RPA
Railway Procurement Agency

# METRO NORTH ORAL HEARING

## PROOF OF EVIDENCE TUNNEL & BELOW GRADE STOP DESIGN

**Paul Brown**

Tuesday April 7th 2009

Railway Procurement Agency
Ghníomaireacht um Fháil Iarnród
Parkgate Business Centre,
Parkgate Street, Dublin 8, Ireland
Phone +353 1 646 3400
Fax +353 1 646 3401
www.rpa.ie

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# Metro North Oral Hearing

# Proof of Evidence

# Tunnel and Below Grade Stop Design

**Paul Brown**

# Tunnel and Below Grade Stop Design

## 1 Personal Details

My name is Paul Brown. I hold an honours degree in Civil Engineering, and I am a Chartered Engineer and a Member of the British Tunnelling Society.

I have been employed in the field of civil engineering for the past 18 years, and in the design, construction and maintenance of major tunnelling infrastructure for over 13 years. This has included the Jubilee Line Extension Project, Singapore North East Line, Hong Kong Sha Tin to Central Link, Dublin Port Tunnel, Singapore Deep Tunnel Sewerage System, Dartford Cable Tunnel and the Dartford Road Tunnels.

I have worked full time on Metro North since August 2006 as Design Manager responsible for the underground sections that include the bored and mined running tunnels, Airport Stop, Griffith Avenue Stop, Drumcondra Stop, Mater Stop, Parnell Square Stop, O'Connell Bridge Stop and St. Stephen's Green Stop.

## 2 Introduction

My evidence firstly explains how the configuration, alignment and layout of the running tunnel structures have been determined. This is followed by an overview of the structural design of the running tunnels to accommodate the determined layouts. Finally my evidence describes the structural design of the below grade stops. Further details of the underground construction methods that may be employed for Metro North and the construction planning undertaken by RPA will be described by the evidence presented by Mr. Richard Tucker and Mr. John McLoughlin respectively.

Details of the internal arrangements of the running tunnel structures described are based on those developed for the Metro North Reference Design. The Reference Design contains the essential elements of the system and has been sized accordingly, however as the design is further developed in detail by the Contractor further opportunities for optimisation of the design may become apparent and can be taken advantage of. It is therefore possible that in some cases the optimisation of internal arrangements will generate small changes that will result in most cases in an overall reduction in structure size.

The structural designs described reflect those selected by RPA as being appropriate considering a number of factors including capital construction costs, future ongoing maintenance costs, construction programme, the environment, and construction risk. The Contractor who is eventually selected to undertake the construction of Metro North will also form his own view of the preferred method of design and construction, and therefore in some cases the structural designs described may differ to those that are eventually implemented. Nonetheless the designs described demonstrate project feasibility, and importantly any design changes made by the Contractor will need to demonstrate that the anticipated impacts remain substantially unchanged.

The tunnels and below grade stops will be constructed using cut and cover, or bored and mined tunnel construction techniques Slide 1. In broad terms cut and cover construction comprises the excavation and construction of the below ground structure from the surface directly above. The structure is then roofed over to form the below grade stop or tunnel. In contrast bored or mined tunnel construction is undertaken wholly underground and does not require excavation at ground level directly above the tunnel or below grade stop structure.

The principle structures of Metro North which this evidence addresses are:

- Approximately 2300m route length of twin bored running tunnel beneath Dublin Airport.

- Approximately 5200m route length of bored running tunnel from Albert College Park to St. Stephen's Green.
- Approximately 2700m route length of cut and cover running tunnels.
- 8 cross passages in the bored airport tunnels and 14 in the bored city tunnels.
- 8 cut and cover running tunnel cross passages.
- 2 underground emergency crossovers.
- 1 emergency shaft in the grounds of St. Patrick's College.
- St. Stephen's Green vehicle turn back facility.
- Westbound Iarnród Éireann Interconnector tunnel crossing of Metro North running tunnels, and
- 9 below grade stops.

The configuration, layout and design of the running tunnels has been determined based on specific codes and standards for metros and railways [i.e. the Guidelines for the Design of Railway Infrastructure and Rolling Stock (GDRIRS), Railway Safety Principles and Guidance (UK) and National Fire Protection Association 130 (United States)], system requirements, requirements of the Dublin Fire Brigade and Railway Safety Commission (RSC), and best practice. Precedence from other recent metro projects has also been considered.

# 3 Configuration, Alignment and Layout of the Running Tunnel Structures

## 3.1 Running Tunnel Configuration

The running tunnels connect the below grade stops and carry the light metro vehicles (LMV's). The running tunnel configurations that have been considered for Metro North Slide 2 are:

- Bored tunnel or cut and cover tunnel containing twin tracks and no central dividing wall between the tracks.
- Bored tunnel or cut and cover tunnel with twin tracks separated by a central dividing wall.
- Two bored tunnels or two cut and cover tunnels each containing a single track.

For the purposes of determining the running tunnel configuration the bored tunnel arrangement was considered in detail. The principles that determined the bored running tunnel configuration also apply to determining the cut and cover running tunnel configuration.

RPA has studied the tunnel configuration options for Metro North including carrying out detailed analysis, cost modelling and consultation with the RSC. The study concluded that a twin bore tunnel configuration with each tunnel bore containing a single track was the most appropriate for Metro North. The principal reasons for this conclusion were:

- The RSC guidelines indicate that a tunnel containing a single track will be considered more favourably for operational safety reasons than a tunnel containing twin tracks that are not physically separated.
- Dublin Fire Brigade has confirmed for fire safety reasons their preference for either:
    - i.) A twin bore running tunnel configuration with each tunnel bore containing a single track or,
    - ii.) for two cut and cover running tunnels each containing a single track or,
    - iii.) a cut and cover running tunnel with twin tracks that are separated by a central dividing wall.
- The disadvantage of a tunnel containing twin tracks and no central dividing wall is that the tunnel lengths between stops are such that additional exit shafts would be required at a number of locations to provide a place of safety for escaping passengers and a safe location from which the emergency services can attend to a fire incident. In an urban environment it is more straightforward and less disruptive to provide single track tunnels connected with cross passages to enable escape from the incident tunnel to the non-incident tunnel rather than via shafts from the surface.

- The advantages of a single track tunnel configuration include:
  - i.) The configuration results in shorter distances to a place of safety for emergency escape and emergency services access compared to a tunnel containing twin tracks with no central dividing wall, since the second non-incident tunnel can be accessed via cross passages and utilised as a place of safety.
  - ii.) In a single track tunnel configuration, the ventilation during a vehicle fire can be segregated from the adjacent tunnel and therefore another vehicle within the adjacent tunnel will not be affected.
  - iii.) The magnitude of surface ground movements generated by the construction of the twin bore tunnel configuration is less than that generated by the larger tunnel excavation required to construct the single bore tunnel containing twin tracks.
  - iv.) Finally the twin bore single track tunnel configuration requires smaller tunnels to be constructed, and therefore the risks from changes in geology or those associated with the control of a larger tunnel excavation are reduced.

### 3.2 Running Tunnel Alignment

The key principles that have determined the tunnel vertical alignment design are:

- Stop accessibility. The depth of the stops has been determined by the desire to provide the quickest means of access to platform level given other below grade stop planning considerations that include the accommodation of a ticket hall, passenger access via escalators and lifts, provision of escape stairs and fireman's lifts, and the accommodation of ventilation shafts and plant rooms.
- Outside of the Stop areas there are a number of considerations:
  - The vertical alignment where possible to follow the natural geology of the land with the preference of passing through bedrock with a minimum of one tunnel diameter of rock cover where practicable.
  - Minimise length of tunnels with a mixed face when transiting between geological layers, particularly the rock interface.
  - Limit the depth of the tunnel to 30m to 35m to keep tunnel lining loads and the potential water pressure within a moderate range.
  - Positioning of the tunnel at sufficient depth to minimise settlement to buildings and infrastructure.
  - A minimum vertical grade of 0.5% for drainage, and location of a sump with a cross passage at each low point.
  - Desire to locate below grade stops at high points to assist LMV breaking when approaching a stop, and LMV acceleration when leaving a stop.

The key principles that have determined the tunnel horizontal alignment are:

- To connect the determined positions of the Stops with as direct an alignment as possible.
- Keep to under roads and open land wherever possible when connecting the Stop locations.
- Consideration of the location of major structures between stops.
- Preference for a track separation of 18m to reduce the magnitude of ground movements generated at the surface by underground construction. The closer the tunnels are located together the greater is the overlap of the ground movements generated by construction of each tunnel resulting in increased settlement at the surface.
- Convergence of the bored tunnels at the interface with the cut and cover tunnels, or where the tunnels exit the ground to minimise construction and excavation impacts at the surface. The track separation at these locations has been set at 12m where alignment constraints permit to allow for a minimum of approximately one tunnel diameter of ground between the two bores.

- Provide a straight alignment at TBM launch and reception sites, and in and out of Stop and other tunnel structures to facilitate the reception and launch of the TBM's.
- Achieve a minimum desirable horizontal track radius of 240 metres.

Further specific key elements of note with regards to the tunnel alignment design for the Airport bored tunnels are:

- The depth and location of the airport portals (tunnel entrances) are constrained by the requirement to maintain a two minute vehicle headway, minimise the length of running tunnels between intervention points, provide one and a half tunnel diameters of ground cover for the launch and reception of the TBM, and to provide sufficient room for ventilation buildings.

  No more than one LMV can be in a single tunnel vented section. The airport tunnels can only be vented from the portals and the Airport Stop since an intermediate ventilation shaft cannot be provided airside for reasons of security and safety of Dublin Airport Authority operations. Therefore it is critical that the length of tunnel between the portal and Airport Stop is minimised to optimise the frequency of the service.

  Furthermore running tunnel intervention points for Metro North are provided with one exception at not greater than 1000m in accordance with GDRIRS clause 1.4.2.2 which states *"Current practice indicates that distances between access points should be in the order of 1km where there are twin single-bore tunnels with adequate intermediate cross-passages…"* The exception to this is the airport tunnels where the length of running tunnel between the Airport Stop and the south portal is approximately 1370m. It is not possible to provide an intermediate intervention point for the same reasons that an intermediate ventilation shaft cannot be provided. Therefore it has been agreed with Dublin Fire Brigade that this length of running tunnel between the south portal and Airport Stop shall be kept to the absolute minimum.

- The Airport tunnel vertical alignment also has a low point centrally located either side of the Airport Stop to minimise the impact of ground movements on airport infrastructure.

For the cut and cover running tunnel alignment from the Northwood portal through Ballymun to DCU Stop, specific elements of note with regards to the tunnel alignment design are:

- Provision of 2 metres of clear ground cover above the cut and cover running tunnel structures to allow utilities to pass over the tunnel roof slab, whilst maintaining a minimum 0.2% gradient for drainage.
- Ballymun and DCU Stops located at sufficient depth to accommodate two levels within the stops so that plant rooms can be accommodated over the tunnels at each end of the Stop.
- Follow the centreline of the road to facilitate the maintenance of two lanes of traffic either side of the cut and cover tunnel whilst it is under construction.
- Provide a minimum of 2m horizontal clearance between No.2 Albert College Lawn located just south of DCU Stop and the cut and cover running tunnel structure. This is to provide sufficient clearance to be able to construct the wall to the cut and cover tunnel without adversely impacting on the structure of No.2 Albert College Lawn.

For the city centre bored tunnels further specific elements of note with regards to the tunnel alignment design are:

- The horizontal and vertical alignment is designed to locate the emergency crossover cavern structure beneath St. Patrick's College sport fields with sufficient rock cover for construction of the crossover cavern.
- A 30m running tunnel horizontal separation is provided at St. Patrick's shaft to accommodate the arrangement of the ventilation and intervention shaft. The vertical alignment low point is designed to coincide with the shaft that also contains the tunnel sump.

- The vertical alignment beneath the railway lines and Royal Canal that are located between Drumcondra and Mater Stops is maintained within the limestone bedrock to minimise the impacts of ground movements generated by tunnelling on this infrastructure.
- The tunnel gradient from O'Connell Bridge Stop to Parnell Square Stop is maintained at the minimum 0.5% grade for as long as possible to maximise the length of the running tunnel constructed in the limestone bedrock, with an upgrade of 4% into Parnell Square Stop to minimise exposure to mixed face tunnelling conditions.
- The horizontal track separation is increased to 23m at the Spire to minimise the impact of tunnelling generated ground movements on the Spire.
- The depth of O'Connell Bridge Stop is determined by the requirement to provide sufficient rock cover for concourse and platform cavern construction.
- The tunnel gradient from O'Connell Bridge Stop to St. Stephen's Green Stop is set at a minimum upgrade of 0.5% for as along as possible to maximise rock cover to the emergency crossover cavern structure and running tunnels, before rising at a 5% grade in to St. Stephen's Green Stop.
- The Loop Line alignment is designed to be restricted to within the footprint of St. Stephen's Green.

### 3.3 Running Tunnel Internal Arrangement

RPA has undertaken detailed studies to determine the size, layout and internal arrangement of the bored, and cut and cover running tunnels. This work has been coordinated with the development of the tunnel fire and life safety strategy, including consultation with the Dublin Fire Brigade and RSC. Based on this work the Reference Design has been developed and the running tunnels sized and arranged as follows: Slide 3

- A 5.8m internal diameter bored running tunnel.
- A cut and cover running tunnel with northbound and southbound tracks separated by a central dividing wall, or two separate cut and cover running tunnel box structures each containing a single track. Each rectangular box structure containing a single track has internal dimensions of approximately 5.4m wide by 5.2m high.

The key features that have determined the size and internal arrangement of the running tunnels are:

<u>Vehicle Envelope and Structure Gauge</u>
The Metro North vehicle envelope has been defined by RPA after consultation with rolling stock manufacturers to ensure sufficient space is provided to accommodate the typical LMV's that might run on the system now and in the future. In addition a further 150mm clearance is provided to the vehicle envelope in accordance with the GDRIRS. The exception to this is the walkway structure where a 75mm clearance has been adopted to reduce the stepping distance in the event of passengers being evacuated from the LMV.

<u>Trackbed</u>
The running tunnels are provided with sufficient depth below rail level to enable either the installation of a floating track slab for noise and vibration attenuation or normal trackslab construction.

<u>Evacuation and Access Walkways</u>
Evacuation walkways and maintenance access space is provided in accordance with GDRIRS, Part 1, Clause 1.4.4. The main purpose of the walkways in the running tunnels is to:

- assist in the efficient and speedy evacuation of passengers,
- provide easy access for emergency personnel, and
- provide a refuge for maintenance workers and access for routine maintenance.

Within the running tunnels, evacuation will be facilitated by a continuous walkway platform running the length of the running tunnels, set at LMV floor level of dimensions

850mm wide by 2000mm high. The evacuation walkway is provided on the right hand side of the running tunnel viewed in the direction of travel so that it allows passengers to evacuate through the cross passages in to the non-incident tunnel without having to cross the tracks. This arrangement also suits the island platform arrangement at the stops, where the evacuation walkway will lead directly on to the island platform. The only exception to this is the side platform arrangement provided at Ballymun Stop. In this case designated walkway crossings are provided at the end of the stop platforms to guide passengers across the tracks from the evacuation walkway to the side platforms.

In addition, a continuous maintenance access space, 450mm wide at rail level and 800mm wide at shoulder height is provided on the opposite side to the emergency walkway to provide a safe work and access space that also facilitates access to rail level.

<u>Fire Fighting Provisions</u>
Fire fighting provision within the running tunnels is made in accordance with Clause 1.4.6 of the GDRIRS and includes:

- A fire main mounted on the tunnel wall. It is protected from LMV derailment by its position at approximately mid height of the tunnel due to the confining geometry of the tunnel.
- Separate charged fire mains provided in each running tunnel with connections to the surface at the end of each tunnel section. In the event of a fire in one tunnel, then the main in the non-incident tunnel is used to fight the fire.
- Fire hydrants provided at cross passage locations every 250m.

Other life safety provisions made include:

- Tunnel lighting. The running tunnels are equipped with emergency lighting to provide adequate illumination for passenger evacuation. In the event of a total power failure, lighting will be sustained for at least the time to complete an evacuation and not less than 3 hours in accordance with the GDRIRS.
- A continuous handrail is provided on the tunnel wall to assist personnel using the evacuation walkway in accordance with the GDRIRS.
- Emergency telephones are provided in the running tunnels at cross passage locations and access points in accordance with the GDRIRS.
- CCTV cameras are provided in the running tunnels to enable approaches to cross passages and entrances to the tunnels to be monitored.

The running tunnel also accommodates tunnel drainage, the Overhead Contact System, signalling and cables including high voltage cables located under the evacuation walkway, and cables mounted off the wall of the tunnel at a position that will not result in damage from an LMV derailment due to the confining geometry of the tunnel. The section of cut and cover running tunnel between Northwood Portal and Ballymun Stop has niches formed in the side walls of the tunnel to accommodate ventilation fans and obviate the need for a ventilation building at Northwood.

### 3.4 Running Tunnel Cross Passage Arrangement

The arrangement of the cross passages is based on the:

- twin bore tunnel configuration or,
- two separate cut and cover running tunnel structures each containing a single track or,
- cut and cover running tunnels containing twin tracks that are separated by a central dividing wall.

Cross passages are provided at a set distance along the length of the running tunnels to:

- Provide for the efficient and speedy evacuation of passengers from an incident in one tunnel to a place of safety in the non incident tunnel.

- Provide access for emergency personnel into the incident tunnel from a place of safety.

Consultation with the Dublin Fire Brigade and a detailed study undertaken by RPA has defined the requirements for spacing, content, size and structural support for the cross passages linking the running tunnels.

Cross passages are provided at a maximum of 250m separation. This is based on NFPA130 requirements and the need to minimise the time taken to reach a place of safety. The passageways are provided for emergency evacuation including mobility impaired persons. Ramped access is provided in the cross passages (i.e. no stepped access) to a maximum slope of 1 in 12.

The internal arrangement of the cross passages for the bored and cut and cover running tunnels Slide 4 has been agreed with the Dublin Fire Brigade. Within each cross passage a clear passenger zone of 1700mm wide (twice the width of the running tunnel evacuation walkway) by 2000mm high is provided to accommodate an LMV straddling a cross passage resulting in passengers exiting the LMV and entering the cross passage from both the left and right hand sides. This space will also permit bi-directional flow through the cross passage to allow emergency services to access the tunnel. Where cross passages are sufficiently long, a set of fire resistant two leaf bi-directional self closing doors are provided at each end of the cross passage. Where cross passages are short due to alignment constraints or are located in the cut and cover sections of the running tunnels, a fire resistant single door set is provided. Slide 5 Where there is insufficient space for a single door set a fire resistant sliding door will be provided as permitted by NFPA130. In both cases the fire rating of the door is increased to 120 minutes compared to the 90 minute fire rating provided for a two door arrangement to match the two hour structural fire resistance of the tunnel and mitigate the reduced redundancy of only having a single door set. All doors are designed not to encroach on the running tunnel evacuation walkway space.

Fire hydrants are provided at the ends of cross passages, internally and externally. This arrangement makes it possible to connect from the incident tunnel to the non incident tunnel fire main without having hoses pass through the doorways obstructing the cross passage whilst also minimising the risk of smoke ingress into the non-incident tunnel.

Any groundwater seepage through the tunnel lining of the cross passages will be directed into the running tunnel drainage system. Drainage sumps are located within the cross passages at alignment low points in the airport tunnels north and south of the Airport Stop, at St. Patrick's Emergency Shaft, and in the city centre tunnels beneath the Royal Canal rather than in the bored running tunnel under the track to enable ease of access.

The following fixed equipment is also provided:

- Lighting luminaries in accordance with Dublin Fire Brigade requirements for normal lighting levels to be provided within the cross passages and running tunnels.
- Permanently illuminated marker lights to indicate the location of the cross passages. In addition cross passages will be clearly numbered, and way finding signage and markings provided in the tunnel.
- Pedestrian hand rails through the cross passages on both sides wherever practicable.

### 3.5 Layout of Underground Crossovers

There are two underground emergency single crossovers located within the bored tunnel sections of Metro North. Their purpose is to enable LMV's to move from one track to the other and will only be used when normal operations are disturbed hence the term emergency crossover.

The underground crossovers are located beneath St. Patrick's College sports fields north of Drumcondra, and south of O'Connell Bridge Stop beneath the land between College Green and Suffolk Street. Their location has been determined taking account of a number of factors including:

- operational requirements,
- track alignment geometry,
- ground conditions, and the
- effect of construction on overlying property.

Two underground emergency crossover layout options were considered by RPA: Slide 6

i.) Bring the tracks closer together and accommodate the crossing in a single cavern.

ii.) Have two bifurcations or step plate junctions and a single track crossover tunnel linking the bifurcations. The term 'step plate junction' refers to the stepped increase in tunnel size to accommodate the increasing separation between the diverging tracks.

Option ii) was selected because:

- It does not require north and southbound tracks to be brought close together which would increase the magnitude of ground movements generated at the surface from construction of the running tunnels.
- It requires less excavated volume than the single cavern.
- It causes less disruption to the tunnel ventilation system.
- It generates less peak settlement. The excavation and construction of a single large cavern to accommodate the single track crossing would not only involve the excavation of space that is not required to accommodate a single track crossing between the running tunnels, but as a result of this over excavation the magnitude of ground movements at the surface will be greater.
- Individual tunnel structures that form the bifurcation have a reduced span compared to the single cavern option.
- It allows greater flexibility in the construction sequence as it does not necessarily disrupt both running tunnels at the same time, since each bifurcation can be constructed independently of one another thereby allowing the contractor the flexibility to maintain one running tunnel unobstructed to transport spoil and materials through. In contrast a single cavern would span both running tunnels and therefore create a greater obstruction to the contractor's construction operation.

The optimum operational location of the underground emergency crossovers is as close as possible to the north end of Drumcondra Stop and the south end of O'Connell Bridge Stop. However the ground conditions and the potential impact of construction on overlying property was a significant factor in determining the location of these crossovers.

The crossover north of Drumcondra Stop has been located beneath St. Patrick's College sports fields within the limestone bedrock to minimise the impact on property adjacent to the sports fields. The crossover south of O'Connell Bridge Stop has also been located within the limestone bedrock to minimise the impact of construction on overlying property.

Slide 7 A review of track separation and turnout angles concluded that a practical layout for the emergency crossovers was a track separation of 18m to minimise ground movements generated at the surface by cavern construction combined with a turnout angle of $10^{o}$. A turnout angle greater than $10^{o}$ combined with a track separation of 18m starts to make the stepped enlargements to form the bifurcation impractical to construct due to their short length. For the emergency crossover south of O'Connell Bridge this arrangement was adopted. However for the emergency crossover located north of Drumcondra Stop the opportunity to construct the crossover cavern beneath the greenfield site of St. Patrick's College sports fields resulted in a track separation of 30m being adopted due to the layout of the adjacent St.

Patrick's Emergency shaft. To minimise the length of the crossover at this location due to the increased track separation a turnout angle of $15^o$ was adopted.

The emergency and evacuation walkway arrangement provided along the length of the running tunnels is maintained through the crossovers so that evacuating passengers can traverse these cavern structures. At the bifurcation the evacuation walkway ramps down at 1 in 12 to a track crossing to maintain a continuous walkway through the crossover structure. The running tunnel fire main and tunnel services are also continued through the underground crossover structure.

### 3.6 Arrangement and Layout of St. Patrick's Emergency Shaft

The distance between Griffith Avenue and Drumcondra Stops is about 1600m, and therefore exceeds the desirable maximum distance of 1000m in accordance with the GDRIRS, and preferred by the Dublin Fire Brigade. Slide 8 The alignment runs under the west sector of the St. Patrick's College site, with the shaft located on the west wing of the campus. This area has a national school and sports pitches and is bounded by residential buildings to the west and by Millbourne Avenue to the south. The site lies partially on the lower college area and partially on the upper sports pitches since the available area by the school on the lower area is not large enough by itself to accommodate the head house structure, or provide parking for emergency vehicles. This location places the shaft about 900m from the end of the platform at Griffith Avenue Stop and 700m from the end of the platform at Drumcondra Stop.

St. Patrick's Emergency shaft has two key purposes. Firstly as an intervention point to provide a safe egress and access route between the surface and the running tunnels, and secondly to provide a tunnel ventilation connection to the tunnels to split the alignment between Griffith Avenue and Drumcondra Stops into two ventilation sections thereby allowing two LMV's in the running tunnel between these stops. It is critical that two LMV's can be present in each of the running tunnels between Griffith Avenue and Drumcondra Stops so that the required level of service, i.e. frequency of LMV's can be provided. In addition the shaft provides:

- a safe and quick access from the surface into the running tunnels for fire fighters and rescue personnel,
- a fire main connection to the surface for pressurisation by the fire tender attending any incident at the shaft location, and
- an outlet for the low point sump in the running tunnels for tunnel drainage.

To accommodate the above, provision has been made for:

- A pressurised 1800mm wide evacuation and access stairway with fire protected lobbies.
- A fireman's lift for personnel and equipment access, and the evacuation of Mobility Impaired Persons and casualties.
- A tunnel ventilation system with separate ducts and grilles for each running tunnel, and tunnel ventilation fans housed within the head house for ease of maintenance.
- Fire main, fire protected lobbies and personnel cross passages between the shaft and tunnels.
- A tunnel drainage system with sumps, collection chamber and pumping station located within the shaft for ease of access.

These facilities will be accommodated within a single vertical circular shaft of about 14m internal diameter, excavated to a depth of approximately 34.5m. A head house structure is positioned over the shaft and contains a personnel exit to the surface via stairs or lift, electrical, mechanical and systems technical rooms, ventilation equipment and louvres, and surface connection to services.

The shaft head house structure is a two storey building approximately 33m long by 18m wide by 8m high above existing ground level, and has been sunk 1.5m below the school ground level. The architectural treatment of the headhouse structure has been presented by Mr. John Smith. The louvres through which the fans discharge are located in the north wall and roof of the headhouse so that any discharge is blown clear of the school and emergency services access.

The headhouse building and compound have been arranged in consultation with St. Patrick's College to minimise the effect on the College and it's development plans and to maintain access around the existing buildings. A retaining wall will be constructed to replace the existing earth slope at the boundary of the sports pitches to release 2100m$^2$ of land to compensate for the 1350m$^2$ occupied by the compound for use by the School that will include a new play area.

The ground level area at the shaft exit is free of obstacles to allow the safe assembly of passengers from the tunnels during an evacuation incident. Dedicated emergency space is provided for the positioning of fire brigade tenders by the hydrant connections and to muster the emergency services. Access for maintenance and equipment is also provided and the shaft is secure and fenced off from the school.

### 3.7 Layout of the Loop Line South of St. Stephen's Green Stop

Slide 9 A Loop Line is provided south of St. Stephen's Green terminus stop to enable vehicles to switch from the inbound southbound track to the outbound northbound track. The proposed arrangement comprises the following key features:

- A 470m long, 60m horizontal radius single track loop tunnel extending approximately 170m south of the St. Stephen's Green Stop box linking the southbound and northbound St. Stephen's Green stop platforms.
- Two siding tunnels that pass beneath the Loop Line and extend approximately 200m straight out in a south easterly direction from the end of the box on a downgrade to stable out of service vehicles. The siding tunnels are on a downgrade to maximise the distance between the tunnels and the foundations of the buildings south of the park should the system be extended in the future.
- Two bifurcation or step-plate enlargements approximately 24m long by 15m wide at the maximum span at the end of both the northbound and southbound platforms of St. Stephen's Green to accommodate the junction between the Loop Line and siding tunnels.
- Two crossing caverns to allow the Loop Line to pass above the siding tunnels.
- A cross passage with pumping sump to collect water draining down the siding tunnels.
- An inclined tunnel connection between the loop tunnel and siding tunnels, reducing the maximum distance between the place of safety at the Stop platform and connection to approximately 230m.
- Two TBM reception and dismantling chambers provided at the end of the siding tunnels for possible future extension of the system south.
- Ventilation adits from the stop box connecting directly to the top of each siding tunnel to enable ventilation of the siding tunnels in the event of a fire incident. At the other end of the siding tunnels a ventilation bypass tunnel links the siding tunnels so that in the event of a fire in the siding tunnel, the incident tunnel can be vented.

The arrangement is based on the Loop Line and siding tunnels only being used by drivers, operational staff and maintenance staff and therefore only a maintenance access space is provided. The siding tunnels are configured and equipped the same as the running tunnels, including provision for a maintenance access space and evacuation walkway should they in the future become part of an extended system south of St. Stephen's Green. Fire main provision for the loop tunnel, siding tunnels and bifurcations is as the standard running tunnel.

Finally by confining the extent of the Loop Tunnel to beneath the park, the potential for ground movements to have an impact on surrounding buildings is minimised.

### 3.8 Metro North / Interconnector Eastbound Running Tunnel Crossing

The planned Interconnector eastbound running tunnel will cross the Metro North running tunnels close to the north end of St. Stephen's Green Stop. Slide 10 To accommodate this crossing Metro North will construct caverns at this location to enable the future interconnector tunnel to be constructed beneath the Metro North track without disrupting the operation of the system. The crossing arrangement comprises the following elements:

- Interconnector / Metro North crossing cavern of internal dimensions approximately 14m high by 10m wide by 30 to 40m long for each of the caverns,
- track bearing slab to support the Metro North track crossing,
- headwalls to form the connection to the running tunnels, and
- provision for openings to enable the Interconnector eastbound tunnel to break in and out of the Metro North caverns.

## 4 Structural Design of the Running Tunnel Structures

### 4.1 Bored and Mined Running Tunnel Structures

Slide 11 The bored running tunnels will be constructed using a TBM erecting segmental tunnel linings. There are also a number of sections of the running tunnels that may be constructed without a TBM, or in advance of TBM arrival. These will be constructed by Sequential Excavation Method (SEM), also referred to as mined tunnel construction in both soft ground and rock.

The design of the bored tunnels involved a review of the anticipated geology, groundwater regime and alignment to enable the magnitude and distribution of loads applied to the tunnel support system to be determined. Cross passages and drainage sumps have been designed using the most unfavourable location conditions. Other structures such as crossovers, the Loop Line, and the Emergency Shaft have been designed based on geological information specific to their proposed locations.

The bored and mined sections of the running tunnels fall into two principle ground categories:

- Soft ground tunnelling conditions that consist of mainly Glacial Till (Boulder Clays) or Fluvial Glacial materials (clay, silts, sands and gravels).
- Hard ground tunnelling conditions which consist of rock (mainly Limestone).

For design purposes all tunnels with at least 1 tunnel diameter of rock cover have been designed as hard rock tunnels. All other tunnels have been designed for soft ground conditions. The main running tunnel design items are:

- A watertight precast reinforced concrete segmental tunnel lining that will be used to construct the majority of the airport and city centre bored tunnels.
- Sequential excavation method tunnel lining used for short sections of tunnel not constructed by TBM, including TBM launch and reception chambers, the cross passages, crossover caverns, Loop Line and Interconnector / Metro North running tunnel crossing cavern. This method comprises an initial lining of sprayed concrete, often referred to as the primary tunnel lining and lattice arch girders in soft ground, and a combination of sprayed concrete, lattice arch girders and rock bolts in the rock sections. A waterproofing membrane encompassing the entire surface of the primary tunnel lining is placed before a secondary concrete tunnel lining is cast to provide a watertight structure. Typically primary linings vary from 150mm thick fibre reinforced sprayed concrete for the smaller tunnels such as cross passages to 300mm thick linings for the larger span caverns. Secondary reinforced concrete tunnel linings vary from 250mm thick for the smaller cross passage tunnels up to 700mm thick for the large span caverns. In the soft ground the optimum tunnel lining geometry is circular.

In rock the optimised tunnel lining geometry is horseshoe shaped with a curved invert to resist the groundwater loading.

## 4.2 St. Patrick's Emergency Shaft

Slide 12 Secant piles anchored in to the limestone bedrock are designed to provide the primary support to the 14m internal diameter shaft through the upper layers of soft ground that extends to approximately 10m below ground level. A secant piling system comprises alternate piles bored along the line of a wall or in this case shaft, leaving a clear space between each for an intermediate pile. The intermediate piles are then driven so that the holes cut in to the first piles can then be concreted to form a continuous wall.

The piles to the shaft are strengthened with temporary ring beams at intervals of 4m from the surface as excavation work proceeds. This element of the primary support will be removed as the secondary lining is progressively installed. The lower part of the shaft in the rock is supported with rock bolts and fibre reinforced sprayed concrete.

The ventilation tunnels and cross passages are designed to be constructed using SEM techniques described previously, as is the secondary lining to the shaft, cross passages and ventilation tunnels.

The base of the shaft is sealed with a reinforced concrete base slab with tension piles provided to resist flotation forces. The sump is sited within a smaller shaft below the main base slab level.

## 4.3 Cut & Cover Running Tunnels

Slide 13 The twin track cut and cover running tunnels between Northwood and the bored tunnel portal in Albert College Park are designed to be constructed bottom-up within temporary excavations formed in made ground and Glacial Till. Three types of structural support will be used to retain these excavations:

1. For the TBM launch pit located at the north end of Albert College Park an excavation of about 25m deep by 22m wide by 30m long with a temporary tunnel portal headwall and sidewalls on three sides will be formed using diaphragm walls. The diaphragm walls are tied back by soil nails, propped at the top of the excavation with a reinforced concrete base slab provided to brace the bottom of the retaining wall and support the TBM's. The use of soil nails instead of internal propping of the excavation is designed to provide greater clearance for lifting and assembling the TBM's. The future tunnel openings in the headwall are designed with Glass Fibre Polymer Reinforcement rather than steel reinforcement to form what is known as a 'soft eye' to enable the TBM to break through the wall when launched.
2. The cut and cover running tunnel excavation within Albert College is formed from temporary cut slopes stabilised using soil nails. The width of the excavation at the base is about 22m to accommodate the twin box cut and cover running tunnel structure, while at ground level the width of the excavation will be about 30m based on a $70^{o}$ cut slope.
3. The close proximity of property along Ballymun Road precludes the adoption of a battered back excavation, therefore a contiguous piled retaining wall system has been designed that comprises of piles being bored sequentially close together and braced with multi-level struts and walings. The stiffness of the wall and the strutting system has been designed to maintain ground movements to acceptable limits. The depth of the excavation is in the region of 8 to 16m by up to approximately 16m wide to accommodate the island platform arrangement at DCU Stop.

Further details of these forms of construction will be presented by Mr. Richard Tucker.

The cut and cover running tunnel box structures are designed as reinforced concrete twin box or single box concrete structures depending on the horizontal track separation. The structure is designed to carry full overburden, surcharge and hydrostatic loading.

### 4.4 Design of Tunnel Portals

Slide 14 Tunnel portals are required at Northwood, and north and south of the Airport where the alignment passes underground.

At the Airport, piled retaining walls are designed to form headwall and sidewall structures, with soft eyes formed in the headwall to allow the penetration of the TBM. The walls are tied back by ground anchors drilled into the surrounding glacial till. The depth of the tunnels at the portal locations have been arranged to provide at least one and half tunnel diameters of ground cover to the crown of the bored running tunnel to avoid excessive ground movement.

Following construction of the tunnels, a building that will house the tunnel ventilation fans will be constructed in the space formed by the headwall and sidewall structures. This will ensure that these ventilation buildings will have a low profile above ground level, thereby minimising the visual impact of these structures on the landscape whilst also avoiding interference with the runway safety clearance zones at the south portal.

At Northwood, jet fans are provided within the tunnels thereby obviating the need for a ventilation building at the portal. An insitu structural concrete headwall and sidewalls have been designed to form the portal.

Dedicated access to, and space at the portals is provided to allow the safe assembly of passengers evacuating from the tunnels and marshalling of the emergency services, including space provided for the positioning of fire brigade tenders by hydrant connections and access to and from track level.

### 4.5 Durability

Design Life
The structures are designed for a 120 year design life.

Design for Fire
The structural integrity of the underground structures will be designed to provide a structural fire resistance of 2 hours and to the ISO 834 fire curve in accordance with the European UPTUN Project recommendations in order to permit evacuation, provide protection to fire-fighting services and protect the infrastructure from collapse.

## 5 Structural Design of the Below Grade Stops

The below grade stops comprise:

- Airport,
- Ballymun,
- Dublin City University,
- Griffith Avenue,
- Drumcondra,
- Mater,
- Parnell,
- O'Connell Bridge, and
- St Stephen's Green

The location of the below grade stops has been described by the evidence presented by Mr. Geoffrey Featherstone and therefore only those location specific elements that have influenced the structural design of the below grade stops is discussed.

The below grade stops are designed as reinforced concrete structures based on geological information specific to their locations and an assessment of loadings resulting from earth pressures, groundwater, internal loading of the structure and external surcharges.

Slide 15 The below grade box structures are designed to be constructed bottom-up or top-down. Bottom-up construction involves a temporary excavation being constructed within which the stop box is built from the bottom of the excavation upwards. Top-down involves the side walls of the box being installed in the ground prior to excavation using piling or diaphragm wall techniques, and then in the case of Metro North, the ground between the walls is excavated to a shallow depth to allow the roof of the box to be placed so that the site above the box can be utilised whilst the box is being constructed below. Access holes provided through the roof of the box enable the further excavation and construction of the box to continue progressively downwards all the way to base slab level, hence the term top-down. The disadvantage of top down construction is that it takes longer to reach formation level compared to bottom up construction. This is a critical consideration when planning the construction of the running tunnels since the timing of the excavation and construction of the stop boxes must be in sympathy with TBM progress to avoid a programme delay resulting from TBM's being stopped outside of a box awaiting the excavation to be completed to depth.

An important element of the below grade stop design is the control of ground movements generated by the excavation of the stop and the potential for these ground movements to adversely impact adjacent property. For each stop the selected method of structural support and its design have been determined to minimise the risk to adjacent property. Further evidence in relation to this important aspect of the below grade stop design will be presented by Professor John Burland.

The stop boxes have been designed to be constructed using bored piles or diaphragm walls. Bored pile solutions used for Metro North include contiguous and secant piles that have previously been described.

Slide 16 Diaphragm walls are formed by excavating a deep trench that is kept filled with a slurry to prevent collapse. Once the trench is completed to design depth, a reinforcing cage is lowered into the slurry-filled trench which is then filled with concrete from the bottom up to form the wall. The concrete displaces the slurry which is pumped out into a retained system for recycling.

Once the bored pile or diaphragm wall is formed excavation of the ground between the walls can proceed, with the bored pile or diaphragm wall used to retain the excavation. Further details of these forms of construction will be presented by Mr. Richard Tucker.

Slide 17 The Reference Design developed is based on the principle of internally bracing the below grade stops and associated excavations, with anchors provided at the foot of the piled retaining walls to restrain the toes of the piles, and rock bolts used to stabilise excavated rock faces. Hence it has been necessary to reference sub-stratum land around the below grade stops to accommodate these anchors and bolts. Ground anchors and rock bolts will be installed by drilling a small diameter hole into the rock from the face of the excavation, inserting the anchor or bolt and grouting it into position. The installation and use of the anchor or bolt will have no impact on the property overhead.

In addition it is also possible that the Contractor will use ground anchors in lieu of struts to tie back the walls of the below grade stops to the surrounding ground. This method has the advantage of providing clear spaces within the excavation itself that will allow the Contractor to optimise his working practices. As previously stated the Contractor who is eventually appointed to undertake the construction of Metro North will form his own view of the preferred method of design and construction. Therefore to avoid unnecessarily constraining the

Contractor's opportunity to optimise his design and construction solution for Metro North, sub-stratum land around all the below grade stops has been referenced.

Irrespective of whether 'bottom-up' or 'top-down' construction is undertaken to construct the stop boxes, excavation is designed to be undertaken in stages with the box propped at each excavation level. The stiffness and spacing of the struts that prop the walls of the retained excavation apart are arranged to optimise the strut forces, bending moments and lateral wall deflections to maintain resulting ground movements within acceptable limits. The struts have been sized to take into account forces from failure of one adjacent strut such that if a strut fails the adjacent struts either side of the failed strut can carry the additional imparted loads. The walings which are beams that run longitudinally along the side of the retaining wall are also sized to span between every first and third strut in the event of a strut failure to prevent the risk of a lower factor of safety resulting in excessive ground movement. Furthermore as an additional safety measure the design assumes a degree of over excavation below the strut before it is placed.

Groundwater drawdown outside of the stop boxes and resulting ground movements are controlled by grouting the soil and rock around the bottom of the piles and diaphragm walls to a sufficient depth to provide a cut off wall to prevent ground water drawdown outside of the excavation. Where necessary the base of the excavation will also be sealed using ground treatment to prevent groundwater inflows. Where piles exhibit water ingress the zone of ground behind the piles will be grouted to form a watertight retaining wall. Likewise where excavations in rock exhibit water inflow of a magnitude that could generate ground movement, fissure grouting will be undertaken to seal the ground.

For all the below grade stops connected by the bored tunnels with the exception of Griffith Avenue Stop, excavation of the stops will be completed before the TBM passes. Where the stop box structure itself has been constructed prior to the arrival of the TBM, the section of the stop wall that the TBM will pass through on entry and exit of the box will be reinforced with Glass Fibre Polymer Reinforcement rather than steel reinforcement to form a 'soft eye' so the TBM can break through the wall.

All the below grade stops are designed as watertight structures with a 120 year design life and a structural fire resistance of 2 hours to the ISO 834 fire curve.

### 5.1 Ballymun and Dublin City University Stops

Both the Ballymun and Dublin City University (DCU) Stops are shallow below grade stops approximately 10m deep that have been designed to be constructed in the Glacial Till using diaphragm walls.

Slide 18 Ballymun Stop is designed to be constructed bottom up, with a central line of columns provided to support the loading from the road traffic that will run within half a metre above the roof slab.

Slide 19 DCU Stop is designed to be constructed top down with the permanent roof of the stop shielding nearby residents from noise generated by the excavation and construction of the box. The roof is designed to create a large internal space above the platforms, and so beams have been arranged above the roof slab but below ground level to provide a clear internal span.

The base slabs of both stop structures are designed to be keyed into the walls of the stop to resist uplift from flotation.

### 5.2 Airport, Griffith Avenue and Drumcondra Stops

Slide 20 The below grade elements of Airport, Griffith Avenue and Drumcondra Stops are all designed to be constructed bottom-up within a temporary excavation formed using bored piles to retain the excavation through the overlying soft ground (made ground and glacial till). In the limestone bedrock the sides of the excavation are designed to be stabilised using a combination of rock bolts and reinforced sprayed concrete. Where space constraints at the surface do not permit a stabilised rock slope to be constructed, piles are bored to the full depth of the stop. The bottom of the bored piles are restrained by vertical shear pins and a row of 10m long ground anchors where they terminate.

<u>Airport Stop</u>
The excavation for the Airport Stop extends to approximately 27.5m below ground level with depth to limestone bedrock ranging from 2m to 12m below ground level overlain by Glacial Till and made ground. The restriction on land take at Dublin Airport necessitates the design and construction of a temporary braced excavation approximately 144m long by 30m wide, enlarged to 46m wide at either end of the box to concourse level, thereafter narrowing to 36m wide below this level to be able to receive and launch the TBM's.

<u>Griffith Avenue Stop</u>
The excavation located on the north side of Griffith Avenue, is approximately 25m deep by 150m long and will pass through approximately 14m of glacial till and 11m of rock. The braced excavation to concourse level is approximately 34m wide at the north end of the box, and 30m wide at the south end. Below concourse level the excavation narrows to 28m wide, widening to 30m at the ends of the excavation to receive and launch the TBM's. A unique aspect of the design will be the requirement to dismantle the running tunnel segmental tunnel linings that will have been erected by the TBM through this section before the stop is constructed to formation level. This results from the TBM launch site being relatively close and there being insufficient time available to complete the stop excavation before the TBM's pass.

<u>Drumcondra Stop</u>
Slide 21 The excavation for the main stop box containing the platform is approximately 27m deep passing through about 10m of soft ground comprising made ground and glacial till overlying limestone bedrock. The braced excavation is approximately 107m long by 20m wide, widening to 25m wide at the ends of the excavation to receive and launch the TBM's. The excavation for the adjoining Ticket Hall basement structure will be about 13m deep, and is constrained by the close proximity of the railway embankment along its south side.

The space constraints at the north and south ends of the stop box excavation due to the houses fronting on to St. Alphonsus Road and the railway embankment structure respectively, as well locally on the east side of the excavation beside No. 7 St. Alphonsus Avenue dictate that the temporary piles to support the excavation will need to be bored very close to where the permanent structural walls of the box will be cast. Hence the piles at these locations have been designed to be bored to the full depth of the stop, as there will be no space available to form cut slopes in the rock due to the extent of the excavation at the surface being constrained. Furthermore the design also provides for a double row of bored piles at the south end of the box to minimise ground movements that might have an adverse effect on the railway.

On completion of these temporary excavations the permanent stop structures are designed to be cast in stages from the bottom up. A waterproof membrane is installed between the temporary wall of the excavation and the permanent box structure to provide a watertight structure. To counter the effect of buoyancy, tension piles installed at formation level are grouted in to the rock to 'anchor down' the box structure. As the stop box and its floors are cast from the bottom of the excavation upwards in stages, the temporary struts and walers are removed and the void between the permanent walls and temporary wall retaining the excavation backfilled and compacted to transfer the lateral loads to the permanent structure.

### 5.3 Mater Stop

Slide 22 The Mater Stop will be located within the Mater Hospital complex, with the east wall of the stop box running next to and parallel with the rear of the two storey residential buildings located on Leo Street. The excavation for the box extends to approximately 25m below ground level and is approximately 165m long by 30m wide. The box will be excavated through made ground approximately 2m thick, glacial soils that contain both sands and gravels, and approximately 2m of limestone bedrock. The box is also designed to carry the load from the new Mater Hospital development that partially overlies the box.

Slide 23 The Mater Stop is designed to be constructed top-down using rigid diaphragm walls extending to rock level that will also form the permanent walls to the box, and therefore negate the need for a second structural wall to be constructed inside the box. The walls are socketed in to the rock below formation level and are restrained at the bottom by vertical shear pins, with tension anchors also installed through the base of the diaphragm walls to resist flotation forces. The walls are designed to be constructed in 3m long panel lengths to enable good control of the excavation. This top down design is necessary to satisfy the requirement to return the site to Mater Campus Hospital Development before construction of the box is completed thereby requiring that the roof of the stop is infilled and waterproofed prior to this. The remaining construction, including the base slab will be completed through holes in the roof slab.

Before excavation of the box commences, bored piles will be installed inside the walls of the box that will extend beyond formation level. The bored piles, often described as ‘king posts’ will in combination with the diaphragm walls be used to support the roof to the box that will in turn allow the site above the box to be used during its construction and the site to be returned to Mater Campus Hospital Development before completion of the stop box. The king posts are also designed to act as tension piles to anchor the base slab and counter the effects of buoyancy of the box once excavation is completed. The box is then excavated in stages, with the installation of temporary props and walers and the permanent floors to the box from the top down as excavation proceeds. As the permanent floor elements of the structure are cast the temporary struts and walers above are designed to be removed. The stiffness and spacing of the temporary struts is designed to maintain lateral wall deflections and resulting ground movements within acceptable limits. The bottom level of struts are designed to be installed close to the formation level and are removed after the concrete base slab to the box is installed.

### 5.4 Parnell Square Stop

Slide 24 Parnell Square Stop is located in the road of Parnell Square East, with the east wall of the box running parallel and adjacent to a four storey Georgian terrace. The depth of the box excavation extends to about 32m below ground level, and is approximately 128m long by 23m wide, increasing in width on the west side of the box over its central section to 38m. The box will be excavated through made ground varying in depth from 2 to 4m, 4 to 7m thickness of glacial till, and 16 to 20m thickness of glacial sands and gravels, with the walls of the box founded in the limestone bedrock. The variation in depths of strata is a result of the inclined ground profile along the length of the stop.

The below grade structure for Parnell Square Stop is designed to be constructed bottom up, but with rigid diaphragm walls extending to beyond formation level that will also form the permanent walls to the box in a similar manner to the Mater Stop. The design uses diaphragm walls due to the space constraints of the site as they will negate the need for a second structural wall to be constructed inside the box. The walls are designed to be constructed in 3m long panel lengths to enable good control of the excavation.

Before excavation of the box commences, king posts will be installed in a similar manner to that described for the Mater Stop to support a temporary road deck beneath which temporary struts and walers will be placed as excavation proceeds. On reaching formation level the floors of the box are then constructed within this temporary supported excavation from the bottom up.

### 5.5 O'Connell Bridge Stop

The ground conditions at the site of O'Connell Bridge Stop comprise made ground approximately 3 to 5m thick and alluvial deposits approximately 3m thick, with limestone bedrock located 7-12m below ground level.

Slide 25 O'Connell Bridge Stop comprises three key structural elements:

- North vertical access box located in O'Connell Street between Abbey Street and Eden Quay,
- south vertical access box located in Westmoreland Street between the quays and Fleet Street, and
- platform and concourse tunnels that connect the north and south vertical access boxes.

North and South Vertical Access Boxes
The excavation for the north vertical access box will be approximately 70m long by 28m wide, narrowing to 17m to a depth of about 30m. The box is locally widened by approximately 12m on the east side to ticket hall concourse level, a depth of approximately 12m.

The excavation for the south vertical access box is approximately 80m long by 30m deep, with a shallower excavation at the south end of the box for escalator access approximately 12m long by 8m deep.

Both the north and south vertical access boxes for O'Connell Bridge Stop are designed to be constructed bottom-up within a temporary excavation in the same manner as previously described for Airport, Griffith Avenue and Drumcondra Stops, with the west side of the north box, and the entire south vertical access box designed with every hard pile drilled to the full depth of the stop rather than to just below the soil rock interface. The reason the stop boxes have been designed in this way is to remove the requirement for the rock faces of the excavation to be angled or sloped to create a stable rock face, thereby reducing the overall footprint of the excavation at the surface.

For the north box in O'Connell Street, the piling is designed to be undertaken in three phases. Secant piles to support the temporary excavation and a temporary road deck in combination with king posts are installed along one side of the central median. Once this piling is completed, the area is excavated to a shallow depth and a road deck is installed before repeating the process along the opposite side of central median. With the temporary road decks carrying traffic in place the stop is then excavated to depth and constructed bottom up entirely from the central median. The south box in Westmoreland Street is designed to be constructed in a similar manner, but with piling undertaken in two phases to enable a bus lane to be maintained along one side of the street at all times while the box is under construction.

Platform and Concourse Tunnels
The platform and concourse tunnels are located beneath the River Liffey and O'Connell Bridge. They comprise three parallel tunnels. The platform tunnels are located to either side and have an excavated span of about 11.5m. Between these tunnels is a passenger circulation adit or lower concourse tunnel with an excavated span of about 12.7m. The three tunnels are separated by rock pillars and are connected by cross passages.

The tunnels are located within the limestone bedrock and have been designed to be constructed using the same SEM techniques (sprayed concrete, rock bolts and lattice arch girders) described previously that will be used to construct the non-TBM constructed running tunnel structures such as the underground emergency crossovers. The geometry of the tunnels is oval reflecting the need for the secondary lining design to be able to carry hydrostatic pressure and provide a watertight structure.

### 5.6 St Stephen's Green Stop

The ground conditions at St. Stephen's Green Stop comprise approximately 2m of made ground, glacial till, and glacial sands and gravels overlying limestone bedrock located approximately 10m below ground level.

Slide 26 The main box for St Stephen's Green Stop is designed to be constructed bottom-up within a temporary excavation in the same way as previously described for Airport, Griffith Avenue and Drumcondra Stops but using diaphragm walls rather than bored piles to support the overlying soft ground. The excavation is approximately 154m long by 34m wide extending to a depth of about 25m. The north end of the box is further extended to approximately 30m deep and widened on the north east side to accommodate the interchange with the Interconnector system, and the Interconnector westbound tunnel that will pass beneath the Metro North St. Stephen's Green Stop.

A shaft excavation on the west side of the box of approximately 58m long by 12m wide by 30m deep will be constructed to contain the Interconnector ventilation system and fire fighting lift and escape stairs for Metro North. This shaft is designed with diaphragm walls constructed to formation level. This is necessary due to the space constraints of the site, where there is insufficient room available to create angled rock slopes to stabilise the excavation.

Slide 27 At the north end of the stop the box extends beyond the park under St. Stephen's Green West and North to accommodate the ticket hall and entrances to the stop. This excavation will be about 13m deep and is designed as a top-down diaphragm wall structure in a similar manner to the Mater Stop box to enable the roof slab to the ticket hall to be constructed before the ticket hall is excavated to depth. This will allow the area around St. Stephen's Green North and West to be reinstated and returned to public use at the earliest opportunity.

## 6 Closing Statement

This evidence has described how the configuration, alignment and layout of the running tunnel structures has been determined. It has also provided an overview of the structural design of the running tunnels and below grade stop structures. These arrangements and designs have been developed by RPA and demonstrate project feasibility taking account of a number of factors including capital construction costs, future ongoing maintenance costs, methods of construction and design, construction programme, the environment, and construction risk. The contractor selected to construct Metro North will have an opportunity to further optimise designs and methods of construction taking account of the aforementioned factors whilst also considering his own preferred methods. This may result in changes to the structural designs, methods of construction and internal arrangements. In many cases this will result in a reduction in the size of structures, but importantly any changes made by the contractor will need to demonstrate that the anticipated impacts remain substantially unchanged from the scheme presented.