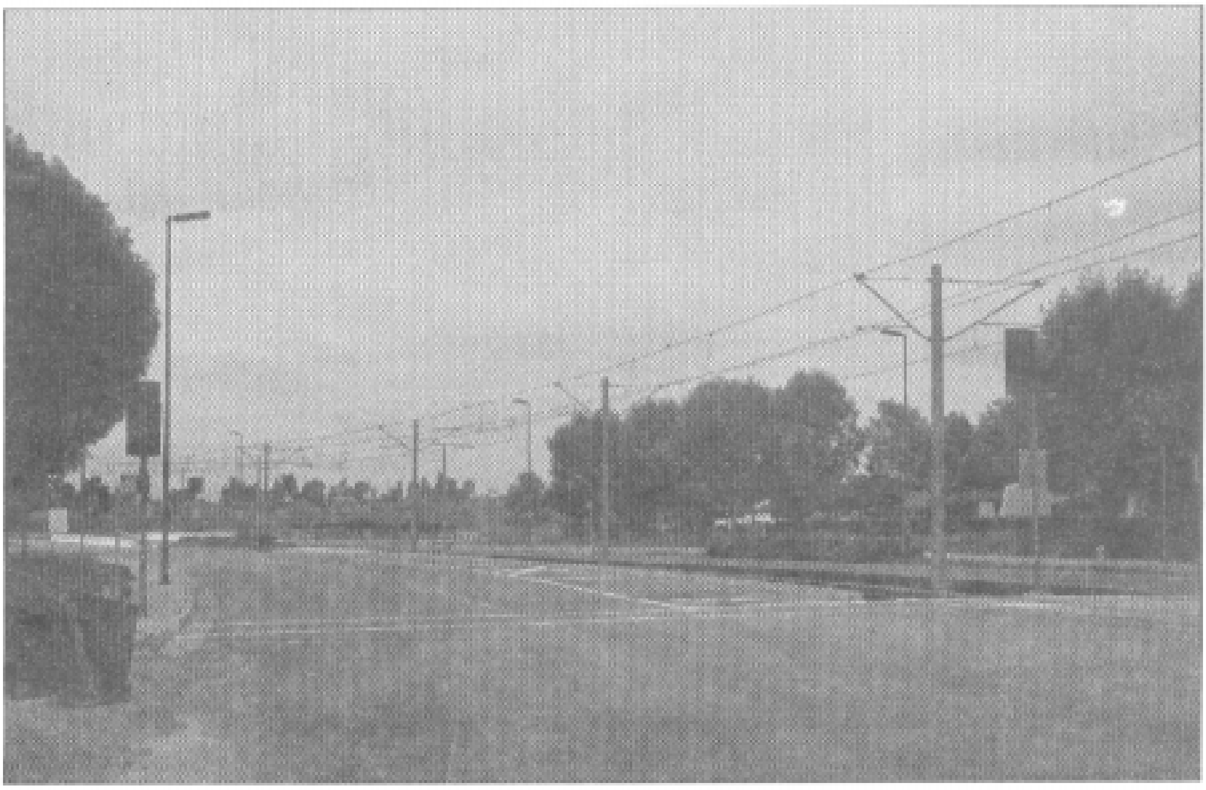

Figure 4-5. Catenary in median—San Jose. This construction is typical of modern LRT systems in both North America and Europe.

Figure 4-6. Constant-tension overlap section on Beacon St.—Boston. This route uses unusually short overlap sections, which require extra poles but minimize the effect of the double catenary.

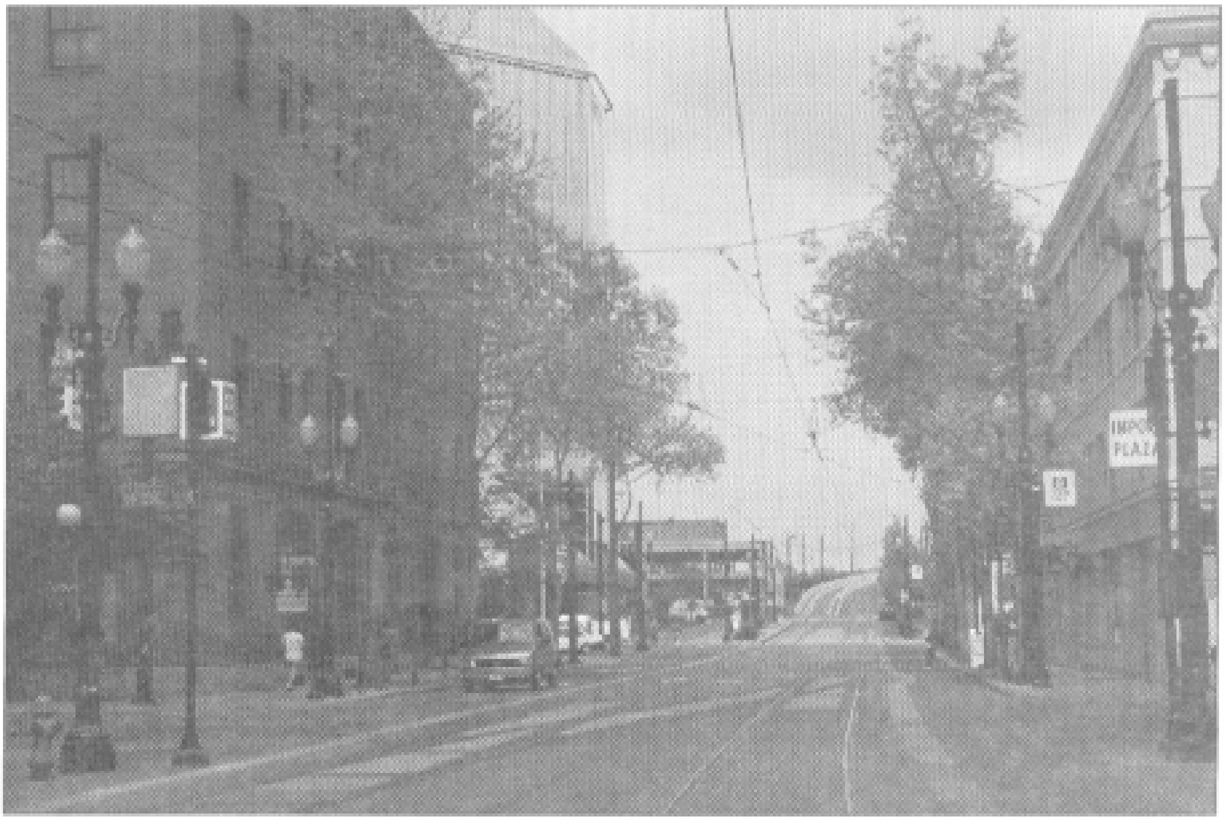

Figure 4-7. Constant-tension direct-suspension OCS—Portland. Note the delta support for the contact wire and the single wire for the crossover in the background.

CHAPTER 5

CURVE DESIGN

TROLLEYBUS CURVE DESIGN

Curves in trolleybus systems should be designed to follow the bus path, as described in Chapter 3. Curves should also be designed so that the wire geometry is appropriate to the normal bus operating speed at the location. For example, a 90° right turn at an intersection is a low-speed maneuver for any type of bus, so that a few abrupt changes in wire angle are acceptable. A gentle bend in a street where traffic does not have to slow for the curve would require more, less abrupt changes in wire angle. Figure 5-1 shows the difference between a 90° turn with three 30° elements and a 90° turn with six 15° elements.

Initially, trolleybus curve construction used a modified street railway design with numerous wire support clamps and a small angular deflection at each clamp. The only difference was that a rigid member connected the positive and negative wires at each clamp to maintain precise spacing and minimize wire tilt. The clamp was a standard tangent wire clamp. This type of construction is still used, and some systems prefer it for high-speed sections. An example of this type of construction is shown in Figure 5-2. Visually, the "ladder" effect of the closely spaced curve hangers is quite obvious.

Recent trolleybus construction uses some form of elongated clamp or runner to provide a smooth curve over a distance between 2 and 10 ft, depending on the amount of angular deflection for each pulloff point. The most commonly used types of curve hardware in North America are the curve segment and the flexible curve clamp. Other types of curve hardware, such as rigid curve clamps and suspended curve runners, are occasionally used, although these are either obsolete or special purpose designs.

Both the curve segment and the flexible clamp can cover most angles that would be found in a typical trolleybus design. The curve segment can be used at very high angles normally needed only for garage OCS. The main difference is that the curve segment uses a separate runner to form the curve with the wire passing behind and above it. The flexible clamp is attached to the contact wire and forms it into a smooth curve. Each type has advantages and disadvantages. The curve segment is easier to install, particularly at high angles, while the flexible clamp provides smoother high-speed running. The curve segment, no matter how carefully installed, has a bump at the transition point between wire and runner that causes wear, particularly at high speeds.

The visual impact of each type is similar. The multiple attachments of the higher angle flexible clamps produce about as much additional clutter as the anti-trap guards of the curve segments. Figures 5-3 and 5-4 show curves with each type of hardware.

The advantage of the flexible curve clamp is that it can simplify construction of high-speed, low-angle curves that otherwise would require conventional curve design. In effect, one flexible clamp can replace two to five curve hanger assemblies. The effect of this change is shown in Figure 5-5, which shows the difference between conventional-curve and flexible-clamp construction on a 20° curve using 6° to 7° curve rails.

To minimize the visual impact of curves or turns, the number of curve segments or rails must be kept to the minimum necessary for satisfactory operation. Typically, for right turns or left turns across narrow streets, three 30° curves are sufficient. Where a left turn is made across a fairly wide street, four 20° to 25° curves or three 25° curves and a 15° trailing switch will improve performance.

Curves must be supported at each point of angular deflection. The angle of support should generally be within 5° of the bisector of the curve angle. The angular load is taken by the support on the outside of the curve. The inside support is primarily needed to keep the curve element level to avoid damaging the trolley shoes and contact wire clamps. The angle of the inside support is less critical and can deviate more from the theoretically correct bisector. It is not necessary to support the inside of every curve element where these are closely spaced, although some systems do so for ease of installation and maintenance.

Trolleybus curves are usually supported by span wire. Span wire support allows considerable flexibility in pole location because the proper support angle can always be obtained by anchoring to two poles. The number of curve elements that can be supported from a single pole is limited only by pole strength. The use of separate supports for each curve element—as opposed to combined support with backbone construction—is a tradeoff between appearance and ease of maintenance. Separate support will substantially increase the number of support wires required. A compromise design is shown in Figure 5-1 where two short backbones are used to support each half of the curve.

Opinions differ as to whether or not to support the inside and outside wires of a two-way curve independently or to use a common support where the inside support of the outer wire forms the outside support of the inner wire. Many systems will use common support for low-angle curves and independent support for sharp curves. Common support is generally installed with full inside support of the inner wire. The low-angle curves in Figure 5-5 are shown with common support.

Using mast arms to support curves is feasible with some limitations. Poles must be precisely located so that the arm will be within the allowable range of support angles. This often requires a separate pole for each mast arm.

A mast arm on the outside of a curve is in tension and a standard arm can be used in most cases. A mast arm on the inside of a curve is in compression and must be designed for the compression load. Edmonton is the only system that makes extensive use of mast arms on the inside of curves. Its only problem with mast arms in compression has been a few pole foundation failures where older pole installations were not designed to be loaded in a direction away from the wire. Various design solutions have been used for compression mast arms, including large-diameter pipe, thick-wall pipe, and I-beam sections. Also, curves supported on compression mast arms will usually require numerous closely spaced poles to obtain the correct support locations.

LIGHT RAIL CURVE DESIGN

Although rail curve design is similar to trolleybus curve design, one important difference is that the wire is not a guideway in the horizontal plane, thus angular deflection does not affect performance. The only limit on the amount of angular deflection at an attachment point is the strength of the contact wire clamp. No special curve hardware is required. The design of light rail curves for trolley-pole operation resembles the trolleybus conventional curve shown in Figure 5-2.

In all OCS design, the use of abrupt vertical curves should be avoided because the current collection device (trolley pole or pantograph) can lose contact at such locations, trolley poles may dewire, and the momentary break in contact may damage electrical components.

The position of the wire is governed by the track location and the width of the pantograph shoe. The primary issue in light rail curve design is the support of the wire. Direct-suspension wire support requires only a contact wire clamp and support wires or mast arms as shown in Figure 5-6. Catenary requires both support for the messenger wire and a steady arm for the contact wire as shown in Figure 5-7. Delta suspension for constant-tension direct-suspension wire will also require steady arms on curves, as shown in Figure 5-8.

Center-pole construction on curves generally requires a pole for every point of angular deflection because there is no place to pull off the outside wire between poles. The problem in such designs is transferring the outward tension, which is needed to keep the outer wire in place, to the pole on the inside of the curve. One exceptionally massive approach is shown in Figure 5-9. A much less obtrusive and fortunately much more common approach is shown in Figure 5-10.

Side-pole and span-wire construction is very similar for tangent and curve construction; however, some catenary designers have used a pole at every angular deflection point, even though outside poles are available for intermediate pulloffs. The difference between a curve with and without intermediate pulloffs is shown in Figure 5-11.

Inclined catenary, in which the messenger serves as the curve pulloff, can be used to reduce the number of poles and steady arms in catenary curve construction; however, its use requires a substantially wider right of way on the outside of the curve than vertical catenary requires. For this reason, inclined catenary is most commonly found in railroad applications.

In summary, engineering solutions have different impacts on visual quality. The designer must determine which is most appropriate for the setting and application.

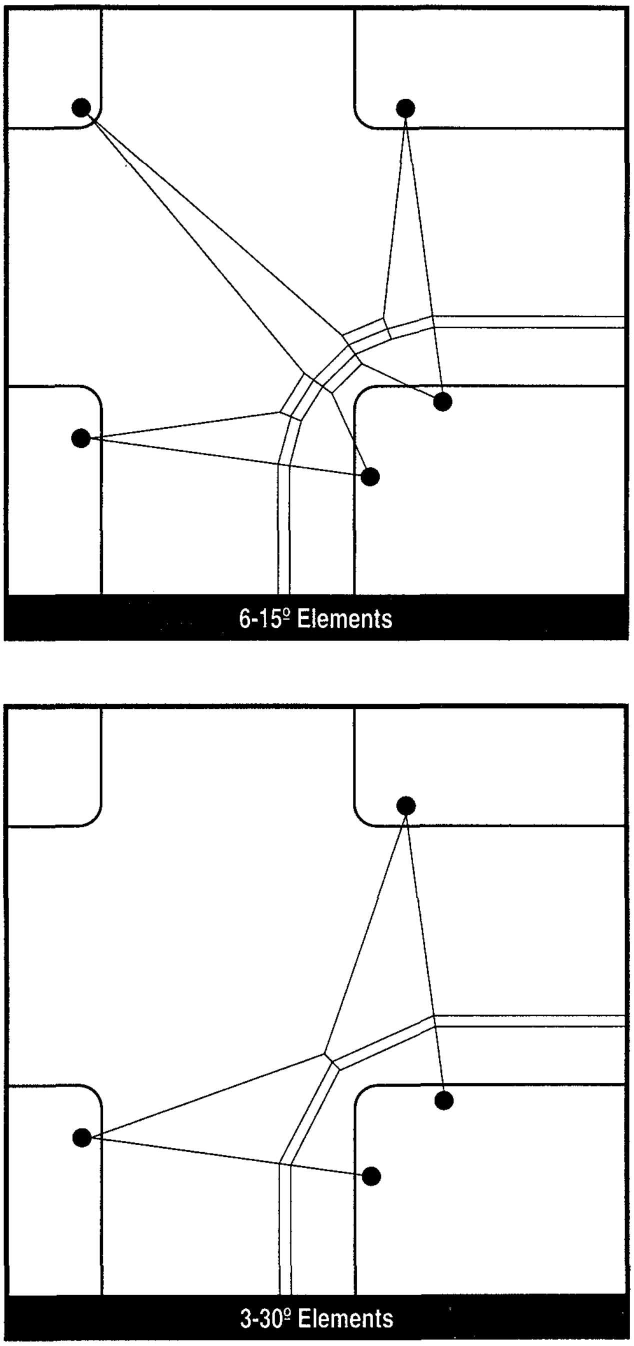

Figure 5-1. Comparison of 90° curve with 3 30° elements or 6 15° elements.

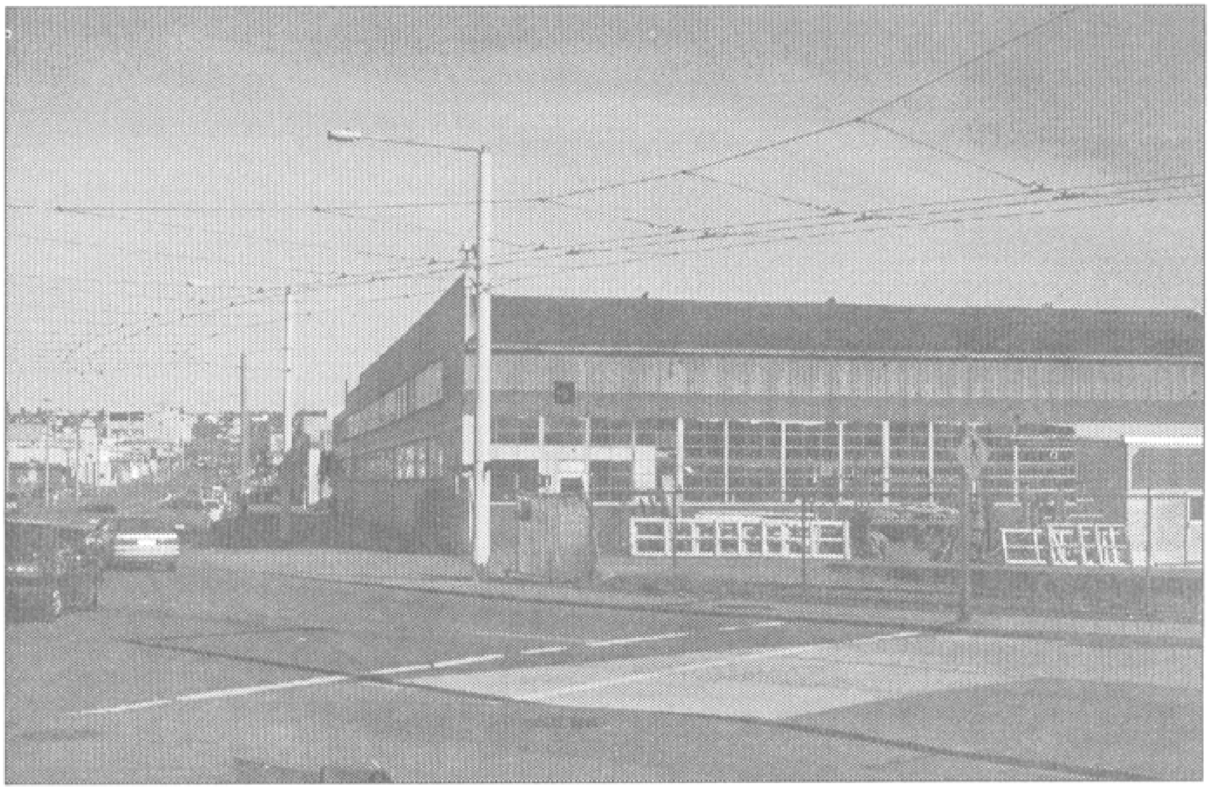

Figure 5-2. Conventional curve construction—Seattle. Note the ladder effect of the frequent pulloffs required for this type of curve.

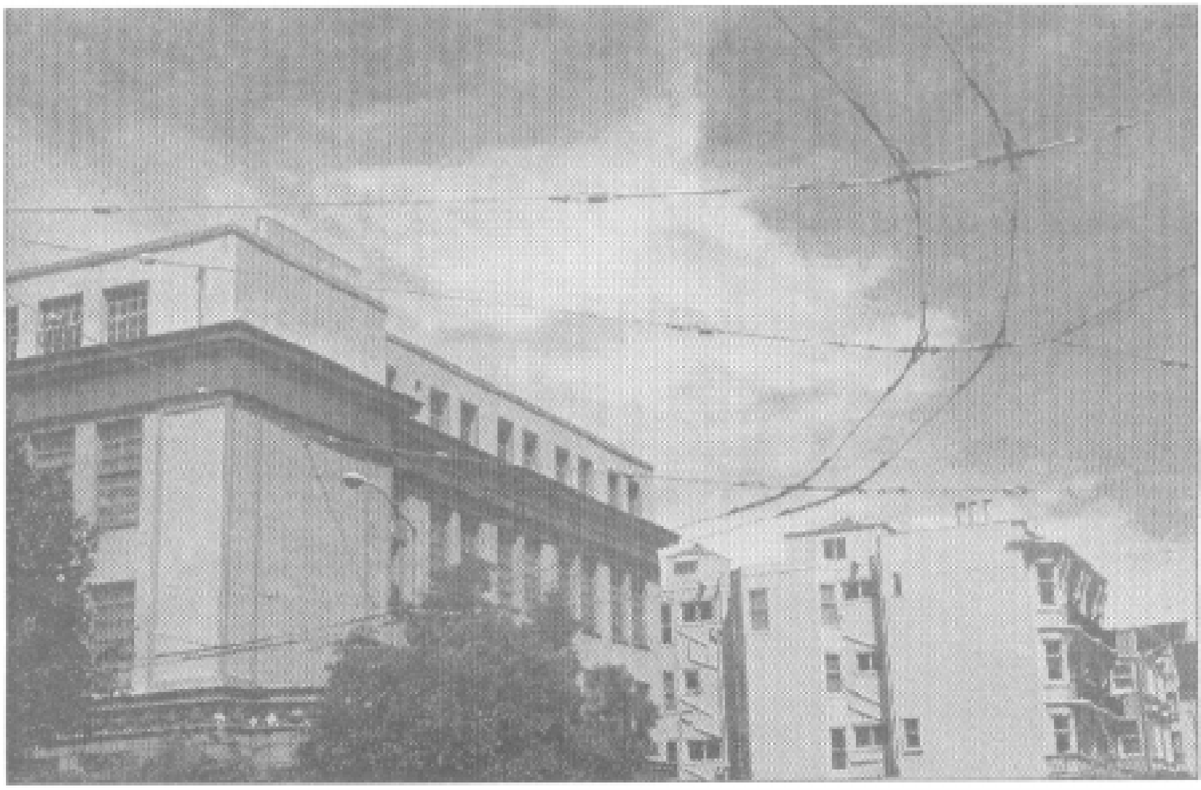

Figure 5-3. Curve segment construction—San Francisco. Note that the inside of each segment is supported, as is standard practice in San Francisco.

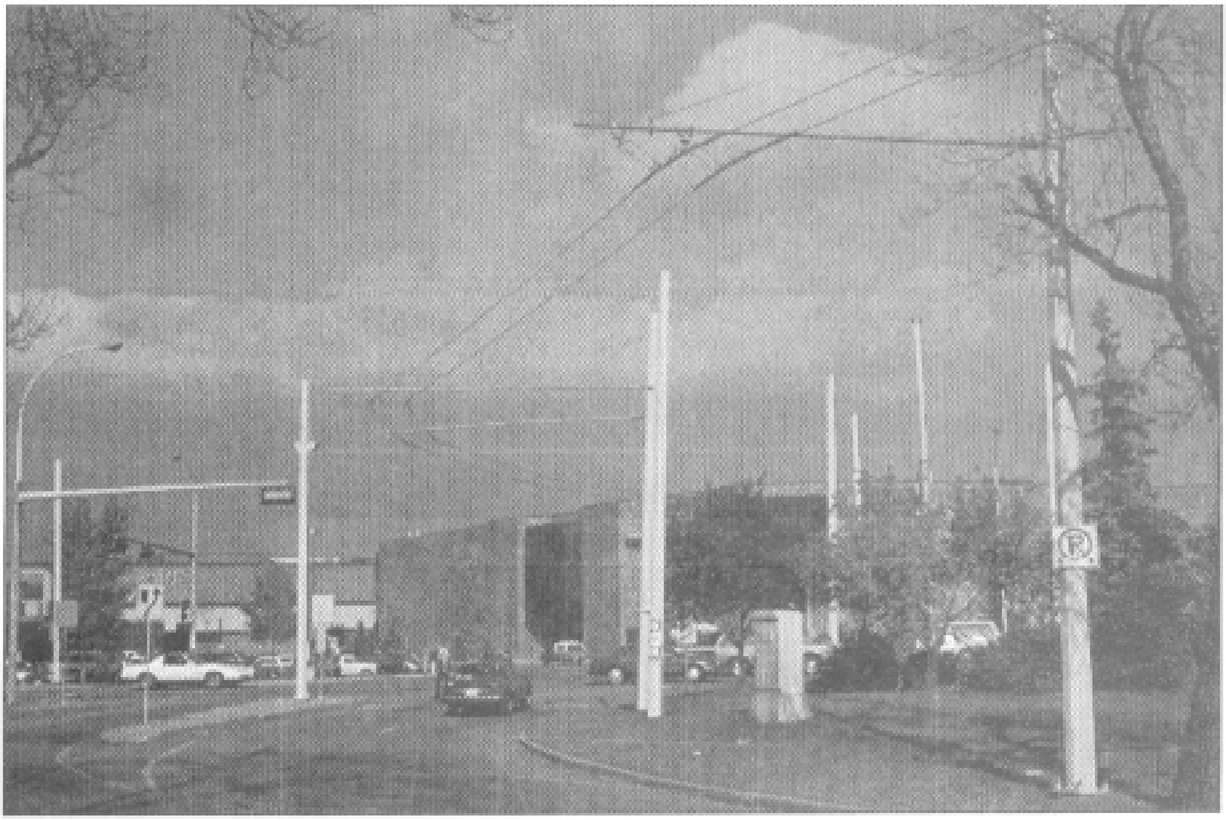

Figure 5-4. Curve clamp construction—Edmonton. Note that the clamps are supported by mast arms in compression, a design approach rarely used elsewhere.

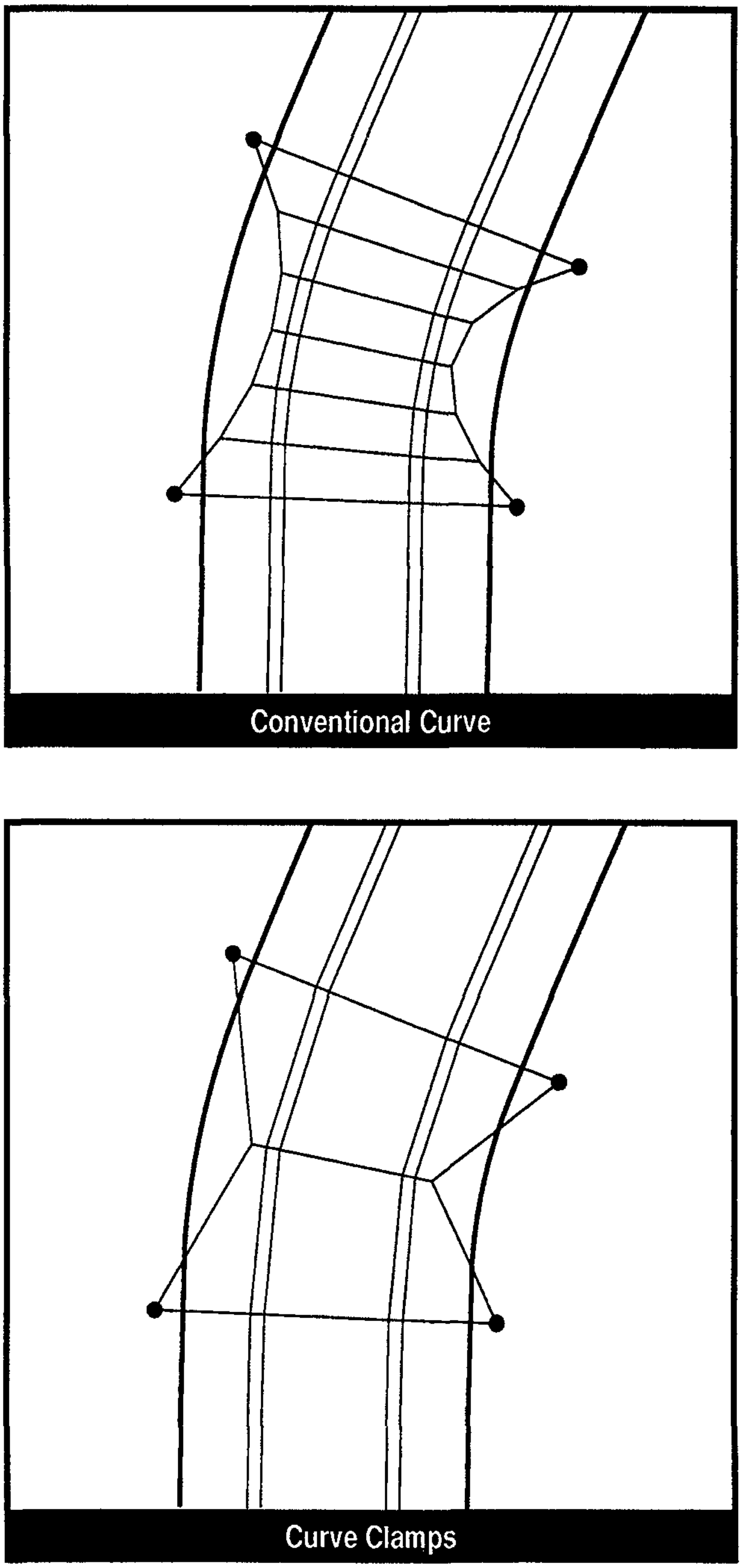

Figure 5-5. Comparison of conventional curve and curve clamps.

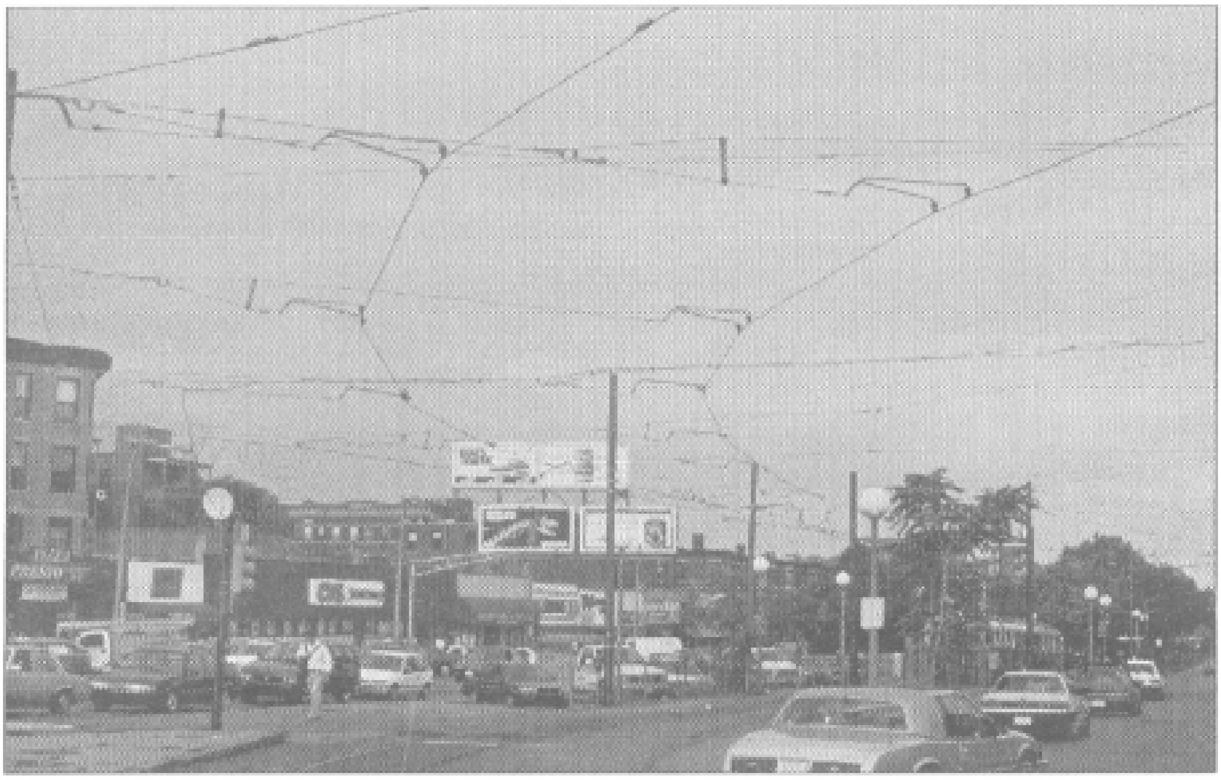

Figure 5-6. Direct-suspension LRT curve—Boston. Note the hanger arms used to keep the end of the pantograph from hitting the pulloffs.

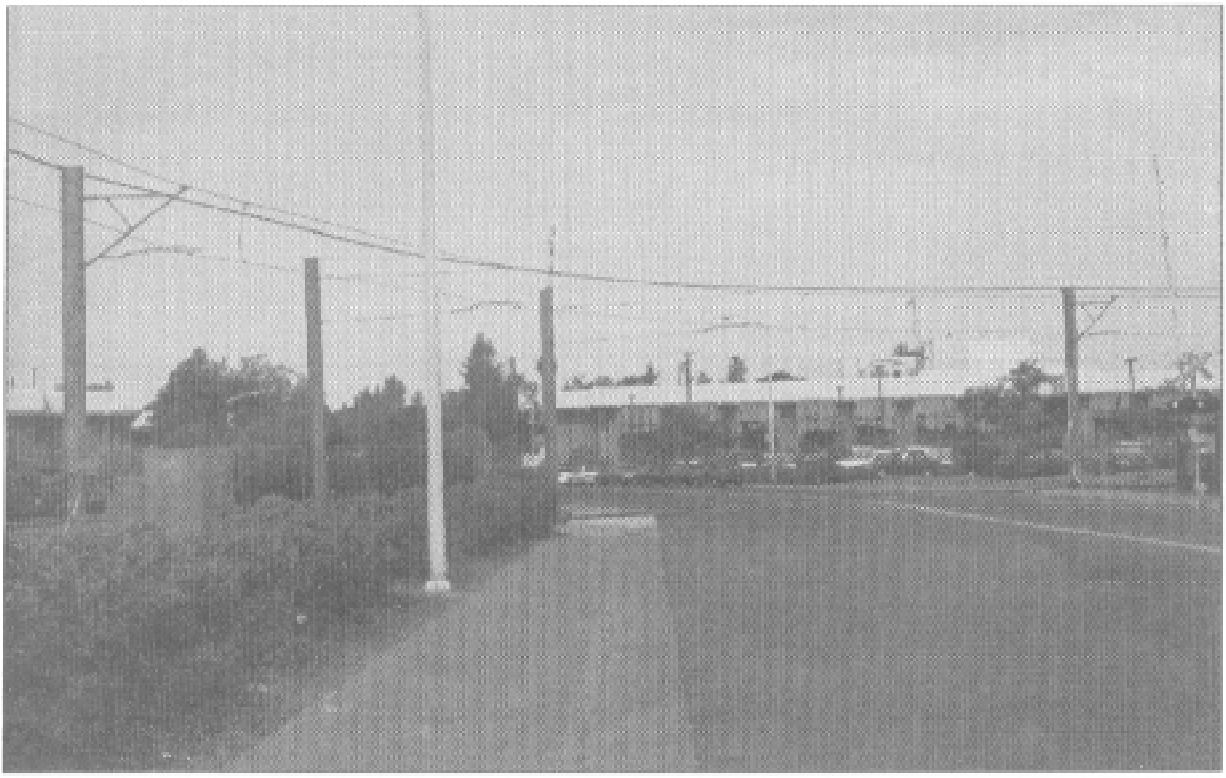

Figure 5-7. Catenary LRT curve—Sacramento. Note that a pole is used at each attachment point because of the very narrow right of way. The two center poles have pulloffs rather than mast arms.

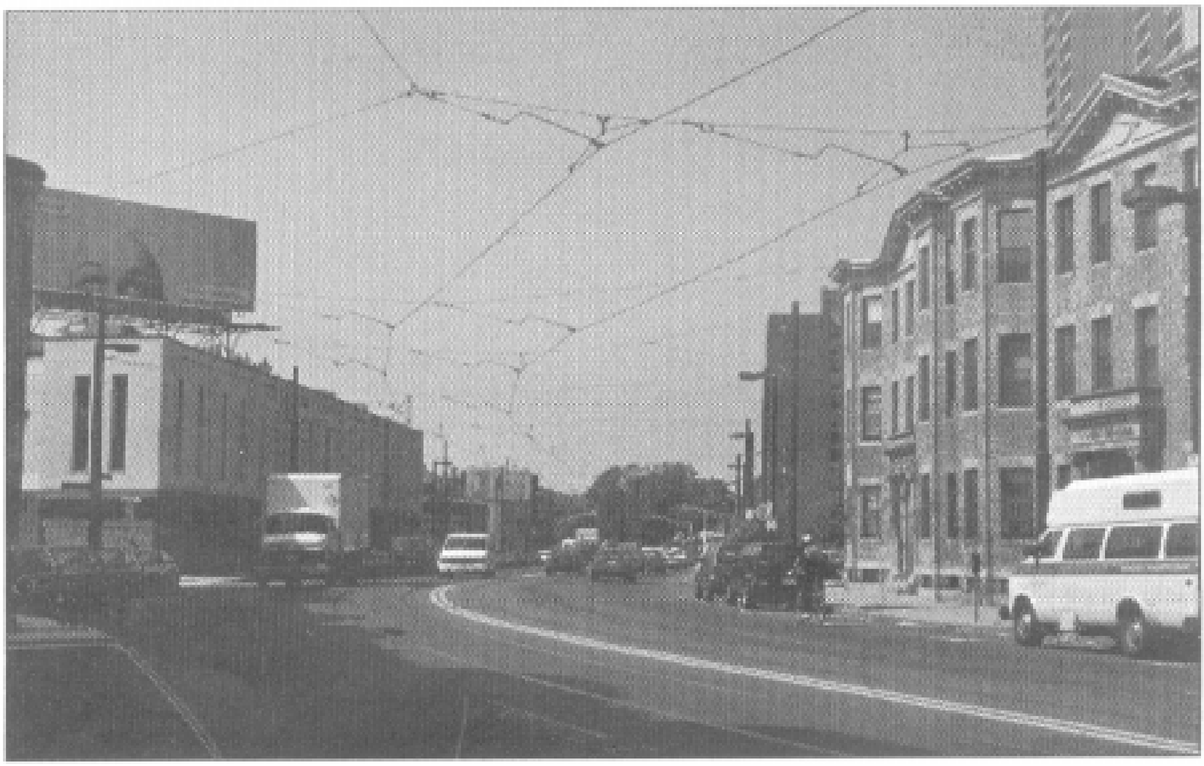

Figure 5-8. Delta-suspension LRT curve—Boston. Note that steady arms are needed in addition to the suspension to keep the wire upright.

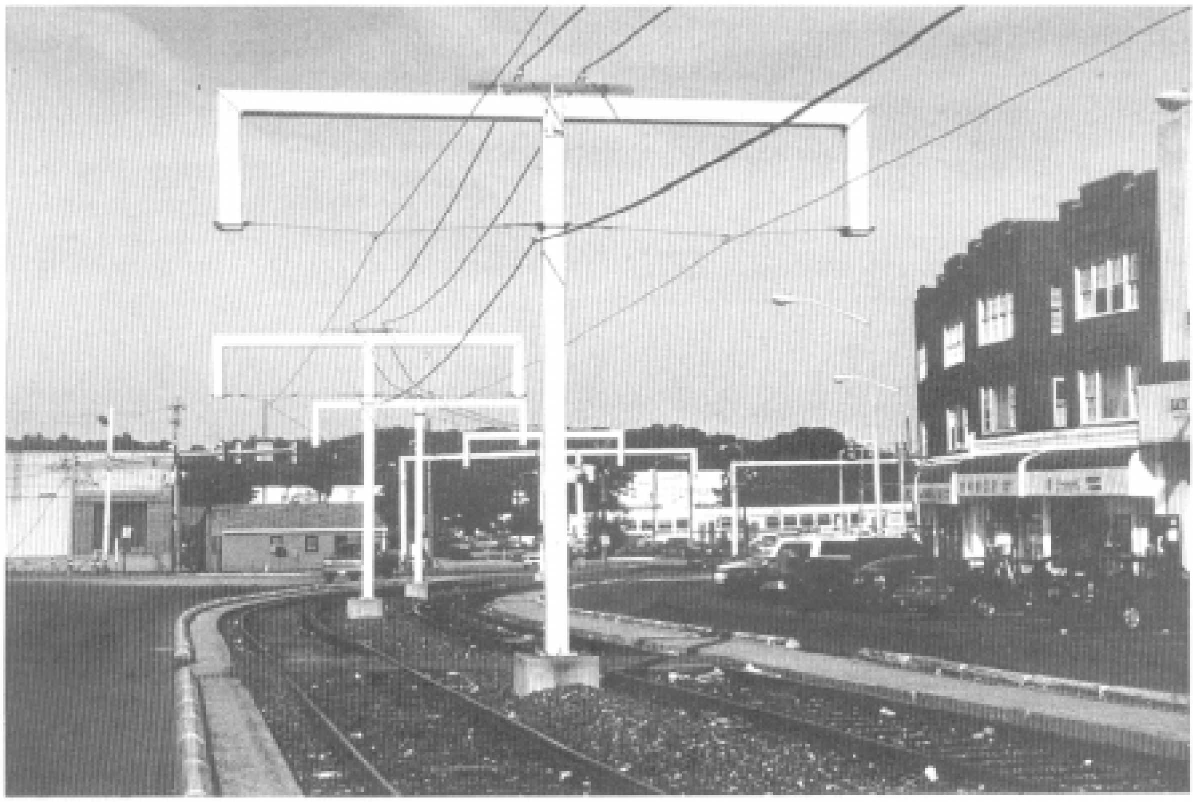

Figure 5-9. "T" structure—Philadelphia. This structure looks even more ungainly with direct-suspension wire than with the catenary for which it was intended but which has not yet been built.

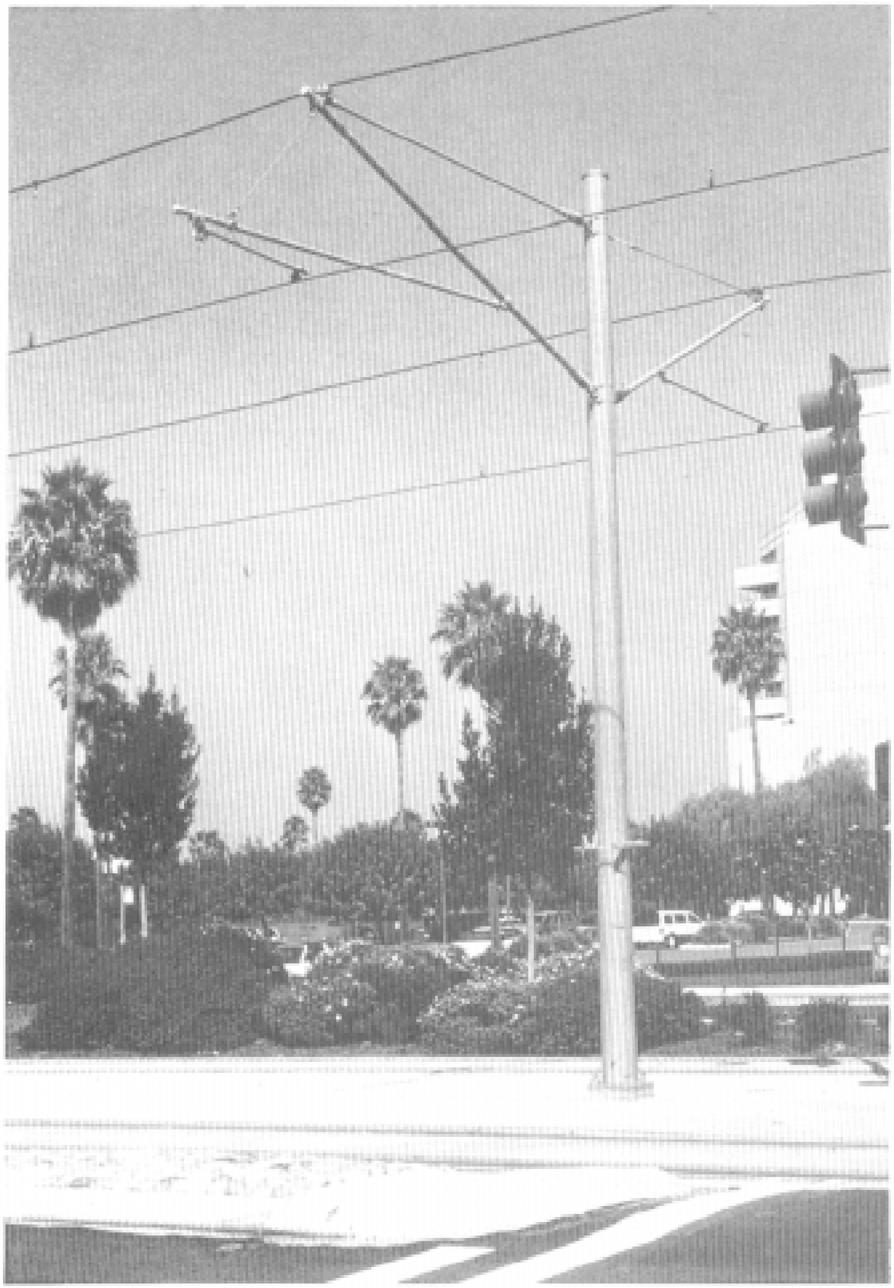

Figure 5-10. Radial mast arm—San Jose. This is the most common approach to handling compression loads on the inside of a curve with catenary.

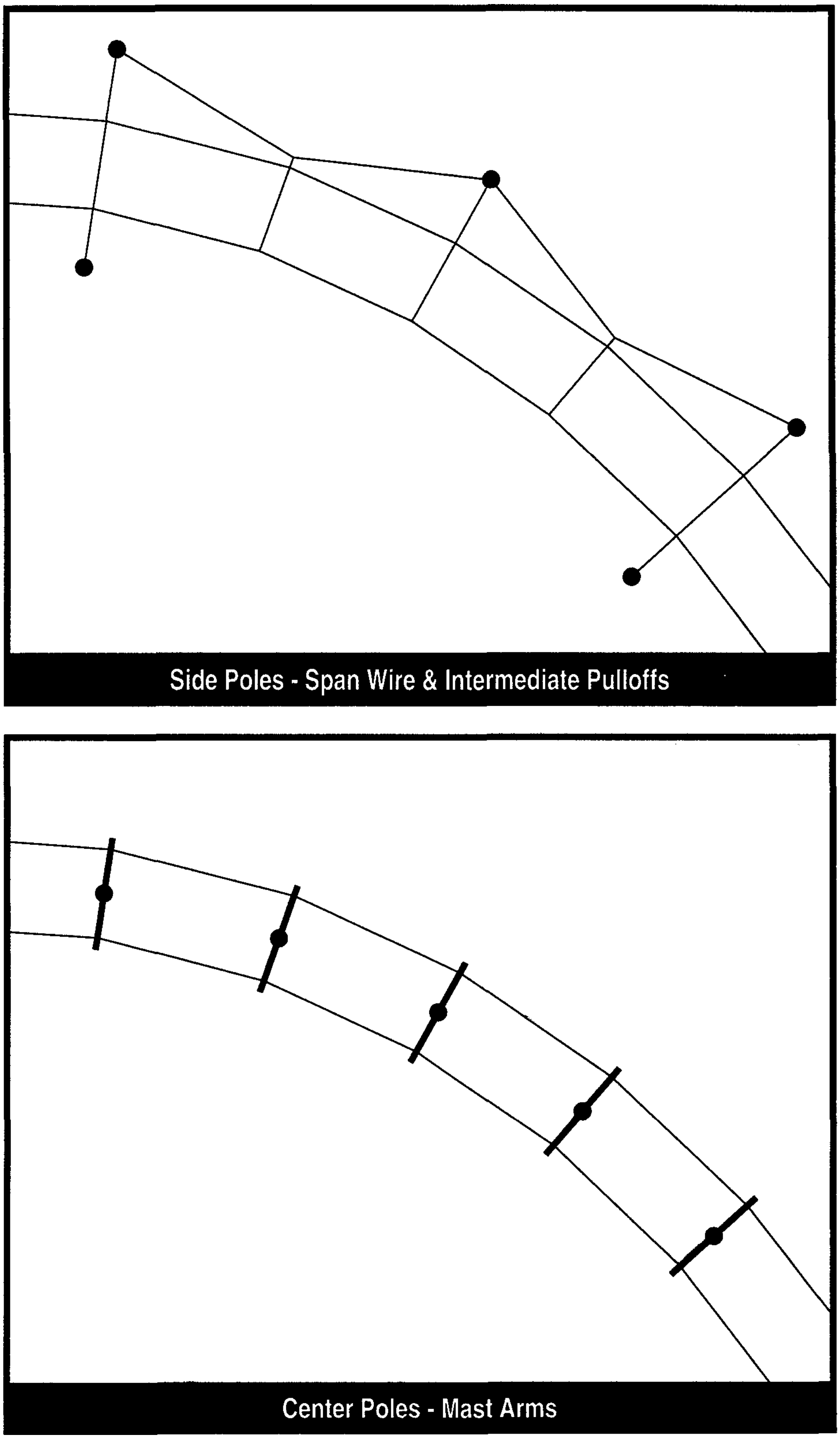

Figure 5-11. Comparison of two types of light rail curve design.

CHAPTER **6**

INTERSECTION DESIGN

TROLLEYBUS INTERSECTION DESIGN

Intersection layout was covered in the previous chapters on system design and curve design. Intersection support and the type of hardware used also affect the appearance of an intersection. Intersection support must support the weight of the intersection components and take up the tension where wire runs terminate at switches. Most intersection support uses span wire. Edmonton uses mast arms to support the weight of switches in some locations along with wire for tension takeup and positioning. The overlapping pattern of support wires and the density of hardware elements make the most complex intersections so visually obtrusive.

In a typical intersection design, a switch will require a pair of support bridles and a tension headguy. Crossovers may require lifting guys (depending on the number of crossovers and their position relative to other support points), whereas curve rails or segments will require pulloffs as described in Chapter 5.

Two types of hardware systems are available for trolleybus special work. In-line special work has the special-work components spliced into the contact wire. Suspended special work has the special-work components suspended below the contact wire, with connections between components and transitions between the contact wire and the special work being accomplished with runners that are not in tension. In-line special work is by far the most common type in North America. Only San Francisco and Edmonton have used suspended special work. Both systems have indicated that they have not been satisfied with it and do not intend to use it in future construction.

Suspended special work is significantly more visually intrusive than in-line special work. Figure 6-1 shows a full-wye intersection constructed with suspended special work. For comparison, a similar intersection using in-line special work is shown in Figure 3-6. Figure 6-2 shows an intersection in San Francisco that was the subject of newspaper stories about its appearance shortly after it was installed in the 1980s. To the researchers' knowledge, this is the only location to generate such controversy, even though San Francisco has a dense trolleybus network with numerous complex intersections.

Recently, there has been some interest in developing trolleybus-intersection hardware that is less visually intrusive; however, trolleybus hardware is a mature technology with a limited market, and the appearance of the hardware has not been an issue in most trolleybus projects. Significant changes to make hardware designs less intrusive are unlikely.

The section insulator has been criticized for being visually intrusive. In trolleybus OCS, the section insulator must be strong enough to (1) absorb the wire tension without deforming, (2) resist the wear of the trolley shoe and the impact damage from dewirements, (3) provide an adequate margin of short circuit protection between polarities, and (4) resist damage from arcing. The current design of section insulators uses separate structural members and a replaceable runner to meet these requirements. To reduce the size of the section insulator substantially, it would be necessary to develop a material that could meet all of these requirements in a one-piece component. It is highly unlikely that the limited market for trolleybus hardware could support the research needed to develop a material that would have both the required electrical and mechanical properties, particularly because it would need to be comparable in initial and maintenance costs to the current designs.

If such a material could be developed, a substantially greater reduction in the visual impact of trolleybus intersections would be accomplished by using this material to fabricate selfinsulated crossover pans. These insulated pans would also reduce the weight of crossovers and switches as well as the number of parts needed. Therefore, the cost of installation would also be reduced.

Some minor improvements can readily be made in the appearance of intersections. One area of improvement is the jumper wire that provides circuit continuity through crossovers. Figure 6-3 shows a crossover assembly and demonstrates that the jumper is the most obvious part of the assembly. One way of reducing the impact of the jumper and the profile of the entire assembly is to bend the jumper over instead of having it stick straight out from the top of the insulators (see Figure 6-4). Occasionally it may be possible to eliminate the jumper where lack of contact wire continuity will not significantly affect electrical capacity; however, even in a system with parallel feeders, the contact wire will typically provide about 30 percent of electrical capacity, and continuity will be needed.

Another design technique to reduce the amount of hardware is to combine section breaks with intersections, i.e., having the same section insulator serve two purposes.

LIGHT RAIL INTERSECTION DESIGN

A light rail intersection for pantograph operation requires almost no hardware, as can be seen from Figure 3-12. Light rail intersections for trolley-pole operation require frog and crossover pans to guide the trolley shoe. These are barely noticeable additions to the OCS. A few cities operate both pantograph-equipped light rail vehicles (LRVs) and historic streetcars with trolley poles on parts of their systems. This requires the addition of depression runners to allow a pantograph shoe to pass under the frog and crossover pans.

A similar approach is used for trolleybus/light rail crossings in Edmonton and San Francisco. Figure 6-5 shows such a crossing. This crossing incorporates both frog pans for trolley-pole operation on the rail route and depression runners for pantograph operation. This crossing is designed for a pantograph shoe that has sufficient width to span the gap between the depression runners in a 90° crossing. If the more common narrow pantograph shoes are used, the crossing angle must be substantially less than 90° so that the runners on each side overlap.

It is common practice to isolate trolleybus/light rail crossings electrically, with the insulation being in the trolleybus wire. Because the negative trolleybus wire has to be insulated from the light rail wire anyway, adding insulators on the positive wire does not affect performance.

In installing trolleybus/light rail crossings, it is necessary to design the wire profile so that the crossing is at a low point in the trolleybus wire. This prevents the ends of the pantograph from hitting the trolleybus wire, which would damage both the pantograph and the wire.

Turning loops are one type of light rail intersection that can have substantial visual impact, as has already been mentioned. There are several ways to reduce the visual impact of OCS turning loops—most important is to provide enough space for the loops so that the support points and points of angular deflection of the OCS are not crowded together. If space is available, outside support is much less obtrusive than inside support. Using pulloff wire support rather than mast arms will also reduce the number of poles, as described in Chapter 5. Finally, catenary construction is totally unnecessary in turning loops.

Figure 6-1. A full wye in suspended special-work construction at Mitchell garage entrance—Edmonton. Compare this collection of hardware with the in-line full wye shown in Figure 3-6.

Figure 6-2. *Special work at California St. and Presidio Ave.—San Francisco.*

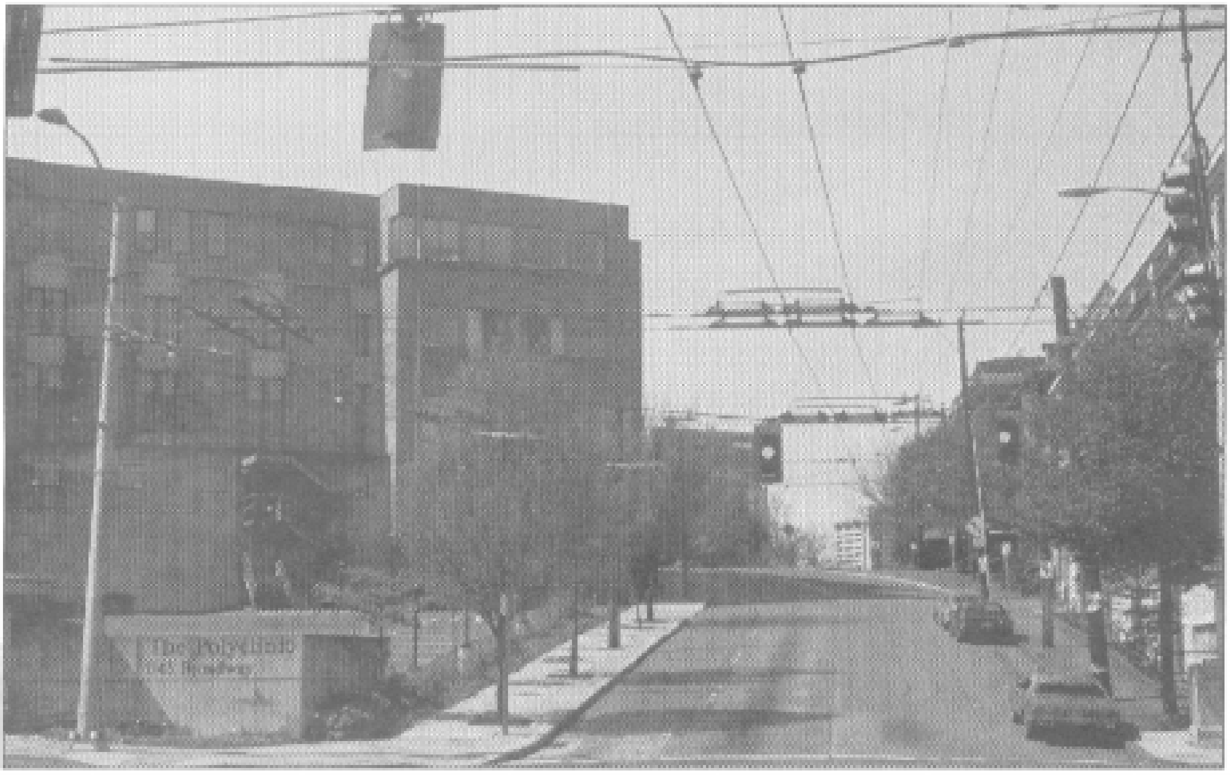

Figure 6-3. *Crossovers at Broadway and E Union St.—Seattle. Note that the jumper wire is the most visible part of the crossover assembly.*

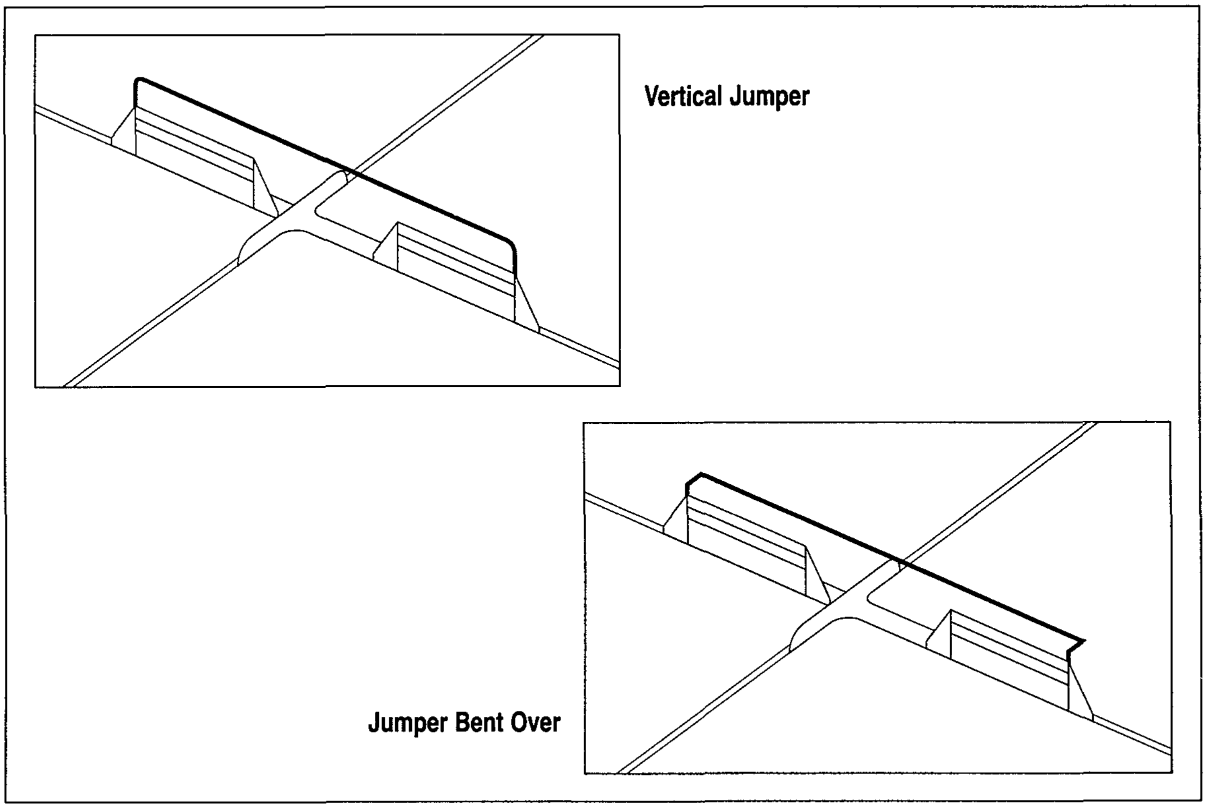

Figure 6-4. Insulated crossover assembly with vertical and bent over jumpers.

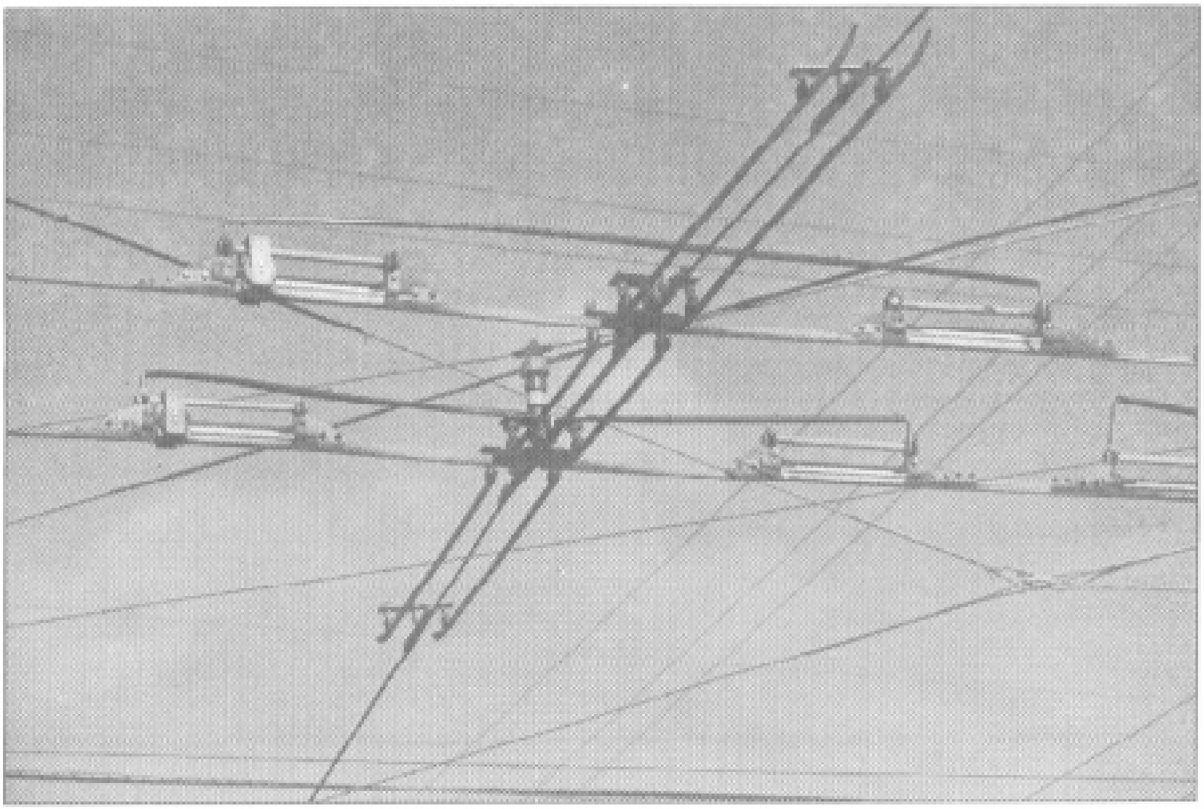

Figure 6-5. LRT/trolleybus crossing detail at Church and Duboce Sts.—San Francisco. This shows the runners that carry the pantograph below the trolleybus wire.