Annex 13 – Case study on tunnels

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1. Executive Summary

Tunnels are among the most complex civil structures in railway works and have a relevant impact on the cost of the entire infrastructure. The direct implication of tunnel complexity is the high number of technical parameters and factors that impact its cost, which make each tunnel practically unique.

Considering the wide range of different configurations tunnels can take and, at the same time, the limited number of tunnelling projects that are developed each year in the railway sector in Europe and for which data is available, identifying standard cases out of which a standard unit cost can be determined becomes a very complex exercise. Coherently, for the purpose of the study on unit rail costs, a specific case study has been tailored to investigate the impact of the main cost impacting parameters on the overall tunnel cost and to quantify such impact in economic terms. The analysis hereunder reported is based on a set of cases of tunnels provided by stakeholders, a review of the literature available and has been carried out with the support of technical experts.

In addition to general construction project factors impacting on costs, which are shared with any capital project (i.e. schedule, project risks, market conditions, etc.), tunnel costs are strongly impacted by the size of technical parameters, and primarily:

- The length of the tunnel;
- Its cross-section;
- The conditions of the ground;
- The construction method used.

The analysis performed on the sample of data gathered during the study enabled to derive certain general statistics on average costs, nonetheless, ranges have been found to be only broadly accountable, as cases where tunnels costs varied widely from the average have been identified.

The cost of tunnels have been identify to range between 25 M€/km and €30 M€/km on average. While this range reflects the average values of the sample, it does not prevent values to reach over 80 M€/km, as found in very complex tunnel construction cases. Overall, the analyses and the literature review supported to identify the following:

- Tunnels constructed with TBM tend to be slightly higher in cost than those constructed with conventional construction methods. Nonetheless it has to be considered that the cost-efficiency of each construction method depends on the conditions of the ground as well as on project-design features. It is not deemed appropriate using the results of this assessment to compare different construction methods, which shall be evaluated through a further more detail approach.
- Cut and cover tunnels are not proper tunnels, from an engineering perspective. Being simpler to be excavated, their cost is sensibly lower than proper tunnels (approximately 60% lower, in the sample analysed).
- The condition of the ground can significantly impact on the cost of excavating tunnels. Differences between average good conditions and averagely bad conditions of the ground have been identified in ca. 20% unit cost variation. Such figures can significantly increase in case of more extreme conditions.

Other factors affecting the unit cost of tunnels have been identified in the literature, yet no sufficient quantitative evidence could be extracted from the data sample available. Examples include logistics and project location, regulatory requirements, material cost and labour cost. These have been investigated through a qualitative analysis.

2. Introduction

Tunnels enable railways to reach nodes more directly, with significant benefits in terms of time savings, length of the infrastructure and environmental preservation, reducing impact of the construction works on surface. At the same time, tunnels represent the most complex engineering structure in railway infrastructure, which often has a significant impact on the costs of a whole-line related railway investment.[1]

Each tunnel project is unique and it has its own complexity. This makes difficult to identify a standard case, out of which a standard-unit construction cost can be identified. Furthermore, statistical analysis on large samples are difficult as a relatively limited number of tunnels is constructed every year in Europe by various tunnelling methods.

A case study has been tailored to investigate the technical parameters, which have a major impact on the costs of the tunnels. The analysis is based on a set of diverse railway tunnels built in Europe in different regions and conditions, and also leverages the results and the experience of a wide range of studies and researches made in the past on the subject.

2.1. Technical characteristics of a tunnel

For the purpose of the analysis **a tunnel is defined as *an excavation or a construction around the track provided to allow the railway to pass under, for example higher land, buildings or water.*** [2]

> **Cut and Cover tunnels**, which are excavated in a trench and roofed over with a concrete support,[3] are *artificial* tunnels, and significantly differ from excavated tunnels. Nevertheless, they are included in the analysis, as they represent a common practice in rail infrastructure deployment when mild ground level variations are present.

Tunnels are primarily defined by two dimensions: **length** and **section**.[4] Both impact on the volumes of material being excavated and ultimately on the complexity of the overall construction works[5].

Length

In terms of length, tunnels are generally long and narrow structures. Compared to it, their cross-section area is indeed much less significant. *The length of a tunnel is defined as the length of the fully enclosed section, measured at rail level* as specified in the Commission Regulation (EU) No 1303/2014.[6] According to such definition, the portals[7] are not considered within the length calculation, as they represent the open end of the tunnel and usually include structures to retain the soil around the opening.[8, 9]

While tunnels are generally long structures, there is no homogeneity in what minimum length must a tunnel have to be considered as such. Different countries tend to have different minimum length to define an underground structure as a tunnel. The lack of a common standards on technical specifications and definitions led to the rise of national differences. Only recently, technical standards for railway

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[1] N. Efron, M. Read. (2012) Analysing International Tunnel Costs – An Interactive Qualifying Project
[2] ERA-CON-2012-05-INT
[3] www.railsystem.net
[4] Bickel. (1995). Tunnel engineering handbook, 2nd edition. CBS Publishers
[5] N. Efron, M. Read. (2012) Analysing International Tunnel Costs – An Interactive Qualifying Project
[6] COMMISSION REGULATION (EU) No 1303/2014 of 18 November 2014 - Concerning the technical specification for interoperability relating to 'safety in railway tunnels' of the rail system of the European Union
[7] The portal is the open end of a tunnel
[8] www.promat-tunnel.com
[9] Portals cost is included in our analyses as it can have a significant impact on the overall tunnel cost.

infrastructures have been defined across European countries.[10] The Commission Decision (EU) No 2008/163/EC considers the minimum length for a tunnel 100 m.[11] Such specification has been taken as reference in the selection of the structures investigated in the analysis.[12]

SECTION

Together with the length, tunnels size is determined by their cross-section and in particular by the:

- The **excavation cross-section**, which represents the entire section excavated, designed on the basis of the required clear cross-section, the space needed for a safe execution of the works, and the placement of the supports need to stabilise the ground convergence around the opening;[13]
- The **clear cross-section**, which is the free space of the tunnel, within the final lining, designed to enable the trains' movement, as well as to accommodate the technical equipment necessary for its proper functioning and safety (i.e. platform, rails, ventilation and exhaust system plants, OCL and the power supply units, signalling and telecommunication systems).[14]

The **excavation cross-section** can be significantly wider than the clear cross-section, depending on the thickness and typology of supports installed. Supports are necessary both temporarily during the excavation process and permanently during the operational phase of the tunnel. The typology and thickness of supports employed depend on the geological context, on the excavation method and the construction requirements (e.g. design life) as well on the designer choice. Supports are traditionally classified as:[15]

- Temporary support, defined as any system designed and installed to support the perimeter of an underground opening between the time it is first excavated up to the time that a permanent lining is in place. Typical temporary supports are shotcrete, rock bolts and/or steel ribs;[16, 17]
- Permanent support, defined as the support that is designed and installed to guarantee the long term stability of the underground structure. Additionally, the definitive support insulates the tunnel from humidity, water infiltrations and reduces the turbulences within the tunnel. Typical permanent supports are cast in-situ concrete lining, precast concrete segments, cast iron, coated steel segments, shotcrete and steel ribs. [18, 19, 20]

On some occasions, the temporary support is taken into consideration for the long term, being considered in such case also as contributing to permanent support action; a particular case is that of precast concrete segments placed by TBMs or certain rock bolts.

The **clear cross section** of a tunnel is determined by a space proofing exercise and is mainly governed by the number of tracks running within the tunnel. The dimension is determined taking into consideration the **loading gauge,** which defines *the maximum-security height and width for railway vehicles and their loads to ensure safe passageway through bridges, tunnels and other structures*, both in static and kinematic condition.[21] The loading gauges are defined by the UIC 505-01.

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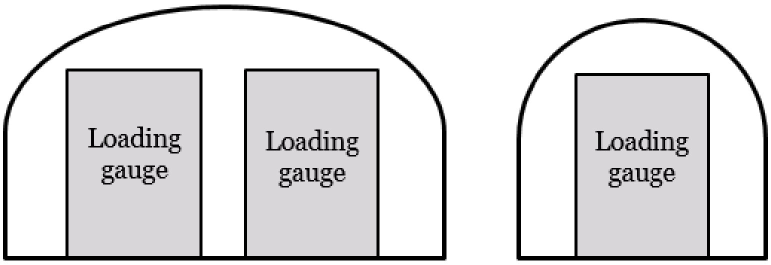
[10] www.era.europa.eu
[11] Commission Decision of 20 December 2007, concerning the technical specification of interoperability relating to 'safety in railway tunnels' in the trans-European conventional and high-speed rail system
[12] Specifically, the shorter tunnel analysed has a length of 400 m.
[13] Interviews to pool of experts lead by Prof. M. Coli
[14] Interviews to pool of experts lead by Prof. M. Coli
[15] Support Systems, International Tunnelling Association (ITA) http://tunnel.ita-aites.org/en/how-to-go-undergound/design/support-systems
[16] www.promat-tunnel.com
[17] Hemphill G. B. (2013). Practical Tunnel Construction
[18] www.promat-tunnel.com
[19] Hemphill G. B. (2013). Practical Tunnel Construction
[20] S. Faramehr (2014). Aerodynamic of the Trains in Tunnels – University of Birmingham
[21] Glossary. Network Rail. Retrieved 2009-05-15.

Figure 1: Loading gauge in single vs double track tunnels



Source: Own elaboration

With regards to the tunnel section, the focus of the analysis is on two alternative tunnel concepts:

- **Single-track tunnels**, containing one track per excavated structure, have a clear section of approximately between eight metres and ten metres;
- **Double-track tunnels**:
    - **Single Bored,** which contains two parallel tracks within the same tube, with a clear section of approximately between ten and twelve metres.[22]
    - **Twin Bored**, which represents two single-track tunnels.

Generalising to the extent feasible, the unit cost of twin bored single-track tunnels requires approximately twice the capital expenditure per kilometre than a comparable single bored double-track tunnel.[23] Indeed, the reduction of the fixed costs (i.e. construction yard and tunnelling machines) per kilometre is outweighed by the construction cost of the bypasses and other connection systems to be created between the two tunnels[24]. Additionally, twin bored single-track tunnels require more work during construction, more muck to be handled, and larger ground surface to seal and secure[25].

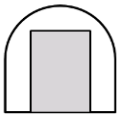
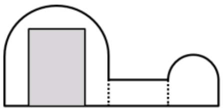
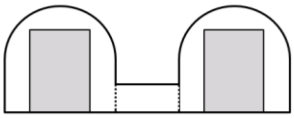
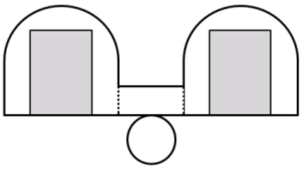
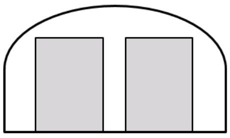
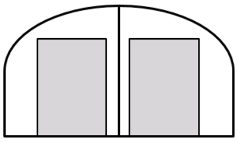
In addition, single or double track tunnels can be complemented with smaller **service/pilot/rescue tunnel.** The construction of service tunnels entails certain benefits in terms of construction efficiency, which in certain conditions favour their choice, despite the higher material being excavated. Among such benefits: excavation of a service/pilot/rescue tunnel[26] for the main tunnel, advance knowledge of geological condition of the ground, chance to treat and improve the ground condition around and/or ahead of the face of the main tunnel during construction, logistic opportunities in construction and services, cable and pipe systems location, access to technical rooms at any time for maintenance, drainage tunnel or safety tunnel.[27]

The decision to build single or double track tunnels, with or without a service tunnel, depends primarily on the assessment of the geological conditions and operational, regulatory and safety requirements. The choice is also driven by cost-benefit considerations and risk analysis.

A broad classification of the possible tunnel sections and the rough estimation of their respective construction costs, is listed in the following figure. [28]

[22] Interviews to pool of experts lead by Prof. M. Coli
[23] Interviews to pool of experts lead by Prof. M. Coli
[24] The two parallel tubes are generally connected with bypass tunnels for safety reasons (every 300-500 m).
[25] Andresen T., Paaske B. J., (2002) Safety in Railway Tunnels and Selection of Tunnel Concept - DNV
[26] A small tunnel or section of tunnelling used to guide the excavation of a main tunnel (www.en.oxforddictionaries.com)
[27] United Nations – Inland Transport Committee (2003). Recommendations of the Multidisciplinary Group of Experts on Safety in Tunnels (Rail)
[28] The cost comparison are very general and only indicative. They do not entail any consideration of the geotechnical, geological conditions.

Figure 2: Tunnel section typologies and cost estimation

Tunnel Type	Section	Cost (single bored single-track=100)
Single bored single-track tunnel		100
Single bored single-track tunnel with service tunnel		160
Double bored single track tunnel with connections		220
Double bored single track tunnel with connections and service tunnel		250
Single bored double-track tunnel		130
Single bored double-track tunnel without safety walls		140

Source: Own elaboration based on interviews to pool of experts lead by Prof. M. Coli

The cost of twin bored tunnels is usually higher than twice that of a single track tunnel, while the cost of a double track tunnel is approximately 30% to 40% higher than a single track tunnel. The cost increase due to a service tunnel for a single bored single-track tunnel is approximately 60%, while such cost of twin bored tunnels is approximately 15% higher if a service tunnel is build.

The design of the tunnel cross-section is strictly related to the technical specifications at European and national level and to the specific project requirements. The main technical specification on tunnel construction at European level are reported in the following paragraph.

Technical Specification

In the EU the need to ensure a homogeneous market and common safety regulations sets standards that necessarily impact on costs of railway infrastructure.

The **Directive 2008/57/EC** and more recently the **Directive 2016/797 on the interoperability of the rail system** establish the conditions to be met to achieve interoperability within the European rail system in compatibility with the provisions of the previous Directive (2004/49/EC). The main aim of harmonising the technical specification is to facilitate, improve and develop international rail transport services within the European Union and with third countries, as well as to contribute to the progressive creation of the internal market in equipment and services for the construction, renewal, upgrading and operation of the rail system within the Community.

Narrowing down to the topic of **safety in railway tunnels**, the main standards at European level are established by the **Directive 2008/163/EC** and the European railway Agency's TSI: **ERA-CON-2012-05-INT**. These define a set of measures for the infrastructure, energy, command-control & signalling, rolling stock and traffic operation & management subsystems in tunnels. The specifications apply to new, renewed and upgraded tunnels longer than one kilometre, and aim both to reduce specific tunnel risks and to harmonise safety conditions in railway tunnels on the European rail network. In addition, special safety investigations and safety measures are required for tunnels longer than 20 km to ensure an acceptable fire-safety environment to interoperable trains (complying with the 2004/49/EC and 2008/57/EC directives).

The technical specifications for **interoperability related to 'safety in railway tunnels'** of the European railway network are set out by the **Regulation UE 1303/2014**. This allows free movement of vehicles under harmonised safety conditions in railway tunnels longer than 100 m, by defining a set of specific measures for the subsystems defined in the Directive 2008/57/EC (i.e. control-command and signalling, infrastructure, energy, operation, and rolling stock).

2.2. Tunnel Construction methods

Over time technology development impacted on the way tunnels have been constructed. While in the past the excavation works were mainly performed using explosives and basic mechanical excavators, nowadays other construction techniques are used, widening the tunnelling applicability and offering better performances and progress rate.[29]

Two main excavation methods are currently used in the tunnelling industry:

- Conventional:
    - Drill & Blast
    - Sequential Excavation
- Mechanized:
    - TBM (Tunnel Boring Machines)
    - Shielded Machines

As anticipated in the previous section, to these it shall be added the Cut and Cover construction technique. The cut & cover is considered within the scope of the analysis, even if it usually not considered strictly a tunnelling method, as it is commonly used in practice to build shallow tunnels for rail infrastructure.

Tunnelling methods shall be carefully considered in light of site conditions, geological setting, design life and project requirements and are selected to best match the construction needs in terms of lower-possible cost and risk management.

The technical parameters that contribute to the choice of the most suitable construction method include, *inter alia,* the **length**, the **diameter** of the tunnel as well as a characteristic parameter which represents the **geological setting,** as defined at international level by the Rock Mechanic Classification systems (RMC) as RMR, GSI, Q system[30].

[29] Interviews to pool of experts lead by Prof. M. Coli
[30] RMR (Rock Mass Rating), Bieniawski Z.T. 1989 Engineering rock mass classifications. New York Wiley; GSI (Geological Strength Index), Hoek E. 1994 Strength of rock and rock masses. ISRM News J2:4–16; Q-system, Barton N. 1994 A Q-System Case Record Cavern Design Faulted Rock. Tunnelling Difficult Conditions - Torino.

RMC considers the features of the discontinuities presents in a Rock Mass Zone[31] and the intact rock UCS (Unified Compressive Strength), geodynamic context and hydrogeological assemblage also give contributions.

The RMCs classify the ground into five Rock Mass (RM) classes, usually in a range between 0 and 100 (or comparable):

Range	Rock Mass class	Rock Mass type	Description
100 - 80	RM I	very good rock-mass	massive hard rock bodies with few large spaced discontinuities
80 - 60	RM II	good rock mass	well interlocked intact rock blocks with systematic ubiquitous discontinuities
60 - 40	RM III	fair rock mass	many interlocked intact rock blocks with several systems of ubiquitous discontinuities
40 - 20	RM IV	poor rock mass	poorly interlocked intact rock blocks intensely disturbed by many discontinuities or sheared
< 20	RM V	very poor rock mass	crushed or highly disturbed rock fragments even sheared, rock filling, debris, ...

These elements are assessed in the preliminary evaluation of most appropriate tunnelling method (Conventional/Mechanized Tunnelling).

The main technical/analytic evaluation tools are:

- The classical **TBM Competitiveness formula**.

The TBM Competitiveness formula[32]

The TBM Competitiveness formula captures the ratio between the length and diameter of the tunnel and the unconfined compressive strength and identify the conditions under which the use of the TBM may result appropriate.

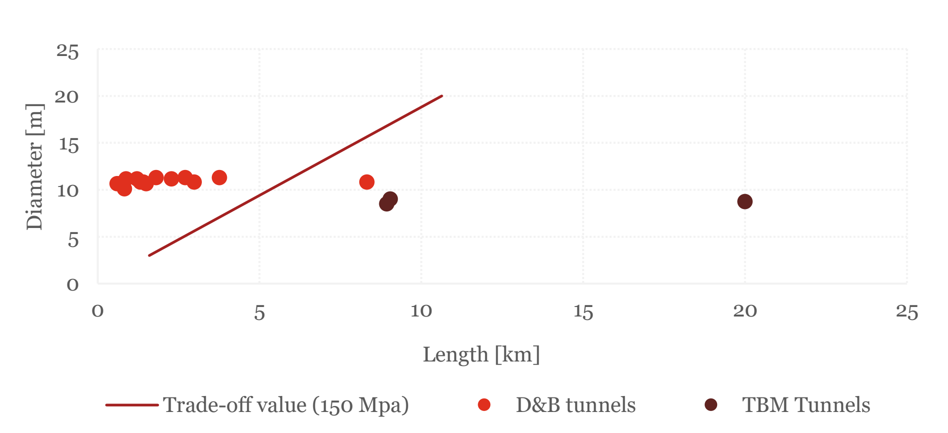
$$TBM\colon \frac{Tunnel\ Length\ [m]}{Tunnel\ Diameter\ [m] \cdot (Unconfined\ compressive\ strength\ [Pa])^{1/3}} > 1.5$$

Specifically, 1.5 represents the trade-off limit between the conventional construction method and the TBM construction method. This value should be consider as a preliminary selection criteria only. Nonetheless, when the result is higher than 3 the TBM is definitely a viable solution, while in case it is lower than 1, the conventional method is usually preferred.

The practical validity of the formula is confirmed through its application to the sample of tunnels considered in the analysis (see Figure 3).

[31] Rock Mass Zone (RMZ), ISRM – Int. J. Rock Mech. Min. Sc. And geomech. Abst., 15, 319-368.
[32] Nord, G., (2006) TBM versus Drill & Blast, the choice of tunnelling method. International Conference and Exhibition on Tunnelling and Trenchless Technology, Malaysia

Figure 3: Choice of the Construction Method through the TBM Competitiveness formula [33]



Source: Own elaboration based on Nord, G., (2006)

The outcome reflects the trade-off value provided by the formula, with only the only exception of the Bleßberg tunnel, which can be justified by the ground conditions (i.e. the tunnel mainly runs through clayey ground).

It should be noted that the TBM Competitiveness Formula can be used only for a high level selection of the construction method. Only through a comprehensive analysis of all the project requirements it is possible to produce a detail evaluation of the proper tunnelling method.

- More recent tools for evaluating the TBM performance to be compared versus the D&B one are:
  - ERMR = Excavation Rock Mass Rating [34]
  - RME = Rock Mass Excavability [35]
  - Q_{TBM} = Q_system for TBM [36]

The following paragraphs outline the construction methods into higher detail.

2.2.1. Conventional Tunnelling (Drill & Blast and Sequential Excavation)

Conventional tunnelling methods can be defined as *the construction of underground openings of any shape, with a cyclic construction process* [37] composed of the following steps:

- Excavation by using explosives (Drill & Blast method) or basic mechanical excavators (e.g. road headers, rippers, hydraulic hammer, etc.);

[33] For simplicity, the unconfined compressive strength was maintained constant for the different cases (at a typical value of 150 MPa).
[34] Jovanovski, M., Pancovska V.Z. & Peshevski, I. 2011 ERMR System – an useful tool in defining of technology for excavation. Organization, Technology and management on construction Int. Journal, 3/2, 302-307.
[35] Bieniawski von Preinl Z.T., Celada Tamames B., Galera Fernández M.J. & Hernández Álvarez M. 2006 Rock Mass Excavability (RME) indicator: New way to selecting the optimum tunnel construction method. Tunnelling and Underground Space Technology - TUNN UNDERGR SPACE TECHNOL. 21. 237-237.
[36] Barton N. 1999 TBM performance estimation in rock using Q(TBM). Tunnels and Tunnelling International. 31. 30-34.
[37] www.tunnel.ita-aites.org

- Muck removal: the muck is loaded and transported outside the tunnel through convey system, trucks, service train; once outside the tunnel, the muck must be transported at the proper disposal site that can also be at tenths or even more than one hundred km away.
- Placing supporting elements (i.e. steel ribs, soil or rock bolts, lattice girder, sprayed or cast-in situ concrete, etc.)

The choice of the excavation technology (D&B or mechanical excavators) is usually made during the design phase, on the basis of the expected geological condition of the ground, of the project location, of the presence of structures nearby and on project requirements.[38] [39]

Examples of tunnels constructed with the conventional excavation method include the Kallidromo Tunnel in Greece and the Bleßberg Tunnel in Germany.

Figure 4: Characteristics of the conventional tunnelling method

Description of the excavation method	• The Drill & Blast method makes use of *explosives for civil use that are applied in holes drilled ahead of the tunnel face. The explosives are detonated in a pre-set sequential order*, to govern the excavation during each cycle and reduce the rock over break;[40] [41] [42] • In the Sequential excavation the cyclical excavation is performed through mechanical excavators, such as mechanical harvesters, hydraulic hammers, road header machines, etc.[43]
Conditions of use	• Conventional tunnelling is preferred for short tunnels and/or changes of the excavation profile;[44] [45] • The Drill & Blast method is properly applied in fair to very good rock masses (RM III → RM I);[46] • The Sequential excavation is mainly used in soils and in very poor to fair rock masses (RM III → RM V).
Advance rate[47]	Between 1 and 6 m/day with 1 m/day representing the advance rate for Sequential excavation in poor soft ground and 6 m/day representing the advance rate for Drill & Blast excavation in good rock mass. [48]
Design and implementation cost	Due to its flexibility, the conventional method requires less detailed studies and preliminary geological investigation than the TBM method, and has thus lower initial cost and lead time.[49]

Source: Own elaboration based on interviews to pool of experts lead by Prof. M. Coli

2.2.2. Mechanized Tunnelling

Since the 1990s, mechanized tunnelling and in particular TBM excavation has took hold as construction method and it currently represents a **cost-effective solution for tunnel constructions in case of**

[38] Interviews to pool of experts lead by Prof. M. Coli
[39] Lunardi P. (2008). Design and Construction of Tunnels
[40] Nord, G., (2006) TBM versus Drill & Blast, the choice of tunnelling method. International Conference and Exhibition on Tunnelling and Trenchless Technology, Malaysia
[41] Kolymbas, Dimitrios (2005). Tunelling and tunnel mechanics: a rational approach to tunnelling
[42] www.promat-tunnel.com
[43] Lunardi P. (2008). Design and Construction of Tunnels
[44] Ehrbar H. (2008). Gothard base Tunnel, Switzerland. Experiences with different Tunnelling *Methods. 2 Congresso Brasileiro de tuneis e Estructuras Subterraneas*
[45] Macias J., Bruland A. (2014) D&B versus TBM: Review of the parameters for a Right Choice of the Excavation Method
[46] Interviews to pool of experts lead by Prof. M. Coli
[47] The advance rate corresponds to the meters excavated per day, in the longitudinal direction
[48] Interviews to pool of experts lead by Prof. M. Coli
[49] Stewart, P. et al., (2006). Bench-mark Drill & Blast and Mechanical Excavation Advance Rates for Underground Hard-Rock Mine Development

long tunnels and well-known ground conditions[50] [51]. The significant improvement of such construction technique in the past twenty years, allowed to enlarge the application range of the TBMs to various ground conditions and diameters.

The most renowned examples of tunnels constructed with the TBM method are the Gotthard Base Tunnel in the Swiss Alps and the Tunnel de Guadarrama in Spain.

Figure 5: Characteristics of the TBM method

Description of the construction method	TBM tunnelling allows to maintain continuous active support onto the tunnel face during the excavation process if required. The tunnel face and excavation area can be completely isolated from the rear tunnel and working area, for example to maintain natural ground water levels or to tunnel safely in contaminated or gassy ground. The TBM itself is a complex machine, which enables to excavate the entire cross-section area of the tunnel at once and, at the same time, sustain the excavation front by avoiding fallings rocks to block the front. This is achieved by removing the muck with a conveyor belt, or other muck-removal equipment (i.e. muck cars or trains) simultaneously to the boring activities and building permanent support with pre-cast segments.[52] [53]
Conditions of use	The TBM must be specifically designed and built **based on the geological condition of the ground**. Its configuration differs significantly from one site to the other according to the geological conditions forecasted. TBM has no flexibility both in terms of profile shapes and ground unexpected condition: • The geometry of the profile in the TBM excavation is limited to circular shapes with constant diameter; • In case of different ground conditions or different profile shapes from the planned ones, the TBM can experience significant slowdowns in the advance rate.[54] • High-pressure water inflow within the tunnel (modern TBMs can withstand pressure up to 16 atm).[55]
Advance rate[56]	The ARAr average is between 15 – 30 meters per day.[57] The speed of the TBM is also affected by the capability of the construction site to supply all the material needed for the TBM to advance.[58]
Design and implementation cost	The TBM method requires a complete and detailed geological investigation at planning phase, as well as accurate studies at design stage. This leads to significant start-up times and investments required in preliminary and design studies, as well as high capital expenditure compared to the conventional construction methods. The initial investment is counterbalanced by lower marginal costs during the excavation phase (provided that a sufficiently high advance rate is maintained).[59]

Source: Own elaboration based on interviews to pool of experts lead by Prof. M. Coli

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[50] N. Efron, M. Read. (2012) Analysing International Tunnel Costs – An Interactive Qualifying Project
[51] Interviews to pool of experts lead by Prof. M. Coli
[52] Hemphill G. B. (2013). Practical Tunnel Construction
[53] www.railsystem.net
[54] In the worst case, the cutter head of the machine should be stopped and a new path needs to be excavated to release the machine, thus leading to a significant rise in time and construction cost.
[55] Interviews to pool of experts lead by Prof. M. Coli
[56] The advance rate corresponds to the meters excavated per day, in the longitudinal direction
[57] The data refers to the Practical Advance Rate (ARAr), e.g. the real advance rate actually achieved during the excavation process. For completeness, it should be noted that the Theoretical Advance Rate (ARAt), which represents the best advance rate achieved theoretically, can reach up to 70 m/g.
[58] Interviews to pool of experts lead by Prof. M. Coli
[59] Holen, H., 1998. TBM vs Drill & Blast Tunnelling

2.2.3. Cut and Cover

The cut and cover is not considered a tunnelling method according to the ERA definition, as specified above.[60] It consists in building a trench or a retained excavation, which is roofed over with a concrete or a pre-casted support and backfilled. It is used to build shallow tunnels in soft ground conditions (i.e. clay, silt, sand or gravel, debris. ...).[61] The cut and cover method is generally simpler and results in capital costs considerably lower than the above-mentioned construction methods. Nevertheless, in particular difficult ground conditions, it can result in costs comparable with the proper tunnelling methods, due to the retaining structures which would be required to support the excavation.[62]

[60] ERA-CON-2012-05-INT
[61] Cut-and-cover tunnels. Tunnels, 2008-09-29.
[62] www.tunnellingjournal.com/tunnelling-journal-september-2017

3. Factors determining the cost of tunnels

Costs of a tunnelling project depend mainly on the required quality level of the final construction, on the construction schedule, risk factors and market conditions.

A thorough analysis of the relevant literature and the consultation of experts enabled to identify the single factors that mainly affect the total cost of a tunnel, which are the tunnel **length** and **cross-section area**, **ground conditions (geological settings, logistics, etc.)** and **construction method**. Other factors affecting tunnel cost have been identified (e.g. geographical location, labour cost, etc.). Nonetheless, in coherency with the other analyses included in the study, the methodological approach followed to normalise cost related to investments carried out in different countries and different time periods enabled to level the impact of these factors.

A brief description of all factors identified is provided in the following paragraphs, while a summary of the main factors determining the cost and their impact is reported in the table below:

Figure 6: Factors determining the cost and their impact

Factor	Possible impact
Length	Choice of the construction method, contingencies allocated
Cross-section	Choice of the construction method, volume of terrain dug, quantity of muck removed, concrete coating volume and number of support structures
Ground conditions	Planning and design phase, choice of construction method, contingencies allocated
Tunnelling Method	Advance rate, planning and design phase, start-up-time, contingencies allocated

Source: Own elaboration

It needs to be taken into account that the procurement model and the payment method may have an influence on the estimated final costs, due to the fact that procurement models with payment methods with asymmetric risk allocations generally lead to higher costs due to the fact that higher risk contingencies are often included by the Contractor or the Owner.

Figure 7: Total costs in function of the payment method (for tunnels construction)

Source: ITA Report n°17 / April 2016: Recommendations on the development process for Mined Tunnels

3.1. Length

There is no doubt that the longer a tunnel, the higher its cost. Nonetheless, the precise relation between the length and the cost in tunnel construction is difficult to determine, due to the combined effect of a number of other factors, including: the geological/hydrogeological condition, the construction method and support types (as shown in the previous section) and the safety requirements.

The safety requirements considerably increase with an increase of the tunnel length. The increase in safety requirements directly influences the cost increment. An example of the safety requirements (evacuation facilities, fire resistance requirements, detection and reaction systems, designated refuge points, emergency communication, etc.) per different tunnel lengths is reported in the following table.

Figure 8: Functional and technical specifications of the subsystem infrastructure in Railway Tunnels

Length [m]	Definition	Safety requirements
Less than 100	Not relevant at European level	Only requirements at national level.
100 - 500	Tunnels of European importance	Escape signage, fire resistance of tunnel structures, prevent unauthorised access to emergency exits and technical rooms.
500 - 1.000	Small tunnels	Safe area, emergency communication and lightning, escape walkways, fire reaction of building material.
1.000 - 5.000	Ordinary tunnels	Emergency plan, firefighting points, access to safe area.
5.000 - 20.000	Long tunnels	Rescue station, segmentation of overhead lines.
More than 20.000	Base Tunnels	Additional safety requirements specifically tailored for the tunnel considered.

Source: Own elaboration based on ERA-CON-2012-05-INT

Additionally, it has to be considered that the increase of the tunnel length has opposite effect on its unit cost:

- The length of a tunnel is inversely related to its unit cost, due to the possibility of creating economies of scale (this is particularly valid for TBM excavation considering its significant capital investment required for the machine);
- On the other hand, the longer the tunnel, the highest the uncertainty of the ground conditions, and, consequently, the higher the planning and design cost, the geological investigation cost and usually the contingencies allocated.[63] [64] The Base Tunnels that underpass the Alps (even more than 50 km) are considerably longer than the average tunnels considered in this case study and face complex ground conditions and safety measures, which, in turn, affect the overall cost of the project.

It is worth mentioning that in case of a significant length, the availability of multiple access points and headings would influence the construction programme reducing the time schedule for excavation and lining. (e. g. the Gotthard Base tunnel was excavated through four access tunnels simultaneously, to half the excavation time[65]).

3.2. Cross-section

The construction cost is highly dependent on the size of the excavation. Indeed the wider the tunnel diameter, the higher the excavated volume, the quantity of muck removed and thus, the volumes of all equipment and the labour force necessary for the operations.

The **size** of the **excavation section[66],** which directly impacts on unit cost, is also affected by the geological conditions. In particular the clear cross-section is generally set in order to fulfil operational and maintenance requirement while the excavation cross section is designed considering the ground behaviour and the required tunnel supports, necessary to sustain the excavation and fulfil the structural requirements.

Being the excavation cost about up to the 80% of the construction cost of a tunnel, an increase in the excavation diameter can have a significant impact on the overall cost.[67]

It is worth noting that designers in different countries generally follow slightly different design approaches, which can have an impact on the tunnel support design and therefore on the excavation cross-section (outer diameter).

- In some countries (e.g. Italy), there is a conservative approach and designers are required to ignore the contribution of the temporary supports in calculating the support capacity of the permanent supports.
- In other countries, where the temporary supports are fully considered into the stabilization at long time of the tunnel, final lining can only consists on thine cast in place concrete layer or prefabricated panels (wood, plastic, fiberglass, ...) to insulate the tunnel from water and ice infiltrations and to avoid turbulence during to the train transit;[68]

The ITA (International Tunnelling Association) Guidelines recommends to consider the contribution of the temporary supports only when their long-term durability is fully ensured;[69]

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[63] N. Efron, M. Read (2012) Analysing International Tunnel Costs – An Interactive Qualifying Project
[64] N. Efron, M. Read (2012) Analysing International Tunnel Costs – An Interactive Qualifying Project
[65] Project data – raw construction Gotthard Base Tunnel – Alp Transit Gotthard
[66] The excavation section refers to the entire section that is excavated
[67] Interviews to pool of experts lead by Prof. M. Coli
[68] The 2008 Kersten Lecture, E. Hoek, C.C. Torres, M. Diederichs, B. Corkun, 56th Annual Geotechnical Engineering Conference, University of Minnesota, Minneapolis, 2008
[69] ITA Guidelines for the Design of Tunnels, Tunnelling and underground space technology, 3/3, 237-249, 1988

3.3. Ground conditions

Ground conditions and in particular the geological setting is among the main parameters affecting the tunnel design and therefore the construction cost[70]. The definition of the excavation method and required tunnel support is in fact dependent on the ground behaviour model and on the hydrogeological conditions.

The ground model (geological and geotechnical-geomechanical model), defined by the description of ground conditions and the expected behaviour of the ground during tunnelling, must be the stable base for the project development in subsequent phases and is assessed based on past experiences available data, borehole data, in-situ test and laboratory test[71] [72].

An accurate anticipation of the geological issues during early design stages is deemed essential to optimize cost and construction programme and reduce the occurrence of unexpected ground conditions which represent a major risk for tunnelling project and may imply:

- Delays in the construction process,
- The need of changing the excavation methods, or
- Change in the alignment
- Accidental occurrences and safety issues
- Contractual disputes

Which would have significant impact on project cost.

The main geological factors affecting the tunnelling costs are:

- Geodynamic context: recent or ancient orogenic chain, inner continental basin, peri-continental basin;
- Geological condition, and in particular:
  - Lithology and fracturing, defining the rock-mass quality (e.g. RMR, Q index, GSI, etc.);
  - *In situ* stresses, mainly related to the tunnel depth or overburden and on the groundwater pressure;
- Geological hazards: presence of gas, asbestos, radiations, dangerous micro-powders, dangerous solutes in the water, faulting, seismicity.

Furthermore, the particular geological/hydrogeological conditions at the open end of the tunnel affect the design complexity of the portals, the construction of which can have an impact up to 25% on the total cost of the tunnel.

3.4. Tunnelling Method

The choice of the excavation method depends on several requirements which vary from one project to the other. Thus, the decision is based on a detailed evaluation of technical aspects as well as on programme and cost assessment. In other words, it should be assumed that the construction method selected is always the best possible choice on the cost-opportunity point of view. As a result, different analyses are performed for different methods and it is not deemed appropriate using the results of this assessment to compare different construction methods, which need to be evaluated through a further more detail approach.

In particular, the tunnel length and diameter, which have a direct impact on the tunnel cost as explained above, affect also the economic convenience of a tunnel construction method. The TBM is in fact more

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[70] Hemphill G. B. (2013). Practical Tunnel Construction
[71] N. Efron, M. Read. (2012) Analysing International Tunnel Costs – An Interactive Qualifying Method
[72] Barton N. (2012). Reducing risk in long deep tunnels by using TBM and drill-and-Blast methods in the same project–the hybrid solution

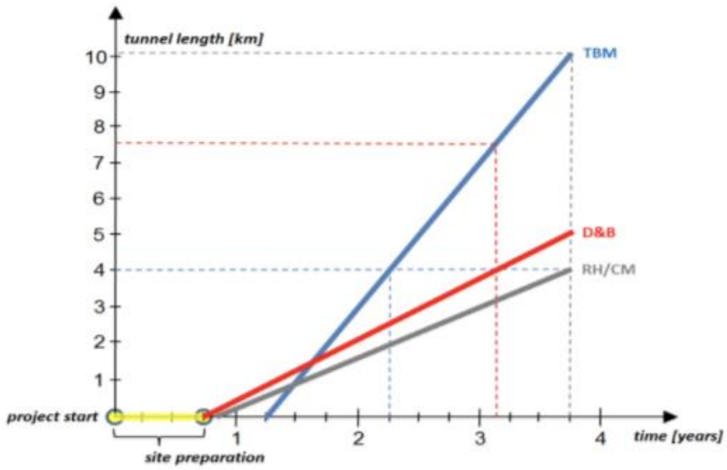
competitive for long tunnels with a regular shaped cross-section, while the conventional method - requiring lower initial cost and start-up time - is more economically convenient for short tunnels with non-uniform cross-section. Regarding the tunnel length, the turning point is at approximately 3-5 km length.[73] [74] [75] Indeed, the considerable capital cost of the TBM can be justified only if distributed over a significant excavation length.

Additionally, the construction method affects the construction time, due to different mobilization times and generally different daily **advance rates** for TBM and conventional tunnelling. Not only the excavation cycle determines the advance rate but also the logistics of the entire supply chain and the type of maintenance requirement of the equipment are key factors, which must be considered when calculating the overall advance rate. While TBM drives require a higher initial investment and a longer mobilization and set up time (lead time), such tunnel method is generally faster for long tunnel drives in homogeneous ground conditions and therefore more economic in such conditions than conventional excavation.

For both Conventional and TBM tunnelling method it needs to distinguish between Average Advancing Rate Theoretical (ARAt) and the Average Advancing Rate Real (ARAr). The first one only considers the excavation performances of the method, the second includes stops and constrains due to the whole yard operability.

Figure below clearly show the impact of the tunnelling method on the construction time for the excavation.

Figure 9: Tunnel methods impact on the construction time



Source: www.therobbinscompany.com/about/advancements/tbms-in-mining

The advance rate

The average advance rate (ARAt) for both the conventional and the mechanized construction techniques (in metres/day), for different geological conditions (quality of the rock mass) is outlined in the picture below.

The experts involved in the analysis and relevant literature allowed to relate the quality of the rock mass and the advance rate of the conventional and the TBM tunnelling methods.

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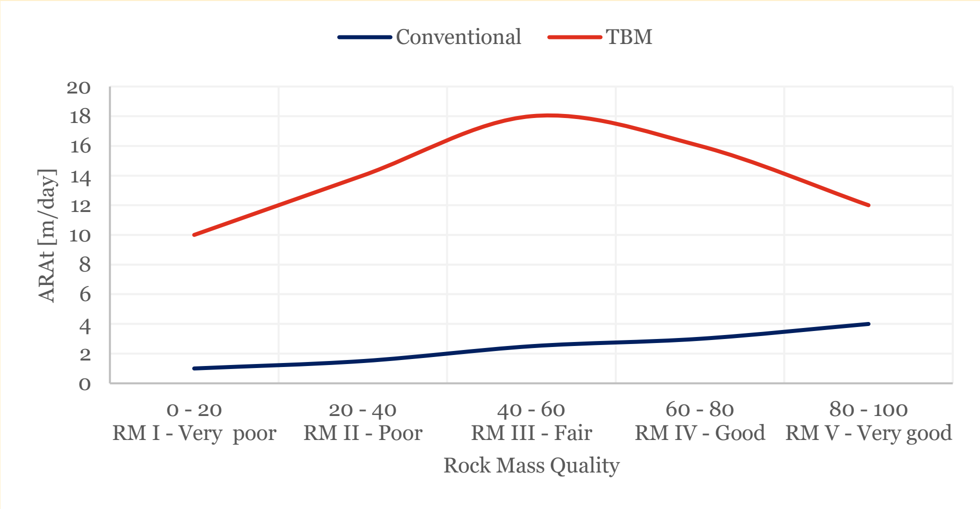
[73] Barton, N., 1999. TBM performance estimation in rock using Q (TBM). Tunnels and Tunnelling,9
[74] Ehrbar H. (2008). Gothard base Tunnel, Switzerland. Experiences with different Tunnelling *Methods. 2 Congresso Brasileiro de tuneis e Estructuras Subterraneas*
[75] Jodl, H.G. & Resch, D. 2011. NATM and TBM – comparison with regard to construction operation

Figure 10: Advance rate (ARAt) of tunnelling techniques



Source: Own elaboration based on Barton, N., (1999) and interviews to pool of experts lead by Prof. M. Coli

The TBM construction method ensures the highest advance rate for fair rock mass conditions (RM III), while showing better performances for all round conditions than the conventional tunnelling method. On the other hand, conventional tunnelling methods increase their advance rate almost linearly with an increase of the quality of the rock mass, reaching values of 6 m/day for very good rock conditions (e.g. RM V).[76] [77]

It is worth to mention that the applicability range of the TBM significantly improved in the last twenty years, due to a significant technological development.[78]

A summary of the costs related to the conventional and TMB construction techniques is reported in the table below.

Table 1 – Costs associated with the TBM and the conventional construction methods

Cost category	Conventional methods	TBM Method
Design cost	Lower	Higher
Initial investment	Lower	Higher
Lead time	Shorter	Longer
Marginal rate	More increased	Less increased
Construction costs	Higher	Significantly Lower

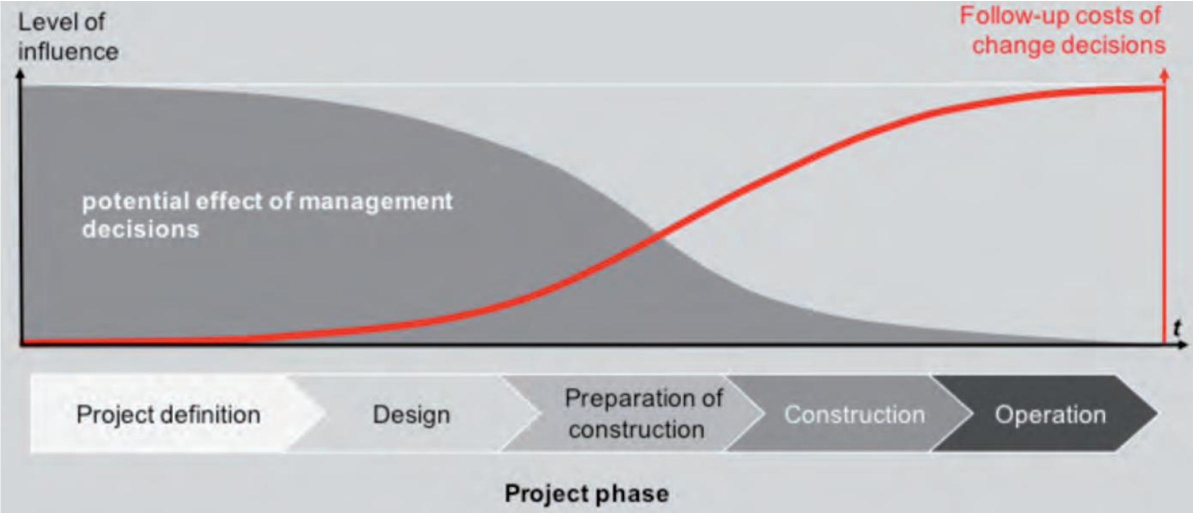
Source: Andresen T., Paaske B. J., (2002) Safety in Railway Tunnels and Selection of Tunnel Concept – DNV

It should be noted that the tunnels constructed by TBM usually combine the TBM with other conventional excavation methods (i.e. Drill & Blast or Sequential tunnelling), in the so called **hybrid solutions**.[79] The hybrid solutions are largely adopted due to the difference in geological conditions of the tunnel. E.g. the Gotthard Base Tunnel was excavated for 65% of the length by TBM and remaining 35% of the length by conventional construction method.[80] [81]

[76] Barton, N., 1999. TBM performance estimation in rock using Q(TBM). Tunnels and Tunnelling Journal
[77] Interviews to pool of experts lead by Prof. M. Coli
[78] Interviews to pool of experts lead by Prof. M. Coli
[79] The TBM is generally used to excavate the large majority of the tunnel length, while the conventional method is used to open new excavation fronts and/or for particular ground conditions in the tunnel path
[80] Andresen T., Paaske B. J., (2002) Safety in Railway Tunnels and Selection of Tunnel Concept - DNV
[81] Detlef J. (2007). The Brenner Challenge – TBMs versus Drill & Blast in High Cover Conditions. Robbins Europe GmbH, Germany

Regarding the topic of tunnelling method selection it is worth mentioning that an unplanned change of is in most cases very expensive and could lead to major cost increase and time delay after the award of contract, as indicated in figure below.

Figure 6: Potential effect of management decisions (e.g. variation of tunnelling method) and potential impact on costs



Source: ITA Report n°17 / April 2016: Recommendations on the development process for Mined Tunnels

3.5. Other factors

Additionally to the factors described in the paragraph above, other elements that could impact on tunnel cost have been identified, which are presented below. However, as mentioned above, in the current analysis their impact is not investigated, since it is levelled by the normalisation approach.

3.5.1. Logistics and Project location

In addition to the ground conditions, local logistic conditions as well as project location (e.g. tunnelling in urban areas[82] or in rural areas) have an influence on project cost.

In particular, the much transport, treatment and disposal could have a strong impact on the construction costs. It varies considerably, depending on the national and local regulations, on the material composition and on the environmental conditions of the site. In particular cases the muck can also be used as construction material, with obvious economic advantages.[83]

3.5.2. Regulatory requirements

Specific requirements may have to be considered in the construction of a tunnel, including:

- Construction regulations regarding types and performances of the construction materials, equipment and plants.
- Safety measures during tunnelling and for the users of the tunnel during the operational phase (e.g. escaping measures, fire detection and fighting systems, ventilation and exhaust systems)[84];

[82] Urban tunnels are not investigated in the present analysis.
[83] Interviews to pool of experts lead by Prof. M. Coli
[84] Andresen T., Paaske B. J., (2002) Safety in Railway Tunnels and Selection of Tunnel Concept - DNV

Human safety regulations, which define the safety measures to be adopted by the workers during the construction process (i.e. safety equipment and insurance)[85].

- Environmental requirements, which impact on tunnel construction costs by imposing the mitigation against environmental impact, the choice of the tunnel alignment in order to minimize or avoid impacts onto environmental protected areas (e.g. EC Guidance Document No. 35 on water protection). The protection of the environmental concerns during construction can affect significantly the costs as well.[86]

3.5.3. Material cost

The cost of material varies substantially from country to country and from construction firm to construction firm, due to inadequacy of standardisation parameters. The ground conditions also have a substantial impact on the type and quantity of the material required for the construction, because they determine the choice of the tunnel temporary and permanent support. The material cost is highly dependent on the local economy and market structure and it could also be purchased nearby or in foreign markets.

3.5.4. Labour cost[87]

The labour cost is significant parameter for the evaluation of the tunnel cost, representing about 20% of its total construction cost. The labour cost is directly dependant on economical (i.e. market structure, level of economic development) and regulating factors (i.e. minimum wages and health insurance)[88].

[85] Andresen T., Paaske B. J., (2002) Safety in Railway Tunnels and Selection of Tunnel Concept - DNV
[86] N. Efron, M. Read. (2012) Analysing International Tunnel Costs – An Interactive Qualifying Method
[87] The impact of labour cost is not investigated in the present analysis, due to the approach followed in the normalization of the data.
[88] N. Efron, M. Read. (2012) Analysing International Tunnel Costs – An Interactive Qualifying Method

4. Analysis on a selected number of cases

Gathering the information provided by literature, a number of cases was investigated in detail to analyse how the differences in terms of the variables that have been previously provided impacted on their cost. The technical characteristics and the results in terms of unit cost of the tunnels investigated are reported in the following paragraphs.

The tunnels analysed were completed between 2002 and 2015 (with the exception of the Brenner Base tunnel, Turin-Lyon tunnels and Kostenets – Septemvri line tunnels), and thus their design relates to construction techniques 15 – 20 years old. As the tunnel construction techniques, and in particular the TBM technology, significantly improved in the last twenty years, the analysis results might be not representative of tunnels currently in a design stage.

The following costs, which has an impact on the overall cost of railway tunnels are excluded from the analysis:

- Land and property
- Railway systems e.g. track, signalling, telecommunications and traction power systems
- Operating and maintaining the tunnel assets

Whilst this assessment seeks to give a good indication of tunnelling costs, **any proposal for tunnelling would require a specific estimate to be prepared**. **Costs for specific tunnels will ultimately depend on many variables** as explained in the report and **the results shown in the paragraph below aim only to provide indicative costs for the type and size of the tunnels described**.

It is worth mentioning that several studies have been carried out in the past in order to build a benchmark of the tunnelling cost in Europe and in the world, but as already explained **tunnels are very complex structure for which it is difficult to determine a standard unit cost.**

4.1. Results

The average unit costs related to difference in construction method and tunnel sections are reported in the following figure.

Figure 11: Tunnels unit cost matrix [M€/km][89, 90]

		Tunnel section	
		Single-track Tunnel	Double-track Tunnel
Construction method	Conventional	24	28
	TBM	25	n. a.
	Cut & Cover	n. a.	11

Source: Own elaboration based on selected project cases, € 2016 XE

[89] The same normalisation approach used for the analysis of the railway investments has been followed (see section *Data normalisation).*

[90] As mentioned above, the Alpine base Tunnels cannot be included in the analysis since the complexity of the design, the geological condition of the ground, the depth below the ground surface and the safety requirements are significantly higher than the other tunnels. The Alpine base Tunnels have been mainly constructed with the TBM construction method, resulting in a unit cost of 80 M€ per kilometre of tunnel.

It needs to be considered that such results are strongly dependent on the selected cases investigated. Other studies as the one carried out by the British Tunnelling Society, which conducted a specific study only encompassing tunnels in order to compare costs between Europe and UK, suggest a figure around £40m/km.[91]

The analysis shows that for conventional tunnelling, the average unit cost of single-track tunnels is approximately 20% lower than average cost of a double track tunnels, within the sample analysed, due to a significant reduction in digging volume, concrete coating volume, and working time.

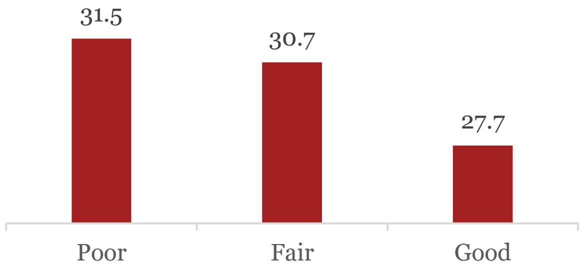
As regards single-track tunnels, the average unit cost of tunnels constructed following the conventional methods results to be only slightly lower than that of a tunnel constructed using a TBM, but this does not represent a reliable result being the project data not entirely comparable. As explained above in fact, the selection of the most appropriate tunnelling method is based on the evaluation of several parameters and in particular on alignment length and geological issues. The choice of the excavation technology is therefore more complex than a simple economic assessment and it is necessary to have an entire overview of the project characteristic, purpose, environmental issues and even social issues to carry out a detail assessment.

The cut and cover construction method (per kilometre) is about three times cheaper than the conventional construction method (per kilometre), but it represents an alternative method only for shallow excavation and soft ground conditions.

As previously mentioned, the results could significantly change for the tunnels designed in the current period due to the enormous technological development in the past decade. In particular, a considerable cost reduction is expected for the tunnels constructed with the TBM.[92]

The influence of the geological conditions of the ground was analysed comparing the unit cost of the sample analysed for different quality of the rock mass.

Figure 12: Average unit cost per quality of the rock mass [M€/km][93]



Source: Own elaboration on sample

In case of poor rock mass conditions the average unit cost recorded in the dataset was approximately 5% higher with respect to fair rock conditions. While in case of good rock conditions, it was about 10% lower than the unit cost of the fair rock condition.

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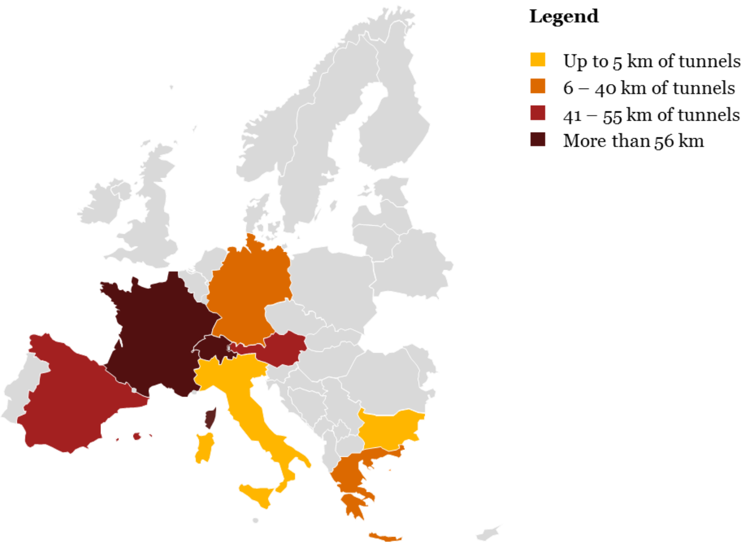
[91] https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/192589/cost_study_technicalnote211210.pdf
[92] Interviews to pool of experts lead by Prof. M. Coli
[93] The Alpine base tunnels have not been included in the analysis, since the cost increase per kilometre is explained by a combination of several factors, such as: the complexity of the design, the complex geological concerns of the ground, the depth below the ground surface and the safety requirements are significantly higher than the other tunnels.

4.2. Technical characteristics of the tunnels investigated

From a geographical point of view, the tunnels investigated cover a total length of 280 km, and refer to structure built in nine MS. Specifically, to ensure the validity and reliability of the analysis, the structures under analysis have been selected to take into account the impact on the unit cost of:

- Overburden ranges and geological characteristics of the ground;
- Level of development of different construction techniques at national level.
- Regulatory requirements at national level;
- Material cost.

Figure 13: Total length of tunnels investigated per Country [km]



Source: Own elaboration

In terms of total kilometres of tunnel, the majority of the sample is represented by tunnels located in Austria, France and Switzerland, due to their high average length (ca. 56 km) of the Alpine base tunnels. While, for Spain and Germany a great number of smaller tunnels have been considered (with a length comprised between 400 m to 9 km length). In Bulgaria and Italy a smaller sample of tunnels was included, with an overall length of 6 km.

Timeframe

A 15-year timeframe has been considered in order to limit the cost variance due to different technologies and regulations[94]. Nevertheless, they refers to tunnelling techniques 15 – 20 years old, which significantly changed in the current period, due to the enormous technological development.

The Gotthard Base Tunnel is the only tunnel for which the construction started before 2002. Nonetheless, it was included in the analysis as it represents an example of best practice in tunnel construction around the world. Oppositely, six of the tunnels investigated are currently under construction: the Tunnel Euralpin Lyon Turin, the Brenner Base Tunnel and the three tunnels on the Kostenets - Septemvri Line.

Technical characteristics

Two different typology of tunnels have been investigated:

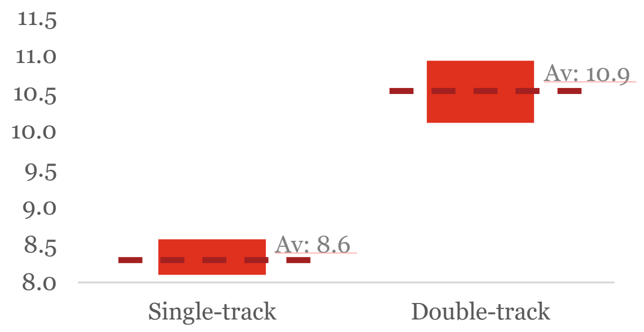
[94] N. Efron, M. Read. (2012) Analysing International Tunnel Costs – An Interactive Qualifying Method

- Single-track tunnels;
- Double-track tunnels.

The former corresponds to approximately 80% of the samples, due to the higher average length. While double-track tunnels account for a total length of about 50 km, with an average length of about 2 km.

The average diameter for the double-track tunnels analysed is 11 m, while the average diameter for single track tunnels is approximately 9 m (see Figure 14). The increase of 20%-25% of the diameter is due to the necessity to guarantee the space of two loading gauges and the safety plants needed to ensure the train operation, on both directions of motion, within the tunnel.

Figure 14: Single and double track Tunnel diameters [m]



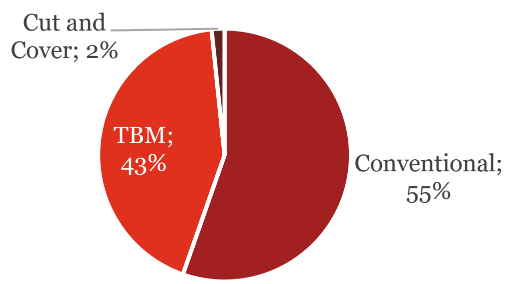
Source: Own elaboration

The tunnels included in the analysis were/ are being constructed using different construction methods:

- Conventional;
- TBM[95];
- Cut and Cover.

The km of tunnel analysed for each construction technique is reported hereunder.

Figure 15: Tunnels length per construction method[96]



Source: Own elaboration

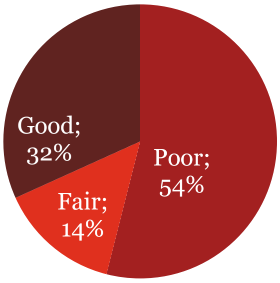
Over 55 km of tunnels included in the analysis regards tunnels excavated with conventional method (Drill & Blast or Sequential excavation). The tunnels constructed with TBM represent approximately 45 km. The Galleria Artificiale di Rondissone on the Turin-Milan High Speed Railway Line represents the only example of cut and cover tunnel, with a length of about 2 km.

95 Usually supported by the conventional excavation method for both opening new excavation fronts and/or for particular ground conditions in the tunnel path

96 The Alpine base Tunnels cannot be included in the analysis since the complexity of the design, the geological condition of the ground, the depth below the ground surface and the safety requirements are significantly higher than the other tunnels.

The length (kilometres) of tunnels analysed per different geological conditions (quality of the rock mass) is reported in the following figure.

Figure 16: Tunnels length per rock mass quality[97]



Source: Own elaboration

The tunnels facing poor rock conditions represent approximately half of the sample of tunnels analysed, with a total length of 50 km. While the tunnels with good rock conditions cover in total approximately 30 km. In case of fair rock conditions only 15 km of tunnels were analysed.

The 32 tunnels analysed are listed in the following table.

Table 2: Tunnels investigated in the analysis

Tunnel Name	Railway Line	Typology
Tunnel Euralpin Lyon Turin	Turin-Lyon High Speed	Twin tunnels single track
Brenner Base Tunnel	Insbruk - Bolzano	Twin tunnels single track
Gothard Base Tunnel	Erstfeld - Bodio railway Line	Twin tunnels single track
Galleria Artificiale Rondissone	Turin-Milan	Twin tunnels single track
Kallidromo Tunnel	Section Tihorea - Lianokladi	Twin tunnels single track
Perthus Tunnel	Perpignan-Figueres	Twin tunnels single track
Tunnel de San Pedro	LAV Madrid-Valladolid	Single tunnel double track
Tunnel de Guadarrama	LAV Madrid-Valladolid	Single tunnel double track
Túnel de Tabladillo	LAV Madrid-Valladolid	Single tunnel double track
Túnel de la Puentecilla	LAV Madrid-Valladolid	Single tunnel double track
Eierberge Tunnel	VDE 8.1 Line	Single tunnel double track
Kulch Tunnel	VDE 8.1 Line	Single tunnel double track
Lichtenholz Tunnel	VDE 8.1 Line	Single tunnel double track
Höhnberg Tunnel	VDE 8.1 Line	Single tunnel double track
Füllbach Tunnel	VDE 8.1 Line	Single tunnel double track

97 The Alpine base Tunnels cannot be included in the analysis since the complexity of the design, the geological condition of the ground, the depth below the ground surface and the safety requirements are significantly higher than the other tunnels.

Rennberg Tunnel	VDE 8.1 Line	Single tunnel double track
Feuerfelsen Tunnel	VDE 8.1 Line	Single tunnel double track
Reitersberg Tunnel	VDE 8.1 Line	Single tunnel double track
Baumleite Tunnel	VDE 8.1 Line	Single tunnel double track
Bleßberg Tunnel	VDE 8.1 Line	Single tunnel double track
Goldberg Tunnel	VDE 8.1 Line	Single tunnel double track
Rehberg Tunnel	VDE 8.1 Line	Single tunnel double track
Masserberg Tunnel	VDE 8.1 Line	Single tunnel double track
Fleckberg Tunnel	VDE 8.1 Line	Single tunnel double track
Silberberg Tunnel	VDE 8.1 Line	Single tunnel double track
Brandkopf Tunnel	VDE 8.1 Line	Single tunnel double track
Tragberg Tunnel	VDE 8.1 Line	Single tunnel double track
Sandberg tunnel	VDE 8.1 Line	Single tunnel double track
Augustaburg Tunnel	VDE 8.1 Line	Single tunnel double track
Tunnel KS 1	Kostenets- Septemvri Line	Single tunnel double track
Tunnel KS 2	Kostenets- Septemvri Line	Single tunnel double track
Tunnel KS 3	Kostenets- Septemvri Line	Single tunnel double track

Tunnel Euralpin Lyon Turin – Mont Cenis Base Tunnel

The project involves the construction of single track-twin bore tunnel on the cross-border section of the 235 km long High Speed Line to connect Lyon with Turin, as part of the Mediterranean Corridor. The preliminary studies for the Mont Cenis Base Tunnel started in 1995. At its completion, expected for 2030, it will connect the Italian cities of Susa/Bussoleno to the city of Saint-Jean-de-Maurienne in Savoy, passing through the Alps.

The length of each tunnel is planned to be 57.5 km, with an excavation diameter of 11.3 m. The total excavation was planned for a length of 160 km, including the twin tunnels and cross passages.

The pilot and service tunnel of La Maddalena (about 9 km in length) has been recently completed by using a TBM; it is lower in between the two main tunnels.

The tunnel excavation is performed by using both conventional method and TBM.

Brenner Base Tunnel

The Brenner Base Tunnel is single track-twin bore railway tunnel, which links Fortezza in Italy and Innsbruck in Austria though the Eastern Alps. It is part of Line 1, the Berlin to Palermo route, of Trans-European Transport Networks. The construction works started in 1999 with the preparatory works and in

2007 with the exploratory section and are planned to be completed by 2025. Such tunnel will represent the second longest high speed rail tunnel in the world[98].

The two twin bored main tunnels are 55 km long each, with a clear section of 8.1 m. A pilot tunnel is currently under construction between the main tunnels. It is used as an exploratory tunnel to anticipate the geological condition along the main tunnel alignment and it will be essential for service and drainage when the BBT becomes operational.

The excavation method is hybrid: 70% of the length by TBM (maximum expected ARAt of 40 m/day) and the remaining 30% of the length by conventional Drill & Blast construction method, due to difficult varying geological conditions[99].

Gotthard Base Tunnel

The single-track twin bore rail tunnel links the cities of Erstfeld (Uri) and Bodio (Ticino) in Switzerland on the Rotterdam–Basel–Genoa Corridor. The construction works started in 1999 under the responsibility of AlpTransit Gotthard AG and ended in 2016.

The Gotthard Base Tunnel is currently the longest high-speed railway tunnel in the world, with a length of 57 km. The minimum excavation section was 9.6 m and the clear section of 8.8 m ca. The two main tunnels are linked approximately every 325 meters with cross passages. The civil structure also includes two multifunction stations to allow trains to change tunnels or to make an emergency stop in case of an incident[100].

In total 152 km of tunnel were excavated, out of which:

- 80% was excavated through TBMs;
- 20% was excavated through conventional (Drill & Blast) method[101].

In order to reduce the excavation time, the construction started from four access tunnels with four TBMs simultaneously. The maximum excavation speed was 25-30 m/day in favourable rock condition.

Galleria Artificiale Rondissone

The Galleria Artificiale Rondissone is a 1.7 km long cut-and-cover railway tunnel, part of the high speed railway line Turin-Milan. The tunnel is located in the metropolitan area of Turin. The construction of the line started in 2002 and ended in 2009.

Kallidromo Tunnel

The Kallidromo Tunnel has been included in the case study as it is the longest twin rail tunnel in Greece, as well as in the Balkans. It was part of the project for constructing the new double high-speed railway line Tithorea-Lianokladi-Domokos, which replaced the mountainous part of the old single-track line. The construction started in 2001 by conventional tunnelling methods. After completion of approximately 1.5 km, the works were interrupted in 2002 due to the significant increase in the construction time and cost mainly due to heading and failures to the support in squeezing ground condition. This considerably affected the final cost of the structure[102]. The design of the remaining part was re-tendered and restarted in 2005. The works were concluded in 2013.

The Kallidromo is a single-track twin bore tunnel with a length of approximately 9 km (18 km in total), with an excavation-section of about 10 m; the span between the bypass tunnels is 500.

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[98] Detlef J. (2007). The Brenner Challenge – TBMs versus Drill & Blast in High Cover Conditions. Robbins Europe GmbH, Germany
[99] www.bbt-se.com
[100] www.alptransit-portal.ch
[101] Project data – raw construction Gotthard Base Tunnel – Alp Transit Gothard
[102] D. Schmitt (2006). The Kallidromo tunnel of the new high-speed railway line Athens-Thessaloniki, construction and design

- The project was particularly challenging, not only for its length, but also because it crosses three completely different geological units, clay, limestone and serpentines, excavated using different techniques:
- In serpentine the excavation was performed by mechanical excavators ;
- In the limestone it was used Drill & Blast method;
- The sections in clay, on a length of approximately 4 km, were excavated by Sequential method, using very heavy supports in order to cope with the squeezing behaviour[103].

Perthus Tunnel

The Perthus tunnel is a single-track twin bore tunnel between France and Spain, passing under the Pyrenees, as part of the Perpignan – Figueres high-speed line. The construction started in 2005 and lasted 6 years, under the responsibility of the TP Ferro consortium.

The two twin bored main tunnels are approximately 8 km long each, with a clear section of 8.5 m. The average excavated section being about 10 m.

The tunnel was excavated by two TBMs working in parallel.[104]

Tunnels on the VDE 8.1 High Speed Line

The analysis concerns the 22 tunnels constructed within the VDE 8.1 High Speed Line, a 107-km long, double-track high speed line which connects Ebensfeld to Erfurt.

The total length of the tunnels is approximately 41 km with an average length of about 1.9 km. The length varies from the 8.3 km of the Bleßberg Tunnel to the 500 m of the Lohmeberg Tunnel. The clear cross-section ranges from 89 to 92 m^2. The only tunnel with a cross-section area of 100 m^2 is the Eierberge Tunnel[105].

These tunnels represent an example of conventional tunnelling method (Drill & Blast) in favourable geological/hydrogeological condition. They are all double-track tunnels excavated in similar geological condition and with similar cross-section area. Furthermore, they are all excavated in relatively shallow hilly ranges: the average depth below the surface is about 80 m.

Tunnels on the LAV Madrid-Segovia-Valladolid

Four major tunnels have been considered on the High Speed Line linking Madrid and Valladolid passing through the city of Segovia:

- Túnel de Guadarrama (twin bored single-track);
- Túnel de San Pedro (twin bored single-track);
- Túnel de Tabladillo (single bored double track);
- Túnel de la Puentecilla (single bored double track).

The Túnel de Guadarrama is the longest tunnel is Spain, with approximately 28 km length and a diameter of 8.5 m. The construction started in 2002 and the works ended in 2005. Three TBMs worked in the tunnel with an ARAr of 16.8 m/day[106]. The main geological difficulty is the crossing of the La Humbria Fault.

The Túnel de San Pedro has a length of approximately 8.9 km excavated with two TBMs with a diameter of 9.45 m. The excavation started in 2005 and was completed in 2006. The TBM encountered serious problems during the construction of the west tube, mainly due to poor rock mass condition.

The Túnel de Tabladillo and the Túnel de la Puentecilla are double track rail tunnels constructed with the conventional construction method. The clear cross-section of approximately 100 m^2.

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[103] SIKA at work – Kallidromo Tunnel
[104] Bocabarteille A., (2012). Geotechnical Site Characterisation of the Perthus Tunnel
[105] www.vde8.de
[106] www.structurae.info/ouvrages/tunnel-de-guadarrama

Tunnels on the Kostenets-Septemvri Line

The tunnels are located on the Kostenets–Septemvri section of the Sofia-Plovdiv railway line, on the on the Orient-East Med Core Network Corridor. The works for their construction will start in 2018 and is expected to require approximately four years.

The tunnels on the Kostenets-Septemvri Line are double track single tunnels, with a length of 2.28, 1.22 and 0.87 km, respectively. The planned clear cross-section is approximately 98 m^2, which corresponds to an equivalent diameter of 11.2 m.

The construction will be performed through conventional construction method.