Performance/Design Criteria for the Airtrain JFK Guideway

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Summary

The AirTrain Light Rail System serving JFK International Airport is an 8-mile dual-track automated system using linear induction motor (LIM) propulsion and is scheduled to start on-airport operations in the fourth quarter of 2002. The design-build contract called for 6.3 miles of single-track and 3.2 miles of double-track aerial guideway structure and required continuous steel rail tracks with direct fixation throughout. In addition, the rail-structure system was required to sustain the local design seismic event with the ability to restore service shortly afterward. To meet the performance criteria developed by the Port Authority of NY and NJ, the design-build contractor utilized continuous multi-span concrete box girders connected by transverse shear keys and supported on seismic isolation bearings. The track rails are completely continuous across all expansion joints in the structures and are only anchored at the two ends where the aerial structures terminate. The contractor chose to design and install an elastic restraint system attached to the seismic bearings. This system resists bearing lateral movement under service loads but will break away in an earthquake to allow the seismic bearings to isolate the box girder superstructure and track.

Overview

John F. Kennedy International Airport is a primary gateway for New York City, a densely populated urban center that attracts people from all over the world. Presently, JFK handles about 30 million passengers annually; in ten years that number could increase to 45 million.

JFK International Airport terminals are located along a two-mile perimeter roadway called the Central Terminal Area (CTA). Passengers transferring between airlines, traveling to rental car facilities, or to long-term parking lots are required to use airport buses. With increased numbers of passengers, the bus transfers have become time consuming and have contributed to significant traffic volumes on the airport roadway network during peak hours of operation. In addition, JFK is also difficult to access by highways from Manhattan and other parts of the Greater Metropolitan area of New York City due to heavy traffic volumes. To mitigate both of these problems and to realize growth potential, the Port Authority, the airport operator, planned the design and construction of a light rail system to relieve traffic congestion and improve access. The system shown in Figure 1 is called AirTrain JFK and consists of 8.0 miles of grade-separated track and ten passenger stations. This system connects airline terminals, car rental, and parking areas of JFK Airport, and also directly connects to the regional transit systems.
AirTrain JFK provides three distinct services as follows:

Terminal Circulation Service – This service is dedicated to the Central Terminal Area (CTA) of JFK airport. During peak periods trains will run in the clockwise direction in the CTA to serve the six stations needed to serve all of the airline terminal buildings in the CTA.

Howard Beach Service – This service begins and ends at AirTrain’s Howard Beach Station, which is integral with the new inter-modal mezzanine being constructed over the NYCT’s Station at Howard Beach for the “A Train” serving Queens, Brooklyn and Manhattan. Trains departing from AirTrain’s Howard Beach Station will serve the Long Term/ Employee Parking Lot Station, Federal Circle Station (Car rental area) and the six CTA stations with trains running in the counterclockwise direction. During peak periods trains will depart the Howard Beach Station every 4 minutes.

Jamaica Service – This service begins and ends at AirTrain’s Jamaica Station, which is integral with the new inter-modal Vertical Circulation Building (VCB) and mezzanine being constructed over the Long Island Railroad (LIRR) platforms in Jamaica with direct access to the NYCT Station for the E, J, and Z lines. Trains departing from this AirTrain’s Jamaica Station will also serve the Federal Circle Station (Car rental area) and the six CTA stations with trains running in the counterclockwise direction. During peak periods, trains will depart from Jamaica Station every 4 minutes and these trains will alternately merge with the Howard Beach trains at Federal Circle such that the frequency of the combined services in the counterclockwise direction in the CTA will also be two minutes.

System Description

While the system uses steel wheel/steel rail technology, AirTrain JFK is not a typical rail system. AirTrain JFK is a fully automatic/driverless system with environmentally controlled stations designed to serve the on and off airport needs of JFK International Airport.
The alignment has a tangent section long enough to reach a top operating speed of 60 mph but also has a significant amount of tight radius curvature with mainline radii as low as 230 feet. The CTA consists of two loop tracks each with a circumference of about 2 miles as can be seen in Figure 2. The six CTA stations are center platform stations, which allow boarding passengers to access all three services from the same platform. The terminal circulation service runs on the inner loop track and the Jamaica and Howard Beach services share the outer loop track. The terminal stations at Howard Beach and Jamaica use a #8 double crossover to turn trains. The junction of the Howard Beach and Jamaica service at Federal Circle also uses #8 turnouts. The remaining mainline turnouts are normally used for failure management operations and may be either #8 or #6 turnouts depending on site constraints.

The track consists of 115 RE rail set on standard gauge on tangent track and gauge widening is used in curved tracks to help equalize wheel wear. The contract required that the rail be continuously welded rail mounted with a direct fixation system.

AirTrain JFK is powered by a top-running contact rail with a nominal voltage of 750 Vdc.
The AirTrain JFK rail cars are 57 feet 9 inches in length and are 10 feet wide at the threshold. There are two doors per car per side. The doors are six feet in width to allow easier boarding for passengers carrying baggage or using baggage carts. The operating capacity is about 75 to 78 passengers per car. This capacity is less than the capacity normally applied in mass transit systems. The capacity reflects the need to allow more space per passenger to account for baggage and to provide sufficient circulation space for a more consistent dwell time at the stations. At the option of the contractor, the cars use a linear induction motor (LIM) rather than the typical rotary motor. The LIM requires a reaction rail located between the running rails. In addition, the cars have steer-able trucks, which will minimize rail and wheel wear.

The alignment is fully grade separated with 5,160 feet of dual track at grade, 1,987 feet of dual track on retained fill, 820 feet of dual track in retained cut, 1,000 feet of dual track in cut and cover tunnel, 33,425 feet of single track on single track aerial structure (equivalent to 16,712 feet of dual track) and 16,675 feet of dual track on dual track aerial structure. The aerial structure consists of externally post-tensioned precast concrete segments supported by seismic bearings. The bearings sit on cast in place concrete columns generally 5 or 6 feet in diameter, which in turn are supported by a pile foundation.

**Project Implementation**

Although the topic of this presentation is technical in nature, understanding the method of project implementation is critical precursor to the technical discussions. The Port Authority of New York & New Jersey decided to implement the AirTrain project using a Design-Build-Operate and Maintain (DBOM) approach. The primary objectives of the DBOM Approach may be summarized as follows:

- To ensure that the LRS is being procured under a negotiated competitive process
- To have a single contractor team be responsible for all aspects of the design, construction and operation of the system
- To minimize the delivery time by allowing the entity that will build and operate the system develop a “fast-track” schedule for design, fabrication, and construction of the system.

The Port Authority was responsible for overall project management, design review and approval, construction management oversight, and project coordination with all affected agencies, airport tenants, and affected communities.

This approach required that the Port Authority issue a request for proposals (RFP) and that various consortiums respond with a proposal that provides management, technical, operating, maintenance and cost information. The Port Authority, through a negotiated procurement process, reviews these
proposals and selects the best proposal based on a detailed evaluation process. Portions of the RFP dictated specific requirements such as the use of 115RE rail and tangential design for the turnouts. Other sections of the RFP provided performance specifications and left the specific solution to the proposer’s judgment. In particular, the type of aerial structure and its supporting systems was left to the proposer. The RFP did not require externally post-tensioned precast concrete segments supported by seismic bearing. This was the choice of the proposer.

Unique performance design criteria were developed to ensure that the selected DBOM team achieves the Authority’s reliability and durability objectives. This includes resumption of service in the event of an earthquake, and the accommodation of a future multi-system rail car that will provide an uninterrupted ride to Manhattan in a later phase.

The successful proposer after contract award is referred to as the DBOM contractor. The successful team was the AirRail Transit Consortium, a joint venture led by Slattery-Skanksa and Bombardier and includes Sordoni for stations and other buildings, Koch-Skanksa for guideway erection and a design team led by STV Inc. The design team for the aerial structure includes Figg Engineers for the superstructure and Mueser Rutledge Consulting Engineers for the foundations, while STV performed analysis of the entire guideway structure and the design for the columns, seismic bearings and track work.

**Guideway and System Design Criteria**

The performance specifications for the project call for the DBOM contractor to design, furnish and construct a fully grade-separated track way on a proposed alignment and preliminary profile. Passenger stations, vehicles, track work, an automatic train control system, communications systems, a supervisory control and data acquisition system, a traction power system, and operations, maintenance and storage facility were also part of the contractor’s scope. The main focus, herein, will be the aerial guideway and track way. There were two general project design criteria that applied to the guideway structures and system technology. These were: that design for durability be based upon a 50-year life and that all technology employed in the system have a proven track record.

**Guideway Design Forces**

Even though the DBOM team will provide custom designed vehicles for AirTrain JFK, the design criteria specified minimum train loading for the design of the guide-way structures. This loading was based on a survey of various light rail transit systems planned or in operation with sufficient capacity to transport the projected volumes of riders at JFK. For vehicle structural strength and crashworthiness, criteria typical for light rail vehicles were specified. A service proven light rail vehicle system comprising steel wheel trucks, running on standard gauge steel rails, and powered by 750V DC top contact third rail was also specified. This, not only assured minimal risks associated with design, construction, operation and maintenance but also provided basic compatibility with the regional transit system comprising the LIRR and the NYCTA.

Because the light rail vehicles differed significantly from the standard rail live load in the AREMA specifications the American Association of State Transportation Officials (AASHTO) Specifications for Highway Bridges and its applicable guide specifications were used with modifications to
incorporate light rail system (LRS) loads and effects including: LRS vehicle weight and impact factors, centrifugal force, rolling force, longitudinal braking and tractive force and rail/structure interaction force. All other forces were similar if not identical to those specified in AASHTO.

A system that utilized direct fixation of the rail to the structure required an analysis for interaction between the rail and structure including the effect of the structure expanding and contracting beneath the rail, the effect of one rail breaking, and the effect of the structure restraining the rail from displacing in the radial direction on horizontal curves.

The standard AASHTO loading combinations were used, with rolling force added to the loading combinations with live load, and rail interaction forces added to the loading combinations with thermal force. Loading combinations for service load design and load factor design were specified. The structural analysis of the multi-span guideway units was performed both with and without the continuous rail in the model. This was done since the rail is not a structural element of the guideway but significantly influences the continuity and distribution of load. The worst-case forces or stresses (with or without the rail) had to be used to design the structure. When the continuous rail was part of the model, the designer STV had to include in the model adjacent up-station and down-station multi-span units, as well as, the multi-span unit being analyzed and designed.

Seismic Design

Seismic provisions are an important aspect of the design criteria. New structures at JFK have been designed for seismic forces since 1987. New York City adopted seismic design for buildings in 1996. Due to the presence of deep loose sands at JFK, soil borings indicate the potential for liquifaction up to a depth of 20 feet under the design seismic event.

The Port Authority’s RFP had a technical section entitled 15.5 STRUCTURAL DESIGN PARAMETERS. This section provided the requirements for the aerial structure including conformance with AASHTO’s Standard Specifications for Highway Bridges, using an acceleration coefficient of A=0.15, using a site coefficient of 1.2 and the need for the design to address rail/structure interaction issues. The RFP also had a technical section entitled 15.6 GEOTECHNICAL DESIGN CRITERIA AND PARAMETERS. This section advised the proposer that the soil conditions in the project had areas that were prone to liquefy under the design earthquake magnitude of 5.75.

The above design requirements however did not convey the Port Authority’s intent for the AirTrain JFK system after experiencing a seismic event. Once a system like AirTrain is in place it is critical that such a system will remain operational, or be restored to operation as soon as possible after a seismic event. The design seismic event for the New York area is at a level that the system can be designed to handle the seismic loads without extensive damage. Therefore the Port Authority added the following requirement to the RFP.

The basis of the Proposer's concepts for the design of the foundations and structures and their cost during Proposal preparation shall be such that the facility could be readily restored to service after the occurrence of a seismic event causing liquefaction to the depths indicated above, i.e., alignment deficiencies should be able to be corrected by adjustment of the rails and the tolerances required for safe operation should be capable of being restored, if necessary.
Furthermore, the Port Authority required the proposers to include in their proposals the following:

* A complete set of sample calculations for the geotechnical analysis and design of aerial structure foundations for a typical 40 foot high dual track structure. The sample analyses should include a narrative describing the approach for each stage of the design and a complete set of geotechnical design and analysis calculations. Separate sample geotechnical analyses should be performed for soil conditions represented by the following borings.

  * Boring No. 4-126
  * Boring No. 4-130

Each proposer had to address this issue by submitting the above analysis with their proposal. The Port Authority gained significant insight into each proposer’s solution by reviewing these analyses and was able to address specific design related issues prior to contract award.

In particular, the use of lead core seismic bearings raised concern about rail/structure interaction and the potential of adjacent superstructure segments to displace in the opposite direction with severe damage to track and cable systems. To address these concerns the following section was inserted into the technical provisions of the contract.

**Elastic Design Deflection Criteria** - The Design Deflection Criteria for the entire System for seismic and non-seismic loading conditions shall be as follows:

1. **Foundation Displacement top of pile cap**

   Foundation displacement shall be designed in accordance with AASHTO Division 1 - Design Section 4.4.7.2.5 “Tolerable Movement”

   Where tolerable movement criteria for horizontal foundation movements are addressed in Design Section 4.4.7.2.5, small vertical displacement shall be defined as less than 1 inch.

2. **Pier Displacement including foundation rotation**

   Less than or equal to L/300 under non-seismic loading conditions and L/200 during the design seismic event, where L is the distance from the top of the pile cap to the bottom of the guideway bearings.

3. **Isolation Bearings under seismic design event**

   Less than or equal to 50% of the maximum shear strain capacity of the bearing or 2 inches, whichever is less computed vectorially. Shear keys at the guideway top slab at expansion joints shall be used and shall be operable during the seismic event.
4. Isolation Bearings under non-seismic loading

The elastic deflection of the seismic isolation bearings under non-seismic loading conditions shall be restrained to 1/8 of an inch in the direction normal to the LRS tracks through the lead core of the proposed bearing or, if the lead core is insufficient, the use of elastic restraint devices in addition to the shear keys indicated in Item 3 immediately above.

The above deflection criteria shall be incorporated into the design of the guideway and guideway appurtenances.

Of particular note is the requirement for shear keys in item 3 which mitigates any tendency for adjacent segments to moved in opposing directions. Keying the segments together will keep damage to the track and cabling systems to a minimum.

Item 4 is a little more interesting. At the proposal stage, the exact behavior of the lead core bearing during a non-seismic event was an unknown. The non-seismic event includes wind, and of particular concern, the thermal forces caused by the continuously welded rail, especially on curved tracks. The lead bearing offered significant resistance but over time the lead can relax and the bearing can deform. On the other hand, during a seismic event it is important that the bearings are free to move in all directions because that movement is essential to damping the forces induced by a seismic event.

Features of DBOM Team Design

Prior to advertising the RFP a 10% to 15% preliminary design was prepared for the guideway to estimate construction costs and to give the proposers a base design which could be developed further into a final design without extraordinary time and effort. The basic components of the preliminary design for guideway structure included:

- Full-length precast pre-stressed twin-box concrete girders for two-track guideways and single box girders for single-track guideways. A steel box construction in composite action with a reinforced concrete deck slab was also given as an optional alternative.

- Cast-in-place reinforced concrete deck slab closure pours, plinths, parapets, catwalks and utility duct-ways.

- Cast-in-place reinforced concrete cap beams with supports for dapped box girders.

- Cast-in-place reinforced concrete round pier columns.

- Cast-in-place reinforced concrete pile caps supported on concrete-filled pipe piles, utilizing batter piles to resist horizontal forces.
Except at particular locations requiring special structural configurations, the preliminary guideway superstructure consisted of a series of simple spans, each supported on fixed bearings at one end and guided expansion bearings at the other end. The maximum modular span was 110 feet.

The notable features of the DBOM design that differed from the preliminary design in the bid documents was as follows:

- The guideway superstructure was designed for precast segmental construction
- The guideway superstructure consisted of box girders continuous over multiple spans
- The guideway substructure is designed based on the concept of seismic isolation
- The parapets and the catwalk/utility duct-way are precast concrete

The DBOM Guide-way superstructure is comprised of two typical cross-sections. The Type I, or single-track guideway box is shown in Figure 4, while the Type II, or dual-track guideway box is shown in Figure 5. Typically, individual spans are longer in the DBOM design. Additionally, post-tensioning tendons are applied across span closures to create multiple-span continuous units. For concrete segmental construction the contract called for adherence to the AASHTO/ASBI Guide Specifications for Segmental Bridges.

The longer spans and continuous units between expansion joints make it a more challenging task to control the possible gaps that may result from a rail break. The analysis prepared by the guideway designer computed the maximum possible gaps due to a break. The DBOM car supplier had to
review and accept the anticipated rail break gap associated with the proposed guide-way structures or as an alternative the contractor has to provide the LRS with a rail-break detection system.

To permit the maintenance of traffic on adjacent streets and highways, the majority of the guideway was built span-by-span with cranes and triangular trusses as shown in Figure 6. Some portions of the guideway were built in balanced cantilever construction for tight curvature or longer spans as shown in Figure 7.

Seismic isolation is achieved by the use of lead-rubber bearings. The superstructure is to “float” on the bearings during a seismic event. For non-seismic loading, however, the bearing must be fixed laterally in the transverse direction (movement limited to a 1/8th inch range) relative to track centerline. The Contractor and bearing supplier developed an Elastic Restraint System (ERS) that will withstand non-seismic loads with an appropriate factor of safety, and will reliably break away at design-level seismic loads. The system consists of galvanized steel plates fastened to the upper and lower bearing plates with stainless steel threaded rods as seen in Figure 8. At mid height of the bearing the galvanized plates are bolted together with stainless steel threaded rods that are necked down to break at a certain seismic shear force that exceeds the service level lateral force needed to laterally restrain the continuous rail. The guideway designer placed the ERS devices at bearings on and adjacent to curved track alignments and in some cases where the bearings are along a highway right-of-way at bearings on tangent track alignments.
As required by the AASHTO guidelines for base isolation design, the bearings were tested at the bearing manufacturers plant with the ERS devices in place. Load cells and displacement measurements showed that the ERS device performed as designed.

Installation Of The Continuous Rail

The concrete plinth was cast-in-place continuously on the erected and post-tensioned multiple span elevated guideway units. All reinforcing steel in the plinth, pre-cast concrete guideway and cast-in-place concrete piers was epoxy coated both for longevity and to provide isolation against stray current. The pre-cast concrete segmental units had protruding loops of reinforcing steel at the interface with the plinth concrete to make the plinth composite with the box girder. The plinth was detailed to provide for adequate drainage pitch to scuppers located adjacent to the expansion joints between multiple-span guideway units. Drain pipes are located within the concrete pier columns with clean-outs located at the top within the interior of the box girder and at the bottom near the column pier bases.

The contractor developed jigs made from rail segments to set and cast the sheathed direct fixation fasteners in their final, surveyed-position within the concrete plinth. A Pandrol clip system was used to fasten the rail to the track bed with neoprene pads providing isolation of current. The LIM propulsion system requires a center LIM “reaction rail” also fastened to the track bed with hold-down anchors to the plinth concrete. The vertical tolerance for setting the LIM rail is very tight since a predefined gap must be maintained between the LIM motor and the reaction rail. There are also safety guide rails in the track bed consisting of steel angle sections that prevent vehicles from derailing. See Figure 9.

Eighty-foot-long segments of rail were fusion welded together into 1,300 to 1,560 foot-long lengths at a point in the system where the AirTrain alignment is on grade. The longer segments were then transported on dollies to their final locations either at grade or along the elevated guideway. The rail was installed at a temperature of 90 degrees Fahrenheit (plus or minus 5 degrees) in accordance with the contractor’s calculations to assure that the rail will not buckle under the extreme operating temperatures. The continuous rail is anchored on elevated guideway structure against longitudinal movement at the Howard Beach Station terminus and at the Jamaica Station terminus. At these locations the contractor provided a pot bearing fixed against lateral movement that could safely resist a longitudinal thermal anchoring force of 250 Kips for each Type I single-track box girder unit. At the terminal locations mentioned above the fastening details for the rail had to be modified to
accommodate the high anchoring force. To do this the spacing of the rail clips in the end span box girder units were reduced from 24 to 12 inches on center. In addition, adjacent to each rail at the end of the span, a second in-board length of similarly fastened rail about 11 feet long was added and horizontally-fastened to the continuous rail with braces and frog-type bolts to transfer the high anchoring force from the rails to the box girder within the simply supported end span. The additional in-board rail could be added because the safety guide rail and LIM reaction rail terminate before the end of the guideway.

In the summer of 2000, the first section of continuous rail was installed at the Howard Beach section of guideway without the ERS system in place, because testing and delivery of the ERS was not yet complete. When the cold winter months approached, the guideway box girders, which were on curved alignments, exhibited a dramatic lateral displacement in the transverse direction (radial direction to the track tangent). This demonstrated the need for the ERS devices since the lead-rubber bearing cannot resist a sustained lateral force because the lead core gradually relaxes. See Figure 10. When the following summer brought warm weather the rail temperature returned to its level at installation and the bearings straightened out. The ERS devices were then installed and since have weathered cold temperatures without any transverse displacement. See Figure 11.

Future LIRR System Compatibility

The project performance specifications called for car widths and station platform heights that are compatible with the LIRR and NYCT transit systems. This leaves open the possibility of providing a “one seat ride” from Manhattan to JFK by directly connecting AirTrain JFK to the LIRR or NYCTA rail systems at either Jamaica or Howard Beach.
For the “one seat ride” service, a new rail car will have to be designed to operate both on AirTrain JFK territory as well as on LIRR/NYCTA territory. This vehicle has to have structural strength and crashworthiness compatibility with the Heavy Rail Vehicles operated by LIRR or NYCT. The AirTrain vehicles are fully automated with a linear induction motor (LIM) traction system and steerable bogies to make the tight turn radii in the JFK CTA. The LIRR and NYCTA systems are manually controlled with conventional electric motor propulsion. It is feasible that a hybrid rail vehicle that could run on both systems can be developed, manufactured, tested, and eventually put into service.

Conclusions

The AirTrain JFK Project is nearly complete. The Terminal Circulation Service and Howard Beach Service will both start operating in the fourth quarter of 2002. The Jamaica Service will start operating in early 2003. Keeping in mind that the DBOM contract was awarded in May of 1998 when final design first commenced, the actual progress is quite dramatic. As far as design and construction is concerned, lessons (from the Owner’s perspective) have been learned and much of the intent of the DBOM approach has been validated. They may be summarized as follows:

- The owner’s role is vital in overall project management, construction management oversight, and project coordination with all affected agencies, airport tenants, and affected communities.
- The submittal review and approval process customary to US public works projects must be modified and accelerated for DBOM contracts.
- Both the contractor and owner must show flexibility, support and trust in reaching the common goal of completing the project in a timely and cost effective manner.
- The responsibility and risk of conforming to the project criteria in designing and in implementing work in the field must be left to the DBOM contractor.
- The DBOM contractor has to take ownership of all elements of his design and provide all the necessary features required to operate and maintain the system in accordance with the contract.
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The DBOM contract was awarded to AirRail Transit Consortium (ARTC). Guideway and track construction is by Slattery Skansa, Inc., Koch Skansa, Inc., and Perini Corporation, members of the ARTC construction joint venture. STV, Inc. is the design engineer for the guideway structures and track with the box girder superstructure design subcontracted to Figg Engineers and the foundation design subcontracted to Mueser Rutledge Consulting Engineers.