SELECTION OF THE OPTIMUM TUNNEL SYSTEM FOR LONG RAILWAY TUNNELS WITH REGARD TO THE ENTIRE LIFECYCLE

H. Ehrbar & C. Tannò

ETH Zurich, Switzerland

H.-P. Vetsch

Vetsch Rail Consult, Bützberg, Switzerland

ABSTRACT: Since more than 30 years long tunnels with a total length of more than 50 kilometres exist. Many of them show a different tunnel system: double track tunnels with service tunnel, two single track tunnels and two single track tunnels with a service tunnel are the existing systems.

The decision on the tunnel system of this long tunnels had to be taken at a time when only few information on operation and maintenance costs were available. Today more information on oration a maintenance is available. The paper shows, how the decision-making process should be made today considering the criteria construction, operation and safety with regard to the entire lifecycle.

Recommendations on the selection of the tunnel system will be given for different boundary conditions, based on the operation experience of the long tunnel railway tunnels under operation.

1. PROJECT REQUIREMENTS OF LONG RAILWAY TUNNELS

Railway tunnel constructions have the purpose of connecting cities, economic regions (Gotthard-Base Tunnel), countries (Eurotunnel, Cross Border Base Tunnel under the Ore Mountains) or even continents (Gibraltar Strait Tunnel) in order to ensure a rapid and environmentally friendly transport of people and goods. Mountains or straits are the typical topographical obstacles that must be overcome with a tunnel. Such tunnels become quickly very long (> 20 km length) due to special topographic boundary conditions for mountain base tunnels and strait tunnels.

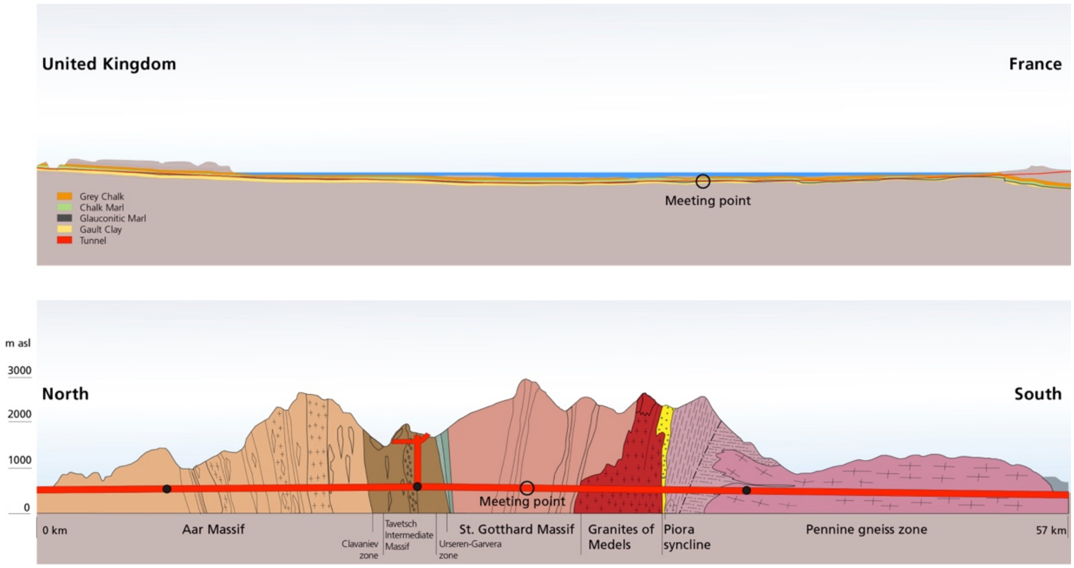

Figure 1: Longitudinal profile of a subsea tunnel (Eurotunnel) and a mountain base tunnel (Gotthard Base Tunnel) (source Wikipedia and AlpTransit Gotthard)

Very long tunnels have to fulfil many project requirements, as each other civil work also. It is generally accepted that every successful project has to meet the requirements of the magic triangle of project management, namely the adherence to the targets of quality, time (milestones) and costs (budget). Whereas cost and time targets are comparatively easy to define, the quality objectives must be carefully and project-specifically derived. ISO 9000's definition ("quality is the degree to which a set of inherent characteristics fulfils requirement") also asks for the definition of project specific attributes. The following definition of the construction quality was used for the Gotthard-Base Tunnel:

Table 1. Definition of the construction quality based on the definition for the Gotthard Base Tunnel

Construction quality is the **technically and economically optimal fulfilment of all stipulated, agreed and prerequisite requirements of the owner** for a construction work in relation to the finished project, i.e.:

- **structures or facilities** (reliability, availability, maintainability, safety)
- **the costs** (investment costs, operating, maintenance and renewal costs and follow-up costs)
- **the time** (planning and construction time, achievement of milestones),

respecting the interests of the society (minimum of pollution, sustainable management of resources, occupational health and safety, ecology, etc.) [1]

The definition of the set of the project requirements is the most challenging task at the earliest phase of the project. The following list of requirements is based on the experiences from the Gotthard Base Tunnel:

Table 2. Typical list of general project requirements for a very long railway tunnel based on the boundary conditions of the Gotthard Base Tunnel

Operation	**structures or facilities**	reliability	100 years of service life for all civil works.
		availability	Optimum operation: high availability at a given capacity.
		maintainability	During the planned service life, no significant operational restrictions (in terms of scope and duration) may occur and no essential structural support may be provided.
		safety	- Self-rescue to a protected area within minutes after the evacuation order. - Rescue services are operable at the place of the incident within 45 minutes. - 90 min maximum evacuation time for passengers at each incident with a passenger train.
construction and operation	**costs**	investment costs	Construction costs within the budget. High cost-effectiveness including operating, maintenance and renewal costs under consideration of the life cycle costs[1].
		operating	
		maintenance costs	
		renewal costs	
	time	planning	Minimum project duration (planning and construction time) by using economically feasible tools and methods.
		construction time	
		achievement of milestones	Compliance with the agreed commissioning dates.
	interests of the society	minimum of pollution	Ultimate state of the art in machines and equipment.
		sustainable management of resources	Processing of the excavated material to concrete aggregates.
		occupational health and safety	Target zero – no major incidents.
		ecology	Compensation of the environmental impact of replacement measures.

The set of requirements should be optimally fulfilled, by choosing a suitable tunnel system. This means a very complex task for very long tunnels as the requirements are not independent.

[1] This criterion was only formulated in the course of the planning of the commissioning (2010). Previously (1993) the political requirement was to minimize investment costs.

2. TUNNEL SYSTEMS

2.1 GENERAL LAYOUT

Theoretically there are no limits on the number of tunnel tubes and their configuration (see Fig. 2), when choosing the general layout of the tunnel system in order to fulfil the listed project requirements.

Railway tunnel systems with more than one tube can consist in a system of pure railway tunnels or in a mixed system of railway tubes and service tunnels, accessible by road vehicles.

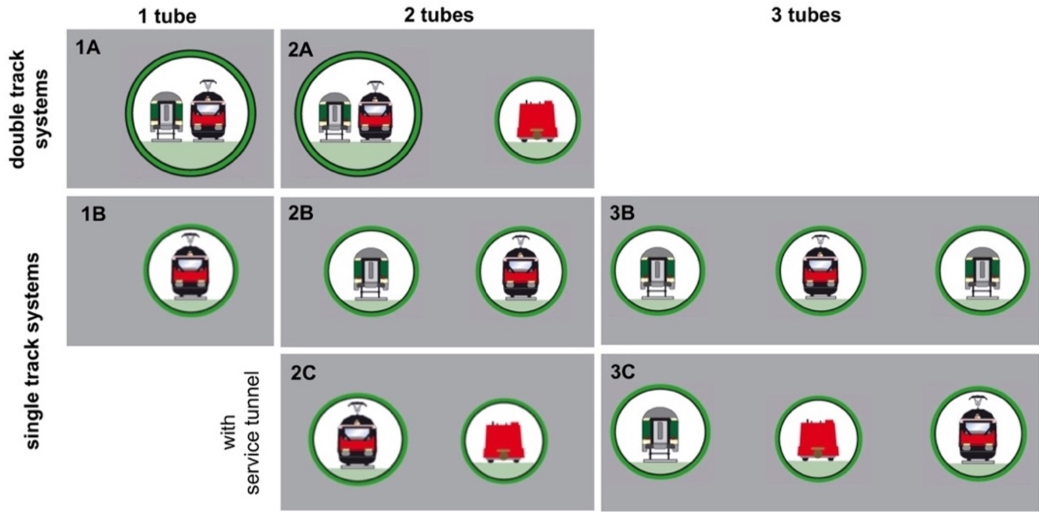

Figure 2. Variants of railway tunnel systems

The historic long railway tunnels through the Alps such as the Mont Cenis Tunnel (1871), the Gotthard Tunnel (1882), the Arlberg Tunnel (1884) and the Lötschberg Tunnel (1913) were created as pure double track tunnels without a service tunnel (system 1A, Fig.1). Only the 19.8 kilometres long Simplon Tunnel (1906/1922) has a system with two separate traffic tubes (system 2B). Better logistic solutions and financial restrictions (widening of the service tunnel to a full-fledged railway tube in a second phase) were the main reasons for this layout.

In 1988 the 53.8 km long Seikan Tunnel was commissioned with. For the first time in history an over 50 km long railway tunnel started its operation. The Seikan Tunnel consists of a double-track tunnel (system 1A in mountain regions), supplemented in the subsea zone by a parallel service tunnel accessible via lateral shafts at the sea shore (system 2C in subsea zone).

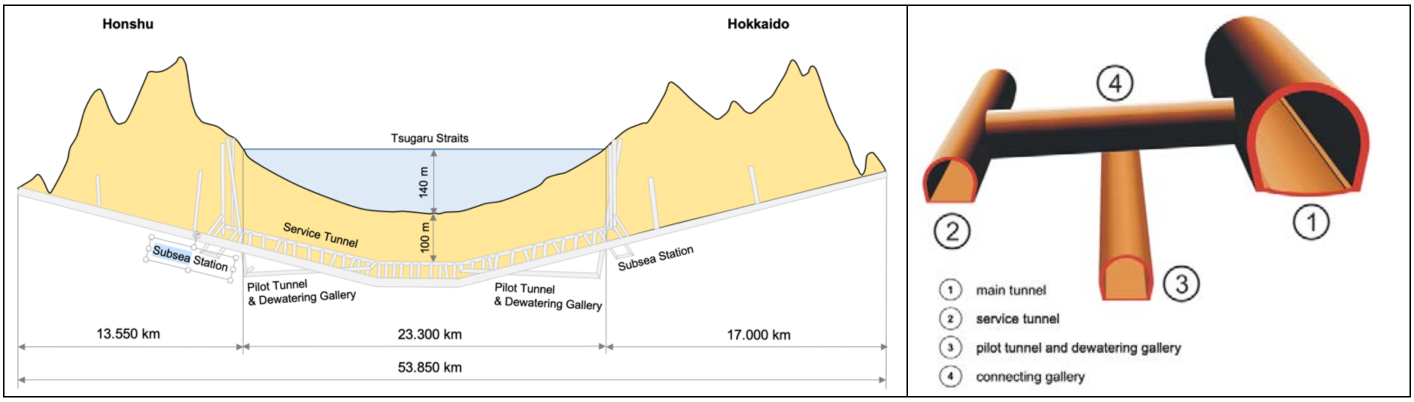

Figure 3. Tunnel System of the Seikan Tunnel (source: Wikipedia)

In 1987 the construction work on the 50.4 km long Channel Tunnel crossing under the English Channel was started. The safety requirements for this tunnel exceeded all existing ones. The tunnel system was implemented with two single-track tunnels and one service and safety tunnel plus an extra complex ventilation system (system 3C). The Channel Tunnel was commissioned in 1994.

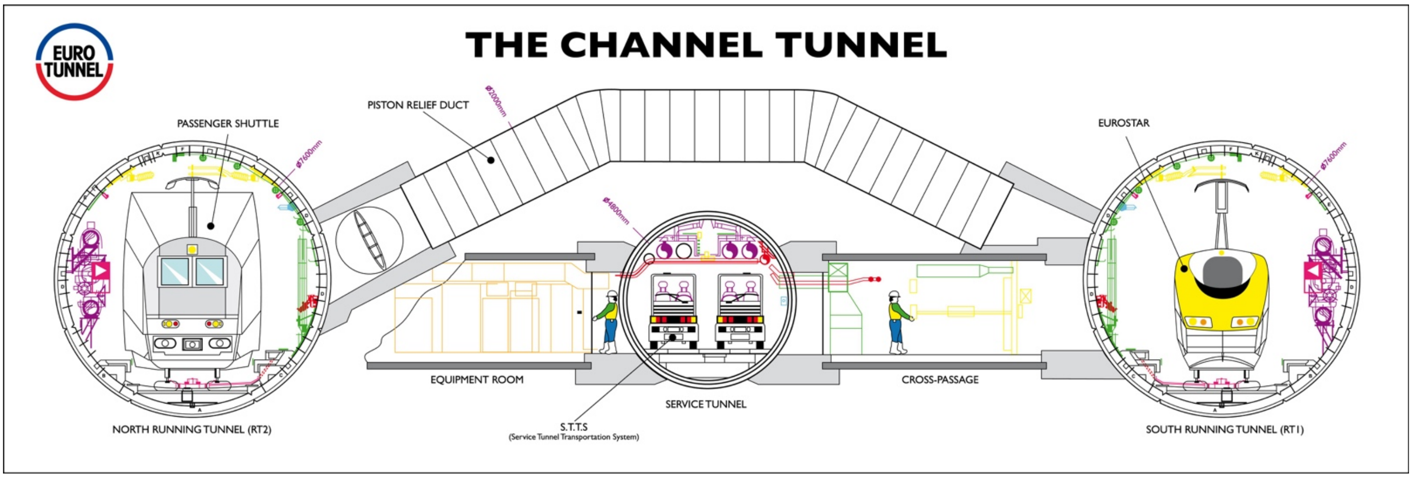

Figure 4. Tunnel System of the Eurotunnel (Source: Eurotunnel)

In 2007 the Lötschberg Base Tunnel started the commercial operation with a mixture of the tunnel systems 2B (on 40% of the length without the installation of the railway installations) and 2C on 20% of the total length according to the definitions of Fig. 2. The reasons for the selection of such a system were financial restrictions and political decisions.

In 2016 the 57.1 km long Gotthard Base Tunnel (actually the longest railway tunnel of the world) followed. It was built following the principles of System 2B with two multifunction stations in the third pointes, dividing the tunnel in sections of 20 kilometres in the maximum (see Fig. 5).

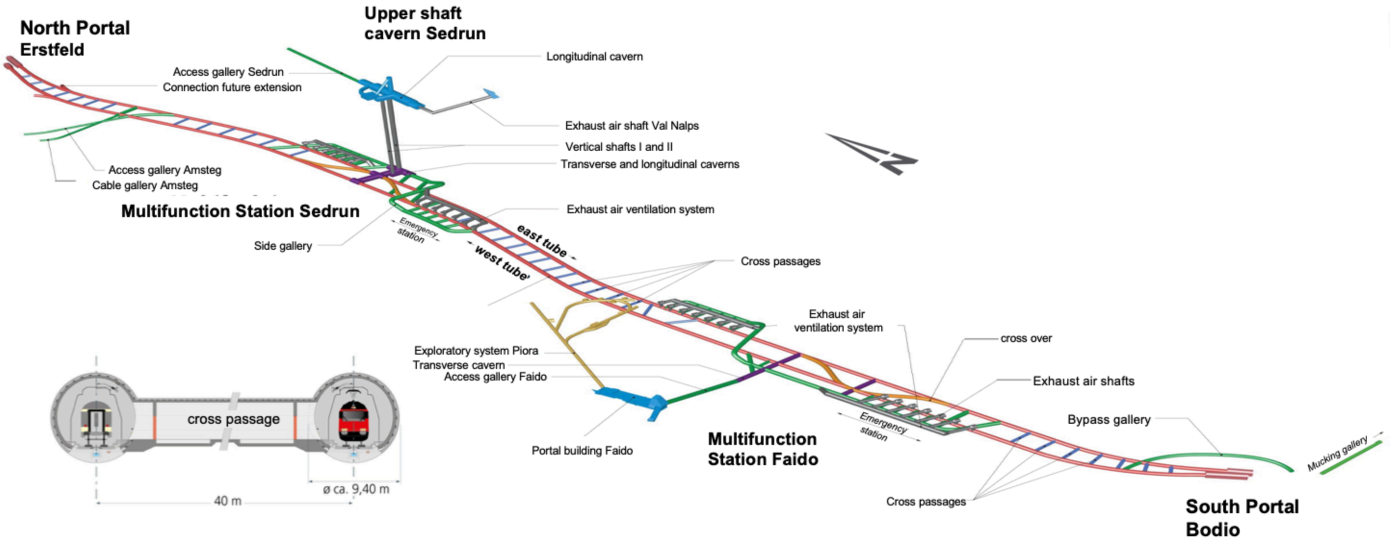

Figure 5. Tunnel System Gotthard Base Tunnel (Source: Amberg Engineering, STS 2016)

Nowadays long and very long railway tunnels with only one double track tube are not allowed anymore in several European countries. The German Federal Railway Authority (EBA) stipulates in the directive on "Fire and Catastrophe Protection Requirements on Building and Operating Railway Tunnels" that became effective on July 1, 1997 [4]:

- The running tunnels must be designed as parallel, single-track tunnels on double-track routes in the case of long (longer than 1 kilometre) and very long tunnels (longer than 20 kilometres) if the operating programme calls for mixed operation of passenger and goods trains. In this case, the deployment of emergency services is effected via cross passages and the neighbouring tunnel tube.
- In the case of double track tunnels passenger and goods trains should not be scheduled to encounter each other.

The requirements of the TSI SRT make it also impossible to build very long double track tunnels [2].

2.2 THE CROSS SECTION – SINGLE LINED VS. DOUBLE LINED TUNNEL

The tunnel cross section has to fulfil may requirements such as:

- Clearance profile for commercial train operation
- Aerodynamic optimum (minimizing traction energy, minimizing pressure waves)
- Ensuring escape routes in case of an incident (walkways)
- Enabling of a ballast-less track structure (slab track)
- Enabling of the installation of easily accessible railway technique
- Cable-ducts for power supply, signalling and communication
- Creation of a usable space along the vault circumference for future constructional purposes
- Waterproofing according to the criteria on the maximum permissible water inflow through the tunnel vault
- Maintenance-friendly, easily accessible drainage facilities.
-

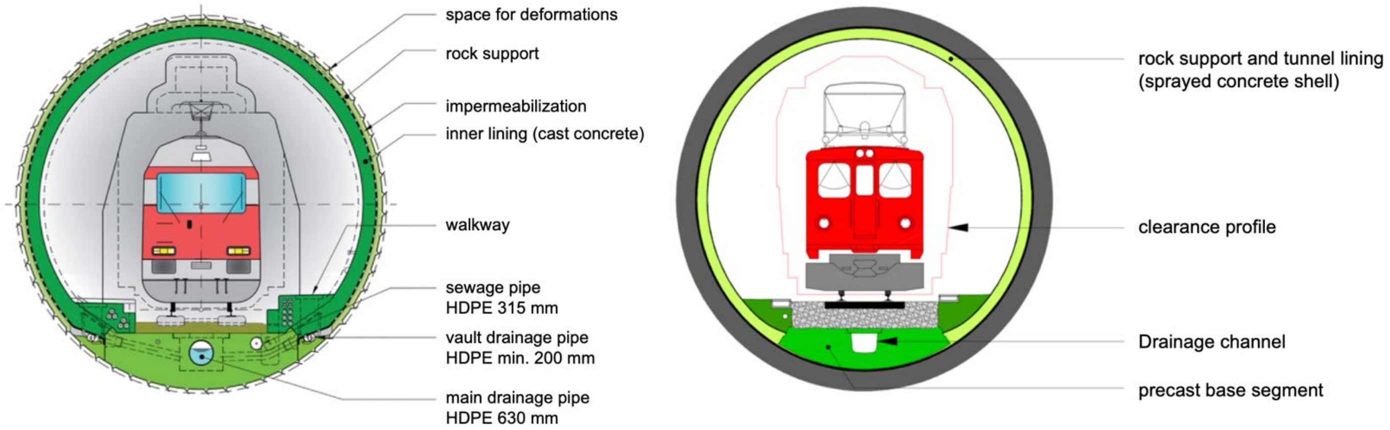

Figure 6. Typical Tunnel cross sections for the double lined Gotthard Base Tunnel (left) and the single lined Vereina Tunnel (right) (Source: Amberg Engineering)

The question of whether the tunnel tube should be as a single-lined or double-lined is often discussed controversially. The final answer on this question must be given, based on the project boundary conditions, such as

- Required service life
- Expected traffic
- Geological / hydrogeological conditions
- Design of impermeabilization measures (impermeabilization grouting / waterproofing foil)

A double-lined design is highly recommended for very long tunnels base tunnels under mountains with a potential water inflow through the tunnel vault. The operations experiences of the single lined Vereina Tunnel (19 kilometres, 1999, Switzerland) and Furka Base Tunnel (15.4 kilometres, 1982, Switzerland) show significantly higher corrosion effects on rails and railway equipment for tunnels with a single shotcrete lining.

3. STAKEHOLDER INTERESTS ON THE TUNNEL SYSTEM

The main goal of the implementation of a tunnelling project is to meet all project requirements within the agreed level of quality, service life and operational requirements (functionality) such as safety, operating (type of traffic, timetable, flexibility, costs) and maintenance etc. Other important requirements are the realization of the project within the fixed milestones and within the given cost budget, respecting the environmental aspects and the interest of the different stakeholders (see Fig. 7). All these requirements are the boundary conditions for the definition of the tunnel system of a long railway tunnel.

Many stakeholders are involved in the processes for the realisation of a major tunnel project. Each stakeholder plays a different role and has his individual interests (see Fig. 3).

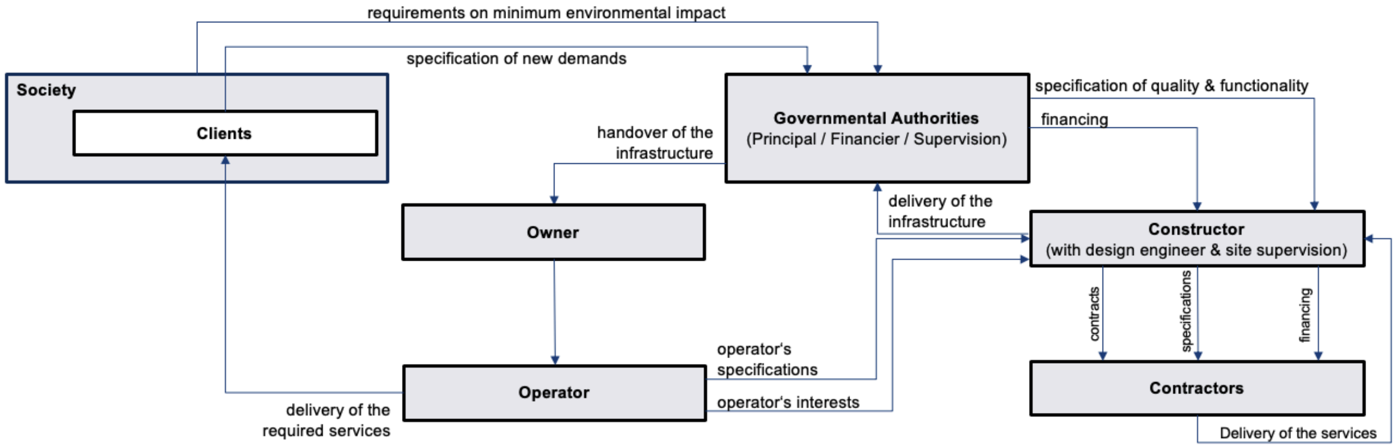

Figure 7: Possible constellation of stakeholders in a long rail tunnel project with public financing

An early stable financing of major tunnelling projects is crucial for a later successful realization. The railway operators usually are not able to create sufficient revenues with their transport services to payback the initial investment. The revenues should at least cover the operation costs. Therefore, almost all the projects get a public funding. Only the Eurotunnel was privately funded, with all the well-known financing problems 10 years after starting the commercial operation (Table 3). The *financier's objectives* are the payment of the interests and the repayment of the debts by the principal on time.

Table 3. Overview on the total costs of selected very large tunnels (based on Tannò, 2018)

Project Name	Country	Total Costs [Bn EUR]	Price Basis	Type of financing
Gotthard – Base Tunnel	Switzerland	8,4	1998	public
Lötschberg – Base Tunnel	Switzerland	3,8	1998	public
Seikan Tunnel	Japan	4,7	1988	public
Eurotunnel	UK – France	4,7 Bn £	1994	private
Guadarrama Tunnel	Spain	1,4	2007	public
Brenner– Base Tunnel	Austria – Italy	estimated 10	2018	public
Lyon – Turin	France – Italy	estimated 10	2018	public

The *key interest of the principal* is the implementation of his order within the required quality and functionality, on time and on budget (minim investment costs), considering the interests of the society. In many projects the principal is not the operator as he hands over infrastructure to a dedicated operator.

The creation of a very long railway tunnel is often a project outside the field of action of the principal's organization. The long project duration allows to build up a specific, temporary organization for design, construction and commissioning. *The constructor* is the creator of the project, the overall project leader. The role of the creator is very demanding, as the existing worldwide knowledge is small. The creator has a pioneering role. A large number of processes have to be defined as usually structures and processes cannot be copied directly from other projects.

After completion of the construction work (commissioning process) *the operator* takes over the responsibility for the operation of the infrastructure. Maintaining deadlines and the delivery of the mutually agreed quality are important to the operator. He has a high interest in a quick and smooth integration of the new infrastructure into the existing network. Finally, he interested in creating high profits. Therefore, the operator has a high interest on a high availability of the infrastructure, while minimizing the operation and maintenance costs. This requirement is usually in a direct contrast to the requirement of the minimization of investments.

The authorities define the legal boundaries for the project by issuing the technical specifications and the approvals for construction and operation. The authorities check the compliance with the legal requirements. Since such centennial projects sometimes go beyond the current legal framework, it must be expanded or adapted.

The main *interest of the designer* is the utilisation of his resources, creating good references and financial profits. The designers are already involved in the very early project phases. They have a great influence on the project.

The *contractors' and suppliers'* demand on the project are the utilisation of their resources or the delivery of their products (suppliers), to generate a reasonable profit and to receive a contribution for a good reputation. The constructability of the project should be confirmed already during the design phase in order to avoid time consuming and expensive changes during construction. Contractors knowhow should be used already in the design phase in such a way that conflicts on the procurement process can be avoided.

Experts bring an independent view on the project on special aspects, such as e.g. tunnelling, environmental and safety aspects. The expert's main interest is his good reputation.

Large tunnel projects often affect also large regions and many people due to the environmental impact during construction and operation. *Acceptance of the project by the society*, politicians, industry and associations is important. A lack of acceptance can cause important delays in financing or in getting legal approvals.

The *end customers* are particularly interested in a high availability of the infrastructure and in cheap, comfortable and reliable transport services.

4. HOW TO SELECT THE OPTIMUM TUNNEL SYSTEM

The different interests of the various stakeholders create a complex situation for the decision-making process. Therefore, the decision-making process is highly depending on a clear definition of the problem statement. Construction, operation and safety

Several methods are available for taking decisions (see Fig. 8). As long as costs are the only main target value, static (cost comparison studies, benefit comparison studies) and dynamic cost calculation methods (amortization studies, net present value studies) are helpful tools to create the information needed for the decision on different variants.

In most of the cases, the projects have to fulfil more than only one target value (usually costs), but also target values on construction, operation and safety (see Chap. 5) which cannot be measured only by cost elements at an early stage of the project. For such cases the value-benefit analysis is among other options an often-used powerful tool.

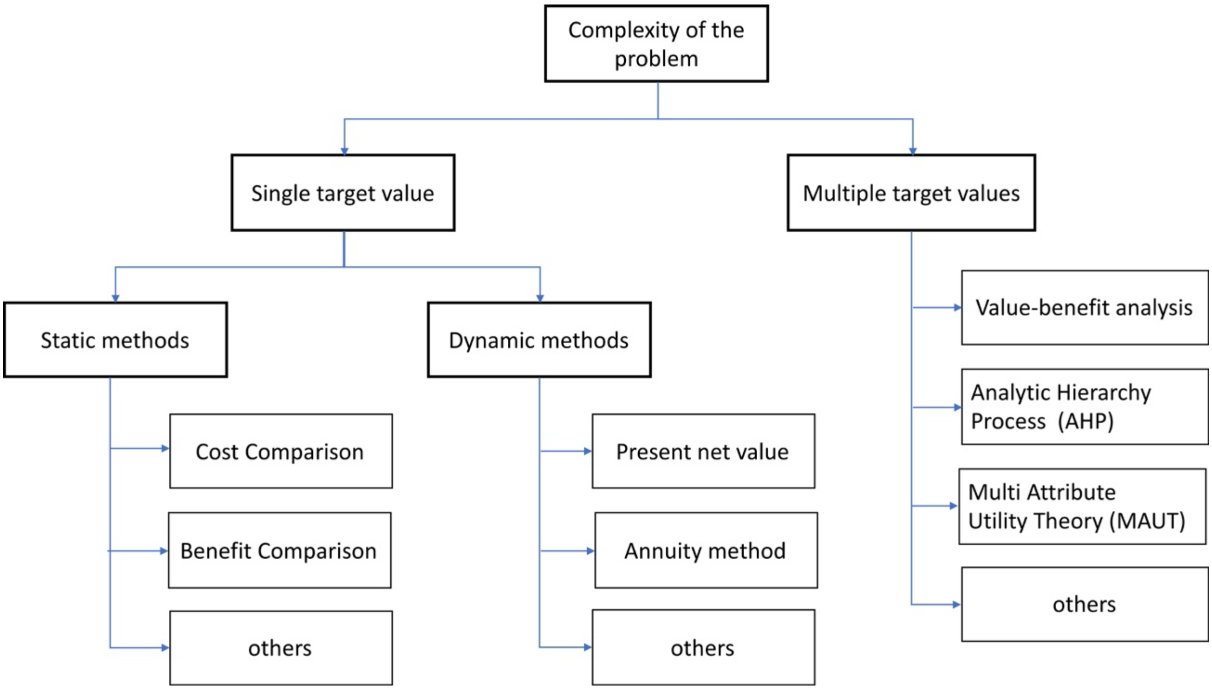

Figure 8: Overview of the various tools for decision-making (Tannò, 2018)

5. REVIEW ON THE DECISION-MAKING PROCESS FOR THE SWISS NRLA PROJECT

In the early seventies of the last century, when the Gotthard Road Tunnel was under construction, Swiss Federal Railway (SBB) elaborated the final design for a 46 km long Gotthard Base Tunnel with one double track tube and a service tunnel. The project was postponed by the political authorities but created the basis for the political decision on the New Railway Line through the Alps (NRLA) by a public vote in 1992. The preliminary design work started immediately after the positive decision by the swiss voters. Strategic decisions had to be taken on the alignment, the type and number of intermediate accesses and the tunnel system.

An expert committee of swiss and international experts was organised under the leadership of the Swiss Federal Office of Transport office (SFOT) to prepare the forthcoming decision on the basis of objective criteria.

A value-benefit analysis (point-scoring model) was used for decision making. This process has advantages when the target values are mostly difficult to be represented only by costs (see chap. 4).

Table 4. Objective system for the value-benefit analyses of the swiss NRLA base tunnels (Ehrbar, 2016)

Overall Target	*Detailed Objective*	*Weighting*	*Detailed Objective*	*Weighting*
Construction	Costs, Cost risks	0,70	Construction Costs	0,80
			Cost risks	0,20
	Project schedule	0,20	Construction time	0,80
			Time risks	0,20
	Environmental Impact	0,10	Management of spoil	0,80
			Impact on landscape at portal zones	0,10
			Material for embankments	0,10
Operation	Requirements of operation	0,30	Quality of production (timetable, travel time, comfort)	0,40
			Quantity of production (Capacity, complete blockings)	0,40
			Productivity	0,20
	Maintenance & refurbishment	0,60	Operating impairment incidents	0,20
			Effort for maintenance	0,50

			Attractive workplaces	0,30
	Aero-/Thermodynamics	0,10	Effort for ventilation	0,80
			Travel comfort (dynamic pressures)	0,20
Safety	Acceptance	0,30	Passengers	0,20
			Employees	0,80
	Risks	0,70	Train accident	0,20
			Fire	0,25
			Dangerous goods	0,30
			Accidents of persons	0,05
			Accidents at work	0,20

Table 4 shows clearly, that construction costs were the objectives with by the far highest weight for the construction. This fact is determined by the political situation at that time, which was characterized by the fact that the cost budget of EUR 9 billion for both NRLA Axes should not be exceeded. Reductions in meeting the deadlines were accepted.

Four alternatives were analysed in this process:

- **Solution 2A**: twin-track tunnel with service tunnel, derived from the 1975 project of Swiss Federal Railway (SBB) and most long railway tunnels built until then,
- **Solution 2B**: two single-track tunnels without a service tunnel but with two underground emergency stations at the third points.
- **Solution 3B**: three single-track tunnels in order to be able to keep two running tunnels open during maintenance,
- **Solution 3C**: tunnel system with two single-track tunnels and a service tunnel, similar to the Eurotunnel solution. The decision whether the service tunnel should be positioned in the middle or at the side, was not decided at this phase. For the cost calculation a lateral service tunnel was assumed.

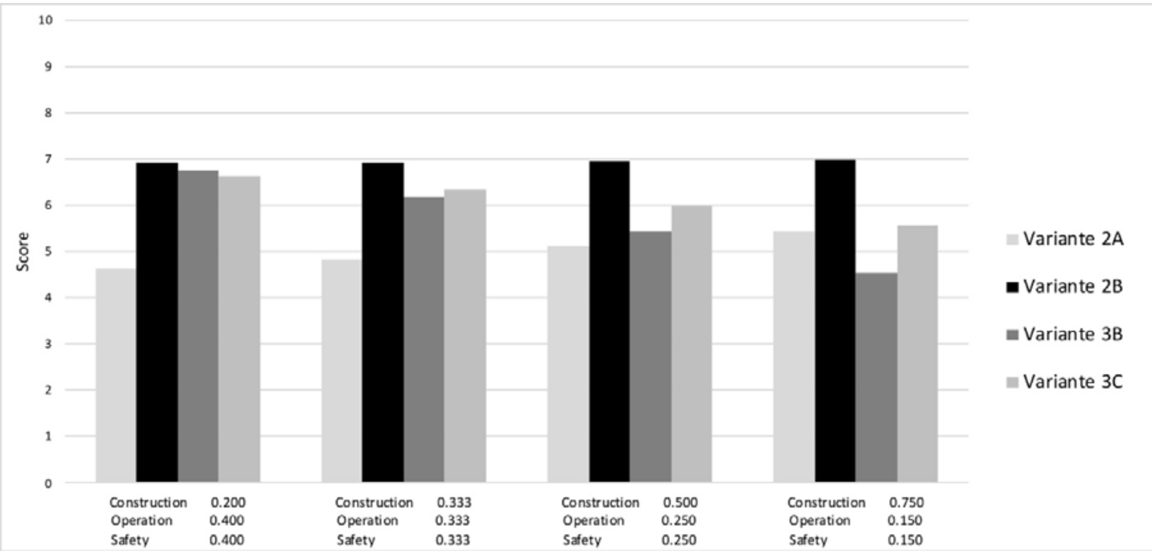

Figure 9: Scores in value-benefit analysis for the Swiss NRLA-base-tunnels (based on EBP, 1993)

The system with the minimum construction volume (tunnel system 2B) achieved the highest score in the value-benefit analysis in all scenarios of the sensitivity analysis in which the weighting among the overall goals construction, operation and safety was widely variated (see Fig. 9). This result is not surprising when one is aware of the high weighting of construction costs in the benefit cost analysis (14% Scenario 1 to 52% in scenario 4). Other cost elements of the lifecycle costs (maintenance, operation, refurbishment and dismantling) were not considered (see Fig. 10) as cost elements, but partially as non-monetary effort (e.g. maintenance).

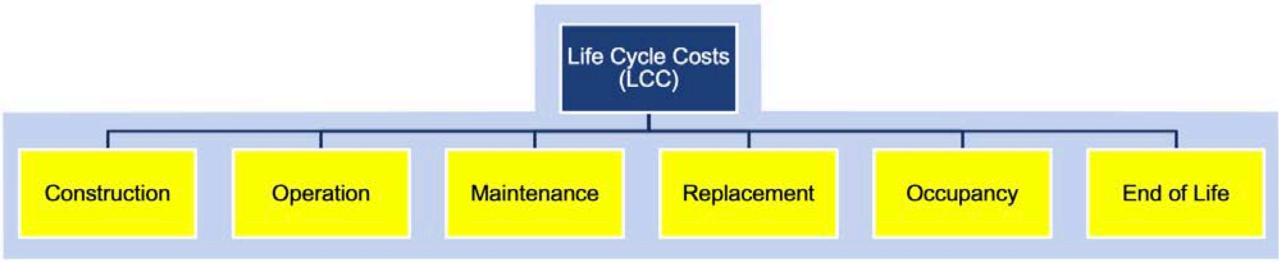

Figure 10: Generic Structure for lifecycle costs

Various additional considerations were made during a master's thesis in 2018 at ETH Zurich (Tannó, 2018). A pure lifecycle cost analysis was tried to carry out, assuming that in the meantime since 1993 a lot information on operation costs should have been produced at the Lötschberg Base Tunnel and at the Eurotunnel. As maintenance budgets not compellingly correspond to the cost structure of the early design phase the usable information content of the provided data was lower than expected. It would be helpful to adapt the operators cost structure in a future digital world in order to create the information needed for such optimization studies.

But not only the lack of cost information limited the validity of such an analysis, but also the fact that the net present values to be determined in such an analysis depend to a very large extent on the assumptions of interest rates and inflation rate (see Fig. 11). Furthermore, a pure cost comparison study assumes the same benefit for all tunnel systems. This assumption is not correct as the availability of a system with three single track tubes is higher than with two single track tubes, creation also different earnings. Therefore, a pure cost analysis does not allow any compelling conclusions about the system selection and should not be used as a unique tool for the decision-making process.

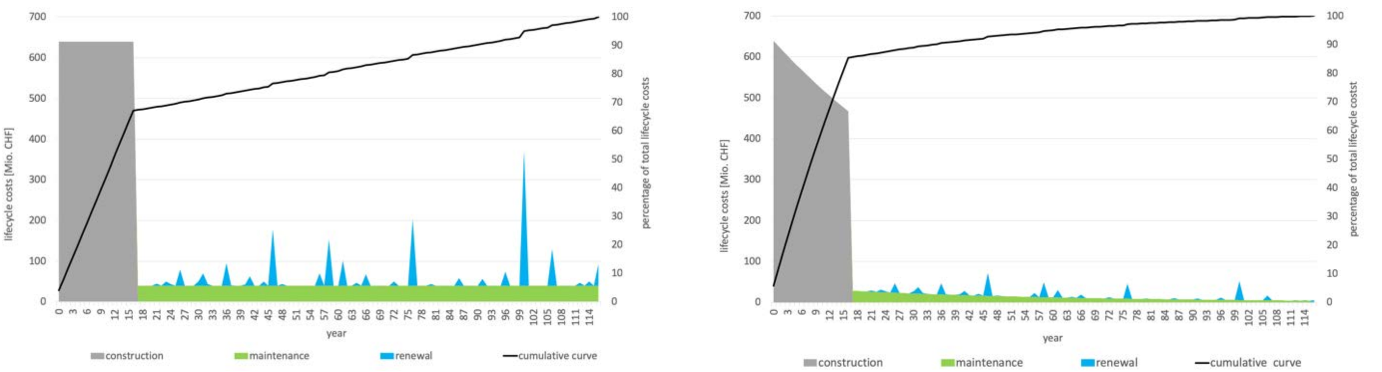

Figure 11: Life cycle cost (17 years construction time, 100 years of operation) without interests and inflation (left) and with 3% interests, 1% inflation (right) (Tannò, 2018)

Therefore, an adapted benefit-value-analysis was carried out with the following assumptions:

- Pure long double track tunnels are not approvable. Therefore, such tunnels were not part of the studies anymore.
- The level of safety of the remaining systems was considered as more or less equal for all remaining systems, as long as the requirements of the TSI are fulfilled
- The overall target "safety" was therefore replaced by a new overall target "refurbishment" (Tab. 5).
- A simplified scoring model was used with a maximum of 3 points instead of 10 points.

Table 5. Objective system for the value-benefit analyses of the swiss NRLA base tunnels (Tannó, 2018)

Overall Target	*Detailed Objective*	*Weighting*	*Detailed Objective*	*Weighting*
Construction	Costs, Cost risks	0,70	Construction Costs	0,80
			Cost risks	0,20
	Project schedule	0,20	Construction time	0,80
			Time risks	0,20

	Environmental Impact	0,10	Management of spoil	0,80
			Impact on landscape at portal zones	0,10
			Material for embankments	0,10
Operation	Quantity of production (Capacity)	0,20		-
	Maintenance	0,40	Maintenance effort	0,60
			Attractive workplaces	0,40
	Disruption of normal operation	0,30	Operating impairment	0,40
			Organization of the remedy	0,30
			Accessibility of the defect	0,30
	Effort for artificial ventilation	0,10		-
Renewal	Renewal expenses	0,30	Major renewals	0,60
			Minor renewals	0,40
	Complexity of renewals	0,30	Major renewals	0,60
			Minor renewals	0,40
	Loss of capacity	0,30	Major renewals	0,60
			Minor renewals	0,40
	Working place conditions	0,10	Major renewals	0,50
			Minor renewals	0,50

Similar to the benefit-value-analysis of 1993 the most recent studies showed also a clear favourite system, this time the system 3C instead of system 2B (see Fig. 12). This result is created by the fact that a third tube can contain parts of railway equipment which has to be placed in the driving tube for the solutions 2B and 3B. Solution 3C allows an independent access for road vehicles which creates many benefits (fewer operating impairment, shorter intervention times).

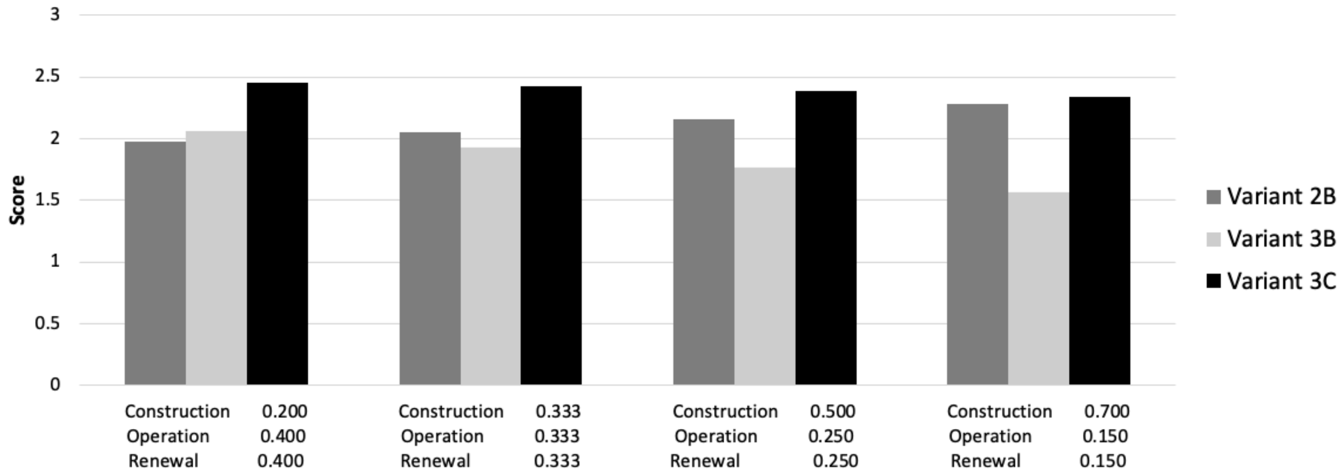

Figure 12: Scores in value-benefit analysis for very long tunnels (Tannò, 2018)

6. RECOMMENDATIONS

More than 20 kilometres very long railway tunnels need additional measurements for a safe operation of passenger trains (one emergency stations every 20 kilometres). For future very long tunnels, it is recommended to construct these emergency stops as simply as possible, but to create additionally to the two railway tubes a continuous service tunnel (Variant 3C). The service tunnel should be placed below the railway tubes, in order to create a spatial separation of traffic and safety infrastructure and operation utilities. This system is actually under construction at the Brenner Base Tunnel.

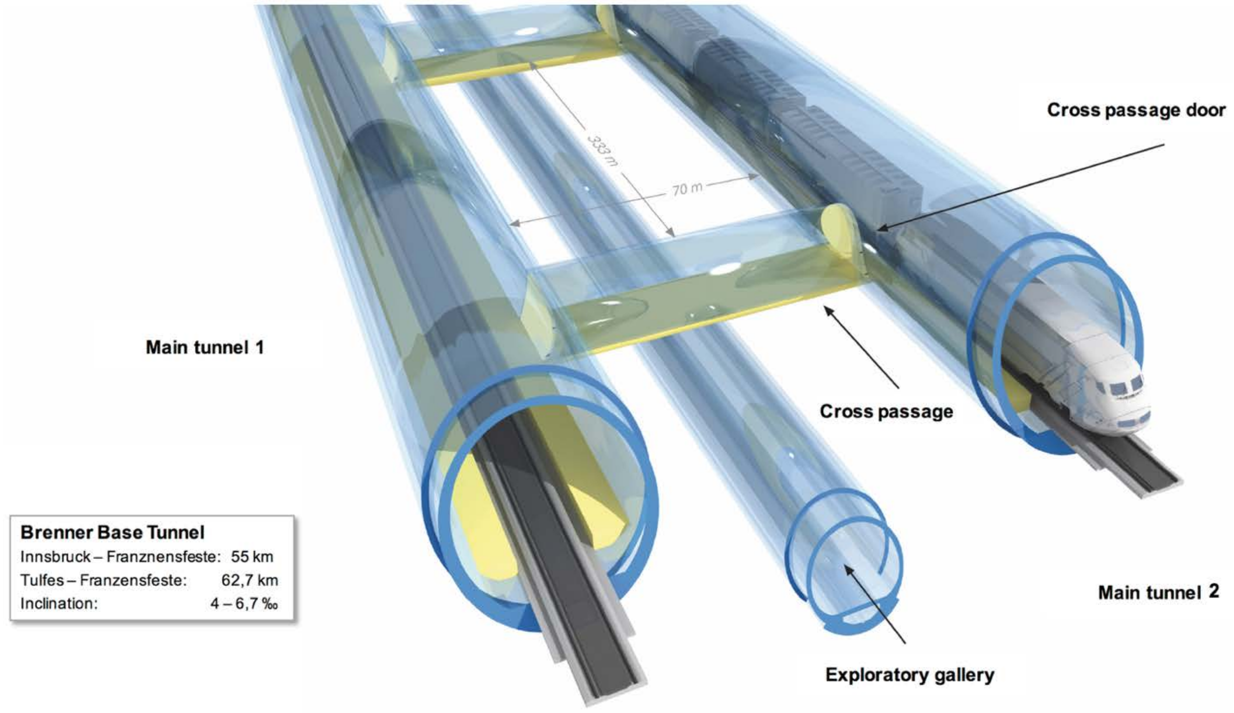

Figure 13: Tunnel System for the Brenner Base Tunnel (source BBT SE)

The main objective of the service tunnel is the creation of a rail independent accessibility to the all the railway equipment, which has not necessarily to be placed in the running tube and the creation of an easily accessible dewatering system for the ground water during operation. The service tunnel should be excavated ahead of main tunnel drive as an exploratory and dewatering gallery.

If the boundary conditions do not allow the construction of an additional service tunnel, it should be considered to use also intermediate accesses as independent service accesses during operation. However, only the system with three single track tubes allows a complete separation of operation and maintenance for bigger renewal work (Variant 3B).

REFERENCES

[1] AlpTransit quality management; reprint to Swiss Baublatt 82/1996

[2] 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

[3] EHRBAR, H., TANNÒ, C., VETSCH; H-P. Optimum tunnel system with regard to the entire lifecycle for long rail tunnels: Proceedings WTC 2019 Naples, 2019.

[4] EHRBAR, H., VETSCH, H-P.; Zbinden, P.; 2016. Long Railway Tunnel System Choice - Review for the future, *GeoResources Journal 2-2016*. www.georesouces.net

[5] Federal Railway Authority of Germany (EBA); Directive of fire and disaster control on the construction and operation of railway tunnels from 01.07.1997 (adaptation as of 01.07.2008)

[6] TANNÒ, C.; 2018. Optimal choice of the tunnel system for long and very long railroad tunnels. Master Thesis ETH Zurich. Switzerland

Ehrbar, Heinz
Place of work: ETH Zurich, Switzerland
E-mail address: hehrbar@ethz.ch

Tannò, Curdin
Place of work: ETH Zurich, Switzerland
E-mail address: tannoc@student.ethz.ch

Hans-Peter Vetsch
Place of work: Vetsch Rail Consult, Bützberg, Switzerland
E-mail address: hans-peter.vetsch@bluewin.ch