Innovation and evolution of urban transportation structures

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Développements innovateurs des structures de transport urbain

Innovation und Evolution bei städtischen Verkehrsbauwerken

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SUMMARY
Advancements in transit guideway design and construction require understanding the transit vehicle technology, the structure, and the urban cityscape. Economies and originality may be promoted by capitalizing on the unique features of transit systems. The historical development of transit guideways is presented and the contributions and benefits of several systems are described. Lessons from these developments and from speciality transit structures can benefit new guideway installations.

RÉSUMÉ
Les progrès dans l'étude et la construction des voies de circulation à guidage implique la connaissance approfondie de la technologie des véhicules de transport, de la structure et du paysage urbain. Il est possible de parvenir à des ouvrages originaux et économiques en tirant profit des particularités exceptionnelles des systèmes de transit. L'article présente l'historique du développement des voies de circulation à guidage et décrit les apports et les avantages de plusieurs sytèmes. Les leçons tirées de ces développements et des structures spéciales de ce moyen de transport peuvent profiter à de nouvelles installations de voies de circulation à guidage.

ZUSAMMENFASSUNG
Fortschritte bei Entwurf und Bau des Fahrwegs spurgeführter Transitsysteme verlangt Verständnis der Fahrzeug-Technologie, des Fahrweg-Tragwerks und der Stadtlandschaft. Wirtschaftlichkeit und Originalität können gefördert werden, indem man Vorteile aus dem besonderen Merkmalen des Transitsystems zieht. Präsentiert werden die historische Entwicklung der Fahrbahntypen sowie die Beiträge und Vorteile der verschiedenen Systeme. Lehren aus diesen Entwicklungen und speziellen Fahrbahn-Tragwerken können bei der Installation neuer spurgeführter Systeme nützlich sein.

1. HISTORICAL BACKGROUND

Virtually all transit systems evolved from the horse drawn streetcars and mine carts. These common ancestors of modern transportation provide the underlying basis for transit and guideway development. As the railroads evolved, it was only logical that transit technology benefit from the advances in rail technology. While steel rail and steel wheels formed the basis for transit development, the sources of propulsion were varied. In the 1880's over 5800 km of transit track criss-crossed the cities of the United States [1]. The majority of the transit vehicles were horse drawn cars riding on rails in the city streets. Yet even at this time horses were in decline and by the end of World War I all horse drawn transit had disappeared from the United States.

In the 1870's San Francisco, California opted to use a cable system to propel its vehicles over the steep hills. Provision of equipment to align, support and guide the cables became one of the first transit "guideway" projects. In other parts of the world, electricity was replacing horses as the power source for transit. In general, guideways remained as steel rails placed in the street.

Elevated transit was the solution to the increasingly crowded city streets. In 1866, Charles T. Harvey designed and constructed a quarter mile section of elevated track in Yonkers New York. The cable driven vehicle was a prototype of a proposed 23 km transit system. The vehicle operated at 23 km/hr, however the system was never completed due to instability of the financial markets.

The first successful elevated transit systems were installed in the United States in the late 1800's. The Chicago Elevated transit system was begun in 1892 and is still in service. The Philadelphia transit system began as a streetcar service, but increased demand required larger cars, and eventually, elevated sections of guideway were constructed to support the commuter rail service.

The early guideway systems consisted of riveted steel structures and tie and rail tracks. The impact on city is immense. Entire city blocks covered by steel and timber. Track and switch technology came directly from the railroads. Noise suppression and aesthetics were not considered part of the design criteria and the resulting impact of noise and urban intrusion is still evident.

Repair and maintenance was of little concern on these early structures. Transit service was more than adequate at the turn of the century. Today, however, traffic volume is so great that agencies such as the Chicago Transit Authority can replace only a few ties per day on heavily traveled lines. Closing lines to create more effective working conditions to implement repairs is impossible due to the heavy ridership.

2. SPECIALIZED GUIDEWAYS AND VEHICLES

While specialized transit had its beginning with the Harvey "monorail" in NYC in the late 1860's. Other creative systems were more successful. The "swaying" monorail over the Wupper River in Wuppertal, Germany is a notable example. The suspended vehicles are hung from a guideway structure constructed over the Wupper River. Not only is the guideway specially designed to provide the support, guidance and power to the vehicle, but the use of the river directly addressed the issues of noise and urban space utilization.

Guideway design and development progressed incrementally for the next several decades. Innovations were primarily in the vehicle technology and supporting systems. The President's Conference Car, PCC, in the late 1920's standardized a vehicle design in the United States. The PCC vehicle allowed some degree of guideway standardization. Better electric motors and better signaling improved performance, safety and reliability.

Specialty transit, such as cable cars were developed and died out. The San Francisco cable car system is one remaining historical cable guideway system still in operation. Newer cable systems, such as the peoplemover at Circus-Circus resort in Las Vegas, Nevada are modern applications of a proven technology. The systems provide transit access between facilities separated by major roads or natural barriers.

3. MODERN CONCRETE GUIDEWAYS

The 1960's inaugurated a new era of guideway structural development with two very different technologies; the Alweg monorails at Seattle Washington and Walt Disney World and the Bay Area Rapid Transit project. The Seattle Monorail was constructed for the 1962 World's Fair in Seattle, Washington, the Disney World Monorail began in 1969, and construction commenced on the Bay Area Rapid Transit (BART) system in San Francisco, California in the mid 1960's. Though vastly different in form and function, monorail and BART projects had an important effect on guideway development for the remainder of the century.

The Alweg Monorail system was developed in the 1950's in Sweden. The monorail guideway is a fully integrated structure. The top surface provides the riding surface, while the sides provide both the steering surface and vehicle retention. Inserts in the sides allow mounting the power rail and signal control systems.

A small monorail system was constructed at Disneyland, in Anaheim California in the late 1950's. The monorail used reinforced concrete beams cast in tangent or circular forms. The resulting transit system, while suitable for the park environment, had many shortcomings. The most significant deficiency was the long term sag that developed in the concrete beams. The discontinuities led to undesirable ride quality conditions.

The Alweg corporation received the contract to design, construct and operate a full size monorail system between downtown Seattle and the World's Fair site in 1962. The Alweg guideway design was predicated on using a prestressed concrete. Prestressing allowed improvement in the ride quality by the elimination of the long term sag conditions which occurred in the Disneyland system. Construction of the Seattle beams pioneered new construction innovations. The most significant concept was the use of adjustable forms to allow the geometric alignment to be integrated into each beam.

The adjustable form allowed high rates of production for a large number of variable members. The net effect of the prestress force in the Seattle monorail was to crate a beam with substantial upward camber. Just as the sag in the reinforced concrete beams in Anaheim affected the ride quality, the camber also detracted from a smooth ride in Seattle.

The Walt Disney World monorail was designed and constructed in Orlando, Florida in 1969-1971. The monorail provides the primary transportation link between the parking lots and the Magic Kingdom, Figure 1. The monorail guideway at Disneyworld was an evolutionary step forward from previous designs. The guideway beams were completely integrated structures, prefabricated in adjustable forms to very precise tolerances [2]. The forms were designed to flex horizontally while adjustable soffit and top chamfers provided the vertical tolerances. High production rates allowed the fabrication of one beam per form per day, even with the large number of geometric changes. The prestress force was designed to produce a long term axial shortening without camber or sag. Continuity was employed to reduce the interior joints, improve ride quality and provide structural redundancy.
Computer aided design and manufacturing techniques allowed coordination of the site geometry with the precast manufacturing.

Fig 1. Walt Disney World Monorail

Switches were installed in the main line of the Walt Disney World monorail structure to facilitate entry and egress of trains to the main loop from the maintenance sidings. These switches and switches used in the Japanese monorail systems have proven to be quite functional and reliable over the decades [3].

The San Francisco Bay Area Rapid Transit, BART, was an even greater forward step [4,5,6]. For the first time in decades, engineers attempted to completely define the transit technology. Vehicles would run on steel rails, but beyond that substantially new technology was incorporated in the design. The BART cars had a non-standard wheel gage, automated control system, wayside power instead of overhead catenary and vehicles designed for ride comfort.

The BART guideway received considerable engineering attention. The guideway beams were to be fabricated of precast concrete. Entire beam segments were cast as complete units and shipped to the site. Beams were made in tangent and curved sections, however, the trackwork was not directly integrated into the beams. The guideway consisted of simple span beams with expansion joints at each end. The rails were fastened directly to the structure by using rail fasteners embedded in a "second pour" concrete segment.

The second pour accomplished two objectives. First, the rails could be electrically isolated from the main beam. This was an important consideration since the continuously welded rails also carried the ground current of the propulsion system. Secondly, the extra concrete placement allowed minor tolerance adjustments to be made without having to adjust the entire structure.

The continuously welded rails and wider body vehicles substantially improved ride quality on the system. The thermal forces generated in the continuously welded rail limited the span capacity to simple spans. Since the beams must expand and contract independently of the rail, structures longer than a single span accumulate too much residual stress.

4. STEEL GUIDEWAYS

The noise and vibration of the Chicago Elevated transit system would not be tolerated in a modern urban transit system. Since these systems use predominately steel structures and the cost of steel was relatively high, steel was not the material of choice when new transit systems were started in the 60's. Nonetheless, composite steel and concrete guideways have evolved as a cost effective acceptable transit guideway alternative. The composite concrete top allows adjustment of tolerances in the field, provides damping for vehicle noise and increase the stiffness of the structure.

Steel allows light weight initial construction and welding makes continuity easy to achieve. Advances in computerized cutting welding and assembly are providing new opportunities for steel structures. Steel beams may also be used with concrete tops for guideways. Both the Atlanta, Georgia and the Washington D.C. transit systems use composite steel guideways.

Elevated guideways for Westinghouse people movers have used steel guideways very effectively, figure 2. Steel WF sections are used for the primary structure and channels are placed on the top flange to increase the section modulus. The channels are filled with concrete to provide the final riding surface. Not only may tolerances be set in the field, but the concrete provides an superior tractive surface for the rubber tired vehicle.

Low velocity peoplemover monorails have adapted advanced fabrication technologies to produce light weight, cost effective structures, figure 3. Beam elements are fabricated for individual spans then welded into a continuous structure. Automated welding techniques reduce the cost of fabrication. Hitachi has developed curved steel guideway beams for its monorail system and steel beams are frequently used for monorail switches.

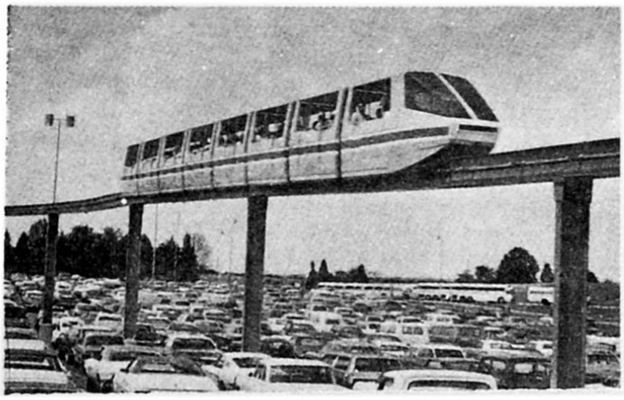

Fig. 2 Westinghouse Guideway
Kings Dominion, Virginia

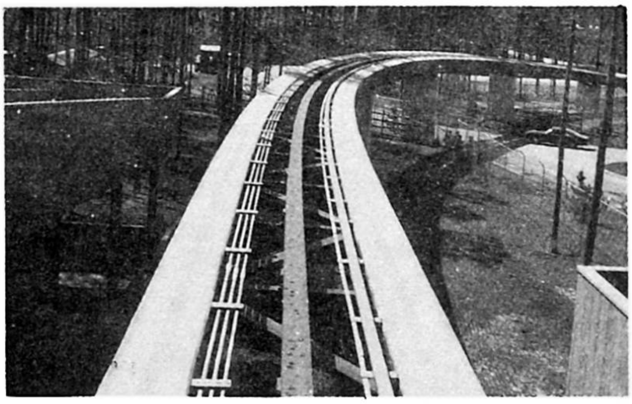

Fig. 3 Minneapolis Zoo
Monorail

4. ENGINEERING INTEGRATION

Throughout this process the structural engineer served as the primary integrator of the technology. In successful designs, the structural engineer incorporated the requirements of the vehicle technology and ride quality, the power supply, the signal systems and the construction industry to complete designs that were economical and aesthetically acceptable.

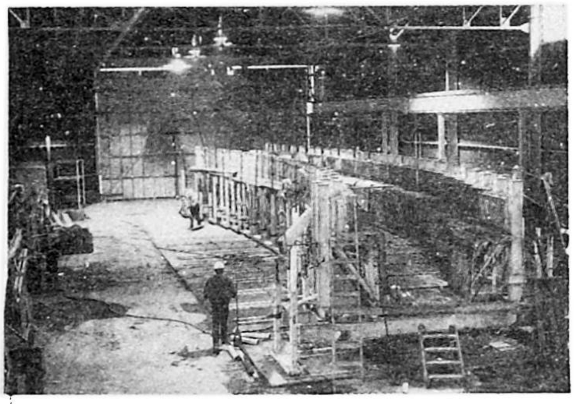

Fig. 4 Adjustable Form for Box Girder Beam Fabrication

High precision adjustable formwork for the variable geometry was a technological breakthrough that continues to benefit guideway design and fabrication. The Vancouver, British Columbia, Canada ALRT and the Detroit, Michigan Downtown People Mover extended the adjustable form technology to box beam sections used rail supported transit systems [7]. Complex forms, figure 4, not only provided the precise geometry needed for the complex route geometry, but also provided fixed cast-in inserts for mounting the rail fasteners and other system hardware. The Vancouver and Detroit systems use two span continuous structures with low friction rail anchors to limit the residual stresses.

The 35 meter radius curves create very large radial forces when thermal expansion of the rails occurs. Consequently, the Detroit system uses expansion joints to relieve the residual rail forces in the guideway. Expansion joints are place at or near the stations to reduce noise created by the vehicle moving over them.

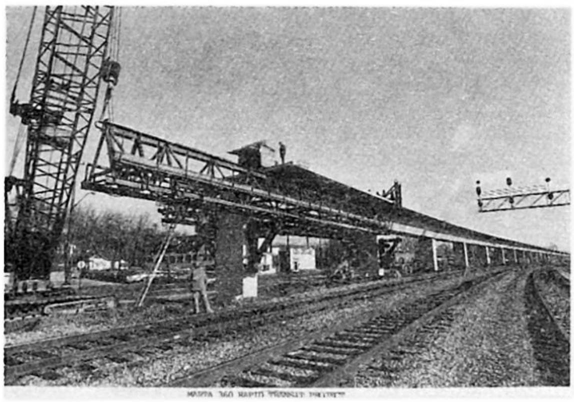

Fig 5. Segmental Construction of the Atlanta Transit System (Courtesy of Figg Engineering Group)

The Metropolitan Atlanta Rapid Transit Administration, MARTA, used another variation of adjustable form casting on a particularly difficult section of their line. Constructing the guideway adjacent to an in-service freight rail right-of-way posed significant construction impediments. Designers elected to use segmentally precast field post-tensioned segmental box beams to solve this problem. The segments could be lifted onto falsework quickly and cranes could work out of the train right of way, figure 5. The smaller precast pieces could be erected on a schedule which allowed uninterrupted train service below.

5. SPECIALTY TRANSIT HYBRID PRECAST CONCRETE

Specialty transit systems have provided a significant array of design concepts which are suitable for urban sites. The Guideway for the Ford Fairlane system in Dearborn, Michigan used a very shallow guideway. This .66 meter deep 3.6 meter wide structure spans 18.3 meters. The construction was similar to the Disney monorail except that the forms were designed to flex vertically with adjustable side walls. Beams were post-tensioned together to provide a continuous structure. The low profile provides improved aesthetics while the width of the guideway offers some protection for pedestrians during inclement weather.

The Airtrans guideway at the Dallas/Fort Worth Airport in Texas uses a straight box section with a curved top flange. This, the Miami Downtown Peoplemover in Miami Florida and the Metropolitan Zoo in Toronto, Ontario, Canada all took advantage of straight casting beds to produce economical sections. The curvature was provided by only changing the alignment of the top flange, figure 6.

Adding to the guideway economy of straight casting was the use of conventional reinforcement to provide negative moment capacity. A second placement concrete topping on the Toronto Zoo guideway further separated the plant construction

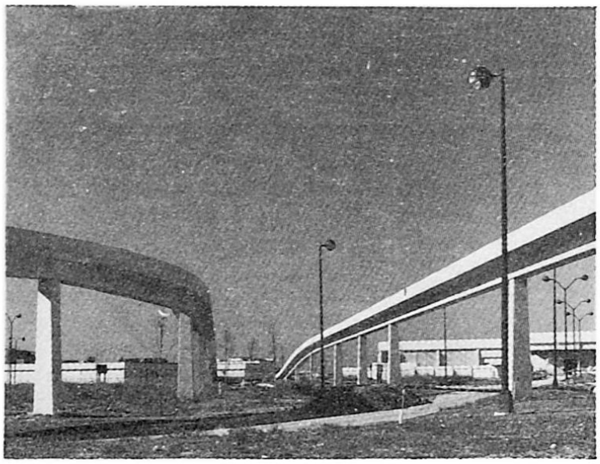

Fig 6. Straight stems and curved decks offer economy during construction at the Dallas/Fort Worth Airport.

tolerances from the field installation requirements.

A transit alternative developed by the Ministry of Transportation in Ontario, Canada uses a central spine beam and cantilevered side structure [10]. The central spine becomes not only the main structural support, but also the emergency walkway. Cross members supporting the rail are open to allow snow and debris from collecting in the structure.

6. ADVANCED STATE-OF-THE-ART GUIDEWAYS

New transit technologies based on magnetic levitation propulsion are being developed in Germany and Japan. The guideways for these installations require the integration of all the design and construction technology to construct cost effective structures. The high operating speeds of these vehicles and the very tight magnet tolerances are primary design parameters. The MBB test track at Emsland, Germany is typical of the design issues [11]. The attractive magnets have very close tolerances for the placement of the supporting rails to assure motor efficiency and control stability. Dynamic amplification of the structure due to passing trains increases the tolerance requirements and creates high impact loads on the columns and substructure. Even with these constraints, reasonable sized guideways are constructed.

Japan Rail's magnetic levitation train uses repulsive magnets to support the train. Efficient magnet use limits the amount of magnetic materials available in the guideway. Consequently, Japan Rail is conducting a research program to qualify non-metallic prestressing and reinforcing materials for concrete guideways.

7. CONCLUSIONS

Transit system guideways have the characteristic of well defined loads, high number of load cycles, and unique interface requirements. Guideway design offers an opportunity to merge design innovation, construction techniques and urban integration. The characteristic features of a transit structures apply to both steel rail supported systems and for specialty transit applications. The guideway designer should be cognizant of the potential for innovation and cooperation with the construction industry. Working as an integral part of the system engineering effort, the structural engineer is a primary position to affect the total cost of the installed transit system. Computer assisted design and construction provide substantial cost advantages. Aesthetically acceptable,cost effective, innovative structures can enhance both the urban setting and the attractiveness of the transit system.

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