



RESILIENT INFRASTRUCTURE

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UNION PEARSON EXPRESS SPUR AND T1 STATION

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ABSTRACT

The Union Pearson Express Spur and station in Terminal 1 is a Design-Build-Finance pursuit by Infrastructure Ontario on behalf of the client/owner, Metrolinx. The rail passenger service line branches off the existing GO Georgetown Rail corridor and connects to Toronto Pearson International Airport with a new passenger station at Terminal 1. The Spur alignment is elevated over its entire length and crosses above major existing airport access roads and existing bridges, and connects to a new UP Express Terminal 1 Station in-line with the existing Automated People Mover Station.

The Spur Elevated Guideway is a 3 km long, multi span structure carrying two railway tracks. The tracks are made of continuous welded rail (CWR), directly fixed to the concrete deck. The deck is supported by pre-stressed concrete beams creating composite action. The substructure consists of seventy single column piers with “hammer head” cap supported on augured caissons; and eleven existing bents that carry both UP Express Spur and Automated People Mover.

To understand and assess the structural behavior between the CWR and the structure, Rail-structure interaction design of the Guideway was performed using non-linear 3D finite-element analysis of the entire structure. The analysis and modelling included all Guideway superstructure and substructure elements, and track structure including direct-fixation rail fasteners with non-linear behavior. The results were used to optimize the design of individual Guideway components.

This innovative approach allowed staged design delivery to meet an accelerated schedule in a design-build environment.

1. INTRODUCTION

UP Express is a new air rail link, connecting Canada’s two busiest transportation hubs – Toronto Pearson International Airport and Union Station in downtown Toronto. UP Express service is to run at 15 minute intervals during the airport operating hours, with each one-way trip taking about 25 minutes. Full revenue service started in spring of 2015 before the 2015 Toronto Pan Am Games.

UP Express service required upgrades and changes along the shared 22-kilometre stretch of the existing GO Kitchener rail corridor, between Union Station and the beginning of the UP Express Spur into the Airport. Those upgrades were part of a separate larger infrastructure project – the Georgetown South Project.

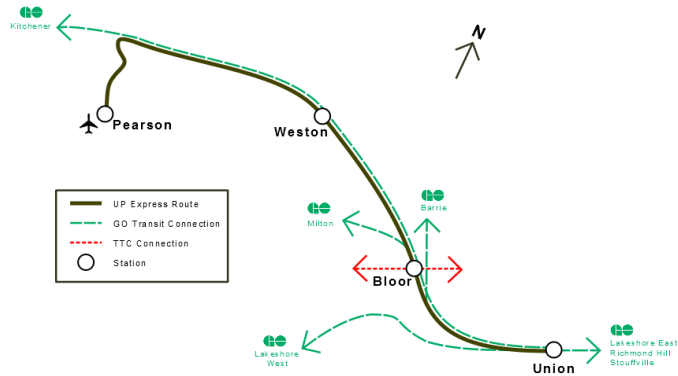


Figure 1: UP Express Service Map

A key element of the UP Express was the construction of a new Spur between the existing GO Kitchener rail corridor and Terminal 1 at the Airport. The design-build-finance contract for the design and construction of the Spur was tendered by Infrastructure Ontario and Metrolinx, and awarded in late 2011 to AirLINX Transit Partners (a joint venture between Dufferin Construction Co. and Aecon Group Inc.) with AECOM as a design consultant.

The Spur is 3 km long and consists of the 300 m at grade section and 2.7 km elevated Guideway that carries two railway tracks. At the end of the Spur a new Terminal 1 Station is located next to the existing Automated People Mover Station.



Figure 2: UP Express Spur

2. EXISTING CONDITIONS

The UP Express Spur branches off the GO Kitchener rail corridor on the west side of Highway 427 (east of Goreway Drive), and from there runs adjacent to Highway 409 to Terminal 1. It crosses over several roadways – Goreway, Zahavey, Network, Viscount and Airport Roads – as well as Mimico Creek. This section of the Guideway, north of Airport Road, was raised above the existing roadways to maintain required clearances up to 10 m above existing grade. Various underground utilities, including pipe lines and transformer grounding grids, dictated the layout of sub-structure, to minimize relocations.

South of Airport Road it crosses the network of Airport access roads and bridges including the Automated People Mover (APM). It ends in a “canyon” between the Terminal 1 frontage roads and T1 Parking Garage, in front of the APM T1 Station.

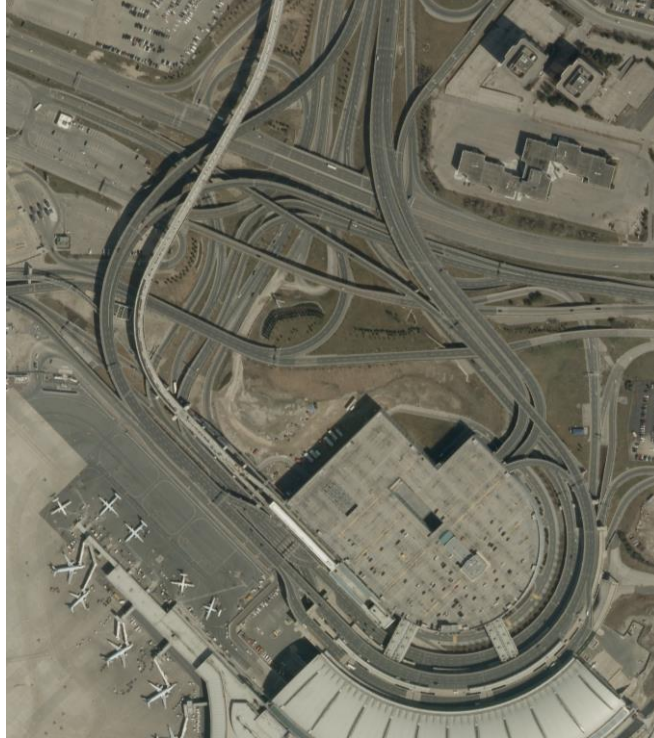


Figure 3: Airport Road Network

The Guideway reaches heights of 28 m above grade in order to cross existing three levels of roads. Guideway sub-structure location was governed by available lands between existing Airport infrastructure elements (roads, bridges, APM, utilities, etc).

The T1 Station and the end segment of the Guideway were constructed on the existing APM bents next to the existing APM Station. These bents were originally constructed to support future Guideway and T1 Station.

Guideway geometry was governed by the track design that had to fit into available corridor lands. This resulted in two sharp curves and profile grades that were maximized.



Figure 4: Existing bridges and Guideway

3. ELEVATED GUIDEWAY

The Guideway tracks consist of 115 lb continuous welded rail, supported by direct fixation fastener system with concrete plinths on concrete deck. It provides two tracks for the entire length of the Spur, including a No. 8 scissor (diamond crossover) immediately north from the T1 Station.

Typical cross section encompasses two UP Express vehicles with future OCS poles located between the two tracks and the walkway envelope (per NFPA 130) on each side.

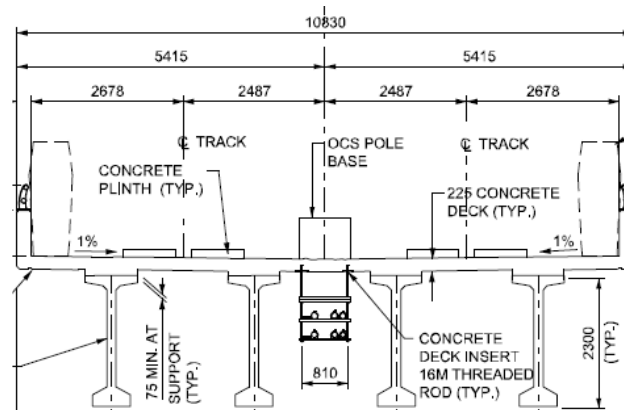


Figure 5: Typical Guideway Section

At the location of the diamond crossover, the cross section is similar to typical, with the future OCS poles located on the outside of the Guideway.

In front and at the ARL Station, the Guideway cross section is divided into two independent cross sections, each supporting one ARL vehicle with the future OCS poles located on the outside of the Guideway, and with the walkway envelope (per NFPA 130) located on the inside of the Guideway between the crossover and the start of the station platform.

Concrete parapet walls (800 mm high) are provided throughout the Guideway with 300 mm railing on top.

Guideway drainage is via deck drains, typically located at every second span.

Guideway superstructure consists of cast in place reinforced concrete deck supported on girders. The deck has a variable width, 10830 mm in the tangent, to 11540 mm in curves, for the double track section; and variable width (4870 mm to 5500 mm) at the single track section adjacent to the T1 Station. The deck depth is 225 mm.

The concrete deck is supported on precast and pre-stressed concrete CPCI Girders between the GO Kitchener line and the Guideway, split in front of T1 Station, and on steel girders at the T1 Station for the single track parts of the Guideway. The girder spans vary between 12.3 m and 38.0 m.

Typically, 4 – CPCI 2300 girders are used throughout majority of the Guideway with the following exceptions:

- 5 – CPCI 2300 at two sharp curves;
- 6 – CPCI 1900 at the Guideway high point to maintain vertical clearance to existing road bridge below;
- 4 – CPCI 1600 at APM crossing to maintain vertical clearance;
- 6 – CPCI 1600 at diamond crossover;
- 2 – WWF 1600 steel girders, per track, at the T1 Station.

Integral pier caps are provided at P1 (Goreway Drive crossing) and EP 19 (APM crossing), in order to maintain required vertical clearance. The remainder of the girders are supported on elastomeric bearings.

Typical Guideway superstructure is a two span continuous system with deck expansion joints provided at every second (even) pier, with the exception of the Guideway structure at track double crossover and in front of the T1 Station.

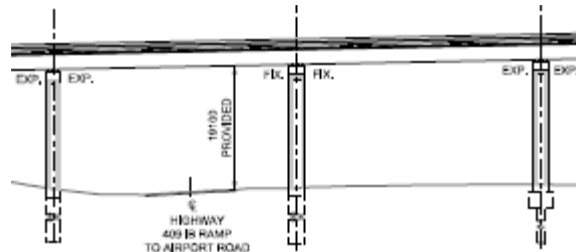


Figure 6: Typical Guideway Elevation

Typically, Guideway superstructure is supported on cast in place reinforced concrete pier caps which are supported on single columns, at each of new 70 pier location (from P1 to P70).

These new columns are typically supported on a single concrete caisson, driven in till layers down to bedrock. Where utility conflicts cannot be resolved by utility relocation, or where increased soil lateral resistance is required, multiple caissons with a caisson cap were used.

Between EP 18 and EP 28, the Guideway superstructure is supported on the existing APM piers. Required modifications/ extensions of existing APM piers are designed and constructed as cast in place reinforced concrete structure. Originally, existing APM piers were designed to carry additional loads from the Guideway and T1 Station.

4. DESIGN REQUIREMENTS

The Project Agreement prepared by the owner, specified various design requirements that had to be met in order to achieve project compliance. The main requirements that governed design were:

- Use of continuous welded rail (CWR) without use of rail expansion joints;
- Use of direct fixation of CWR to concrete superstructure utilizing concrete plinths and direct fixation fasteners (DFF);
- Track design and construction in accordance with AREMA and CN Rail standards;
- Structure design using Canadian Highway Bridge Design Code (CHBDC);
- Project Agreement specified Diesel Multiple Unit (DMU) rail vehicle loading (Live Load, Dynamic Load Allowance, Rolling/Lurching, Centrifugal Forces, Hunting/Nosing, Breaking, Vehicle Mishap Load);
- Project Agreement specified additional base loads accounting for rail-structure interaction (radial and tangential DFF restraint forces, thermal rail forces, broken rail forces) and design load combinations, modifying CHBDC requirements to suit the rail carrying structure; and
- Design and construction of provisions for future electrification of the Spur, such as OCS supports, grounding and bonding.

5. RAIL-STRUCTURE INTERACTION ANALYSIS

The interaction between the CWR and the elevated Guideway takes place through direct-fixation rail fasteners which have nonlinear force-displacement behaviour to facilitate slips between CWR and the superstructure under temperature changes. Factors that have significant influence on this interaction include the following:

- superstructure type and articulation
- type and spacing of rail fasteners
- heights and sizes of piers and caissons
- stiffness of soil
- properties of guideway bearings
- trackwork properties

To analyze this complex interaction mechanism, nonlinear three-dimensional (3D) finite-element analysis of the entire Guideway structure was carried out using commercially available software - MIDAS Civil. This model was used to analyze dead loads, temperature, acceleration and braking forces, broken rail forces, and live loads.

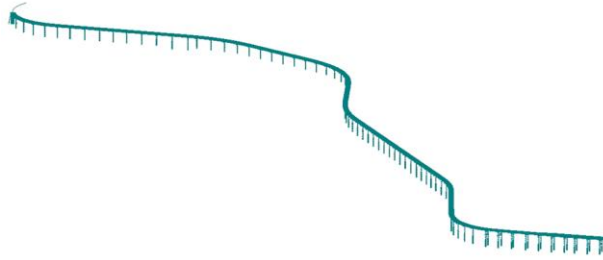


Figure 7: Entire Guideway 3D Model

The results from this rail-structure interaction analysis are combined with the results from separate simplified analysis for additional load cases including live loads, wind loads, mishap loads, etc. for the design of the various Guideway structural components.

The 3D model was built in accordance with the actual horizontal and vertical geometry. All structural components including rails, DFF fasteners, composite deck and girders, piers, and caissons were modeled.

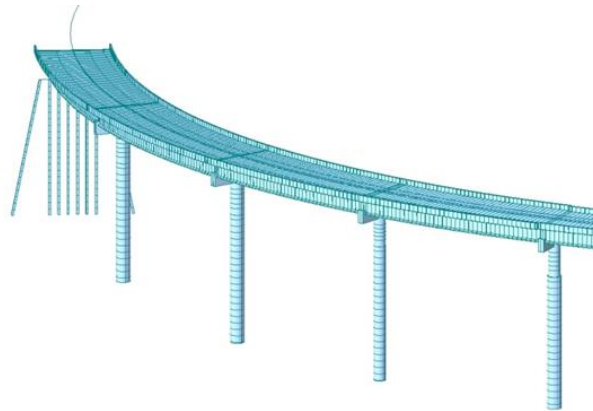


Figure 8: Partial 3D Model

Four rails were modeled with a single element. Individual rails move separately in the section and therefore, the total moment of inertia in vertical axis at the Guideway centre is the sum of the inertia of each individual rail. Separate analysis was carried out to verify this approach.

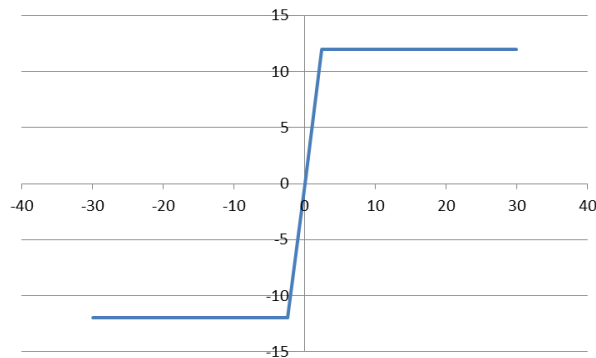


Figure 9: DFF force-displacement properties

Elastic link boundary elements were used for DFF fasteners. At each fastener location, elastic springs were used in the vertical and transverse directions, and elasto-plastic non-linear springs were used in the longitudinal direction, to account for non-linear behavior of DFF. Properties were based on the DFF fastener actually installed on the Guideway.

The stiffness of the founding soils was modeled with soil springs corresponding to actual horizontal subgrade reaction values. Bottoms of caissons are embedded into bed rock and modeled with fixed boundary conditions.

To simplify the model, all bearings in one support line were modeled with one equivalent spring support. To calculate properties of equivalent springs, in each direction, independent models were used. In these models, bearings were modeled with springs, as per the properties provided by the bearing manufacturer, and rigidly connected. Unit forces were applied in the direction of each degree of freedom. Displacement results were used to calculate equivalent spring values of the supports.

6. INTERACTION ANALYSIS FINDINGS

Results of interaction analysis were used for design of structural elements. Following observed findings are specific for this type of guideway structure and associated specific checks were required to ensure structural compliance of the rail-structure system.

The interaction between the curved rails and the guideway structure under temperature changes is generally the governing load case for the design of piers, caissons and bearings. The tangent guideway segments are generally governed by hunting forces and wind loads. Under temperature changes, the superstructure expands or shrinks in tangent portions of the guideway, while rails do not move noticeably in the longitudinal direction.

In curved portions of the guideway, under the temperature changes, both rails and superstructure expand/shrink and move in radial direction. The Guideway structure is articulated to have a series of 2-span continuous bridges with close to equal span lengths on a middle fixed pier, and expansion piers at both ends. This is to reduce/eliminate tangential interaction forces through symmetrical expansion/ shrinkage of the structure. The radial interaction forces are governing load cases for design of piers and caissons in the transverse direction.

Longitudinal forces due to braking and acceleration are distributed over multiple spans through the rails due to relatively high axial stiffness of the rails in comparison to the flexural stiffness of the substructure in the longitudinal direction. Consequently, longitudinal forces by individual pier or caisson are relatively small and do not govern the design of piers and caissons.

Broken rail force effect is typically larger than interaction since this load case adds to the force effect of temperature drop. However, this load case is an exceptional load with load combination factor 1.0, and is not combined with the other major load cases. Therefore, broken rail force is not a governing load case for the design of the substructure. The broken rail gap varies mainly depending on the articulation of the guideway superstructure. Maximum calculated broken rail gap is 50 mm.

Additional rail stress due to the rotation and longitudinal deformation of the deck at expansion joints were also checked using specified extreme load combination. The load combination included rail-structure interaction under low temperature, live load including impact load with snow and ice on vehicle, and temperature gradient of 5°C. Due to the temperature variation and deformation shape, only the temperature drop case with inverse gradient was considered. Position of the vehicle was chosen to create maximum rotation angle at expansion joint. This analysis could not be elastically superimposed due to the non-linear behavior of the Guideway. All individual relevant loads were combined in single load case used for the non-linear analysis. Maximum stress in the rail at expansion joint locations was calculated under temperature drop case and compared to the initial internal stress in CWR under temperature drop without DFF interaction. The resulting additional stress introduced in the rail due to the fasteners and deck deformation was 30.3 MPa and lower than the allowable limit of 140 MPa.

Lastly, maximum relative rotation about vertical axis at expansion joints was calculated to ensure that the Guideway has met serviceability requirements. Maximum rotation at the expansion joints was calculated at 0.0015 radian and within allowable limit.

7. DESIGN-BUILD-FINANCE ENVIRONMENT

This project was delivered through a design-build-finance model. This model stipulates a fixed price and schedule, therefore providing the owner with additional insurance that the project will meet overall operational and service targets and milestones.

The project agreement requires that all design submissions undergo the compliance review by the owner and owner's engineer to ensure that design meets Project Agreement requirements. It adds additional pressure to the design delivery schedule that was accounted for.

The design-builder (contractor) cost and schedule goals are main driving forces influencing the design type and delivery. It was necessary to understand these requirements and approach the project in a pro-active manner and adjust the design process to suit. To achieve this following decisions and commitments were made during the design-build proposal stage and at the beginning of the detailed design stage.

The precast concrete girder structure with cast in place deck was chosen based on the cost and constructability advantages over segmental concrete structure types, early during the proposal stage.

Concrete caissons driven to bedrock were accepted, from the project start, based on the soil's conditions and previous bridge construction experience within the Airport Lands by the design-build team.

Properties of the direct fixation fastener including the type and supplier, as well as bearing properties were chosen during the proposal stage. This ensured that interaction detailed design could start early and be done accurately.

The rail-structure interaction analysis was completed at the outset of the design phase and refined throughout any later structure adjustment and modification.

The results were used to design the Guideway substructure.

Individual two span continuous superstructures were analyzed independently and the results were superimposed with the interaction analysis results, to complete the design of superstructures. This allowed the superstructure designs to be completed in stages in the order of the construction schedule.

The type of precast girders and the girder supplier was selected at the end of the proposal stage. It ensured that the shop engineering support from the precast supplier was available from the start of the detailed design phase.

The project compliance, process driven by the owner, was achieved through multiple smaller submissions, independently done for foundations, substructure and superstructure. Allowing the owner and owner's engineer to be continuously involved in the review process of smaller submissions, eliminated review bottleneck and schedule delays.

This approach allowed the commencement of substructure construction only four months after the start of the design. The design-builder did not have to encounter additional risk of proceeding with construction without the owner's buy-in, and used reviewed and compliant construction documents.

8. CONCLUSION

UP Express Spur design to substantial construction completion schedule (November 2011 to July 2014) required an innovative design approach to enable early construction start. Working closely with the design-builder key design decisions were committed to early in the project and the design was segmented to follow construction schedule. This ensured that the project is ready for revenue service, scheduled to start in spring of 2015.