Furthermore, it is incorrect to assume that the overall evaluation process was of a linear nature, i.e., if 1.6-km (1-mile) spacing is superior to a 0.8-km (0.5-mile) one, then a 3.2-km (2-mile) spacing would be better than 1.6-km (1-mile) spacing and so on. Thus, the extreme solution was not a line with only one terminal station. This study identified only two points on the evaluation curve, and it is incorrect to extrapolate beyond this area by concluding that the longer the spacing is the better the line will be. In fact, it is extremely doubtful that, unless population densities at the terminal are inconceivably large and the densities along the line are correspondingly small, the demand and user savings associated with a line with a single terminal station would be greater than that of a line with 1.6-km (1-mile) or 0.8-km (0.5-mile) spacing.

From an empirical standpoint, the average station spacing on the rapid transit systems in cities such as Chicago, Boston, Cleveland, Washington, and Atlanta (including closely spaced downtown stations) is greater than 1.6 km (0.5 mile). Furthermore, in Chicago, the closely spaced stations on the Congress Rapid Transit Line constructed in the late 1950s were recently closed because of low ridership levels. Since the capital cost of constructing a subway station is in the vicinity of $15 000 000 to $20 000 000 and the annual operating cost of the station is approximately $200 000, it is questionable whether the number of stations on rapid transit lines should be overdesigned to minimize the possibility of adding stations in the future.

In summary, Vuchic has not shown that the evaluation methodology is deficient in any fashion. Furthermore, there is no indication that the analytical results are compromised. Finally, the basic conclusion of the paper is not to determine the optimal station spacing, but rather to systematically and empirically evaluate different station spacings on proposed rapid transit lines.

Abridgment

Design of Elevated Guideway Structures for Light Rail Transit

J. R. Billing and H. N. Grouni, Research and Development Division, Ontario Ministry of Transportation and Communications

Currently, all levels of government in North America realize the need for making transit a real alternative to the personal use of the automobile in major urban centers. The innovative use of the diesel bus has proven effective in a number of cities, but there remain corridors with sufficient demand to justify a fixed-guideway system. The rail mode is the only system that uses widely proven technology, and it is most efficient when operating in an exclusive right-of-way. In many cases, full right-of-way does not exist in these corridors; therefore, it must be created. With new subway construction costing around $32.5 million/km ($50 million/mile) and the acquisition of surface property a time-consuming and unpopular process, it appears that the objections to the elevated guideway must be reviewed if the service and operating cost benefits of a fully (or largely) exclusive right-of-way are to be obtained at a reasonable capital cost.

The earlier generations of transit vehicles were noisy, and the unsightly three-quarter century old elevated guideway structures such as those of New York and Chicago amplified this noise. Thus, elevated guideways have a reputation as an undesirable urban neighbor. The modern transit vehicle is significantly quieter than its predecessors, and a growing understanding of the wheel-rail mechanisms that generate noise and of noise barrier design gives promise of noise reductions to come. Furthermore, modern structural design techniques in both steel and concrete can produce serviceable and elegant structures that might enhance the streetscape of commercial and industrial areas in cities of North America.

This paper outlines a rationale for designing an elevated guideway for urban rail transit, and applies this rationale to a design of a double-track guideway for a proposed light rail transit (LRT) line.

DESIGN RATIONALE

The rationale for designing elevated guideway structures for LRT presented here organizes the thinking of the designer and his or her approach to the design problem. It superimposes the overall objective of the project on the guideway design effort and insists that all factors that affect the design, including those factors beyond the control of the designer, are recognized and understood. These factors are organized into three groups: (a) performance requirements that specify guideway function; (b) constraints that limit the choices available to the designer; and (c) design considerations that tell the designer how to choose among options, all of which satisfy the performance requirements and constraints. The priorities of factors in these groups may change with time. For instance, low cost may be a design consideration in the early stages of a project, but when capital budgets are allocated it becomes either a performance requirement or a constraint.

Performance Requirements

Performance requirements specify the function of the guideway and are quantifiable. An elevated guideway for LRT must provide safe and reliable support and guidance for trains and support for other system components in a secure right-of-way that facilitates the operator's

inspection and maintenance tasks.

The structure must withstand all stresses and strains imposed on it through its lifetime under serviceability and ultimate limit states. If derailment or crash occurs, trains must be contained within the guideway, must be restrained from crossing onto other tracks, and must not cause irreparable damage to the primary structure. Support piers in areas of public vehicular access must be protected against vehicle impact, or the guideway superstructure must remain standing if any single pier is demolished. The guideway must be secure against unauthorized access, and it must be protected against accumulation of debris such as snow and ice. The guideway must have a walkway to provide access for inspection and maintenance personnel and for controlled evacuation of passengers in an emergency. It must provide secure support and attachment for other system components such as rails, power distribution equipment, and signals. The elevated guideway must be acceptable in the neighborhoods through which it passes. Airborne and groundborne noises and vibration due to train operation must conform to standards set for the various land uses adjacent to the line.

Constraints to Design

Constraints limit the choices of the designer in meeting the performance requirements for the structure and may cause special, more costly features to be imposed on the design. Typically, constraints arise from the route corridor available, e.g., topographic and existing structural features and station locations may require special curvatures or restrict pier placement, and vehicles and other system components may require geometric compatibility.

Constraints may be real or arbitrary. Real constraints are based on engineering difficulty and cost of choosing a particular option. Arbitrary constraints arise from irrational preferences, inadequate study, or political activity and must be recognized and closely questioned.

Design Considerations

Design considerations provide the designer with the logic to choose between design alternatives that satisfy all performance requirements and constraints. The major design considerations are cost and aesthetics.

A low-cost design process requires a clear understanding of the purpose of the guideway and a detailed knowledge of the cost and availability of materials and construction techniques. The two most important means of ensuring low cost are thorough planning and insistence on standard design. Good planning ensures that adequate property is available for access and construction sites, utility and road relocations are minimized, and other municipal projects are coordinated with transit construction to share costs. Standard design requires that readily available materials, well-known construction techniques, and simple and repetitive details are used in the structure. Special structures such as crossovers and stations integral with the guideway structure should be minimized. The design should have enough flexibility so that it can be built with a minimum of change over a range of span lengths. Specifications, tender documents, drawings, and contracts should be complete and unambiguous so that bidders can make reliable estimates that include low contingency allowances. Design alternatives should be provided such that they can be used to increase competition in bidding.

In the planning stages of a project, guideway architecture probably has little to do with the acceptability of the guideway in a particular location. However, a slender and elegant structure that is carefully integrated with the location might find increasing acceptance with time, especially if it provides efficient transit service.

DESIGN STUDY

This rationale is applied to designing a section of an elevated guideway for a specific LRT line. Initially, this line will use a shared right-of-way and will be operated by unidirectional light rail vehicles (LRVs) with doors on one side and street level loading. Later, an exclusive right-of-way will be developed that will be operated by new bidirectional vehicles with doors on both sides and platform loading. This design study develops a suitable guideway configuration and examines in some detail a typical four-span structure.

Vehicle Specifications

The LRV is 15.5 m (51 ft) long, 2.6 m (8.5 ft) wide, and 3.4 m (11 ft) high. It draws propulsive power from an overhead wire 4.3 m (14 ft) above the top of the rail. The vehicle has two bogies, and each bogie has two axles. A lateral clearance of 15.3 cm (6 in) is required on each side of the vehicle to accommodate its dynamic envelope. The vehicle has a mass at crush load of 34.93 Mg (77 kips) that gives a loading of 87.32 Mg (19.25 kips)/axle. Vehicles may operate as trains of two or four units.

Guideway Cross Section

Figure 1 shows the performance requirements, vehicle dimensions, and design considerations of a double-track guideway. The primary structural member of this guideway is the central spine girder. From each side of the girder a deck supporting the track system is cantilevered, and at each end of the decks are the outside barrier walls. The spine girder and barrier walls confine vehicles in the event of derailment or crash, act as barriers for airborne noise, and provide support for signal and power cables. Compared with the same guideway without barrier walls, when the barriers are given a good absorptive treatment, they are estimated to provide a noise attenuation of about 8 dBA for an observer at ground level away from the guideway.

The top of the spine girder is a walkway, which utilizes otherwise unusable space for maintenance personnel. Compared to the alternative of two exterior walkways, use of this location reduces overall guideway width and hence cost. The walkway is made level with the vehicle floor to facilitate emergency evacuation from the vehicles and to perform as an effective noise barrier. The LRV that will operate on the line initially requires an emergency exit panel to be added for compatibility with the guideway cross section. Rungs are provided for access to the deck from the walkway, and a handrail may be installed along the centerline of the spine girder for the safety of personnel. Poles mounted on the spine girder carry the overhead electric supply wire and guideway lighting. Adequate space is available on the deck for conversion to a third-rail power supply. The barrier wall is visually integrated with the guideway because it hides the spine girder and part of the vehicle.

Superelevation can be applied to this cross section by twisting the spine girder. This retains relationships between track, spine girder, and barrier wall so that the clearances required for curvature are minimized. Two free-standing platform structures that share a control area at grade beneath the guideway provide a station that is independent of the guideway structure.

The guideway cross section may appear to be a snow

trap. However, if frequent train operations prove inadequate to disperse snow accumulations, then an occasional pass by a snowplow that is attached to a train or a blower with an elephant trunk that throws snow over the barrier wall should keep the guideway sufficiently free of snow for operation. This snow clearance must be coordinated with the authorities responsible for street

snow clearance to protect the passersby and to avoid undue buildups below.

Structural Design

The guideway structure consists of the spine girder, a deck that transfers loads laterally into the spine girder, and a barrier wall. Preliminary designs were made for a constant depth spine girder with four continuous spans of 24.4, 30.5, 30.5, and 24.4 m (80, 100, 100, and 80 ft). Figure 2 shows the three deck options that were considered: a solid tapered slab, an open grillage, and a grillage with a 10.2-cm (4-in) cover slab.

For span lengths of around 30.5 m (100 ft), an economical and structurally adequate spine girder with a prismatic section of prestressed concrete has a depth-to-span ratio of 1:17. For greater spans, the spine girder may be haunched over the piers at the same depth-to-span ratio with depth at midspan about 70 percent of that over the piers. Both the prismatic and haunched options give a guideway an appearance that is generally pleasing, as shown in Figure 3. A spine girder depth of 1.8 m (6 ft) was adequate for resisting all combinations of flexural, shear, and torsional loads in both service and ultimate limit states. Maximum flexural and shear stresses are produced by fully loading both tracks simultaneously, whereas maximum torsion stresses are produced by fully loading only one track. The design criteria followed the American Concrete Institute's recommendations (ACI-443). These recommendations provide for an impact factor of 30 percent of live load for dynamic effects, a rolling factor (between the rails) of 10 percent for torsional analysis, a longitudinal force factor of 10 percent for operational braking, a centrifugal force factor of 20 percent on curved tracks, and a derailment force factor of 40 percent that acts normal to the barrier wall over a distance of 3.1 m (10 ft).

The girder is solid in the negative moment regions and anchorage zones and hollow with a 22.9-cm (9-in) wall thickness for the rest of its length. Prestressing is provided by multistrand or multiwire tendons that have low relaxation characteristics. Concrete and steel requirements are similar to those for normal highway bridges. At some increase in weight, the solid deck provides greater ultimate shear and torsional stiffness strength than the grid. For structural purposes, use of the grid option necessitates a slight increase in beam depth. The dimensions for this beam for the chosen span lengths fit very well with the geometric requirements of the vehicle (Figure 1), but variations in the

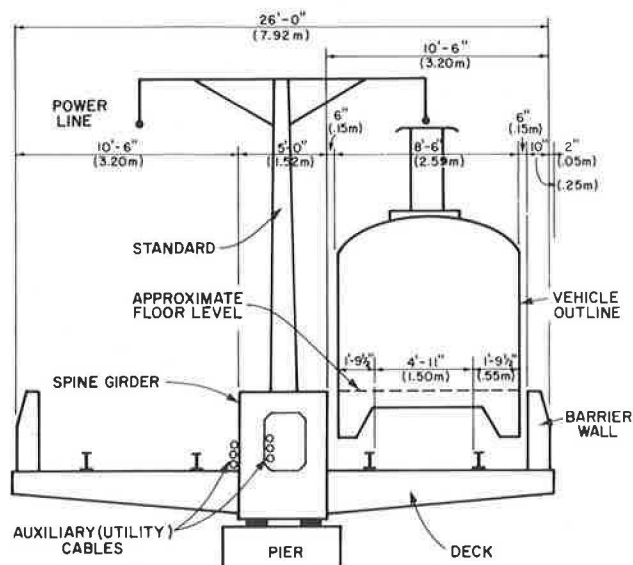Figure 1. General layout of double-track guideway.

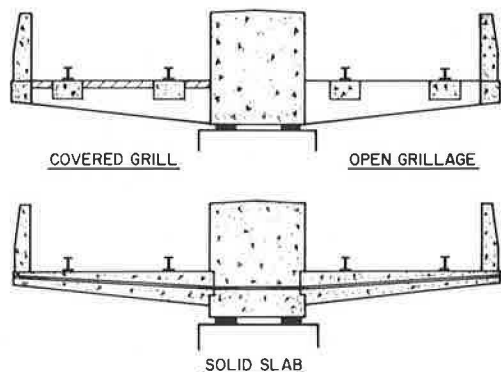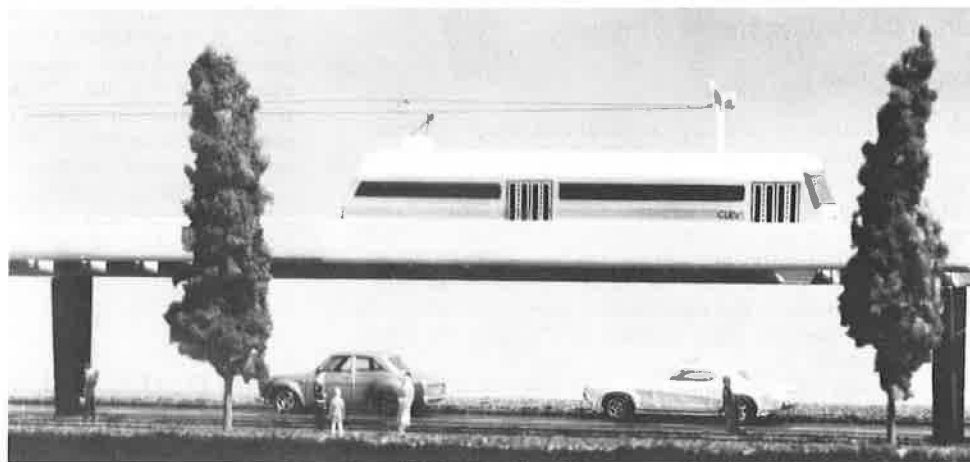Figure 2. Deck options for a guideway structure.

Figure 3. Scale model of a guideway structure.

spine girder cross section are possible. The open or partially closed grid may prove attractive in areas where heavy snowfall is experienced, provided that noise is not a problem. The open grid requires a wire mesh attachment for the safety of track personnel.

The structure is quite stiff with a maximum live load plus impact deflection less than $\frac{1}{1600}$ of any span, and it has a first mode natural frequency of about 4 Hz. Continuity of the structure and continuous welded rails guarantee an excellent ride, which may be maintained if the rails can be shimmed relative to the deck.

The piers are of standard reinforced concrete design and support the spine girder on neoprene bearing pads that allow expansion. The girder-pier support system resists overturning of the guideway under the most adverse loading conditions on both straight and curved tracks without special anchorage details.

Construction Options

There are a large number of construction options for this guideway structure because the spine girder, deck, and barrier walls can be made structurally independent of one another.

The spine girder may be cast in place or precast and posttensioned after erection. The deck may be cast in place or precast in short segments and added to the girder by using a transverse posttensioning to reduce construction time and cost. Separate crews may be used for girder and deck erection. The segmental construction technique may be applied at sites where there is limited access or along streets where traffic disruption is to be minimized. The girder and deck are integrally precast in segments that are 3.05 to 6.1 m (10 to 20 ft) long and are erected by cantilevering from both sides of the piers without falsework. Continuity is provided by posttensioning the segments longitudinally as they are erected and also after closure. For any of these construction options, the barrier wall may either be cast in place or precast and bolted to the deck.

Cost

Several construction options have been costed in detail, and each option is estimated within ±10 percent of $1969/m ($600/ft) in 1975 Canadian dollars. This estimate includes foundations on spread footings, piers, and a double-track guideway structure, which is built under ideal conditions. The estimate excludes tracks, power, signals, and installation costs. Physical complications on a specific route might raise this cost substantially; however, the span length flexibility and construction options available within this guideway concept provide the best opportunity for coping with these difficulties without the need for special structures.

CONCLUSIONS

The significance of guideway considerations in vehicle design is most apparent in the initial cost and operational strategy of the system. The guideway absorbs an appreciable portion of the capital cost of a transit system. Hence, compromises in guideway configuration to accommodate an existing vehicle design might be adversely reflected in the overall cost of present as well as future systems. The operational aspects in terms of safety, convenience, and service might also be seriously hampered.

A rationale has been presented for the design of elevated guideway structures for LRT. This rationale is neither a specification nor a code, but it should form the basis for either. It identifies performance requirements that must be met for the structure, constraints that limit the designer's range of choice in meeting the performance requirements, and design considerations that provide the basis for making design choices.

By using this rationale, a guideway concept has been developed for a proposed LRT line. This concept features a central spine girder that acts both as the primary structural member and an access walkway and from which decks are cantilevered to carry the tracks. Barrier walls are mounted on the outside of the decks for vehicle containment and noise abatement. The basic guideway concept has considerable structural and construction flexibility so that the variant or variants that best suit a particular route may be chosen to gain maximum benefit from mass production. The guideway is estimated to cost $1969/m ($600/ft) for foundations, columns, and double-track structure. Since the structural depth is hidden by the barrier wall, the guideway is a slender and elegant structure.

ACKNOWLEDGMENTS

Discussion

Vukan R. Vuchic, Department of Engineering, University of Pennsylvania

The proposed design of an elevated structure for light rail transit is apparently both economical and aesthetically pleasing. It requires a very small total width. However, it appears that two potentially serious problems have not received sufficient attention.

The first problem is snow removal. Although the rail vehicles are least susceptible to impedance by snow, a heavy snowfall can, in this case, require physical removal rather than only running the vehicles at certain intervals. An open grill bottom could not be used because it allows dripping of oil and minor particles on the area below the structure. For this reason, grills are illegal on elevated structures in many countries. A possible solution may be to have a vehicle with a blower that would throw the dispersed snow from the aerial structure.

The second problem is that the proposed design makes it impossible to have access to the vehicles from the side below their bodies. Since many minor mechanical or electrical failures in vehicles can be repaired from this side, it is always essential that access to the trucks, control, and other equipment be available along each side of the vehicle. This requirement is absolute, and it must be given careful consideration in determining the distance between the vehicle profile and concrete fence on each side of the track.

These two problems should be carefully studied and adequate solutions found before any further testing and implementation of this design are undertaken.

Authors' Closure

The serious problem of snow removal was briefly discussed in the paper, and it is recognized as an area of

doubt until actual operational experience is obtained. Since our paper was written, further information (1) has come to our attention. This information indicates that snow removal can be achieved for elevated guideways by a satisfactory mechanical means. The open grill would not be contemplated in cases in which dripping of oil or other debris might be hazardous; its primary use might be in cases in which the guideway is inaccessible to the public and airborne noise is not a problem.

The second problem clearly illustrates the need for recognition of guideway constraints in vehicle design as well as the more usual converse. A subway vehicle operating in tunnel provides essentially no opportunity for access to vehicle components. Thus, in the event of failure, the other vehicles of the train provide a self-rescue capability. There are only two cases for the Toronto Transit Commission subway in which there is a need for access underneath the vehicle: if the operator needs to free a tripped emergency brake and to free a suicide victim from the vehicle undercarriage. The LRT line for which this guideway is designed would operate multicar trains; therefore, the need for operator

intervention is reduced since it is preferred policy for a faulty vehicle to be towed out of service rather than for the operator to attempt to repair it. If there are some functions the operator must reset after a fault, it should be a straightforward matter to modify the vehicles with reset mechanisms that are accessible from the walkway, if not from the vehicle interior. In this study, it is preferred to modify the vehicles rather than the guideway on the line because it is expected that the initial existing LRV operating on the line will ultimately be replaced by a vehicle designed for exclusive right-of-way operation. Thus, the guideway concept is designed to reflect ultimate rather than immediate needs.

REFERENCE

1. B. K. Barrowcliff. Operating the Ford ACT System in a Snow and Ice Environment. In Personal Rapid Transit, Univ. of Minnesota, 1976.

Model for Cost-Effective Maintenance of Rail Transit Vehicles in Urban Mass Transit Systems

Stephen R. Rosenthal, Jerome D. Herniter, and U. Peter Welam, School of Management, Boston University

A new computer-based model to assist rail transit management in determining maintenance schedules for rail transit vehicles is presented. The model evaluates the aggregate cost and service implications of conducting prescheduled inspections and preventive maintenance activities for the various components of a transit vehicle. The model also consolidates information on size of vehicle fleet, cost of maintenance and repair of vehicle parts, relations between maintenance frequency and subsystem failures, and historical patterns of the different types of in-service breakdowns. On this basis, the model determines relations among preventive maintenance alternatives, average number of transit cars available for peak service, expected number of in-service car failures, and the total cost of maintenance and repair. The model was originally developed for use by the Massachusetts Bay Transportation Authority in Boston. Preliminary findings in the initial application of the model to generate and evaluate alternative maintenance schedules for the authority's Red Line suggest that use of the model could result in noticeable, though probably not dramatic, savings for this particular line. The authority intends to refine the data used in these analyses and to extend the use of this model to its other lines. The model is a conversational FORTRAN program. It can be adopted for use in any rail transit system that has the required data on vehicle maintenance and repair activities.

Transit vehicles, like most complex pieces of equipment, are prone to unforeseeable failure. Although preventive maintenance programs may keep the frequency and nature of nonscheduled repairs within acceptable bounds, the notion of acceptability is subjective from the rail transit management's point of view. In-service breakdowns will disrupt the scheduled flow of cars along the line and directly inconvenience or even endanger the passengers. Up to a point, a transit system manager

will naturally desire to keep the cars in working order through a regular program of preventive maintenance. Maintenance, however, is a non-revenue-producing activity and must be kept within reasonable bounds. If service reliability is satisfactory and accidents are rare, then transit managers are unlikely to expand their preventive maintenance programs. The costs and impacts of vehicle inspection and repair activities must be identified before a sense of the economic trade-offs between preventive and remedial work can be gained.

To aid transit managers in appreciating these trade-offs and to help them in evaluating alternative vehicle maintenance schedules, we have developed the Maintenance Analysis and Scheduling System for Transit Management (MASSTRAM), which is a computer-based model. MASSTRAM analyzes the cost and service implications of alternative preventive maintenance strategies for various subsystems of the vehicle and displays tabular and graphical data that identify various trade-offs between costs and service loss. MASSTRAM is programmed in FORTRAN and is designed for conversational interaction with the user.

This paper describes the vehicle maintenance problem and the basic concepts and capabilities of MASSTRAM. Preliminary findings are presented for the initial application of the model by the Massachusetts Bay Transportation Authority (MBTA) to a rapid transit line in the Boston area. The application efforts described include plans for the implementation of a controlled experiment in which the effect of alternative