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Trend Analysis of Long Tunnels Worldwide

Jae-Ho Pyeon
San Jose State University

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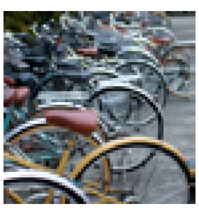
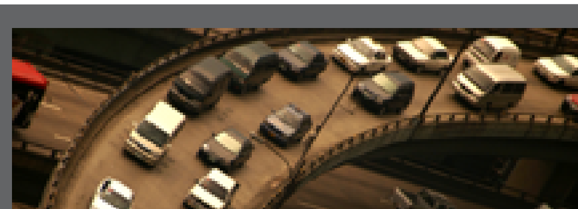
Trend Analysis of Long Tunnels Worldwide



MTI Report WP 12-09



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REPORT WP 12-09

TREND ANALYSIS OF LONG TUNNELS WORLDWIDE

Jae-Ho Pyeon, Ph.D.

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16. Abstract

High-speed rail construction projects have frequently required long tunnels to reduce travel time and distance. The California High-Speed Rail (CHSR) authority is considering a tunnel up to 16 miles long for a direct route from Palmdale to Burbank. With advances in tunneling technology, the many long tunnels in use around the world today hold valuable lessons for CHSR, particularly with respect to minimization of ground disturbance and improved passenger and operator safety.

The primary objective of this project is to determine the state of the art for construction and operation of long tunnels used for high-speed rail. With an abundance of long tunnels successfully completed and already in use around the globe, an examination of those projects can provide the State with the benefit of their experience at little cost.

The research began with a review of the literature on long tunnels around the world, with a focus on characteristics and the research team constructed a detailed database of information on the projects behind the world's long tunnels. Based on the data, this report presents data on 67 tunnels longer than 4.5 miles, including 32 high-speed railway tunnels, located in 28 countries around the world.

The research team analyzed the data to determine the factors that should be considered in planning long tunnels for HSR projects. Analysis results were documented in a systematic manner to compare with potential tunnels for the Palmdale-to-Burbank segment of the California HSR system. It is hoped that the trends identified from the aggregate data will help inform decisions for the tunnel projects being considered for the Palmdale-to-Burbank segment of California High-Speed Rail.

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EXECUTIVE SUMMARY

RESEARCH BACKGROUND AND OBJECTIVE

The California High-Speed Rail Authority sought a desktop survey of long tunnel projects worldwide as well as a comparison of these tunnels to tunnels under consideration in the Palmdale-to-Burbank segment of the California High-Speed Rail project. As a desktop study, this project relies on a review and analysis of existing research and other systematically recorded information, specifically, descriptions and technologies used in construction and operation of long tunnels. This document reports the results of the analysis, identifies trends in long tunnels, and presents a comparison of existing long tunnels to tunnels under consideration for the proposed Palmdale-to-Burbank segment of the California HSR system.

The primary objective of this project is to determine the state of the art for construction and operation of long tunnels used for high-speed rail. Thus, the research is limited in scope to a review of the literature on this topic, collection and summarization of project data from the literature, trend analysis, and comparison of the data to tunnels being considered for the Palmdale-to-Burbank segment of California HSR.

RESEARCH METHODOLOGY

The research team began with a literature review, focusing on the following characteristics of long tunnels worldwide:

- Tunnel name and location
- Tunnel purpose and function (e.g., rail, road, water, utilities, freight/passenger/both, etc.)
- Completion date
- Construction duration
- Length of completed tunnel
- General topography
- Geology and groundwater hydrology
- Major geoseismic hazards critical to design and construction, and the specific solutions adopted to address them
- Design
- Tunnel technologies and construction methods

- Lengths of subsections used in construction
- Tunnel configuration and dimensions
- Access
- Ventilation
- Safety features
- Power characteristics

The team also reviewed as much information as was available at the time on potential California HSR long tunnels, with a focus on the above characteristics.

A data analysis to identify trends for long tunnel projects was performed. The results were documented in a systematic manner, and a comparison with potential California HSR Palmdale to Burbank segment tunnels was made.

RESEARCH OUTCOMES

No precise definition of a “long” tunnel currently exists. A tunnel of only one or two miles may be considered “long” for a roadway; while a one- or two-mile high-speed rail tunnel is typically not considered long. Due to the limited time available for collecting the data, the research time arbitrarily chose to define “long” as no less than 4.5 miles in length. The research team identified 67 tunnels worldwide meeting this criterion and constructed an extensive project database containing data on all 67, including 32 high-speed railway tunnels. Also include in the database is information for the proposed Palmdale-to-Burbank HSR tunnels.

The following potentially useful trends and insights were gleaned:

- A total of five HSR tunnels of the same length or longer than those proposed for the Palmdale-to-Burbank segment of CHSR have been successfully completed worldwide, and another six are currently under construction or in planning.
- Among the eleven longest HSR tunnels globally, five are longer than 30 miles and eight are longer than 20 miles. This indicates that HSR tunnels longer than 16 miles are considered feasible.
- Tunnels configured for two single tracks connected by cross passages are becoming more popular due to increasingly demanding safety requirements.
- Among all tunnels longer than 20 km, the one-double-track configuration is preferred only in Japan. Two railway tunnels with a parallel service or escape tunnel was deemed the safest design by many researchers, although it is the most expensive from a construction standpoint.

- Inclusion of refuge areas in long tunnels is extremely important for safety during emergencies.

- Cross passages are frequently used in twin-tube tunnels to allow passengers to escape safely in an emergency. Appropriate spacing of cross passages is also important.

- Ventilation to control smoke dispersion is one of the most important systems in a long tunnel. Twin-tube tunnels equipped with cross passages significantly shorten the escape distance and allow easier access by rescue and firefighting personnel.

- Overall, both tunnel boring machines (TBMs) and the conventional tunneling method – drilling and blasting or other mechanical excavating methods – are popular for HSR and rail tunnel projects. The conventional method was used, at least in part, by 70% of the projects studied, and the TBM method was used, at least in part, by 80%. The conventional method is popular for projects involving challenging or highly variable rock formations or composition, as well as projects with a high risk of water inflow under high pressure.

- The selection of tunneling methods depends on several factors, such as tunnel length, geological conditions, and rock/soil conditions. The methods used for the tunnels in this study are summarized by the topography, rock classifications, and geological difficulties of each project. The summaries can serve as good examples for CHSR tunnel projects with similar geological conditions.

- All of the HSR tunnels studied used one of the following five electrification systems: 750 V DC, 15 kV AC (16.7 Hz), 15 kV AC (50 Hz), 25 kV AC (50 Hz), and 27.5 kV AC (50 Hz).

- Most long high-speed rail tunnels serve both passenger and freight rail. However, the Abdalajis tunnel in Spain, the Iiyama in Japan, and the CTRL HS1 tunnel in England were designed only for passenger rail tunnels.

- Approximately 80% of the European HSR tunnels use the two single-track configuration. However, only 50% of the tunnels in Asia use this configuration. This is mainly because Japanese HSR tunnels were designed for one-double-track configuration.

- Although TBM showed significantly higher advance rates than conventional tunneling, the conventional tunneling method has many advantages over mechanized tunneling methods in terrains having difficult rocks and highly variable rock conditions, and with projects that have a higher risk of water inflow under high pressure.

- Construction of long tunnels involves dealing with a variety of ground conditions. Some projects employed a combination of tunnel boring machines and the New Austrian Tunneling Method (NATM), also known as the Sequential Excavation Method (SEM), which offers economic advantages by leveraging the geological strength inherent in the surrounding rock to help stabilize the tunnel.

- Many of the projects demonstrated that varying ground conditions can reduce the advance rate of a tunneling project. A well-developed tunneling strategy can significantly reduce the negative impact of varying ground conditions on construction time.

- Based on the research, it is highly recommended that CHSR tunnel projects consider using tunnel segmentation to allow application of different excavation methods depending on geological conditions.

I. INTRODUCTION

BACKGROUND

Tunnels are used in a wide range of physical infrastructure systems, such as aquatic systems, wastewater systems, and passenger and freight transportation, to directly connect destinations and reduce surface impacts,. High-speed rail construction projects have frequently required long tunnels to reduce travel time and distance. With advances in tunneling technology, the many long tunnels in use around the world today hold valuable lessons for CHSR, particularly with respect to minimization of ground disturbance and improved passenger and operator safety.

The California High-Speed Rail authority is considering a tunnel up to 16 miles long for a direct route from Palmdale to Burbank. A shorter alignment from the Palmdale Transportation Center to a station at the Burbank airport will provide benefits for the traveling public in terms of reduced travel time. However, concerns have been raised about safety in both the construction and operation of a long tunnel, as well as the environmental impacts. With an abundance of long tunnels successfully completed and already in use around the globe, an examination of those projects can provide the State with the benefit of their experience at little cost.

Thus, the California High-Speed Rail Authority sought a desktop survey of long-tunnel projects worldwide and a comparison of them to tunnels under consideration for the Palmdale-to-Burbank high-speed rail segment. As a desktop study, this project reviews existing research and other systematically recorded information, such as project descriptions and construction technologies and methods. Fortunately, examples of completed long tunnels abound in other parts of the world, and several more are currently in the planning stages or under construction. By analyzing these projects, it is possible to identify trends in long-tunnel project design and construction and compare completed projects to those that may be considered for the Palmdale-to-Burbank section of the California High-Speed Rail system.

OBJECTIVE

The primary objective of this research is to determine the state of the art in construction and operation of long tunnels for high-speed rail by examining others that have already been completed.

SCOPE AND METHODOLOGY

This research includes a review of the literature on long-tunnel projects around the world, a summary of project information, and an analysis of that information to identify trends.

The research began with a review of the literature on long tunnels around the world, with a focus on characteristics. This was followed by an examination of long tunnels that could potentially be used for the Palmdale-to-Burbank segment of California HSR.

Data on existing projects was then collected and assembled. To the extent available, the data include:

- Tunnel name and location
- Tunnel purpose and function (e.g., rail, road, water, utilities, freight/passenger/both, etc.)
- Completion date
- Construction duration
- Length of completed tunnel
- General topography
- Geology and groundwater hydrology
- Major geoseismic hazards critical to design and construction, and the specific solutions adopted to address them
- Design
- Tunnel technologies and construction methods
- Lengths of subsections used in construction
- Tunnel configuration and dimensions
- Access
- Ventilation
- Safety features
- Power characteristics

The research team analyzed the data to determine the factors that should be considered in planning long tunnels for HSR projects. Analysis results were documented in a systematic manner to compare with potential tunnels for the Palmdale-to-Burbank segment of the California HSR system.

II. LITERATURE REVIEW

LONG TUNNELS AROUND THE WORLD

Hilar (2009) studied the modern world's longest railway tunnels and identified 31 longer than 4.4 miles. Table 1 lists the 15 longest of these – all of them high-speed rail tunnels – along with the rail configuration of each. Five of the eleven are completed; six are currently under construction or in planning. The longest is the Gotthard Base Tunnel, a high-speed rail tunnel that runs for 35 miles under the Alps.

Table 1. List of Modern Longest Rail Tunnels with Rail Configuration

Tunnel	Location	Length (Mi)	Commis-sioning	Status	Configuration	Safety measures
Gotthard	Switzer-land	35.4	2015	Construction	Two single-track tunnels	2 multiple-function stations
Brenner	Austria - Italy	34.7		Construction	Two single-track tunnels with a parallel escape gallery	3 multiple-function stations with an access to the surface
Seikan	Japan	33.5	1988	Operation	One double-track tunnel with an escape gallery	2 emergency stations, service tunnel connected with the main tunnel every 650 – 1100 yards (shafts, galleries)
Lyon - Turin	France - Italy	33	2020	Planning	Two single-track tunnels	4 emergency stations with an access to the surface
Eurotunnel	England - France	31	1994	Operation	Two single-track tunnels and one service tunnel	2 crossover chambers
Gibraltar	Spain - Morocco	23.5		Planning	Two single-track tunnels and one service tunnel in the middle	Parallel service tunnel through-out the length
Lötschberg	Switzer-land	21.5	2007	Operation	Two single-track tunnels (partially a single-track tunnel and a gallery)	2 stations – one service st. and one escape st.
Koralm	Austria	20.5	2016	Construction	Two single-track tunnels	Emergency station in the middle of the tunnel length, without access to the surface
Guadar-rama	Spain	18	2007	Operation	Two single-track tunnels	540-yard-long rescue tunnel in the middle; cross passages every 55 yards; emergency chambers every 2460 yards.
Hakkoda	Japan	16.5	2010	Construction	One double-track tunnel	
Iwate-Ichinohe	Japan	16	2002	Operation	One double-track tunnel	
Pajares	Spain	15.5	2010	Construction	Two single-track tunnels	
Prague-Beroun	Czech Republic	15.5	2016	Planning	Two single-track tunnels	Escape exit in the middle
Iyama	Japan	14	2013	Construction	One double-track tunnel	
Wushaol-ing	China	14		Operation	Two single-track tunnels	

Source: Hilar 2009.

Among the eleven longest HSR tunnels globally, six, or 55% of the total, are under construction or in planning. Five of the tunnels are longer than 30 miles and eight are longer than 20 miles. The large number of tunnels over 16 miles long that are either built or planned indicates that tunnels of such length are widely considered feasible.

For today's long railway tunnels, the dominant configuration is two single-track tunnels. Among all of the world's tunnels longer than 14 miles, only those in Japan use the one-double-track configuration.

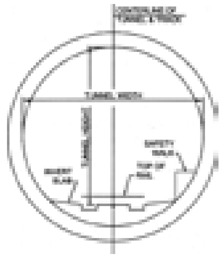
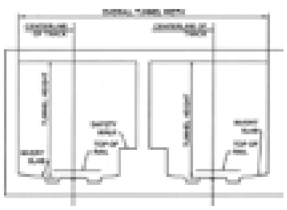
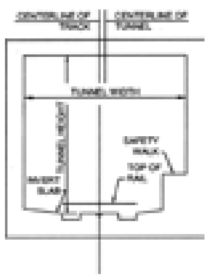
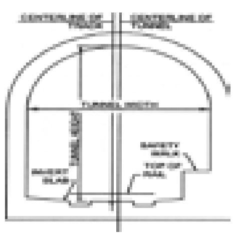
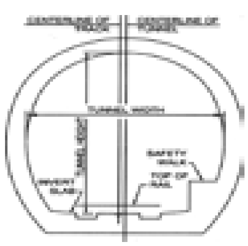
Hilar (2009) emphasized that for railways carrying heavy freight traffic, such as the Eurotunnel (also known as the Channel Tunnel or "Chunnel"), the safest design is the two-railway tunnel configuration with a parallel service or escape tunnel, although it is the most expensive to construct. The same configuration is planned for the Brenner Base Tunnel connecting Austria and Italy.

Among all tunnels longer than 20 km (12.4 miles), the single-double-track configuration is preferred only in Japan. The Seikan tunnel (33.8 miles) is the longest operating single, double-track tunnel with an escape gallery; however in Europe single, double-track tunnels typically do not exceed 6.3 miles in length. Italy's Vaglia (11.9 miles) and Firenzuola (9.4 miles) tunnels are exceptions (Hilar 2009).

RAIL TRANSIT TUNNEL TYPES

Types of rail transit tunnels vary by shape, liner type, invert (the base of the tunnel supporting the track bed, which may be flat or may continue the curve of the tunnel arch), construction method, and tunnel finishes. The shape of a rail tunnel is typically determined by the ground condition and tunneling methods (FHWA/FTA 2005). The shape may change within the length of the tunnel, with the changes typically occurring at station transitions or cross passages. The most popular shapes and their descriptions are shown in Table 2.

Table 2. Rail Transit Tunnel Types

Typical Example	Name and Description
 Circular tunnel with single track and one safety walk.	**Circular Tunnel** Typically designed with a single track and one safety walk. Invert slab is placed on top of liner.
 Double box tunnel with single track and one safety walk in each box.	**Double Box Tunnel** Typically designed with a single track and one safety walk in each box. Depending on location and loading conditions, center wall may be solid or composed of consecutive columns.
 Single box tunnel with a single track and one safety walk.	**Single Box Tunnel** Typically designed with a single track and one safety walk in each box. Tunnel is usually constructed beside another single box tunnel for opposite-direction travel.
 Horseshoe tunnel with single track and one safety walk.	**Horseshoe Tunnel** Designed for single track and one safety walk. This shape typically is used in rocky conditions and may be unlined within stable rock formations.
 Oval tunnel with single track and single safety walk.	**Oval Tunnel** Designed for a single track and single safety walk.

Source: FHWA/FTA 2005.

Reinke and Ravn (2004) discussed the various possible designs used for rail tunnel systems, which are shown in Figure 1. Considering ventilation and safety, this figure also illustrates the difference between a double-tube, single-track system and a single-tube, double-track system.


(a) Typical Double-Tube, Single-Track with Possible Configurations


(b) Typical Single-Tube, Double-Track Tunnel with Possible Configurations

Figure 1. Variants of Double- and Single-Tube Rail Systems

Source: Reinke and Ravn 2004

Reinke and Ravn (2004) reported that high-speed rail tunnels are increasingly designed as double-tube, single-track systems because they are considered safer and better for escape, rescue, maintenance, and operation. However, higher construction and operating costs are a major drawback.

EXCAVATION METHODS

Generally speaking, tunnel excavation involves either conventional methods – i.e., drilling and blasting – or boring through the rock with tunnel boring machines (TBMs). The New Austrian Tunneling method, or NATM, (also known as the Sequential Excavation Method, or SEM) uses conventional excavation but offers economic advantages by leveraging the geological strength inherent in the surrounding rock to help stabilize the tunnel. Currently, TBMs are the most popular method of excavation for long tunnels.

Tunnel Boring Machines (TBMs)

Various types of tunnel boring machines (TBM) are shown in Table 3. Two common types are pressurized and non-pressurized. Pressurized TBMs can operate in open or closed mode, whereas non-pressurized machines operate only in open mode. Each has advantages in its special geological range of application. The primary determinant of boring method is the condition of the ground. For example, if the excavation face is self-standing in hard rock, either an open-type or shielded TBM can be used (FHWA 2009).

Table 3. Commonly Used TBM Types and Descriptions

TBM Type	Description
Main Beam (Open)	• Can be continuously steered • Allows quick access directly behind the cutterhead for installation of rock support • Ideal for unlined tunnels
Single Shield (Closed)	• Machine enclosure (shield) protects workers from broken rock • Boring and installation of lining are performed sequentially • High-speed segment erectors for rapid tunnel lining installation
Double Shield (Closed)	• Used with precast concrete tunnel lining • Allows simultaneous boring and installation of lining • Can be operated in single-shield mode if the ground becomes too weak to support the gripper shoe pressure • Used for a wide range of geologic conditions
EPBM (Closed)	• Used primarily for unstable ground conditions from soft soils to weathered rock: Loose sedimentary deposits with large boulders • Urban environment • Used when ground contains water under pressure • Sealed against the fluid pressure of the ground outside the machine • Can be maneuvered through small turning radii

Source: FHWA 2009.

There are a variety of TBMs designed for different soil and rock conditions (FHWA 2009). Figure 2 illustrates a general classification of commonly used tunnel boring machines and the ground conditions for which they are best suited.

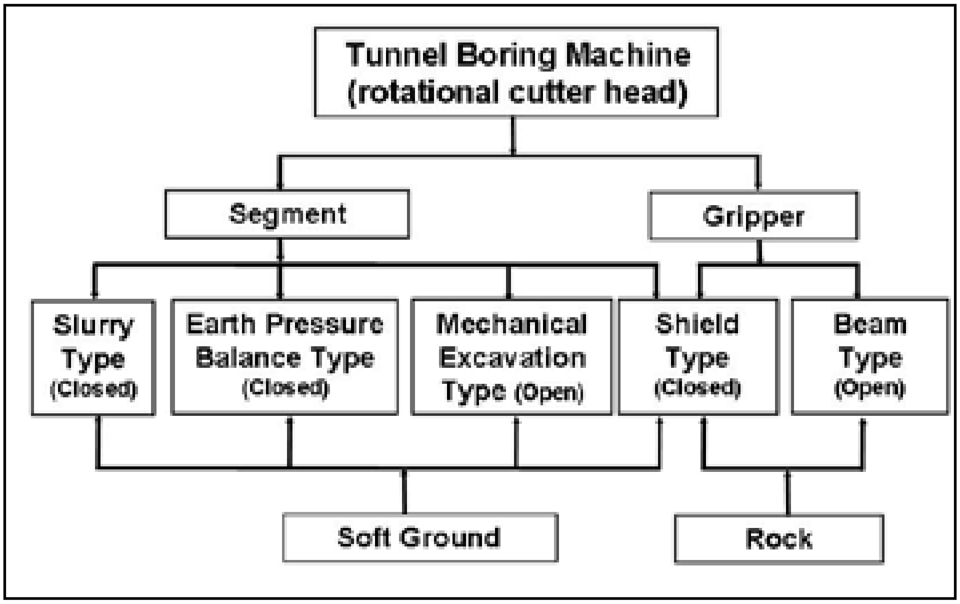


Figure 2. Classification of Tunnel Boring Machines

Source: FHWA 2009.

Originally, TBMs were limited to projects that had specific soil conditions, but Tarkoy and Byram (1991) reported that, thanks to technological advances, TBMs can now be used to bore through harder and more difficult rock, and their popularity has grown. They also stated that, although the TBM method has been popular in North America and worldwide, conventional drill-and-blast excavation methods are still in frequent use in many parts of the world (such as Hong Kong) where the following conditions exist (Tarkoy and Byram 1991):

- Hard granitic and volcanic rock;
- Plentiful, low cost labor; and
- Short lead time before start of tunneling.

Korea Institute of Construction Technology (KICT) reported that the TBM method was most popular for long-tunnel projects worldwide and, as of 2010, was used in the construction of (KICT 2010):

- More than 60% of the world’s long mountainous tunnels;
- More than 80% of the world’s long urban tunnels; and
- More than 80% of under the world’s long river/sea tunnels;

KICT also reported that the popularity of the TBMs continues to increase in Europe, where more than 90% of urban tunnels under construction or in design have been using this method. Japan, on the other hand, has used boring machines for only about 40% of its long tunnels. NATM has been the method of choice for approximately 50% of Japan's long tunnels due to challenging geological conditions. However, Japan's use of TBMs for urban tunnels is on the rise, with more than 80% using that method. China used a total of 138 tunnel boring machines between 2002 and 2006 was 138 (each project can use multiple machines), and the total distance spanned with this method was 372.8 miles (600 km). In 2004, more than 70% of China's metro tunnel construction projects used the TBM method (KICT 2010).

In Japan, approximately 75% of the TBM market is for shield-type machines. In Europe, however, open TBMs comprise approximately 60% of the TBM market due to differences in geologic conditions (KICT 2010).

EMERGENCY OPERATIONS

The existence of refuge areas in long tunnels is very important for safety in case of emergency. Minimizing passenger travel, strategically placed safety stations are equipped with sufficient space and adequate ventilation to allow passengers to wait safely for rescue (Hilar 2009). The high-speed rail tunnels from Table 1 that have safety stations include:

- Gotthard Base Tunnel (35.4 miles) - two underground stations;
- Brenner Base Tunnel (34.7 miles) - three underground stations;
- Lyon–Turin Tunnel (33 miles) - four underground stations;
- Lötschberg Base Tunnel (21.5 miles) - one underground station;
- Koralm Tunnel (20.5 miles) - one service station
- Guadarrama Tunnel (18 miles) - one 312.5-yard-long area with a service tunnel

For high-speed rail tunnels with one station, the distance from the safety station to an exit ranges from 10 miles to 11.25 miles. For high-speed rail tunnels with more than one safety station, the distance between stations or from a station to an exit ranges from 6.25 miles to 11.9 miles. Considering the operating speed of high-speed trains, these distances suggest that passengers on the train during an emergency can expect to reach either a safety station or an exit within five minutes.

Hilar (2009) reported that the majority of long, two-single-track rail tunnels have crossover connections between two tunnels although, Koralm tunnel has none. Hilar also reported that cross passages are frequently used in twin-tube tunnels to for escape. Appropriate spacing of the cross passages is important. The spacing of cross passages or escape exits in long tunnels is summarized in Table 4. The spacing of cross passages depends on many factors (Hilar 2009), including:

- Requirements of fire brigades
- Anticipated emergency scenarios
- Tunnel dimensions
- Properties of tunnel and train materials

In the United States, the maximum distance between tunnel-to-tunnel cross passages is 800 ft., as specified in the National Fire Protection Association's Standard 130 (NFPA 130) entitled "Fixed Guideway Transit and Passenger Rail Systems." (NFPA 2014).

Table 4. Spacing of Cross Passages and/or Escape Exits for Long Rail Tunnels

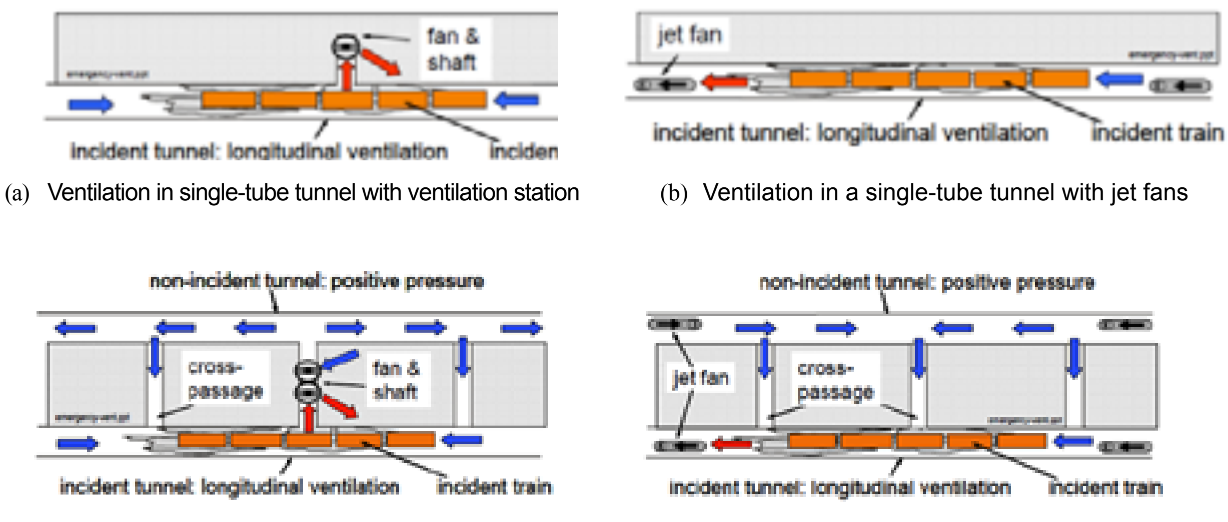
Tunnel	Length (Mi)	Commis-sioning	Configuration	Spacing of Cross Passag-es and/or Escape Exits
Groene Hart	4.45		One double-track tunnel with a dividing wall	Doors – 164 yds.*
Perthus	5		Two single-track tunnels	218 yds.
Storebaelt	5		Two single-track tunnels	273 yds.
Guadarrama	17.6	2007	Two single-track tunnels	273 yd
Ceneri Base Tunnel (CBT)	9.5	2018	Two single-track tunnels	350 yd
Gotthard	35.5	2015	Two single-track tunnels	355 yd
Lötschberg	21.5	2007	Two single-track tunnels (partly one single-track plus a gallery)	364 yd
Brenner Base Tunnel (BBT)	35		Two single-track tunnels	364 yd
Abdalajis	4.5		Two single-track tunnels	383 yd
Eurotunel	31	1994	Two single-track tunnels plus one service tunnel	410 yd
Lyon - Turin	33	2015	Two single-track tunnels	437 yd
Bussoleno	8	2015	Two single-track tunnels	437 yd
Koralm	20.5	2016	Two single-track tunnels	546 yd
Katzenberg	6	2012	Two single-track tunnels	546 yd
Wienerwald	8	2012	Two single tracks 6.72 miles One double track 1.48 miles	546 yd
Seikan	33.5	1988	One double-track tunnel	656 – 1095 yd
CTRL	12	2007	Two single-track tunnels	820 yd (original plan: 383 m yd)
Lainzer	6.5	2012	Two single tracks 1.44 miles One double track 5.2 miles	Spacing of escape exits: 131 – 655 yd
Vaglia	11.5	2008	One double track	Spacing of escape exits: up to 4921 yd
Firenzuola	9.5	2008	One double track	Spacing of escape exits: up to 5468 yd
Marseille	5	2001	One double track	Without escape exits
Vereina	12	1999	One single-track (3.75 mile double track)	Without escape exits

* The Groene Hart tunnel has a single tube with a bidirectional train circulation. The tracks are separated by a central wall that includes escape doors 164 yards apart.

Source: Hilar 2009.

VENTILATION SYSTEMS

Compared with road tunnels, fires in rail tunnels are very rare. However, their consequences could be disastrous because of "the high density of people and generally less-efficient escape and rescue conditions" (Reinke and Ravn 2004). Therefore, a ventilation system to control smoke dispersion is one of the most important tunnel systems.. Reinke and Ravn (2004) introduced different ventilation principles for single- and double-tube tunnels, as shown in Figure 3.



(a) Ventilation in single-tube tunnel with ventilation station

(b) Ventilation in a single-tube tunnel with jet fans

(c) Ventilation in a twin-tube tunnel with ventilation station

(d) Ventilation in a twin-tube tunnel with jet fans

Figure 3. Rail Tunnel Ventilation Systems

Source: Reinke and Ravn 2004.

Reinke and Ravn (2004) provided ventilation system examples of eleven European rail tunnel projects longer than 7 km (4.35 miles), as shown in Table 5. All were designed as twin-tube systems. The exception was the shortest tunnel – Groene Hart tunnel in Netherlands at 7 km (4.35 miles) – which uses longitudinal ventilation by jet fans and ventilated emergency exits. Katzenberg tunnel in Germany uses two ventilation shafts near the highest point for natural ventilation and smoke extraction; it has no mechanical ventilation system.

The Palmdale-to-Burbank proposed tunnel section is similar in length to Guadarrama tunnel (17.4 miles), which does not have any intermediate shaft for ventilation. The ventilation requirements specified in the California High-Speed Rail Project Design Criteria (CHSRA 2012) depend primarily on 1) tunnel configuration, 2) size and length of the running tunnels, 3) type and frequency of the rolling stock, and 4) fire/life safety strategy.

Table 5. Examples of Ventilation Measures for European Rail Tunnels

Rail tunnel	Length / System	Major Ventilation Measures
• Alpine Base Tunnels at Brenner • Gotthard • Lötschberg • Lyon–Turin (Austria, France, Italy, Switzerland)	• 35 to 57 km (21.75 – 35.42 miles) • 2 x single track for mixed traffic	• Simultaneous air supply and extraction by ventilation stations; fully redundant ventilation; • Ventilation objective: Critical velocity in incident tube; smoke-free cross passage and non-incident tube.
• Ceneri Base Tunnel (Switzer-land)	• 15 km (9.32 miles) • 2 x single track for mixed traffic	• Simultaneous air supply and extraction by ventilation stations; fully redundant ventilation; • Ventilation objective: Critical velocity in incident tube up to fires of freight trains of 250 MW
• Groenehart Tunnel (The Netherlands)	• 7 km (4.35 miles) • single-tube with perforated separation wall for passenger high-speed trains only	• Longitudinal ventilation by jet fans; ventilated emergency exits; • Ventilation objective: Critical velocity in incident tube up to fires of passenger trains of 40 MW; no smoke dispersion through doors
• Guadarrama Tunnel (Spain)	• 28 km (17.4 miles) • 2 x single track for passenger high-speed trains only	• Fresh air supply and smoke extraction by fan stations at the portals on both tunnel sides; doors for closure of rail at all four portals; • Ventilation objective: Critical velocity in incident tube up to fires of passenger trains of 50 MW; no smoke penetration in cross passages
• Katzenbergtunnel (Germany)	• 10 km (6.21 miles) • 2 x single track for mixed traffic	• No mechanical ventilation; 2 shafts near highest point for natural ventilation and smoke extraction; • Ventilation objective: Smoke extraction with thermal buoyancy effect
• Le Perthus Tunnel (France-Spain)	• 8 km (4.97 miles) • 2 x single track for mixed traffic	• Jet fans in rail tunnels; • Ventilation objective: Critical velocity in incident tube up to fires of passenger trains of 100 MW; no smoke penetration in cross passages
• Stoerebaelt Tunnel (Den-mark)	• 8 km (4.97 miles) • 2 x single track for mixed traffic	• Jet fans in rail tunnels; • Ventilation objective: Critical velocity in incident tube up to fires of passenger trains of 100 MW; no smoke penetration in cross passages
• Wienerwald Tunnel (Austria)	• 11 km (6.84 miles) • 2 x single track for mixed traffic	• Smoke control by fan stations in rail tunnel; • Ventilation objective: Critical velocity in certain parts of tunnels for passenger trains of up to 20 MW

Source: Reinke and Ravn 2004.

SPOIL MANAGEMENT

Thalmann et al. (2013) reported that spoil management has been recognized as one of the key components of long tunnel construction. It should be planned before construction and organized well during tunnel construction. In addition, they stated that effective spoil management can help limit sound, dust, transport and environmental emissions as well as a cost-efficient way.

They summarized 20 years of spoil management experiences in Switzerland with respect to the Lötschberg and Gotthard Base Tunnel projects. A total of 16.5 million and 28.2 million tons were excavated from Lötschberg and Gotthard Base Tunnel projects, respectively. More than 30% of the excavated rocks were processed and used for concrete production, as shown in Table 6.

Table 6. Key Parameters for Lötschberg and Gotthard Base Tunnel Spoil Management

Project	Total Excavation (Million Tons)	Processed Proportion of the Total Excavation (Million Tons)	Used Aggregate Proportion (Million Tons)
Lötschberg	16.5 (100%)	5.2 (31.5%)	4.8 (29.1%)
Gotthard	28.2 (100%)	9.4 (33.3%)	6.5 (23.0%)

Source: Thalmann et al. 2013.

Lieb (2011) also reported the use of excavated rock in Gotthard Base Tunnel concrete and shotcrete production, as shown in Table 7. A total of 9.4 million tons (33.3%) were suitable for aggregate for concrete production and utilized for aggregate for concrete production, sales to third parties, processing losses, and slurry.

Table 7. Gotthard Base Tunnel Spoil Classification and Utilization

<table>
<tr><th>Spoil Production</th><th>Spoil Classification</th><th>Spoil Utilization</th><th>Percent (%)</th></tr>
<tr><td rowspan="3">Gotthard Base Tunnel Total:
28.2 Million Tons
(100%)</td><td>Suitable as aggregate for concrete production:
9.4 million tons</td><td>Aggregate for concrete production
Sales to third parties
Processing losses
Slurry</td><td>23.0
3.2
2.8
4.3</td></tr>
<tr><td>Unsuitable as aggregate for concrete production:
18.6 million tons</td><td>ATG use for embankments
Landfill and renaturing
Ballast to third parties</td><td>16.0
44.3
5.7</td></tr>
<tr><td>Slurry from the drives:
0.2 million tons</td><td>Reactor landfill</td><td>0.7</td></tr>
</table>

Source: Lieb 2011.

Lieb (2011) summarized some important findings regarding spoil management from the

Gotthard Base Tunnel:

- One of the greatest logistical challenges is to manage the excavated material at the time it is produced and to ensure supplies of the required aggregates.

- The tunnel construction sites are in operation 320 days a year. During this time, the removal of excavated rock, as well as the supply of aggregate for concrete and shotcrete production, must be assured 24 hours a day, 7 days a week, summer and winter, even in mountainous conditions.

- Underground transportation takes place either by belt conveyor or by soil-removal train. A total length of around 44 miles of belt conveyors was installed on the construction sites of the Gotthard Base Tunnel.

- The key influencing factor for spoil management is the decision whether to perform final concreting of the inner lining (invert and vault) in parallel with driving, or subsequently.

- Due to the potential noise disturbance, overground spoil processing can generally take place only in the daytime on weekdays; thus, huge temporary storage areas are required at the processing sites.

Thalmann emphasized that “an optimal control concept for the recycling of rock material begins with the choice of the right excavation method, such as TBM with greater cutter spacing or drill and blast” (Thalmann 1999). Thalmann also reported that it is necessary to make an effort to obtain “a high share of coarse components in the rock material cut by the TBM in order to produce a sufficient amount of concrete aggregates greater than 16mm after crushing and washing” (Thalmann 1999).

In addition, it is reported that “the spacing between cutter rollers exercises the most important influence on the grain size distribution of the cut material. The actual cutter spacing in the face area of a common hard rock TBM is about 80–90mm.” (Thalmann 1999). Table 8 shows that “an increased gap between the cutters enhances the component size and the quantity of coarser fragments in the muck” (Thalmann 1999).

Table 8. Muck Produced in Mass Percentages by Various Tunneling Methods

Type of Tunneling Method	Cutting Disc Spacing (mm)	0/4 mm	>32 mm	>100 mm
Conventional Drill and Blast (Crystalline Rock)	-	2-5	85-95	75-85
Back Cutting Technique (Sandstone)	-	15-20	65-75	45-60
Roadheader Drive (Jura Limestone)	-	15-40	5-35	0-5
TBM with Bits Cutter	60-70	30-50	2-20	0
TBM Drive with Disc (Sediments, Crystalline Rocks)	65-90	5-50	5-50	0-10
TBM Drive with Enlarged Cutting Roller Spacing (Plutonit)	86 129 172	45 40 20	20 30 35	0 5 15

Source: Thalmann 1999

EUROPEAN HIGH-SPEED RAIL TUNNEL SYSTEMS

In 2004, Reinke and Ravn distilled a set of guidelines or practices for high-speed rail tunnel systems based on tunnels that, at the time, were in the conceptual and planning stages in some European countries. These are shown in Table 9.

Table 9. Guidelines for High-Speed Rail Tunnel Systems in Europe (in 2004)

Country	Guidelines or Practices for High-Speed Rail Tunnels at Conceptual or Planning Stage
France	• Existing high-speed rail lines with only a few tunnels, mostly double track • New tunnels with mixed traffic and a length of more than 5km are built as twin-tube systems
Germany	• Distinction between short tunnels (1,640–3,280 ft); long tunnels (3,280 ft–16,404 yds); and very long tunnels (>16,404 yds) • Single-tube, double-track tunnels are used for passenger trains only • Passenger and freight trains: only single-tube, double-track tunnels for lengths over 3,280 ft. • Passenger and freight trains: tunnel lengths of 1,640 ft–3,280 ft; scheduled trains should not meet in tunnel
Italy	• Mainly single-tube, double-track tunnels on new high-speed lines
Netherlands	• Double-tube, single-track for new high-speed lines (e.g., Groenehart)
Switzerland	• Project-dependent • Tunnel purely for passenger trains: single-tube, double track • Tunnel for mixed traffic: double-tube, single-track
International Union Railways (UIC)	• Project-dependent • Twin-tube tunnels recognized as a high-risk mitigation for long tunnels

Source: Reinke and Ravn 2004.

- Reinke and Ravn (2004) mentioned that, traditionally, decisions about high-speed rail tunnel systems were based on geology, location, function, and cost, but currently (in 2004) decisions were often based on an evaluation of each individual project. They also mentioned four factors influencing tunnel safety decisions:
    - The possibility of self-rescue on escape routes;
    - The presence of cross passages or emergency exits;
    - Availability of emergency services; and
    - Ventilation, drainage system, exposion prevention, and the operation concept (e.g., passenger trains, mixed traffic, shuttle trains, etc.).

In summary, the authors concluded that, "[i]n the past, single-tube, double-track tunnels were most common for short and long tunnels," and "[t]win-tube tunnels were mainly used for very long distances." (Reinke and Ravn 2004) They also concluded that "twin-tube is currently [in 2004] preferred for increasingly shorter tunnel length because of several safety features", and "most modern long, high-speed tunnels are planned as twin-tube system [sic]" (Reinke and Ravn 2004). In addition, it was also found that twin-tube tunnels equipped with cross passages made better use of mechanical ventilation and significantly shortened escape distances, allowing better access for rescue and firefighting operations.

GOTTHARD TUNNEL REVIEW

Scheduled to open to the public June 1, 2016, Switzerland's 57-km (35.42-mile) Gotthard Base Tunnel, is the longest railway tunnel in the world. The complete tunnel system consists of 153.3 km (95.3 miles) of access tunnels, shafts, railway tunnels, connecting galleries, and auxiliary structures (Ehrbar 2008).

Using both TBM and conventional excavation methods, excavation of this tunnel began from several sites simultaneously to shorten construction time. The length of the tunnel was divided into five sections, with access points at Erstfeld in the north and Bodio in the south; three intermediate access points through tunnels at Amsteg and Faido; and two vertical shafts at Sedrun (Ehrbar 2008). Figure 4 provides an overview of Gotthard Base Tunnel. Figure 5 shows the longitudinal profile and excavation methods for the five sections, including the length and direction of TBM boring .

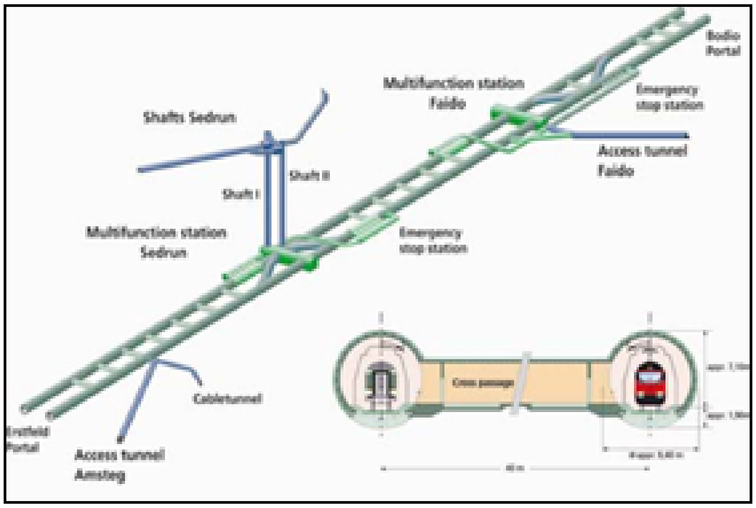


Figure 4. Overview of Gotthard Base Tunnel

Source: Ehrbar 2008

Ehrbar (2008) insisted that "conventional tunneling is the best method for projects with highly variable rock conditions or variable shapes" and emphasized that the conventional tunneling method, in association with various auxiliary construction methods, allows "experienced project managers to make the most appropriate choice to achieve safe and economic tunnel construction even in situations with changing or unforeseen rock conditions." Both conventional and TBM methods were used for the Gotthard tunnel; approximately 20% of the excavation was performed with conventional methods.

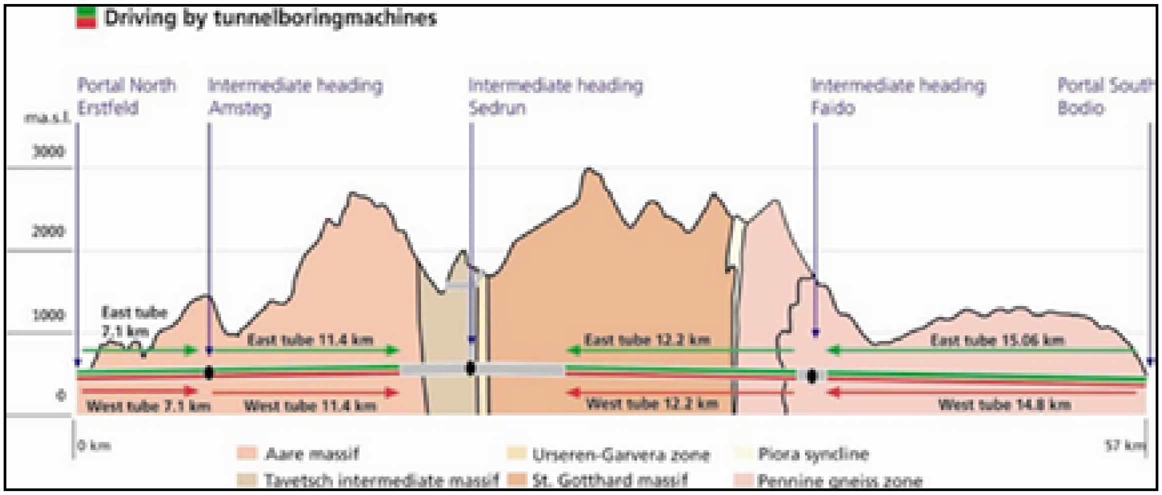


Figure 5. Excavation Methods for Gotthard Base Tunnel

Source: Ehrbar 2008

The Gotthard Base tunnel used open-type "gripper" TBMs, which Ehrbar (2008) described as appropriate for projects characterized by:

- Comparatively homogenous ground conditions; and
- A comparatively low risk of water inflow under high pressure

The average TBM advance rates ranged between 38 and 82 ft. per working day. When TBM was faced with a horizontal fault zone, the average production rate dropped dramatically close to the minimum – 9.8 ft. per working day. However, the TBM still permitted significantly higher advance rates than would have been possible with conventional tunneling (Ehrbar 2008).

III. DATA COLLECTION

This chapter describes the methods used to collect data and the types of data collected. It also provides a sample of the data collected for one project. The author identified 24 categories of data that could be useful in planning and designing tunnels for the Palmdale-to-Burbank segment of the California High-Speed Rail System. The categories were populated with data obtained from printed and digital media, including journal papers, conference proceedings, technical reports, websites, and Internet searches.

Table 10 identifies the 24 categories and displays a data sample from a single project: the Lötschberg Base Tunnel project.

Table 10. Data Categories and Sample Data for the Lötschberg Base Tunnel Project

Category	Data
Tunnel Name	Lötschberg Base
Location	Switzerland
Tunnel Category	Rail
Tunnel Type	HSR
Operation Speed (mph)	155
Length (mi)	9.079
Width/Diameter (yd.)	7.66
Number of Tubes	2
Construction Start	1999
Construction End	2006
Tunneling Method	TBM
Tunnel Function	Passenger + Freight
Topography	Crossing of the Swiss Alps
Rock Type	Crystalline rocks such as granite and gneiss.
Ground Water	Yes
Geological Difficulties	Weak beds and zones, including faults, shear zones, and altered areas weakened by weathering or thermal action
Seismic Hazard	Yes
Production Rate	Range of 40–60 ft per day
Electrification System	16 kV AC system, 50 Hz
Signal Control System	ERTMS/ETCS Level 2
Configuration	Two single-track tunnels (partially a single-track tunnel and a gallery)
Cross Passage Spacing (yd.)	364
Safety Measures	2 stations – one service and one escape
No. of Stations	2

Over a period of less than two months, the authors collected data on a total of 67 long tunnels worldwide. The 67 tunnels included 43 rail tunnels – 32 high-speed, 4 standard, and 7 subway; 14 roadway tunnels, 7 water tunnels, and 3 hydroelectric tunnels. Table 11 shows the breakdown of the 67 projects by type. Figure 6 shows the relative contribution (in terms of the number of projects) of each project type to entire body of data from all 67 projects.

Table 11. Number of Tunnels Collected by Tunnel Type

Tunnel Type		Number of Projects
Hydroelectric		**3**
Rail		**43**
HSR	32	
Rail	4	
Subway	7	
Road		**14**
Water		**7**
Grand Total		**67**

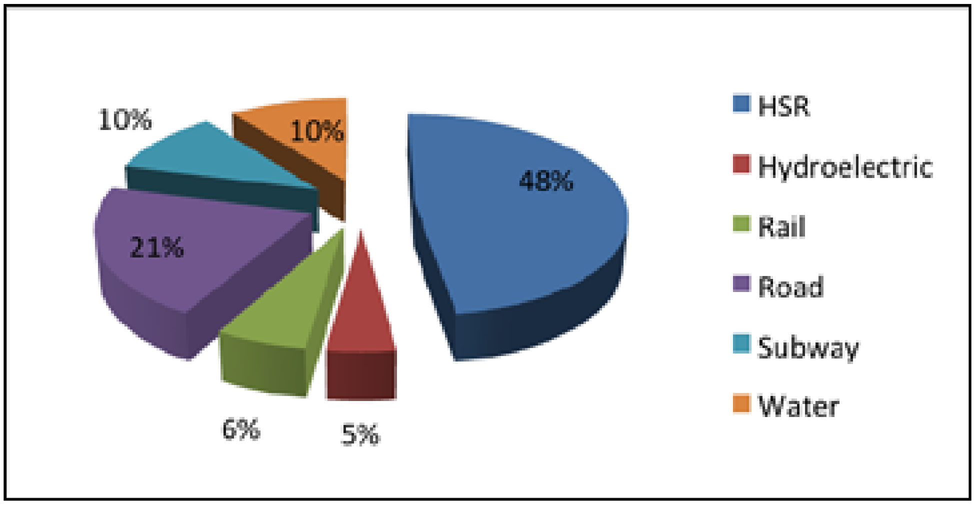


Figure 6. Contribution to Tunnel Project Data by Tunnel Type

Data on the duration of tunnel projects is scarce. Most tunnel construction projects provide only the start and end years of construction.

For example, a precise date was available for the start of construction for the Seikan tunnel: Sep. 28, 1971. The main tunnel was bored through on March 10, 1985 (Matsuo 1986). However, the construction completion date is identified only by year – 1987 – and the opening date only by month and year – March 1988 (Ikuma 2003).

Other examples: Gotthard Base Tunnel construction began in 1996. The eastern tunnel was completed on October 15, 2010, and the western tunnel on March 23, 2011. Barrandov Tunnel, a 24.7-km-long high-speed railway tunnel between Prague and Beroun in Czech Republic, was initiated in 2005 and the design took place between 2006 and 2009. Construction started in 2011 and the project is expected to be completed in 2016.

For many tunnels, there is also a dearth of data on the duration of the design and construction phases. Thus, while tunnel construction start and end years were included in the database for analysis, tunnel design duration was not.

ROBBINS COMPANY TUNNEL DATA

Robbins Company, a manufacturer of TBMs, provides data on their website for tunnel projects that made use of their products. Data on 54 tunnel projects were collected from the Robbins Company website. Of that 54, there were 30 high-speed rail or rail tunnels longer than 5 miles, and those were included in the database for analysis. The remaining high-speed rail or rail tunnels were summarized in a separate database.

For the thirty Robbins Company projects, the “main beam” boring method was the most popular. Table 12 summarizes the Robbins Company tunnel projects by type .

Table 12. Robbins Company Tunnel Projects by Tunnel Type

Tunnel Type	Number of Projects	
Cable		**1**
Main Beam TBM	1	
Hydroelectric		**5**
Main Beam TBM	4	
Single-Shield TBM	1	
Rail		**6**
Double-Shield TBM	1	
EPBM	2	
Main-Beam TBM	3	
Waste Water		**5**
Double-Shield TBM	3	
EPBM	1	
Main-Beam TBM	1	
Water Transfer		**12**
Double-Shield TBM	3	
Main Beam TBM	8	
Single-Shield TBM	1	
HSR		**1**
EPBM	1	
Grand Total		**30**

CALIFORNIA HIGH-SPEED RAIL PALMDALE-TO-BURBANK TUNNEL

In June 2015, California High-Speed Rail Authority published a Supplemental Alternatives Analysis for the Palmdale-to-Burbank section of CHSR, which included ten alternative alignments for this segment (CHSRA 2015). Details of the tunnels required by each alternative are summarized in Table 13.

Table 13. Tunnels Required by Proposed Alternatives for Palmdale-to-Burbank Segment of CHSR

Tunnel Name	Total Tunnel Length (mi)	Number of Tunnels	Route Length (mi)	Landslide Hazard (mi)	Liquefaction Hazard (mi)	Methane Hazard (mi)	Faults (mi)	Fire Risk	Seismic Hazard	Oil Hazard	Geology
E1a	20.2	2	41.2	0.77	0.1	3.4	0.5	High	YES	Former oil exploration areas	Sub-watersheds, springs, domestic wells, perennial streams
E1b	22	2	41.6	4.8	0.03	3.2	0.5	High	YES	Former oil exploration areas	Sub-watersheds, springs, domestic wells, perennial streams
E2a	19.5	2	37.7	2.3	0.46	1.9	3.51	High	YES	Former oil exploration areas	Sub-watersheds, springs, domestic wells
E2b	21.3	2	38.2	3.7	0.4	3.3	3.51	High	YES	Former oil exploration areas	Sub-watersheds, springs, domestic wells, perennial streams
E3a	21.2	2	36.2	3.3	0.26	0	1.92	High	YES	Former oil exploration areas	Sub-watersheds, springs, domestic wells, perennial streams
E3b	23	2	36.6	4.4	0.3	0.65	1.92	High	YES	Former oil exploration areas	Sub-watersheds, springs, domestic wells, perennial streams
SR 14-1	20.7	2	49	4.2	2.6	0.25	1.04	High	YES	Oil field	Sub-watersheds, springs, domestic wells
SR 14-2	18.9	2	49	6.4	1.3	0.25	0.77	High	YES	Oil field	Sub-watersheds, springs, domestic wells
SR 14-3	20	2	49.4	4.2	2.6	0.25	1.04	High	YES	Oil field	Sub-watersheds, springs, domestic wells
SR 14-4	18.2	2	49.4	5.3	1.3	0.25	0.77	High	YES	Oil field	Sub-watersheds, springs, domestic wells

Source: CHSR 2015.

IV. DATA ANALYSIS

The purpose of analyzing data from the world's long tunnels is to identify trends that could help inform decisions for the Palmdale-to-Burbank segment of CHSR.

PROJECTS BY LOCATION

Data for 67 long tunnel projects around the world were collected and analyzed. The 67 tunnels are located in twenty-eight different countries, including fifteen countries in Europe, eight in Asia, two in North America, two in Oceania, and one in Africa. Table 14 shows the countries, the number of tunnel projects in each that were analyzed, and the total tunnel lengths. The 34 projects in Europe had a combined total length of 460.4 miles. The 27 projects in Asia had a total length of 377.5 miles. Figure 7 graphs the long tunnel project data by location.

Among the projects for which data were collected, nine, including four high-speed rail tunnels with a combined length of 55.5 miles, are located in China. The combined total length for all nine tunnel projects from China is 123.5 miles.

Table 14. Locations, Quantity, and Total Length of Tunnels Analyzed

Country	Number of Tunnels	Total Tunnel Length (mi)
Africa	**1**	**28.3**
South Africa	1	28.3
Asia	**27**	**377.5**
China	9	123.5
India	4	48.2
Japan	7	99.2
Korea	1	32.5
Singapore	1	22.2
Taiwan	2	16.0
Thailand	1	5.9
Turkey	2	30.0
Europe	**34**	**460.4**
Austria	4	43.9
Austria-Italy	1	34.0
Czech Republic	1	15.3
Denmark	1	5.0
England	1	11.8
England-France	1	31.4
France	1	4.8
France-Italy	4	56.0
Germany	1	5.8
Greece	1	18.3
Italy	2	21.1
Netherlands	1	4.5
Norway	2	21.4
Spain	5	58.6
Spain-Morocco	1	23.4
Sweden	1	10.6
Switzerland	6	94.7
North America	**3**	**33.2**
Canada	2	15.6
USA	1	17.6
Oceania	**2**	**13.7**
Australia	1	7.7
New Zealand	1	6.0
Grand Total	**67**	**913.1**

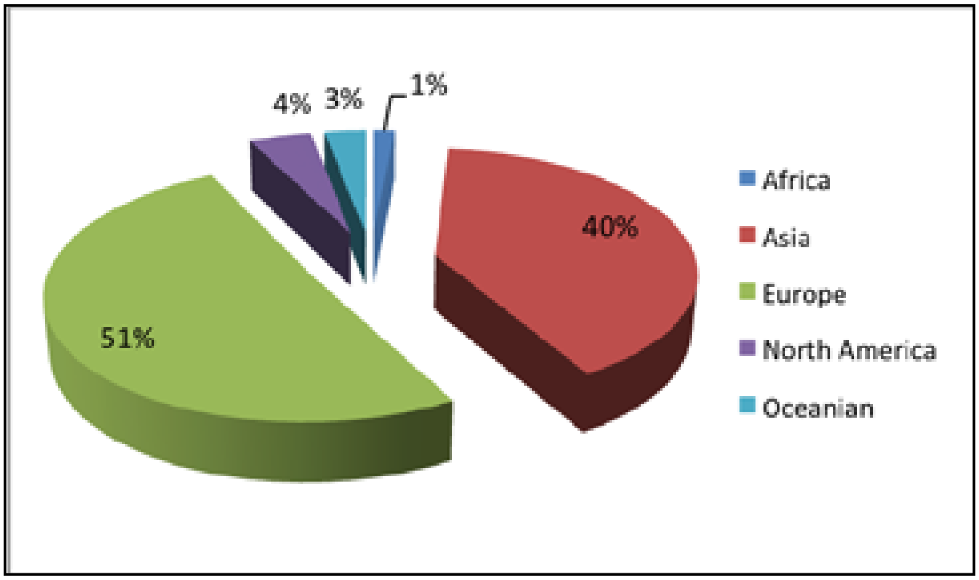


Figure 7. Long-Tunnel Project Data Share by Location

With respect to long HSR tunnels exclusively, Switzerland boasts the largest number (five) as well as the longest (35.5 miles). The total length of Switzerland's long HSR tunnels is 84.2 miles. Figure 8 shows the number and total length, by country, of long HSR tunnels included in the analysis, . Europe is home to 78% of the HSR tunnels analyzed; the remaining 22% are located in Asia, China and Japan.

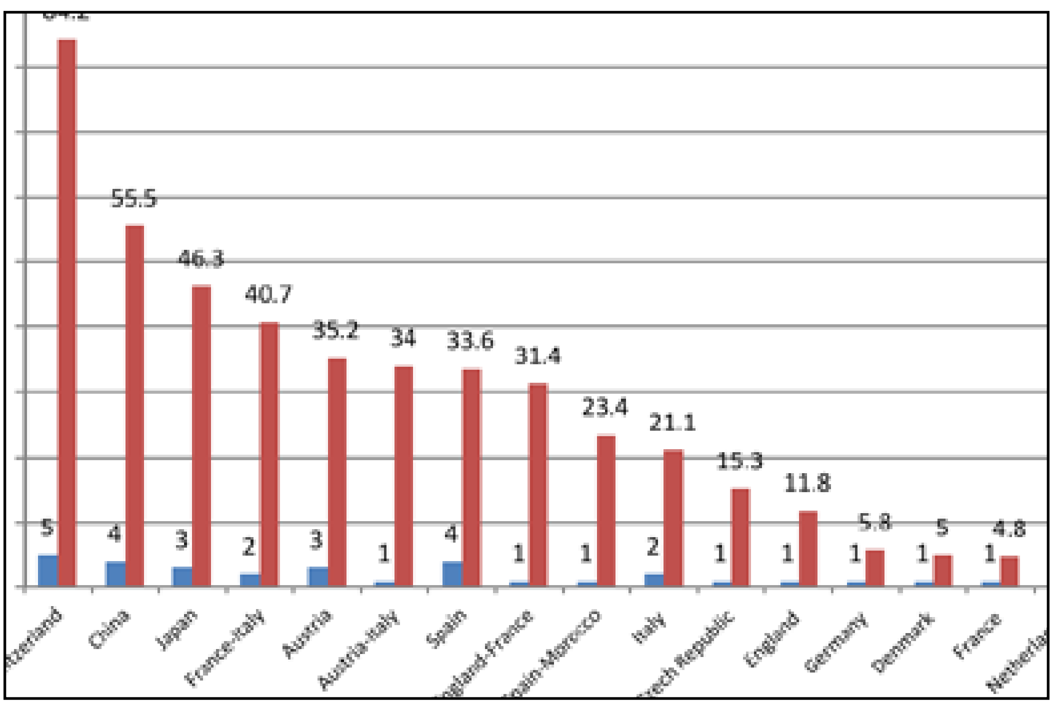


Figure 8. Number and Length of HSR Tunnels by Country

TUNNELING METHODS

Overall, both TBM and conventional tunneling methods are popular for HSR and rail tunnel projects. In summary, 70% of the long tunnel projects used the conventional method at least in part, and 80% of the long tunnel projects used the TBM method at least in part. Tunneling methods are summarized by project type in Table 15.

Table 15. Tunneling Methods by Project Type

Tunneling Methods	Number of Tunnels	Total Tunnel Length (mi)
HSR	**32**	**452.5**
Conventional Method	8	110.2
TBM	6	39.5
TBM and conventional method	12	245.6
Unknown	6	57.2
Hydroelectric	**3**	**18.7**
TBM	3	18.7
Rail	**4**	**57.2**
Conventional method	1	6.8
TBM	2	16.8
TBM and conventional method	1	33.5
Road	**14**	**118.0**
Conventional method	8	68.5
TBM	4	26.2
TBM and conventional method	2	23.2
Subway	**7**	**131.3**
Conventional method	1	32.5
TBM	3	51.4
TBM and conventional method	3	47.4
Water	**7**	**135.6**
TBM	7	135.6
Grand Total	**67**	**913.1**

Selection of tunneling methods depends on several factors. Besides the length of the tunnel, among the most important factors are the geological conditions. Geological difficulties and tunneling methods are summarized in Table 16 (HSR tunnels), Table 17 (rail and subway tunnels), Table 18 (roadway tunnels), and Table 19 (hydroelectric and water tunnels). Table 20 summarizes tunneling methods based on topography and rock classification.

Table 16. Geological Difficulties and Tunneling Methods: HSR Tunnels

Project	Geological Difficulties	Tunneling Method Used	Tunnel Length (mi)
Abdalajis	Methane intrusions, water Inflows	TBM	4.5
Channel	Water inflows on the French side of the tunnels	TBM and conventional method	31.4
Gotthard Base	Landslide near river	TBM and conventional method	35.5
Hakkoda	Location near an erosion control dam and a well that provides water for local residents	Conventional method	16.5
Iwate-Ichinohe	The Mabuchi and Kitakami rivers run near the tunnel's Tokyo portal	Conventional method	16.0
Lötschberg Base	Weak beds and zones including faults, shear zones and altered areas weakened by weathering or thermal action	TBM and conventional method	21.5
Lyon–Turin	Squeezing and time-dependent behavior of coal-bearing schist	TBM and conventional method	33.0
Prague–Beroun	Occurrence of karst phenomena, tapping of karst cavities, water irruptions etc.	TBM and conventional method	15.3
West Qinling	Extremely poor ground in some parts (hazard of earth falling)	TBM and conventional method	10.3

Table 17. Geological Difficulties and Tunneling Methods: Standard Rail and Subway Tunnels

Project	Geological Difficulties	Tunneling Method Used	Tunnel Length (mi)
Rail			
Epping-Chatswood Rail	Fault line	TBM	7.7
Seikan	Invasion of sea water and high water pressure	TBM and conventional method	33.5
Subway			
Circle MRT Line	Rapidly changing geology, water seepage	TBM	22.2
Metro Madrid	Ground loss	TBM and conventional method	25.0
MRT Blue Line	Soft clay has high plasticity and low strength, groundwater	TBM	5.9
Shenzen Metro	Carbon monoxide release	TBM	23.3

Table 18. Geological Difficulties and Tunneling Methods: Road Tunnels

Project	Geological Difficulties	Tunneling Method Used	Tunnel Length (mi)
Arlberg	Intensively fractured areas and fault zones	Conventional method	8.7
Frejus	Slope stabilization was the main problem	Conventional method	8.1
Hida	Weak geological features and a large amount of spring water	TBM	6.7
Hsuehshan	Fractured rock and massive inflows of water	TBM	8.0
Kan Etsu	Complex orogenic movement and remain highly stressed	Conventional method	6.8
Laerdal	Broken and cracked Zones	TBM and conventional method	15.2
Mont Blanc	High flow of water and floods, As well as geological collapses	Conventional method	7.2
Rohtang	Unstable rocks	Conventional method	5.5
Stockholm Bypass	Proximity to lakes and sea	Conventional method	10.6
Tokyo Bay Aqua	High water pressure and a soft foundation.	TBM	5.9

Table 19.Geological Difficulties and Tunneling Methods: Hydroelectric and Water Tunnels

Project Type/ Project	Geological Difficulties	Tunneling Method Used	Tunnel Length (mi)
Hydroelectric			
Manapouri	Heavy water inflows	TBM	6.0
Meråke	Six different rock types along the tunnel route, including relatively soft phyllite; mixed-face rocks, such as greywacke and sandstone; and hard metagabbro.		6.2
Niagara	Large rock blocks started to fall from the crown before rock support could be placed	TBM	6.5
Water			
AMR	Severely blocky ground/flood waters	TBM	27.0
Evinos-Mornos	Methane inflow, about 16% of the tunnel was driven through very adverse ground with soil-like characteristics that could not be classified by RMR system.	TBM	18.3
Pinglu	40-ft.-thick coal seams and abrasive sandstone that required intensive monitoring of tunnel air for particulates	TBM	15.8

Table 20. Tunneling Methods Based on Topography and Rock Classification

Topography and Rock Classification	Number of Tunnels Per Method	Total Tunnels Per Rock Class	Total Tunnel Length (mi.)	
Mountain Area				
Hard Rock		**2**		**19.0**
Conventional method	2		19.0	
Medium Rock		**5**		**68.5**
Conventional method	2		13.6	
TBM	1		6.7	
TBM and conventional method	2		48.2	
Soft Rock		**8**		**87.5**
Conventional method	2		31.9	
TBM	5		49.8	
TBM and conventional method	1		5.8	
Mixed Rocks		**12**		**208.3**
Conventional method	6		69.7	
TBM and conventional method	6		138.6	
Plains				
Medium Rock		**1**		**8.9**
TBM and conventional method	1		8.9	
Soft Rock		**1**		**23.3**
TBM	1		23.3	
Mixed Rocks		**2**		**34.1**
TBM	2		34.1	
Under River/Sea				
Hard Rock		**1**		**10.6**
Conventional method	1		10.6	
Soft Rock		**2**		**36.4**
TBM	1		5.0	
TBM and conventional method	1		31.4	
Mixed Rocks		**1**		**13.5**
TBM and conventional method	1		13.5	
Urban Area				
Soft Rock		**2**		**30.9**
TBM	1		5.9	
TBM and conventional method	1		25.0	
Mixed Rocks		**2**		**27.2**
TBM	1		22.2	
Not identified	1		5.0	

Rock and soil conditions are also a key factor in tunneling method selection. Table 21 provides a detailed summary of rock and soil conditions for the HSR tunnel projects analyzed, and the tunneling method(s) chosen for each project.

Table 21. Rock/Soil Conditions and Tunneling Method Chosen for HSR Tunnels

Project	Rock/Soil Conditions	Tunneling Method Used	Tunnel Length (mi)
Abdalajis	Dolomitic limestone, quartzite, conglomerates, and sandstone	TBM	4.5
Brenner Base	Brixner granite (6.83 mi) and the Innsbruck quartz phyllite (3.1 mi) rock formations	TBM (77 mi) and conventional method (33 mi)	34.0
Ceneri Base Tunnel	Schist, Swiss molasse, and Ceneri orthogenesis	TBM and conventional method	9.6
Channel	Chalk marl, glauconitic marl, stiff clay	TBM and conventional method	31.4
Firenzuola	Sandy silt	TBM	9.5
Gotthard Base	Kakirite zones, both hard and soft rocks	TBM (91.3 mi) and conventional (22.7 mi) method	35.5
Guadarrama	Crystalline rocks such as granite and gneiss	TBM and conventional method	17.6
Hakkoda	Mudstone, pyrite, igneous rocks	Conventional method	16.5
Iiyama	Mudstones, sandstones and volcanic tuffs. The surrounding rocks are characterized by extrusion	Conventional method	13.8
Iwate-Ichinohe	Mesozoic and Paleozoic strata (hornfels and chert)	Conventional method	16.0
Katzenberg	Clay, marl, limestone and sandstone	TBM	5.8
Koralm	Tertiary sediments, crystalline basement	TBM (43.9 mi) and conventional (21.1 mi) method	20.4
Lötschberg Base	Crystalline rocks such as granite and gneiss	TBM (19.8 mi) and conventional (48 mi) method	21.5
Lyon–Turin	Squeezing coal schists	TBM and conventional method	33.0
New Guanjiao	Fissured rock	Conventional method	20.3
Pajares Lot 4	Sandstone, shale, limestone, molasse, and volcanic rocks	TBM	6.5
Prague-Beroun	Strata of ordovician and devonian sediments and volcanites, quartzite	TBM and conventional method	15.3
Storebaelt	Large boulders, marl, limestone	TBM	5.0
Vaglia	Marly limestones and limy marls with marly strata	Conventional method	11.6
Vereina	Crystaline rocks	Conventional method	11.8
West Qinling	Sandstone and phyllite rocks, phyllite and limestone with high quartz content	TBM and conventional method	10.3
Wienerwald	Flysch and molasse	TBM	8.3
Zimmerberg	Lacustrian sediments of sand and silt and in coarse-grained fluvial sediments	TBM and conventional method	5.8

TUNNEL CONFIGURATION

Eight of the sixty-seven tunnels – three in Asia and five in Europe – were designed for one double track. A total of 21 tunnels – three in Asia and eighteen in Europe – were designed for two single tracks. Approximately 80% of the European HSR tunnels used two single tracks. In Asia, however, the two-single-track configuration is used for only 50% of the tunnels, primarily because Japan's HSR tunnels are designed for one double track. Table 22 summarizes HSR tunnel configuration by location and tunnel function. Table 23 summarizes cross passage spacing for two-single-track tunnels.

Table 22. Configuration and Function of HSR Tunnels

Configuration	Passenger Only	"Passenger-Only" by Configuration	Passen-ger and Freight	"Pass. and Freight" by Configuration	Unknown	"Unknown" by Configuration	Total Tunnels
One Double-Track Tunnel		**2**		**3**		**3**	**8**
Asia	1				2		3
Europe	1		3		1		5
Two Single-Track Tunnels		**0**		**17**		**4**	**21**
Asia	0		2		1		3
Europe	0		15		3		18
Total HSR Tunnels	**2**		**20**			**7**	**29**

Table 23. Cross Passage Spacing for Two-Single-Track HSR Tunnels

Tunnel Name	Length (mi)	Diameter/Width (yd)	Cross Passage Spacing (yd)
Brenner Base	34.0	9.0	364
Bussoleno	7.7		400
Ceneri Base Tunnel	9.6	9.6	320
Channel	31.4	9.7	410
Gotthard Base	35.5	8.8	355
Guadarrama	17.6	9.3	273
Katzenberg	5.8	11.8	500
Koralm	20.4	8.6	547
Lötschberg Base	21.5	7.7	364
Lyon–Turin	33.0	11.5	400
Storebaelt	5.0	8.4	250
Wienerwald	8.3	11.6	500

V. CONCLUSIONS

The author reviewed the literature and constructed a detailed database of information on the projects behind the world's long tunnels. In addition, the database included data on the tunnels required by each of the ten alternative alignments for the Palmdale-to-Burbank segment of CHSR as described in the Supplemental Alternatives Analysis.

Based on the data, this report presents data on 67 tunnels longer than 4.5 miles, including 32 high-speed railway tunnels, located in 28 countries around the world. The following is a summary of the findings. It is hoped that the trends identified from the aggregate data will help inform decisions for the tunnel projects being considered for the Palmdale-to-Burbank segment of California High-Speed Rail:

- A total of five HSR tunnels of the same length or longer than those proposed for the Palmdale-to-Burbank segment of CHSR have been successfully completed worldwide, and another six are currently under construction or in planning.
- Among the eleven longest HSR tunnels globally, five are longer than 30 miles and eight are longer than 20 miles. This indicates that HSR tunnels longer than 16 miles are considered feasible.
- Tunnels configured for two single tracks connected by cross passages are becoming more popular due to increasingly demanding safety requirements.
- Among all tunnels longer than 20 km, the one-double-track configuration is preferred only in Japan. Two railway tunnels with a parallel service or escape tunnel was deemed the safest design by many researchers, although it is the most expensive from a construction standpoint.
- Inclusion of refuge areas in long tunnels is extremely important for safety during emergencies.
- Cross passages are frequently used in twin-tube tunnels to allow passengers to escape safely in an emergency. Appropriate spacing of cross passages is also important.
- Ventilation to control smoke dispersion is one of the most important systems in a long tunnel. Twin-tube tunnels equipped with cross passages significantly shorten the escape distance and allow easier access by rescue and firefighting personnel.
- Overall, both tunnel boring machines (TBMs) and the conventional tunneling method – drilling and blasting or other mechanical excavating methods – are popular for HSR and rail tunnel projects. The conventional method was used, at least in part, by 70% of the projects studied, and the TBM method was used, at least in part, by 80%. The conventional method is popular for projects involving challenging or highly variable rock formations or composition, as well as

projects with a high risk of water inflow under high pressure.

- The selection of tunneling methods depends on several factors, such as tunnel length, geological conditions, and rock/soil conditions. The methods used for the tunnels in this study are summarized by the topography, rock classifications, and geological difficulties of each project. The summaries can serve as good examples for CHSR tunnel projects with similar geological conditions.

- All of the HSR tunnels studied used one of the following five electrification systems: 750 V DC, 15 kV AC (16.7 Hz), 15 kV AC (50 Hz), 25 kV AC (50 Hz), and 27.5 kV AC (50 Hz).

- Most long high-speed rail tunnels serve both passenger and freight rail. However, the Abdalajis tunnel in Spain, the Iiyama in Japan, and the CTRL HS1 tunnel in England were designed only for passenger rail.

- Approximately 80% of the European HSR tunnels use the two single-track configuration. However, only 50% of the tunnels in Asia use this configuration; Japan's HSR tunnels use the one-double-track configuration for a variety of reasons, including underground conditions, operating speed, and the fact that a larger tunnel area reduces the impact of shock waves.

- Although TBM showed significantly higher advance rates than conventional tunneling, the conventional tunneling method has many advantages over mechanized tunneling methods in terrains having difficult rocks and highly variable rock conditions, and with projects that have a higher risk of water inflow under high pressure.

- Construction of long tunnels involves dealing with a variety of ground conditions. Some projects employed a combination of tunnel boring machines and the New Austrian Tunneling Method, also known as the Sequential Excavation Method, which offers economic advantages by leveraging the geological strength inherent in the surrounding rock to help stabilize the tunnel.

- Many of the projects demonstrated that varying ground conditions can reduce the advance rate of a tunneling project. A well-developed tunneling strategy can significantly reduce the negative impact of varying ground conditions on construction time.

- Based on the research, it is highly recommended that CHSR tunnel projects consider using tunnel segmentation to allow application of different excavation methods depending on geological conditions.

APPENDIX

Table 24. Global Long Tunnel Data: High-Speed Rail

Tunnel Name	Country	Completion (Yr)	Length (Mi)	Width (Yd Dia)	Tunneling Method	Topography	Rock Classification	Ground Water	Speed (mph)	Electrification Systems	Signal Control Systems	Configuration	Cross Passage Spacing (Yd)	Function
Abdalajis	Spain	2006	4.5	9.6	TBM		M & S	Yes	186	25 kV AC, 50 Hz	ETCS/ERTMS L1		350	P Only
Brenner Base	Austria-Italy	2026	34.0	9.0	TBM & CM	Mountain	H & M	Yes	155	25 kV AC, 50 Hz	ETCS/ERTMS L2	Two single-track	364	P & F
Bussoleno	France-Italy	2020	7.7			Urban	Hard				ETCS/ERTMS L2	Two single-track	400	P & F
Ceneri Base	Switzerland	2015	9.6	9.6	TBM & CM	Mountain	M & S	No		25 kV AC, 50 Hz	ETCS/ERTMS L2	Two single-track	320	P & F
Channel	England-France	1994	31.4	9.7	TBM & CM	U. River/Sea	Soft	Yes	100	25 kV AC, 50 Hz	TVM 430	Two single-track	410	P & F
CTRL HS1	England	2007	11.8				Soft		165	25 kV AC, 50 Hz	TVM 430	One double track	750	P Only
Firenzuola	Italy	2010	9.5		TBM	Mountain	Soft			25 kV AC, 50 Hz		Two single-track		
Gibraltar	Spain-Morocco	2013	23.4				Soft			25 kV AC, 50 Hz		One double track		P & F
Gotthard Base	Switzerland	2017	35.5	8.8	TBM & CM	Mountain	H & S	Yes	155	15 kV AC, 16.7 Hz	ETCS/ERTMS L2	Two single-track	355	P & F
Groene Hart	Netherlands	2004	4.5	16.0		Urban			185		ETCS/ERTMS L2	One double track	150	
Guadarrama	Spain	2007	17.6	9.3	TBM & CM	Mountain	H & M		220	25 kV AC, 50 Hz	ETCS/ERTMS L1	Two single-track	273	P & F
Hakkoda	Japan	2005	16.5		CM	Mountain	H & S	Yes				One double track		
Iiyama	Japan	2013	13.8	10.4	CM		Soft		100	25 kV AC, 50 Hz		One double track		P Only
Iwate-Ichinohe	Japan	2000	16.0	10.7	CM	Mountain	H & M	Yes				One double track		
Katzenberg	Germany	2012	5.8	11.8	TBM	Mountain	Soft	Yes	155			Two single-track	500	P & F
Koralm	Austria	2022	20.4	8.6	TBM & CM	Mountain	H & S	Yes	143	15 kV AC, 50 Hz	ETCS/ERTMS L2	Two single-track	547	P & F
Lainzer	Austria	2012	6.5		CM	Urban			143			Two single-track		P & F
Lötschberg	Switzerland	2006	21.5	7.7	TBM & CM	Mountain	H & M	Yes	155	15 kV AC, 50 Hz	ETCS/ERTMS L2	Two single-track	364	P & F
Lyon-Turin	France-Italy	2020	33.0	11.5	TBM & CM	Mountain	Medium		136	25 kV AC, 50 Hz	ETCS/ERTMS L2	Two single-track	400	P & F
Marseille	France	2001	4.8			Urban						Two single-track		
New Guanjiao	China	2014	420.3	8.0	CM	Mountain	Soft	Yes	100			Two single-track		
Pajares Lot 4	Spain	2009	6.5	10.9	TBM		H & S	No	185	25 kV AC, 50 Hz	ETCS/ERTMS L1	Two single-track		P & F
Perthus	Spain		5.0	9.5		Urban	H & M					One double track	200	P & F
Prague-Beroun	Czech Republic	2016	15.3	10.4	TBM & CM		H & M	Yes				One double track	400	P & F
Qinling	China	2002	11.2	14.1	TBM & CM				124	27.5 kV AC, 50 Hz		Two single-track		P & F
Storebaelt	Denmark	1997	5.0	8.4	TBM	U. River/Sea	Soft	Yes	100			Two single-track	250	
Vaglia	Italy	2010	11.6	12.5	CM	Mountain	Soft			25 kV AC, 50 Hz	ETCS/ERTMS L2	Two single-track		P & F
Vereina	Switzerland	1999	11.8	8.4	CM	Mountain	Hard			25 kV AC, 50 Hz	ETCS/ERTMS L2			P & F
West Qinling	China	2015	10.3	11.2	TBM & CM		M & S	No	100	27.5 kV AC, 50 Hz		Two single-track		P & F
Wienerwald	Austria	2010	8.3	11.6	TBM	Mountain	Soft		143	25 kV AC, 50 Hz		Two single-track	500	P & F
Wushaoling	China	2009	13.7		CM				100	25 kV AC, 50 Hz				
Zimmerberg	Switzerland	2003	5.8	13.5	TBM & CM	Mountain	Soft	Yes				Two single-track		P & F

ABBREVIATIONS AND ACRONYMS

ATG	AlpTransit Gotthard
BBT	Brenner Base Tunnel
CHSR	California High-Speed Rail
CHSRA	California High-Speed Rail Authority
EPBM	Earth Pressure Balance Machine
ERTMS	The European Rail Traffic Management System
ETCS	European Train Control System
FHWA	Federal Highway Administration
FTA	Federal Transit Administration
HSR	High-Speed Rail
KICT	Korea Institute of Construction Technology
NATM	New Austrian Tunneling Method
NFPA	National Fire Protection Association
OECD	Organisation for Economic Co-operation and Development
TBM	Tunnel Boring Machine
UCS	Unconfined Compressive Strength
UIC	International Union Railways
UNECE	United Nation Economic Commission for Europe

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