



High Speed Two

A Guide to Tunnelling Costs

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1 Introduction

1.1 Background and Purpose

On the 26 March 2015 the House of Commons Select Committee for the High Speed 2 (London to West Midlands) hybrid Bill published their "First Special Report". Paragraph 75 states:

"The merits of tunnels should be assessed on the basis of their own cost and potential benefit, not their percentage contribution to overall project costs. We have requested that the Promoter make available a guide to tunnel costs to assist petitioners arguing the case for more tunnelling."

This Guide provides a general description of the principal cost elements for bored (or mechanised) tunnels constructed using either an 'Earth Pressure Balance Machine' (EPBM) or a 'Slurry' machine. EPBMs are typically used in the geological deposits beneath London and are likely to be also used for the Bromford tunnel in Birmingham. A 'Slurry' machine is expected to be used through the Chalk of the Chilterns.

The indicative cost of a tunnelled section of route may be calculated using the rates set out in the body of the guide and an example of an indicative cost estimate, based on the guide, is provided in Appendix A. For ease of use the rates generally avoid the use of ranges. However, indicative costs generated using the guide sit within a range of potential outcomes. The guide rates seek to represent the costs that a principal contractor would charge to the employer and therefore exclude the employer's corporate, project management and design costs.

Section 4 references the Infrastructure Cost Review published by the HM Treasury and Infrastructure UK in December 2010.

<https://www.gov.uk/government/publications/infrastructure-cost-review>) and shows how the example tunnel estimate in Appendix A compares with other similar tunnels.

The websites of the British Tunnelling Society (<https://www.britishtunnelling.org.uk/>) and The International Tunnelling Association (ITA) (<http://www.ita-aites.org/en/>) both provide a great deal of other useful information on the need for, and construction, of tunnels.

1.2 Basis and Coverage

All estimates in the guide are given at the project base date of 2nd quarter 2011 and are based on the cost estimates prepared in support of the Estimate of Expense that formed part of the HS2 Phase 1 hybrid Bill submission in November 2013.

The estimates in the guide include the following components:

- Purchase of specialist plant
- Construction site establishment, maintenance and removal on completion
- Contractor's project management, design, controls, supervision and administration staff
- Excavation and construction of the tunnels and associated structures.
- Supply, installation, testing and commissioning of the mechanical and

electrical systems

- Contractor's overheads and profit

1.3 Exclusions

The estimates in the guide exclude the following components:

- Land and property
- Railway systems e.g. track, signalling, telecommunications and traction power systems
- Employer's corporate, project management and design teams
- Allowances for employer's opportunities and risks e.g. contingency
- Cost escalation above the base date of 2nd Quarter 2011 e.g. inflation
- Operating and maintaining the assets following commencement of passenger services

Please note that some of these excluded items would be included in the assessment of a defined proposal in a known location e.g. land and property.

1.4 Limitations

Whilst the guide seeks to give a good indication of tunnelling costs, any proposal for further tunnelling would require a specific estimate to be prepared. Such a specific estimate would capture elements that the guide does not e.g. the impact on land and property, local road networks, and the cost of the works in the route section displaced by the new or extended tunnel.

HS2's designs and associated cost estimates are at an early stage of development and are therefore based on many assumptions.

Costs for specific tunnels will ultimately depend on many variables including length, topography, ground conditions and logistics. The guide will only provide indicative costs for the type, size and lengths of the tunnels described. The example in Appendix A assumes a length of 7km and this guide is generally suitable for tunnels lengths of between 3km and 15km.

1.5 Sources

The guide is based on the design and estimating work carried out in support of the hybrid Bill submission process by a number of the Country's leading engineering companies.

2 Scope and Programme Assumptions

2.1 Outline Scope

For HS2, the bored tunnels comprise a pair of circular tunnels approximately 8.8m internal diameter spaced approximately 20m apart (centre line to centre line), constructed using tunnel boring machines and lined with 400mm thick precast concrete segments. The tunnels connect to portal structures at either end, and are connected together along their length by cross passages and ventilation shafts. Viewed from London towards Birmingham, the left tunnel allows trains to travel to Birmingham, and the right tunnel allows trains to travel in the opposite direction. The tunnels and associated structures are designed to allow trains to travel safely and comfortably within them at speeds of up to 360km/hr.

2.2 Construction Programme

The assumed rates of progress for tunnel construction are expressed as a 'long' average in metres per week. This is defined as the total length of tunnel divided by the total estimated period of construction from the start of boring using the tunnel boring machine (TBM), until the completion of tunnelling at the reception site. Experience shows that the tunnelling rate of progress is typically slow at the commencement of tunnelling before gradually speeding up to peak towards completion. However, in longer tunnels, tunnel boring machine maintenance and more frequent equipment breakdowns may become more dominant time factors later in the programme.

For the purposes of this guide, a 'long' average tunnel construction rate of 80m per week has been assumed for both 'slurry' and 'earth pressure balance' tunnel boring machines.

Upon completion of tunnelling, the tunnels are stripped of temporary construction equipment and cleaned. A concrete base for rail systems, together with concrete walkways either side of the tunnel, are then constructed. Together these work activities are assumed to be carried out at a rate of approximately 400m length of tunnel per week.

The construction of the twin tunnels is assumed to be concurrent. There will be significant mobilisation, preparation and demobilisation activities that add to the overall duration, but for the purposes of this guide all the relevant costs are contained within the two production phases described above.

3 Principal Cost Elements

For the purposes of this guide, costs have been separated into the following categories:

- Purchase of Tunnel Boring Machines (TBMs)
- Tunnelling Support
- Tunnel Construction
- Disposal of Excavated Material
- Portal Construction
- Shafts Construction

- Mechanical and Electrical Equipment Installation

3.1 Purchase of Tunnel Boring Machines

For most of the tunnelled sections along the route each tunnel has been assumed to be constructed with a dedicated tunnel boring machine, and therefore that assumption has been adopted for this guide.

Rates:

| | |
|-------------------------------|------------------|
| Slurry Tunnel boring machine: | £16,000,000 each |
| EPB Tunnel boring machine: | £18,000,000 each |

3.2 Tunnelling Support

Tunnelling support costs include those relating to the contractor's site establishment, project management and supervision. These costs are split into fixed and time-related to allow a more representative estimate to be prepared.

The construction site required at the tunnel boring machine launch end of any tunnel needs to be of sufficient size to service the tunnelling operations. The size of the construction site at the reception end of any tunnel can be much smaller. The cost of the land associated with these sites is not included in this guide as costs vary substantially depending on the location and the existing land use.

3.2.1 Fixed Cost Elements

Fixed costs elements are those not influenced by time or tunnel length and include establishing a secure site compound that contains serviced site offices, workshops, testing laboratory and stores. Space is required for the delivery and storage of tunnel segments to line the tunnel as tunnelling proceeds. Gantry cranes adjacent to and above the portal enable the tunnel to be serviced with segments and other essential materials.

Construction sites also need to have sufficient space to temporarily store and treat the excavated material arising from the tunnels.

In order to support tunnelling further fixed cost items are required including a high voltage electrical supply to the TBMs, the fitting of equipment to provide a 'mini' railway to move people and materials between the portal and the TBM, the fitting of equipment to transport excavated material from the TBM face to the portal comprising a conveyor system for an EPBM TBM and a pipe(s) for a slurry TBM, and tunnel ventilation equipment.

For a slurry TBM, a slurry treatment plant represents a substantial fixed cost. Not only is slurry required to be continuously fed to the TBM during boring, but slurry is also received from the TBM. The slurry received from the TBM is then treated to separate out the original slurry which is then re-circulated and reused. When separated, the residual material is very wet and substantial fixed equipment is required to treat and remove the water so that it is capable of being transported off site. Clay excavated material arising from an EPBM by contrast has a consistency that has been compared to stiff toothpaste, and needs no treatment prior to its transportation off site.

Rates:

| | |
|-------------------------------|------------------|
| Fixed costs (slurry machine): | £45,000,000 each |
| Fixed costs (EPB machine): | £35,000,000 each |

3.2.2 Time Related Elements

In addition to the fixed costs, other variable or time-related costs arise that can be represented as costs 'per week', with the number of weeks dependent on the duration of the construction activity which is, in turn, dependent upon the physical length of tunnel. Time-related costs include labour costs for management, supervision and general site based labour, hired plant and equipment servicing the site, security, cleaning and maintenance costs.

Rates:

| | |
|---------------------|---------------------|
| Time related costs: | £1,100,000 per week |
|---------------------|---------------------|

3.3 Tunnel Construction

This element comprises the excavation of material from the face of the tunnel and its transport along the tunnel to the tunnel construction site, the cost of the pre-cast concrete linings and their transport and installation in the tunnel, tunnel cleaning and strip out of temporary construction equipment upon the completion of tunnel boring, and the installation inside the completed tunnel of a concrete base incorporating drainage pipes, a concrete evacuation walkway and a concrete maintenance walkway.

Additionally, this element includes the construction of cross passages that link the twin running tunnels at nominal 380m centres. In the event of an emergency in one tunnel rendering the train unable to continue to an open section of the route, the cross passages allow passengers to evacuate from the affected tunnel to the unaffected tunnel. The cross passages are mined (a mixture of hand and machine excavation, but not utilising a TBM) following extensive ground treatment and/or under compressed air, and are lined typically with either spheroidal graphite iron (SGI) lining rings or sprayed concrete.

The rate for tunnel construction is expressed as a cost per route metre i.e. two single tunnels. (Note: The benchmarking data provided in Section 4 is per single tunnel, not per route metre of twin tunnel).

Rates:

| | |
|---------------------------------------|--|
| Tunnel Construction (slurry machine): | £25,000 per route metre of twin tunnel |
| Tunnel Constructed (EPB machine): | £22,000 per route metre of twin tunnel |

3.4 Disposal of excavated materials from tunnels

Excavated material that arises from bored tunnelling, either from a slurry or an EPBM machine, is generally too wet to be used for engineering purposes on the route. It is therefore required to be transported off site. For purposes of the guide it has been assumed that the excavated material will be transported to commercial disposal sites or used in sustainable placement sites depending upon environmental considerations.

Rates:

Disposal of excavated material in a commercial tip: £4,500 per route metre of twin tunnel

Use of excavated material in sustainable placement: £3,000 per route metre of twin tunnel

3.5 Tunnel Portals

Portals are approximately 30m wide structures that allow trains to travel between ground level and the bored tunnel headwalls (and vice versa), at gradients no steeper than 3%. The depth of the portal (rail level) at the tunnel's headwall must be at least twice the diameter of the tunnel, or about 20m, below ground level in order to safely commence bored tunnelling. In flat topography portal structures may be approximately 700m long, but where tunnels pass under a hillside and ground levels are rising, the portal structures will be shorter.

Portal structures are typically constructed of concrete and comprise parallel concrete ground retaining walls with a concrete base. In some circumstances the portal is also required to be propped close to ground level using either permanent individual concrete props or a roof slab.

A specific design feature associated with high speed trains travelling through tunnels is the need to control the air pressure pulse that is created in front of the train as it enters a tunnel. This is achieved through the introduction of 'porous' portal hoods, comprising enclosed portal structures with openings.

Rates:

Tunnel Portal (depending on topography): £20,000,000 to £65,000,000 each

3.6 Tunnel Shafts

For tunnels of sufficient length, ventilation shafts are required to be constructed that connect both of the tunnels to the surface. The shafts provide ventilation and intervention access for emergency services and during operation & maintenance, but are not designed for passenger evacuation in an emergency.

For the purposes of this guide, ventilation shafts are assumed to be required typically every 3km.

Vent shafts have an approximate cross section on plan of 45m x 25m (or equivalent area). The bottom of the shaft is connected into the tunnels and the top of the shaft comprises a head house. The shaft is fitted out with a lift and utility and power services.

In country areas the shallower shafts are generally rectangular and are centred directly over the tunnels.

In urban areas it is very difficult to locate a vent shaft directly over both tunnels and hence additional tunnel connections are constructed from a shaft. These features increase the cost of a vent shaft in an urban area.

In certain circumstances consideration would be given to either launching a TBM from a vent shaft, or receiving a TBM after it has completed tunnelling. When used in this way larger vent shafts would be required.

Rates:

Ventilation shaft (depending on location): £10,000,000 to £30,000,000 each

3.7 Mechanical and Electrical Systems in Tunnels

Mechanical and electrical systems are required in the tunnels, cross passages and ventilation shafts to light, drain, ventilate and cool the tunnels. Fire and life safety equipment is also required comprising fire hydrants, signage and communication systems.

Rates:

Systems in tunnels: £4,000 per route metre

4 Comparisons with Other Tunnels

4.1 Tunnel Length

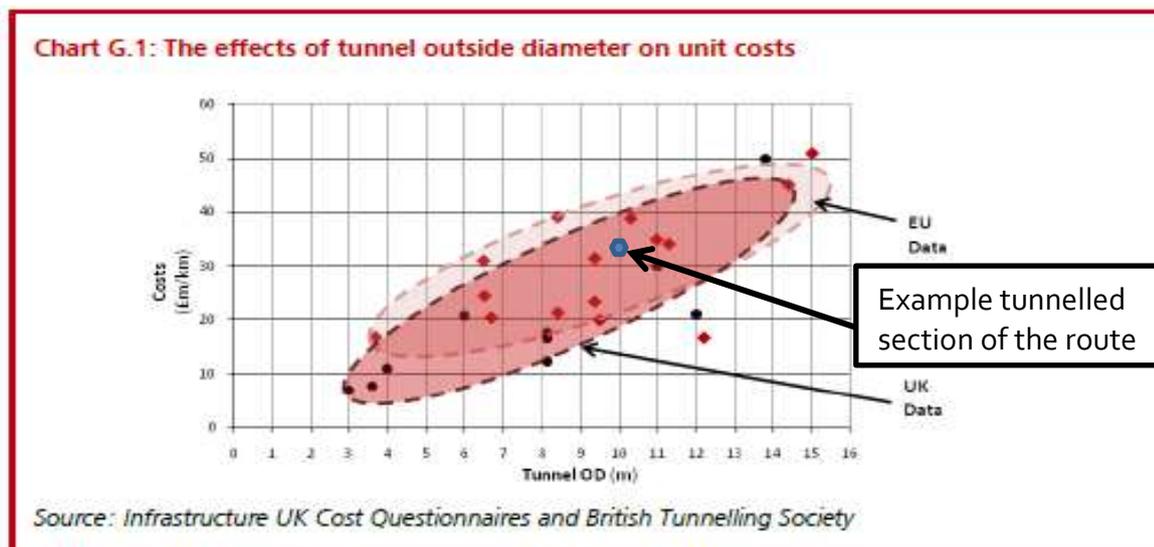
In October 2010 the British Tunnelling Society carried out a cost benchmarking exercise for tunnels, as part of Infrastructure UK’s Infrastructure Cost Review, and as reported in the Infrastructure Cost Review: Technical Report, Annex G, published by HM Treasury and Infrastructure UK (<https://www.gov.uk/government/organisations/infrastructure-uk>). Of the thirty five tunnels investigated, four were more than 15km long and the median tunnel length was approximately 7km long. This median length of 7km has been selected for the tunnel estimate example in Appendix A

4.2 Tunnel Cost

In 2010 the HM Treasury and Infrastructure UK published an Infrastructure Cost Review that comprised an investigation into how to reduce the cost of delivery of civil engineering works for major infrastructure projects. The Infrastructure Cost Review Technical Report, Annex G comprised a benchmarking study for tunnels.

Cost data was collected on the tunnelling aspects of projects in the UK, France, Germany, Spain, Switzerland, Greece, Austria, Switzerland, Norway and the Netherlands. Data was adjusted to account for exchange rate fluctuation and construction inflation and the data gathered showed no established trend of greater costs for the tunnelling aspects of projects in the UK as compared with tunnel projects in Europe. The results are shown in the graph below¹:

Chart G.1 of Infrastructure UK’s Cost Review, reproduced in Figure 2 below, shows the effects of tunnel outside diameter on unit costs for both UK and European projects versus the tunnel cost in £m/kilometre/tunnel.



The light pink envelope encompasses all the European tunnels (red diamonds) with the exception of one outlier. The darker envelope encompasses all the UK tunnels (black circles), again with the exception of one outlier. The tunnel estimate example in Appendix A is also shown, and

¹ Graphic from 'Infrastructure Cost Review: Technical Report (HM Treasury, Infrastructure UK, December 2010) - https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/192589/cost_study_technicalnote211210.pdf. Accessed 11 June 2015.

demonstrates that the cost rates set out in this guide are within the range of the collected data in Infrastructure UK's cost review.

Appendix A – Tunnel estimate example

| This example assumes a 7km tunnel is constructed using slurry machines in a rural location with hilly topography. | | | | | | |
|---|-----------------------------------|---|--------------|--------------|-----------------|--------------------|
| Tunnel Duration: | | 7,000m of tunnelling (productivity 80m/week) | 87.5 | Weeks | | |
| | | 7,000m of clear out (productivity 400m/week) | 17.5 | Weeks | | |
| | | Total Duration | 105.0 | Weeks | | |
| Ref | Item | Description | Quantity | Unit | Rate | Total Cost |
| | | | | | £ 2Q2011 | £ 2Q2011 |
| 3.1 | Purchase of TBMs | Slurry TBMs | 2 | Nr | 16,000,000 | 32,000,000 |
| | | EPB Machines | 0 | Nr | 18,000,000 | 0 |
| 3.2 | Tunnelling Support Costs | Fixed costs (slurry TBM) | 1 | Sum | 45,000,000 | 45,000,000 |
| | | Fixed costs (EPB machine) | 0 | Sum | 35,000,000 | 0 |
| | | Time related costs | 105 | Week | 1,100,000 | 115,500,000 |
| 3.3 | Tunnel Construction | Twin tunnels - (slurry TBM) | 7,000 | Route m | 25,000 | 175,000,000 |
| | | Twin tunnels - (EPB machine) | 0 | Route m | 22,000 | 0 |
| 3.4 | Disposal of Excavated Materials | Disposal off site to a commercial tip | 7,000 | Route m | 4,500 | 31,500,000 |
| | | Disposal off site to a sustainable placement area | 0 | Route m | 3,000 | 0 |
| 3.5 | Tunnel Portals | Tunnel portal (assumed hilly topography) | 2 | Nr | 20,000,000 | 40,000,000 |
| 3.6 | Tunnel Shafts | Ventilation shaft (assumed rural location) | 2 | Nr | 12,000,000 | 24,000,000 |
| 3.7 | Mechanical and Electrical Systems | Mechanical and electrical systems in tunnels | 7,000 | Route m | 4,000 | 28,000,000 |
| Total cost for example tunnelled section of the route | | | | | | 491,000,000 |
| Tunnel costs shown in the graph in section 4.2 of the report are per single tunnel km and for civil engineering works only i.e. excluding mechanical & electrical systems | | | | | | |
| Therefore Total cost for items 3.1 - 3.6 above | | | | | | 463,000,000 |
| Total length of single tunnel (km) | | | | | | 14 |
| Civil engineering cost per single tunnel km | | | | | | 33,071,429 |