EU COMMISSION

DIRECTORATE GENERAL FOR ENERGY AND TRANSPORT

Study TEN-Energy Tunnel for the analysis of synergy between transport and energy sectors by high voltage transmission in rail-road tunnels in EU25 (including Bulgaria, Romania, Croatia)

Final Report

MVV Energie AG

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0. Preamble

Referring to the contract ref. TREN/CC/05-2005 and the discussions during the kick-off meeting of November 4th, 2005, the present Intermediate report applies the methodology already described in the Inception report.

The important aspects that have been retained are the following:

1. The analysis of electricity cross-border countries congestions and the selection of rail/road tunnels for synergy.
2. The analysis of available transmission cable technologies including AC or DC voltage choice, dry or gas insulated cables selection, protection, reliability and costs.
3. The feasibility of installing HV links in the tunnels where the need has been identified.

1. Analysis of electricity cross-border countries congestions

Problem statement

- Identification of possible locations for synergy between trans-European rail/road transport tunnels and the reinforcement of cross border electricity interconnections.

Methodology

- Analysis of electricity cross-border countries congestions in EU 25 based on existing studies.
- Check if road or rail tunnels (will) exist at the locations where it will be necessary to reinforce or create new cross-border electrical interconnections.
- Select a priority list of rail/road tunnels (existing or future tunnel projects) for which a possible synergy with electric priority axes is identified.
- Tunnel selection for a more detailed study, using a simplified multi-criteria analysis.

Major results

- The selection of priority tunnels is:
  - future Brenner rail basis tunnel (Austria - Italy);
  - future Lyon-Turin rail basis tunnel (France - Italy);
  - future Monte Ceneri rail basis tunnel associated with Gothard and Zimmerberg basis tunnels (Germany - Italy through Switzerland);
  - existing submarine rail Eurotunnel (France - England).
- Additional opportunities:
  - disaffected Somport railway tunnel re-used as safety gallery for road tunnel (Spain - France);
  - future safety gallery of Frejus road tunnel.

1.1. General methodology

The proposed methodology is based on the Scope of Work defined in the TOR included in the Task Specifications attached to the Request of Services.

The objective pursued is first to identify possible locations for synergy between trans-European rail/road transport tunnels and the reinforcement of cross border electricity interconnections. This will be achieved in two phases:

- the analysis of electricity cross-border countries congestions;
- the determination of a list of priority rail/road projects for which additional high voltage transmission cable would help relieve or solve cross-border congestion.

1.2. Electricity cross-border congestions

This section aims at identifying the bottlenecks and congestion at the cross borders of the different countries of EU25 (including Bulgaria, Romania, Croatia and Switzerland) expected to occur in the future.

1.2.1. Introduction

The analysis of the studies carried on to assess the cross-border congestions in Europe highlights the following fact:

It is worth distinguishing two main issues relating to cross-border congestion:

- on one hand, the commercial transit constraints;
- on the other hand, the actual technical transmission constraints.

Indeed, the maximal electric flow crossing the border between two operation areas may depend not only on the maximal capacity of the cross-border lines but also on investments made inside one of the operation areas itself.

This is for example the case for increasing the cross-border export capacity from Poland to Germany. Any investments on the Polish-German border are unlikely to increase the available transfer capacities, if not supplemented by major reinforcements in the Polish network itself (see ref. KEMA study).

The general approach of the Transmission System Operators (TSO) to determine the transmission capacities available for imports and exports between countries is based on the determination of the so called Total Transfer Capacities (TTC) and Net Transfer Capacities (NTC)

The following definitions can be reminded:

The TTC values are generally related to commercial transactions. Such a transaction only means that the electricity generated in a country A can be used in a country B: only the two countries are involved here. The technical flow from country A to country B resulting from this commercial transaction can indeed be different, due to the physical laws of meshed transmission networks.

The Total Transfer Capacity (TTC) is determined by increasing commercial exchanges between two countries until network security limits are breached (thermal or voltage limits, etc …).

In order to define the transfer capacity that could be offered to the market, The TTC is reduced with the so called Transmission Reliability Margin (TRM). This difference results in the Net Transfer Capacity: NTC=TTC-TRM

So, the NTC is the best estimated limit of transfer capacity available between two countries or operation areas. NTC values are calculated by the different TSOs.

NTC values are published by the TSOs. A synthesis of the NTC values attached to the different cross-border as published in ref (Consentec) is shown in Table 1.

From Region	To Region	Net transfer capacity in MW	
		Summer Months	Winter Month
BE & GL	NL	3,600	3,600
F & A/CH	IT	5,000	5,400
F	BE & GL	2,600	3,750
F	A/CH & IT	4,600	4,950
NL	BE & GL	3,600	3,600
GL	F	1,750	2,250
GL	A/CH	2,700	3,650
GL	NL	3,600	2,800
GL	NORDEL	1,720	1,720
GL	CE	2,000	1,200
F	GL	2,350	2,850
F	A/CH	2,800	2,950
F	BE	1,500	1,800
F	GB	2,000	2,000
F	IT	1,800	2,000
A/CH	GL	2,600	2,600
A/CH	F	no realistic limit	no realistic limit
A/CH	IT	3,200	3,400
A/CH	CE	1,100	2,000
BE	F	1,600	2,500
BE	NL	2,200	1,400
NL	GL	no realistic limit	1,350
NL	BE	1,700	1,700
GB	F	2,000	2,000
IT	F	no realistic limit	no realistic limit
IT	A/CH	no realistic limit	no realistic limit
NORDEL	GL	2,210	2,210
CE	GL	2,350	2,250
CE	A/CH	1,400	1,400

Table 1
NTC values (source Consentec study - Dec. 2001)

1.2.2. Cross-border capacity auctions in central Europe

Cross-border capacities auctions can be considered as an indicator of congestion as well as the congestion rent between the corresponding countries. Various auctioning methods are used by the European TSOs to allocate cross-border transmission capacities.

These methods are analysed and quantified in reference … (Kema). This study focuses on the accession countries and congestions in Central Europe. This analysis shows that for this part of Europe the average per-MW prices for cross-border capacity are increasing. Table 2 gives these prices for 2005 and highlights at which borders and in which directions congestion is the most severe.

Border		Available annual capacity (MW)[44]	Average price, annual auction (€/MW/a)	Total income (million €)
CZ	AT	200	46,172	4.78
AT	CZ	600	0	0.00
HU	AT	200	17,581	2.39
AT	HU	100	3,504	0.35
SI	AT	325	1,170	0.28
AT	SI	212	15,358	2.58
HR	HU	50	1,092	0.05
HU	HR	300	5,389	1.62
SK	HU	450	49,783	22.40
HU	SK	400	354	0.14
CS	HU	50	6,394	0.32
HU	CS	25	2,233	0.06
RO	HU	50	11,116	0.56
HU	RO	50	1,786	0.04
CZ	DE(E.ON)	750	58,674	44.01
DE(E.ON)	CZ	400	15	0.01
SK	UKR	450	0	0.00
UKR	SK	450	1	0.00
CZ	SK	800	1,664	1.31
SK	CZ	800	312	0.25
PL	CZ	?	0	0.00
CZ	PL	?	8,935	0.71
DE(VE-T)	CZ	?	0	0.00
CZ	DE(VE-T)	?	53,261	17.04
DE(VE-T)	PL	?	0	0.00
PL	DE(VE-T)	?	101,187	48.57
PL[45]	SK	450	0	0.00
SK	PL	100	438	0.04
Total				147.51

Table 2
Auctions results for 2005 in Central Europe
(Source Kema study on possible congestions within Accessing Countries - 2005)

These results confirm the following statements that:

- there exists considerable congestion from the Accession Countries to Germany;
- in addition, there is a strong demand for export capacities from the Czech Republic and Hungary to Austria, from Austria to Slovenia, and from Slovakia to Hungary.

These observations highlight the conclusions of different studies and general belief that the demand for cross-border capacity is the highest:

- in the direction of North-Eastern Central Europe to Germany on one hand;
- in the direction of Italy on the other hand.

Spare electricity is available in central European countries and needed in Italy and other EU Member states. The difficult Alpine terrain means that Capacity in Austria is limited and needs to be upgraded.

1.2.3. Detailed analysis of cross-border congestions

The purpose of this section is to identify the bottlenecks and congestion at the cross borders of the different countries of EU25 (including Bulgaria, Romania, Croatia and Switzerland) expected to occur in the future.

The present analysis of future electricity cross-border congestions is based on simplified criteria and on existing studies. Indeed, it is not foreseen in the scope of the present study to simulate on computer models the future operation of the UCTE interconnected networks (moreover such simulations would not be possible due to the lack of available data, the large extent of the European networks and the extremely high budget this would require).

The analysis of cross –border congestions refers to the list of projects, including projects of European interest, to be carried out on each priority axis as defined in annex1 of the position of the European Parliament adopted in June 2005.

References for these priority projects are:

- P6-TA(2005)0211 document;
- Brochure "Energizing Europe's infrastructure".

The priority axes are the following:

- EL.1. France - Belgium - Netherlands - Germany
  Electricity network reinforcements in order to resolve congestion in electricity flow through the Benelux
- EL.2. Borders of Italy with France, Austria, Slovenia and Switzerland
  Increasing electricity interconnection capacities
- EL.3. France - Spain - Portugal
  Increasing electricity interconnection capacities between these countries and for the Iberian peninsula and grid development in island regions

- EL.4. Greece - Balkan countries - UCTE System
  Development of electricity infrastructure to connect Greece to the UCTE System and to enable South-Eastern Europe electricity market
- EL.5. United Kingdom - Continental Europe and Northern Europe
  Establishing/increasing electricity interconnection capacities and possible integration of offshore wind energy
- EL.6. Ireland - United Kingdom
  Increasing electricity interconnection capacities and possible integration of offshore wind energy
- EL.7. Denmark - Germany - Baltic Ring (including Norway - Sweden - Finland - Denmark - Germany - Poland - Baltic States - Russia)
  Increasing electricity interconnection capacities and possible integration of offshore wind energy
- EL.8. Germany - Poland - Czech Republic - Slovakia - Austria - Hungary - Slovenia
  Increasing electricity interconnection capacities
- EL.9. Mediterranean Member States - Mediterranean Electricity Ring
  Increasing electricity interconnection capacities between Mediterranean Member States and Morocco - Algeria - Tunisia - Libya - Egypt - Near-East Countries - Turkey

Among this list, two axes are not relevant for the present study: EL.1. and EL.9. will not be considered as no tunnels exist between the related countries.

The review of existing studies on the capacities and possible congestion in the interconnected European networks enables to identify the main following structural cross-border congestions.

1.2.3.1. Italy <> France, Austria, Switzerland and Slovenia (Priority axis EL2)

At the Northern Italian border, GRTN's grid is connected to neighbouring networks by nine 220 kV and six 380 kV circuits.

- The situation of congestion is as follows, for the different borders involved:
- The cross-border tie-lines are not distributed homogeneously: especially the Austrian-Italian interconnection is very weak (only one 220 kV circuit).
- Italy is currently a high price area. As a result, there is a strong demand for power import.
- Congestion is due to the violation of thermal current limits when importing from France, Switzerland and Austria.
- At the French-Italian border, the critical incident is the simultaneous loss of both 380 kV circuits Albertville-Rondissone.

- At the Swiss-Italian border, thermal overload may occur either on the 220 kV or on the 380 kV level. The Swiss export capacity is fully used all the time, with little variations of actual export only resulting from inadvertent exchange and from natural flow distribution between the different tie-lines.
- At the Austrian-Italian border, there is only a single 220 kV line Lienz- Soverzene. This line is strongly loaded even in the sane state, because of the great distance to the neighbouring tie-lines to Switzerland and Slovenia, and of the dominant position of the 220 kV level in Austria (due to the delay of 380 kV grid extensions).
- The connection with Slovenia is of great importance because it can be used for transit from Austria and from the east European countries. In particular, connecting the substations of Udine (IT) to Okroglo (SL) has already been planned for decades, but never performed. Because of the environmentally highly sensitive region, it is expected that such link be built partially underground, which has a significant influence on the costs. As a result, a synergy with a transmission through a tunnel in this area must be searched.

Market participants as well as the involved TSOs report permanent congestion.

1.2.3.2. Spain <> France (Priority axis EL3)

The Spanish and the French networks are interconnected by two 380 kV lines (in the western and eastern part of the border respectively) and two 220 kV lines (in the western and the central part of the border respectively).

The situation of congestion is as follows:

Most of the year, there is a strong demand for import from France to Spain. However, depending on the availability of hydraulic power from the Pyrenees, there are also periods of power export, mostly during winter.

In the western part of the border, when import to Spain takes place on the 380 kV line Cantegrit-Hernani, the almost parallel 220 kV line Arkale-Mouguerre is load in the opposite (northbound) direction. This last line does practically not contribute to import capacity today.

According to REE (E), the main effects that actually limit cross-border capacity occur in peak hours: the dimensioning incident is the outage of a nuclear power plant in north-eastern Spain (leading to voltage beyond its lower limit at the Spanish end of the eastern 380 kV interconnection (Vic substation).

Export to France is limited by the thermal ratings of internal Spanish lines.

Market players as well as the TSOs state that the Spanish - French border is permanently congested, at least in the direction from France to Spain.

1.2.3.3. Spain <> Portugal (priority axis EL3)

According to the TSOs (REE and REN), congestion on this border is an occasional, non permanent event, mostly related to specific hydraulic generation patterns.

This congestion occurs when different conditions simultaneously occur (surplus of hydro generation in north-western Spain, load concentration in Madrid, …) inducing an overload of the Oriol-Aranuelo double circuit line i.e. the continuation of the interconnection Pego-Cedillo line towards central Spain.

Globally, the main factor of congestion is the combination of generation in the West (Portugal) and of load in the area of Madrid.

1.2.3.4. France<> Great Britain (priority axis EL5/6)

The transmission networks of NGC (UK) and RTE (F) are connected together by a DC link with a capacity of 2000 MW in both directions.

This DC link is usually fully used in the direction from France to Great Britain. From the results of the auctions published by the TSOs, it comes that there is almost permanently a congested situation.

1.2.3.5. Denmark<> Germany (priority axis EL7)

The German network is linked to the eastern Danish (Elkraft) network by means of a 600 MW DC link and to the western Danish (Eltra) network by four AC tie-lines (two in 380 kV and two in 220 kV).

The situation of congestion is as follows:

In recent years, both Denmark and northern Germany have been facing a strong increase of installed wind power. In the daily operation, the uncontrollable amount of wind generation can induce a local power surplus and, in case this happens in Denmark, southbound export to Germany.

On the other hand, the Eltra system serves (via its DC interconnection) as a transfer platform between Germany and Norway or Sweden. As a result, the congestion on this border may occur in both directions.

In summary, the German-Danish border is affected by severe congestion due to a superposition of causes. In the future, this situation will still be exacerbated by the ongoing increase in wind generation.

1.2.3.6. Germany <> Poland (priority axis EL7)

The Polish network has been connected to the UCTE system since 1995. The analysis of auctions shows that commercial flows of electricity usually are in the direction from the Czech Republic, Slovakia and Poland to Germany.

Current studies show notably that:

- Exports from Poland to Germany mainly flow through the transmission grid of the Czech Republic.
- Investments in direct links from Poland to Germany would have a tangible effect only if upgrades within the Polish grid itself are also achieved.

Current projects aim notably at upgrading the existing connections to 400 kV.

1.2.3.7. Poland <> Lithuania (priority axis EL7)

With the planned decommissioning of the first section of the Ignalina nuclear power plant, Lithuania needs to increase its cross-border capacity. This has to be considered in relation to prior development of networks and interconnections on the western border of Poland in parallel with upgrades within the Polish grid.

1.2.3.8. Impact of wind power in Germany

Wind power generated in the North of Germany has a major impact on the physical electric flows in this part of Europe. The unpredictability of this renewable energy source makes the planning and operation of the system uncertain. This volatile production in northern Germany is balanced through the use of classic power plants often located in the south of Germany.

Consequently, German network must be reinforced. This impact of wind energy has consequences in further countries to the south of Europe.

1.2.3.9. Central Europe: Austria, Czech Republik, Slovakia and Hungary (priority axis EL8)

These four countries are located close to each other. In terms of network planning, the grids of the Czech Republic, Slovakia and Hungary have been connected to the Austrian network only recently.

For Austria, this implies that it became a country in the centre of the interconnected UCTE network instead of a country located on the outskirts. Together with the abandoning of the central generation planning due to the opening of the electricity markets, this has led to highly increased transit flows over the Austrian transmission network.

In response to these developments, the Austrian TSO (APG) started the construction of the Austrian 400 kV transmission network. In these context, increased transits will occur through Austria not only with Slovakia and Hungary but also with Slovenia and furthermore to Italy.

1.2.3.10. Austria <> Switzerland (priority axis EL 2)

Austria and Switzerland are connected by one 220 kV and two 380 kV circuits.

The situation of congestion is as follows:

- In the spring, high hydroelectric generation in western Austria (VKW area) in combination with low generation in the eastern Swiss (NOK) region may lead to congestion on the 220 kV interconnection.
- However, this congestion is not frequent and remains of minor and regional importance.

1.2.3.11. Austria <> Germany

Germany and Austria are linked by a large number of 380 kV and 220 kV lines (nine 220 kV and three 380 kV circuits).

Also about twenty additional 110 kV circuits provide another 2 GVA of tie line capacity.

The border is intensely used for bilateral exchanges between Germany and Austria as well as by transits and parallel flows from the CENTREL area.

Congestion may occur, but rarely, on the St Peter - Simbach 220 kV tie-line.

Owing to the small occurrence and to the availability of network related countermeasures, this congestion is of minor importance.

1.2.3.12. Finland <> Sweden (priority axis EL7)

The networks of Finland and of Sweden are linked by two 380 kV lines and one 220 kV line in the North as well as a DC cable in the south.

Power transfer from Finland to Sweden is limited by static stability (oscillation between generators).

Power transfer from Sweden to Finland is characterized by thermal limits as critical factor, but depending on the scenario, voltage stability may also be critical.

Today, congestion from Sweden to Finland is a non permanent seasonal problem. It occurs mostly in summer when few thermal plants are connected and there is predominant south bound electric flow from the hydroelectric plants of northern Finland to the load centres in the south.

In the future, there are plans for a significant amount of new generation in Finland and as a result congestion will probably become less frequent.

1.2.3.13. Norway <> Sweden (priority axis EL7)

Sweden and Norway are linked, along their long common border, by:

- one 400 kV and one 220 kV line in the northern section of the border;
- one 300 kV line in the central section of the border;
- two 380 kV lines in the southern section of the border.

During peak hours, there is a demand for transmission of hydro power to the load centres in south-eastern Norway and Sweden, but also to Denmark and to the UCTE system in direction of the south.

For the northern section of the border transfer capacity is limited by a potential loss of static stability after a line failure.

For the central section of the border, the thermal current rating of the interconnection Järpströmmen - Nea constitutes the most restrictive limit.

Power transits from Denmark and Germany via Sweden to Norway are also restricted by thermal limits, notably on an internal line in south-western Sweden.

Since power exchange from Norway to Sweden is often related to further transport to Denmark and Germany, it might additionally be restricted by an internal Swedish limit for power transfer to the south. Here, the critical factor is the risk of voltage collapse. The shutdown of the first block of the nuclear power plant at Barsebäck and other thermal units all located in southern Sweden has further increased north to south power flow, and thus exacerbated this internal congestion.

In general, the congestion between Norway and Sweden depends on the variability of hydro production. This also influences the frequency and direction of congestion.

1.2.4. Conclusion

In section 1.2, the situation and the level of possible cross-border congestion have been analysed for different European countries. From this analysis, two main conclusions can be drawn:

- First, significant price differences exist within the European internal market. These differences result in increased demand for commercial electricity transit at specific borders. The demands for commercial transit are reflected notably by the prices of cross-border capacity auctions. On the continent, the demand for cross-borders capacities is the highest:

  - in the direction of North-Eastern Central Europe to Germany on one hand;

  - in the direction of Italy on the other hand.

  It is worth mentioning also the particular case of congestion between the continent and Great Britain and the impact of increased future wind generators capacity in the north of Europe that will exacerbate the north-south cross border congestions.

- Second, there is still a low and un-sufficient level of electricity cross border trade due to technical, political and environmental constraints and principally to the difficult Alpine and Pyrenean terrains.

These two conclusions are illustrated in Figure 1.0. that shows the correlation existing between the missing electricity links and the price differences observed on the internal market.

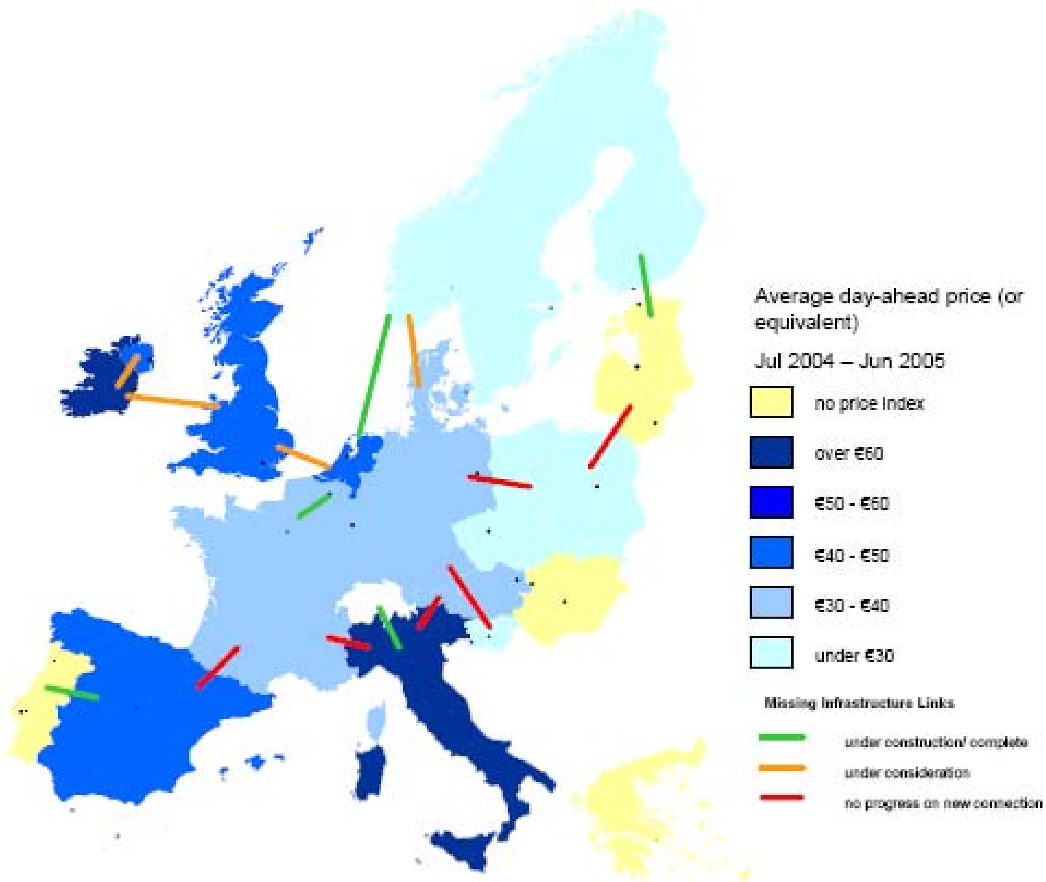


Figure 1.0.
Correlation between missing electricity links and price differences on the internal market (source: EC-DG TREN November 2005)

This figure shows the need for cross-border import, for example:

- from north and north-eastern countries characterized by a lower day-ahead electricity price (under index 30 EUR) to central countries (index 30-40 EUR);
- from central countries (index 30-40 EUR) to Great Britain and Spain (index 40-50 EUR);
- and especially from France, Germany and Austria (index 30-40 EUR) to Italy (over index 50 EUR), passing directly through one border or indirectly through Switzerland.

1.3. List of priority rail/road projects for synergy

The approach used consists in carrying out the following tasks:

- Check if road or rail tunnels (will) exist at the locations where it will be necessary to reinforce or create new cross-border electrical interconnections.

- Select a priority list of rail/road tunnels (existing or future tunnel projects) for which a possible synergy with electric priority axes is identified and for which the feasibility of installation of high voltage cable can be analysed.

- Analyse the electrical point of view and civil works aspects of several tunnels selected in the list before.

- Among this list, three tunnels (cf. Inception Report § 1.3.) will be selected, using a simplified multi-criteria analysis. These tunnels will be:

  - either three rail tunnels;

  - or two rail tunnels + one road tunnel.

These tasks have been carried out on the bases of the existing list of priority projects for rail/road inter-European electricity transport (see appendix for the rail/road projects and appendix for electricity transmission projects).

Table 3, Table 4 and Table 5 present a first selection or priority list of rail/road tunnels (existing tunnels or future projects) for which synergy with electric cross-border transmission needs has been identified. This selection of tunnels is presented on the left side of the tables and can be compared to the corresponding electricity priority axes mentioned on the right side of the table. In these tables, tunnel projects are sometimes mixed (or replaced) by bridges. In some cases, tunnels that do not pertain to cross-border area but that are in relation with electric priority axes have also been considered.

RTE-T tunnel (bridge) projects			Electricity TEN-E priority projects
section and type of work		**calendar**	**section**
n°1 railway axis Berlin-Verona/Milan-Bologna-Napoli-Messina-Palermo			*EL 2: borders of Italy with France, Austria, Slovenia, Switzerland*
Brenner tunnel	Rail basis tunnel(56 km)	2007-15	feasibilitry study under way (2003-2005) for 400 kV link
additional tunnels between Brenner and Verona. (project promoteur: BBT)		under study	idem
n°1 railway axis Berlin-Verona/Milan-Bologna-Napoli-Messina-Palermo			*EL 9: Mediterranean ring*
Bridge on Messina strait		2005-15	maybe useful if the intercon. project Tunisia-Sicilia is achieved
n°2 high speed railway Amsterdam-Brussels-London			*EL 5/6: United kingdom-Continental Europe*
Eurotunnel Dover-Calais	(50km)	in operation	priority project: location of line to be determined
n°3: high speed railway axis South-West of Europe			*EL3: France-Spain-Portugal*
Guadarrama tunnel	bi-tube railway tunnel (28km)	under cst	to be assessed: no specific TEN-E project
n°3: high speed railway axis South-West of Europe			*EL3: France-Spain-Portugal*
Tunnel Figueras-Perpignan	bi-tube railway tunnel (8km)	2005-08	new line project Baixas - Bescano-sentmenat for 2006-7
(studies and construction: TP Ferro concession "EUROFERRO")		under cst.	
n°16 freight railway axis Madrid-Parid			*EL3: France-Spain-Portugal*
Rail connection France-Spain in middle of Pyrenees	(long distance tunnel)	2013-20	priority project: location of line to be determined
Railway Somport tunnel	(rail tunnel re-used as safety	existing	
Road Somport tunnel	gallery for the road tunnel)	existing	
Road tunnel Bielsa ?		existing	
Road tunnel pico de Aneto ?		existing	
Road tunnel of Puymorens? (Andorra)		existing	possible connection with 400 kV line project Penalba-Salas??
studies underway by regions (Aragon, Aquitaine, Midi-Pyrénées) and TCP organism			

Table 3
Selection of rail/road tunnel with possible synergy with electricity priority axes - Part 1

RTE-T tunnel (bridge) projects			Electricity TEN-E priority projects
section and type of work		**calendar**	**section**
n°6: railway axis Lyon-Turin			*EL 2: borders of Italy with France, Austria, Slovenia, Switzerland*
Mont Cenis railway base tunnel	53km +bridge+12km	2004-18	priority project: location of line to be determined
project promoteur is Lyon-Turin Ferroviaire			
+additional tunnels in France & Italy	16km tunnels on Italian side		(existing 400kV line: La Praz Villarodin)
Frejus road tunnel		existing	
+ New safety gallery		under study	
n°6: railway axis Lyon-Turin-Divaça			*EL 2: borders of Italy with France, Austria, Slovenia, Switzerland*
Rail tunnel between Trieste and Divaça Italy-Slovenia		2015	
n°11: fix Oresund link (DK-SU)			*EL 7: Denmark-Germany-Baltic ring*
Oresund Road+railway link	Tunnel-island-bridge 4+4+7.5 km	existing since 2000	Priority axis: Increasing interconnection capacities in addition to the existing Konti-Skan cable
n°20: New axis of Fehmarn strait			*EL 7: Denmark-Germany-Baltic ring*
Fehmarn Road+railway link (DK)	Tunnel(or bridge) of 19 km	2007-15	priority axis
n°12: road/railway axis			*EL 7: Denmark-Germany-Baltic ring*
Tunnel Hallandsas Ridge (SU)	17 km double way tunnel	2011	priority axis Denmark-Sueden-Finland location of line to be determined
n°24: Railway axis Genova- Basel -Duisburg *Inside Switzerland*			*EL 2: borders of Italy with France, Austria, Slovenia, Switzerland*
New railway tunnel of Gothard	basis tunnel 57 km	2013	
Road tunnel of St Gothard	16 km	existing	
New railway tunnel of Zimmerberg	basis tunnel 20 km		
New railway tunnel of Lötschberg	basis tunnel 42 km	2007	
Rail tunnel of Lötschberg (Kandersteg)	35km	existing	

Table 4
Selection of rail/road tunnel with possible synergy with electricity priority axes - Part 2

RTE-T tunnel (bridge) projects			Electricity TEN-E priority projects
section and type of work		**calendar**	**section**
n°24: Railway axis Genova- Basel -Duisburg			*EL 2: borders of Italy with France, Austria, Slovenia, Switzerland*
Tunnels Switzerland-Italy			
Road tunnel of San Bernardino	7.5km	existing	
Rail tunnel of Simplon	18 km	existing	
Road tunnel of Grand St Bernard	7km	existing	
Road tunnel of Mont-Blanc	12km	existing	
Road tunnels on highway A2-E35:			Interconnection project Bovisio (IT)-Magadino(CH)
tunnels between Como and Lugano			HVDC :feasibility confirmation and basic engineering study
followed to the north by:			underground cable parallel to motor way and other variants (5var.)
Monte Ceneri motorway Tunnel		existing	
Monte Ceneri railway base Tunnel	15.4 km	under cst.	
see: possible connection with tunnel Passo de S. Bernardino (to Austria)			
with tunnel St. Gothard (57 km to Germany)			
and with Zimmerberg (20 km to Germany)			
Rail base tunnels Zimmerberg+Gothard+Monte Ceneri=axis Basel-Milano			
Tunnels Germany-Austria-Italy			*EL 2: borders of Italy with France, Austria, Slovenia, Switzerland*
Arlberg road tunnel (Austria- Vorarlberg)	16km	existing	
Felbertauern road tunnel (Austria)	8km	existing	possible synergy with 400 kV project lines: St-Peter-Tauern
Tauern railway tunnel (Austria)	18km	existing	and Lienz-Soverzene-Cordignano-Venezia for 2010
Katschberg road tunnel (Austria)	12km	existing	
Tunnels Austria-Slovenia			*EL 2: borders of Italy with France, Austria, Slovenia, Switzerland*
Karawanken road tunnel (Jecenice)	8km	existing	
Loibl roadtunnel	5km	existing	

Table 5
Selection of rail/road tunnel with possible synergy with electricity priority axes - Part 3

Figure 1.1. hereafter shows the geographical position in Europe of all above RTE-T tunnel (bridge) projects.

LEGEND

1: Brenner rail basis tunnel
2: Lyon-Turin rail basis tunnel
3: Frejus road tunnel safety gallery
4: Monte Ceneri rail basis tunnel
5: Gotthard rail basis tunnel
6: Zimmerberg rail basis tunnel
7: Simplon rail tunnel
8: Lötschberg rail basis tunnel
9: Somport rail tunnel
10: Eurotunnel

11: Perpignan-Figueras rail tunnel
12: Guadarrama rail tunnel
13: Bridge on Messina strait
14: Oresund link (tunnel,island, bridge)
15: Fehmarn link (tunnel,bridge)
16: Hallandsas ridge rail tunnel
17: Mont-Blanc road tunnel
18: Tauern rail tunnel
19: Katschberg road tunnel

Fig 1.1

1.3.1. Comments on the priority rail/road tunnels for synergy on electrical and civil works points of view

Taking into account the main trends about the electric cross-border congestions described here-above in section 1.2, the following comments can be given on the main tunnels for which a possible synergy has been detected in Table 3, Table 4 and Table 5.

1.3.1.1. Brenner tunnel

The Brenner basis tunnel represents the most important element for the HS line (Berlin - Monaco - Verona - Bologna - Palermo) and will be finalized in 2015. With a total length of 56 km this tunnel presents the greatest chance for a synergy with the HV transmission network, for the following reasons:

- As mentioned in section 1.2, Austria became a country in the centre of the interconnected UCTE network in the frame of the opening of the electricity markets. In response, the Austrian TSO (APG) had to start the construction of the Austrian 400 kV transmission network. As a result, this country will be crossed by increased north to south transits implying Germany, Slovakia, Hungary but also Slovenia and Italy. The need for imports to Italy is due to the lack of installed capacity and to the high level of supply costs inside Italy. The opportunity of commercial transactions is a strong incentive for north - south transit.

- From the economic point of view, the Brenner tunnel offers better conditions because it is a base tunnel implying a long length (56 km). As a consequence the cost per km of implementing transmission by cables in the tunnel is lower. For instance, the fixed cost of building network infrastructure to access inside the tunnel from the external grid can be spread on a longer transmission distance. The cost of possible end-substations can be shared with the cost of substations and incoming HV connections from the grids that are anyway required for the railway supply itself.

- The project foresees a twin tube tunnel with pilot gallery (see figures 1.2. and 1.3.). The main tubes are circular with an internal radius around 4.1 m. The pilot gallery also circular offers an additional chance to have enough space to install HV transmission. The cross section of main galleries and pilot gallery where seen on figures 1.3. and 1.4. These sections represent the tunnel build with TBM (Tunnel Boring Machine).

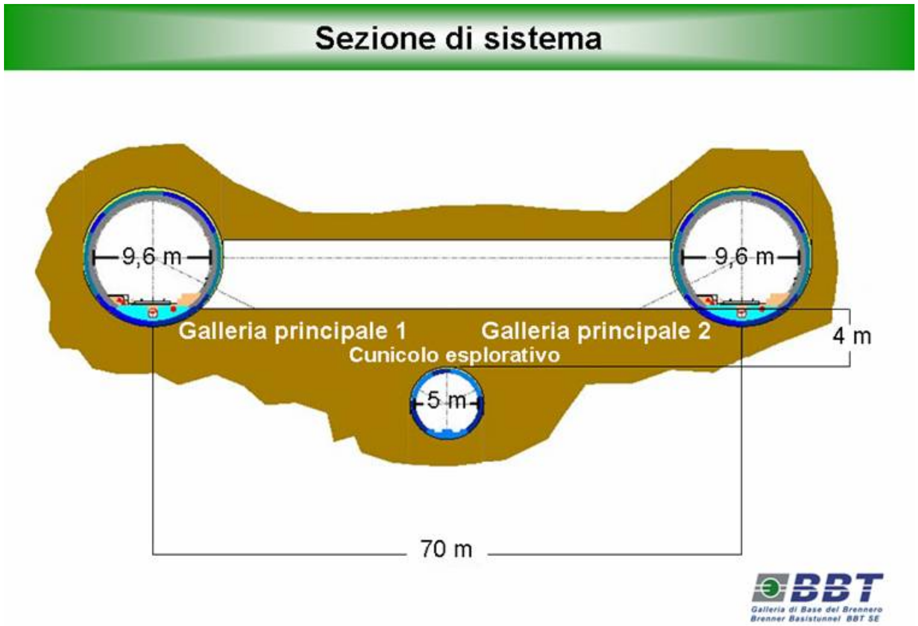


Figure 1.2.
Typical cross-section of the main galleries and the pilot gallery of the Brenner Basis Tunnel (source BBT SE)

Figure 1.3.
Visualisation of the Brenner Basis Tunnel with the pilot gallery (yellow line) between the 2 main galleries (source BBT SE)

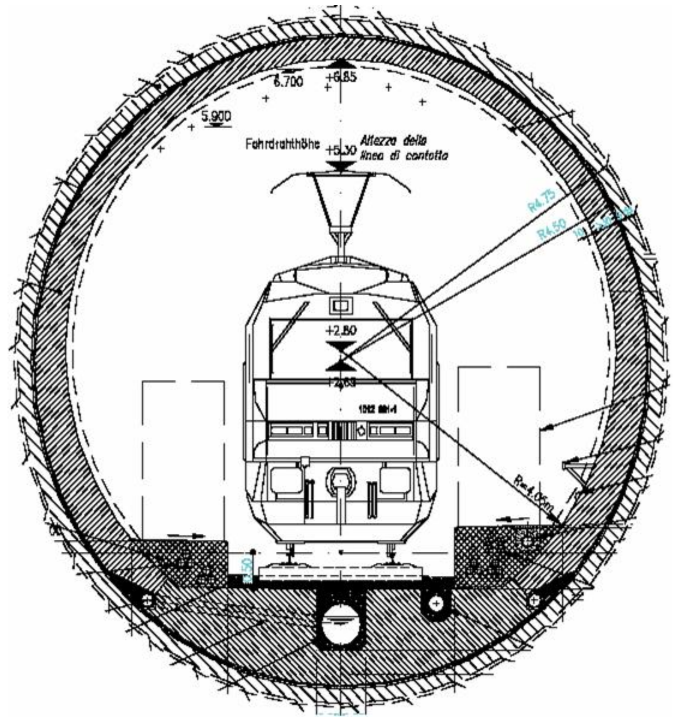


Figure 1.4.
Brenner Tunnel - Main gallery cross section with TBM construction
(source BBT SE)

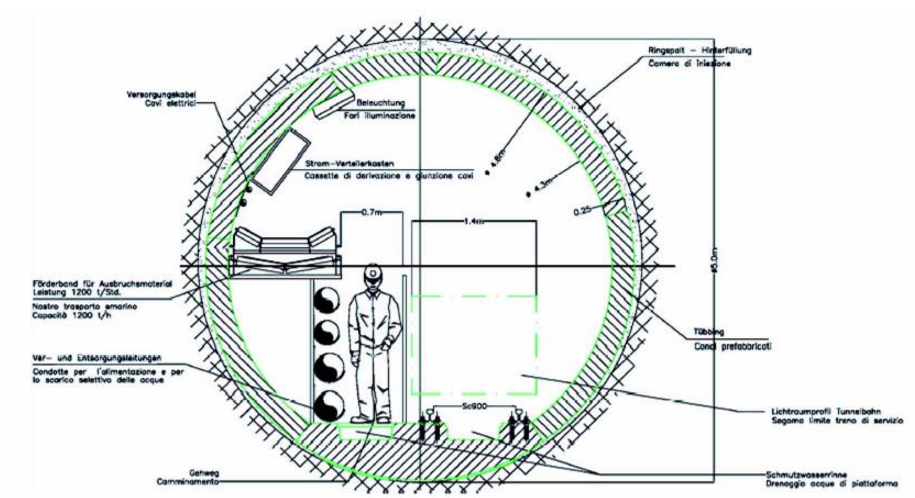


Figure 1.5.
Brenner Tunnel - Pilot gallery cross section with TBM construction
(source BBT SE)

- The distance between the tunnel and the Austrian grid is smaller (about 10 km) than the distance between the tunnel and the Italian grid. The project would be the opportunity to rationalize the development of the local networks existing presently at a voltage lower than 400 or 220 kV and to better integrate the local hydro generation. However, some additional links would be necessary notably in Austria due to the increase of internal transit.

There are plans under study to connect the tunnel entry (Franzenfeste) with the 380 kV Italian network by extending the local 220 kV to 380 kV (Franzensfeste - Bozen - Nogarole axis) as shown in Figure 1.6.

Figure 1.6.
Possible variant to connect the entry of the Brenner tunnel with the 380 kV grid in Italy

It can be noted that, according to local TSOs a new transmission link at 400 kV through the tunnel seems more adapted because for instance a 220 kV link as alternative would quickly be saturated due to the international transits that would occur through Austria to Italy.

The Italian and the Austrian TSO's confirmed that on both sides in Austria (Tyrol) and in Italy the new connection could increase the security of the supply, help to secure better market conditions (higher capacity) and open for new regions the possibility to use renewable hydroelectric power resources from the alps. In addition, it can be mentioned that the backbone transmission network had to be rebuilt, but not only caused by a possible new north-south connection, but also because of the age and in connection with a possible rationalisation of the HV-grid.

1.3.1.2. Lyon - Turin basis Tunnel (Mont Cenis)

Like the Brenner tunnel, the future railway Lyon-Turin basis tunnel presents global characteristics that should be favourable to the insertion of HV transmission link.

It covers a long distance as seen on the figure 1.7.: after the Basis tunnel (53,1 km), the HSL crosses the Val Cenischia and continues his way through the Bussoleno tunnel (12.2 km).

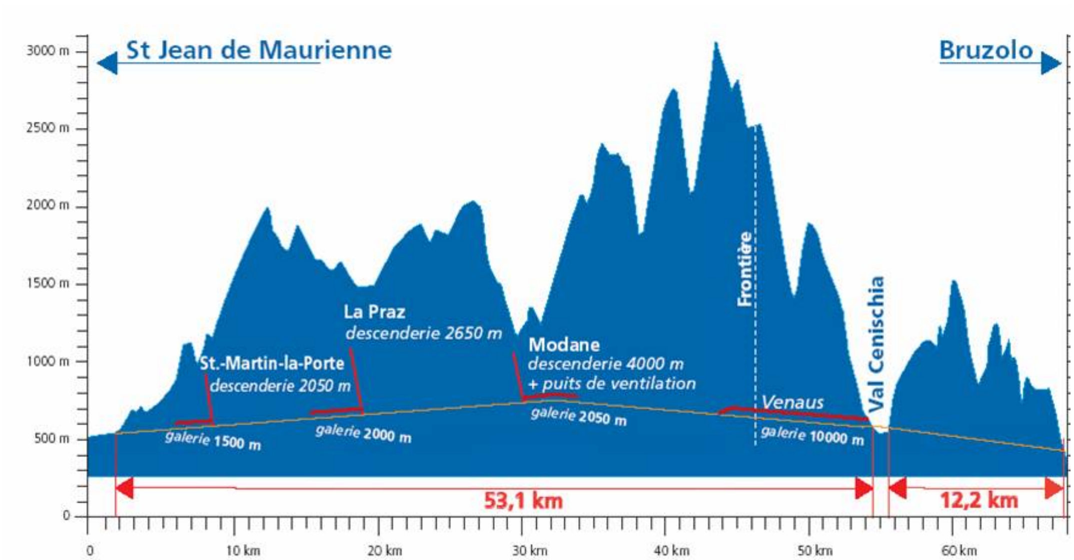


Figure 1.7.
Lyon Turin Tunnel - Bridge - Bussoleno Tunnel (source LTF)

The studies are still under way and its routing corresponds to a strong need for an additional electric cross-border interconnection to reinforce transit capacity from France to Italy. The existing 400 kV line La Praz-Villarodin-Venaus-Piossasco is old and a project of new 400 line in this axis (using the valley of the Maurienne) had to be cancelled about 10 years ago due to strong local opposition.

Different technical solutions can be studied to connect the entry of the tunnel to the French transmission grid: a connection to local 225 kV substations (Saussaz, St Jean de Maurienne) or a connection to the 400 kV (coming from Albertville or from Grande-Ile, …). On the Italian side, only 380 kV exist near the border.

On civil works point of view, the Lyon - Turin Basis tunnel is a twin tube tunnel without safety gallery. The internal section with TBM is circular with an internal radius around 4.20 m (see cross section figure 1.8.). The tunnel works were foreseen for 2008-2010 with an operational opening to railway traffic planned for 2018-2020.

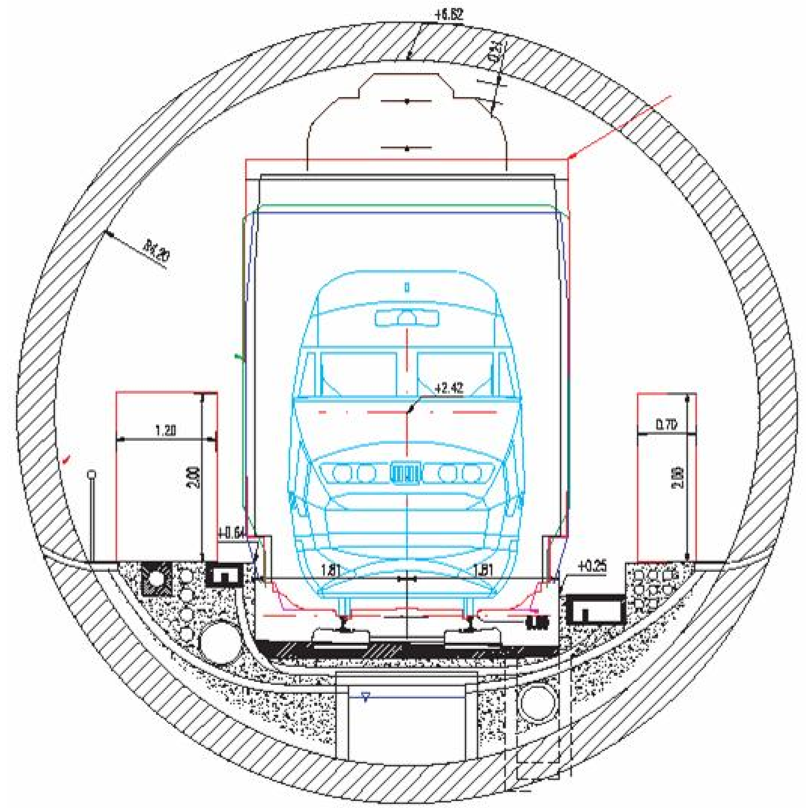


Figure 1.8.
Lyon - Turin Tunnel - Main gallery cross section with TBM construction (source LTF)

1.3.1.3. The Monte Ceneri basis tunnel (Gothard-Zimmerberg)

The Monte Ceneri basis tunnel (15.4 km) is part of an important basis railway axis under construction that will enable to cross Switzerland from Germany to Italy and that will also include the future basis tunnels of Gothard (57 km) and of Zimmerberg (20 km) (see figures 1.9. and 1.10.). This chain of basis tunnels is unique because it will get Germany at a shorter distance from Italy.

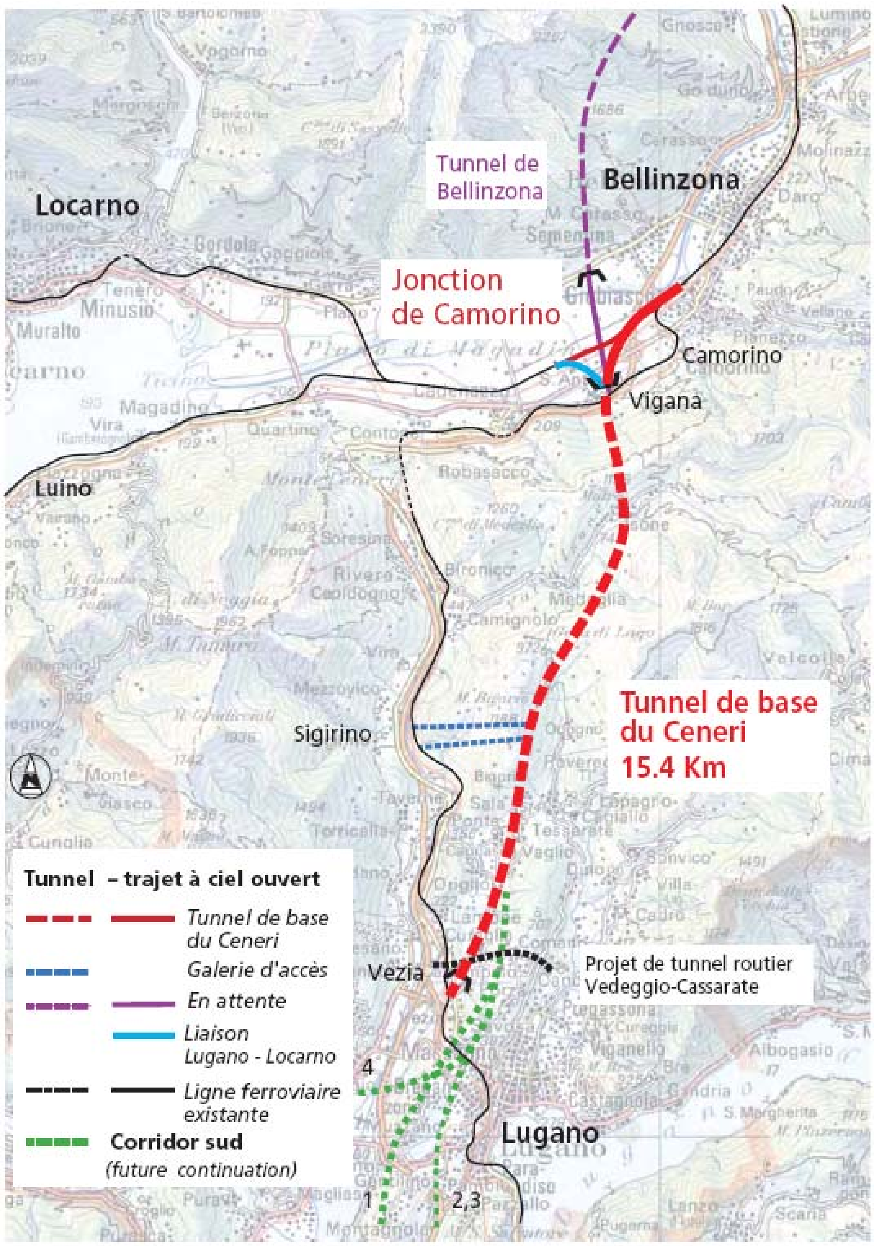


Figure 1.9.
Route of the Monte Ceneri basis tunnel
(source AlpTransit Gotthard Ltd)

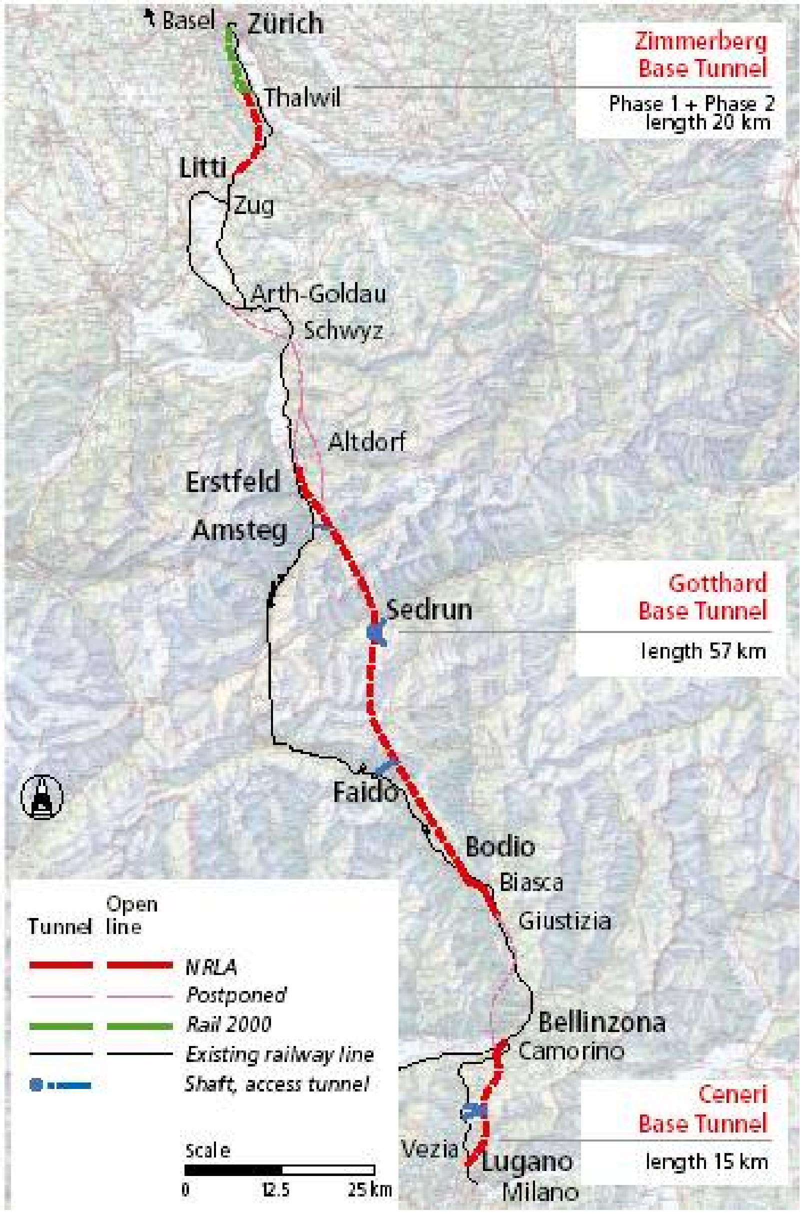


Figure 1.10.
Route of the future Gothard and Zimmerberg basis tunnels
(source AlpTransit Gotthard Ltd)

On November 25, 2005, AlpTransit Gotthard Ltd awarded the contract for preparatory work lots of the Ceneri Base Tunnel. The tunnel works are in progress (see figure 1.11.) with an operational opening for 2018.

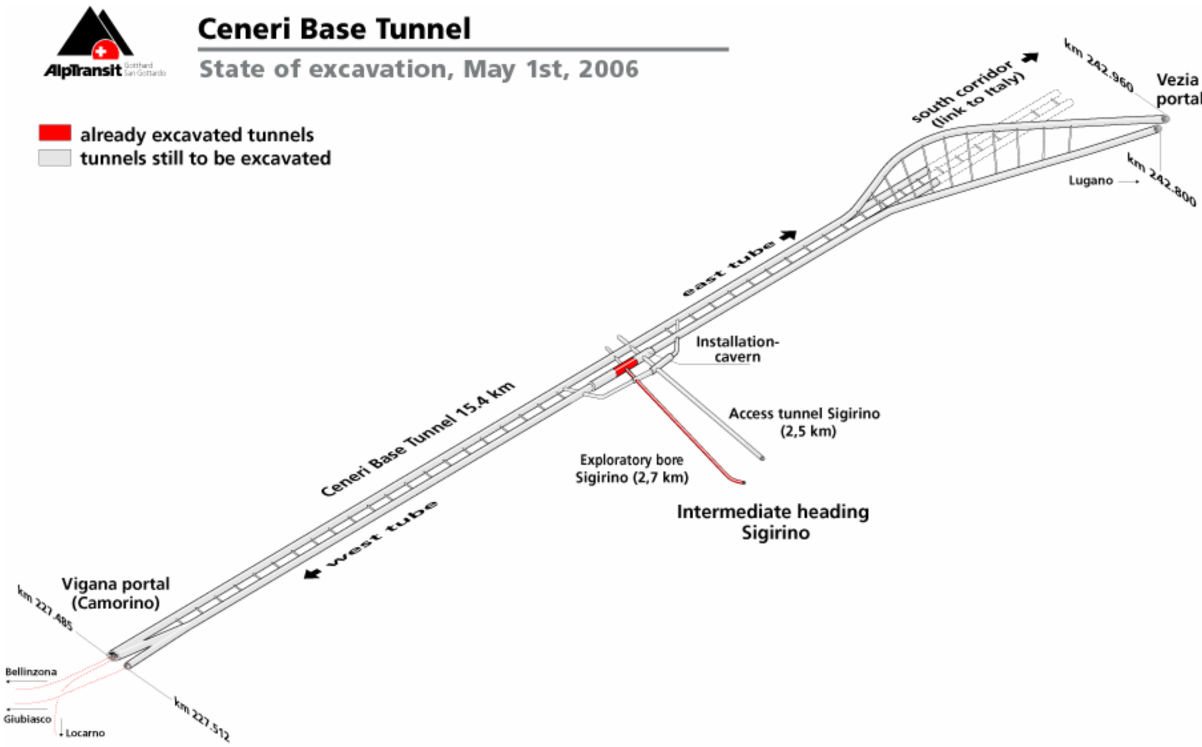


Figure 1.11.
Monte Ceneri Tunnel - State of excavation
(source AlpTransit Gotthard Ltd)

The Monte Ceneri tunnel has a circular internal section with an internal free radius around 4.10 m (see cross section figure 1.12.) It is interesting to note that for the tunnel build with traditional methods the section will be more a horse shoe section as shown on figure 1.13.

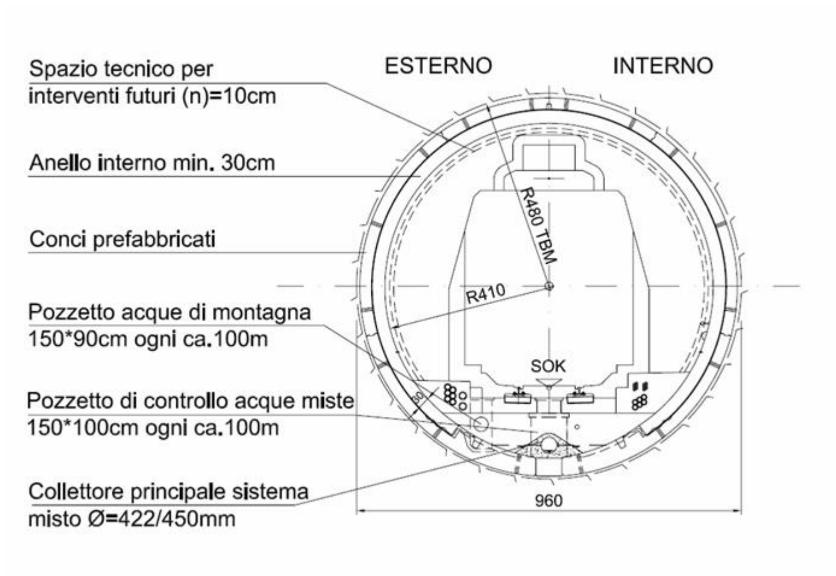


Figure 1.12.
Monte Ceneri Tunnel - Main gallery cross section with TBM construction
(source AlpTransit Gotthard Ltd)

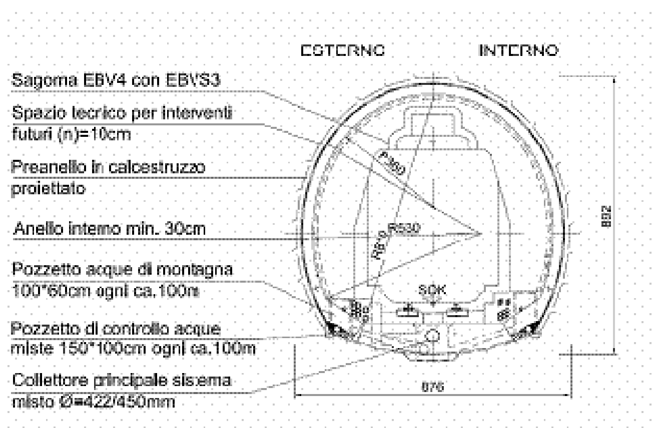


Figure 1.13.
Monte Ceneri Tunnel - Main gallery cross section with traditional construction
(source AlpTransit Gotthard Ltd)

If it could be technically associated with electricity transmission links, the following advantages would be merged:

- The possibility to have a direct electric link between Germany and Italy in the present context which fulfils the European cross-border transit needs.
- The possibility to implement electricity transmission in a set of long tunnels what is a sine qua non condition for economic feasibility.
- The possibility to implement transmission in tunnels for which a service gallery is also foreseen, what offers additional chance to have enough space to install the transmission link, to avoid interacting with other tunnel functions and to guarantee a higher reliability level.
- The possibility to combine this axis (Zimmerberg-Gothard-Monte Ceneri) with existing projects for installing new electricity transmission from the south of the Monte-Ceneri tunnel (near Lugano) to the Bovisio 400 kV substation in Italy (for example the 400 kV Magadino-Bovisio project of Edison).

This tunnel is far and away more interesting than the Motorway Monte Ceneri tunnel A2 - E35 of 1.430 km length as seen on figure 1.14.

Figure 1.14.
Map motorway Monte Ceneri tunnel
(source Michelin)

1.3.1.4. Motorway tunnel (16km) as base route for the Magadino - Bovisio transmission project

The Magadino-Bovisio project consists in implementing a new 1000 MW electric connection between the 400 kV Bovisio substation and a 380 kV substation Magadino located near Locarno in the South of Switzerland.

The base route of that project (94 km) consists in implementing a HVDC (High Voltage Direct Current) link between these two substations. The HVDC cable would be ground layed, along the motorway to Milano, using thereof 16 km in tunnel. From Magadino to the north, new 380 kV OH-lines in the direction of Lavorgo are presently envisioned.

To avoid problems due notably to the difficulty of installing the connection while maintaining the main road in service, an alternative route could also consist in using a longer route (113 km) through Livo by combining overhead DC line, submarine cable (in the Como lake) and underground cable along national roads (Livo-Magadino).

If such a 1000 MW link can be achieved, it could be a good synergy to combine it further from Magadino to the north with a transmission link implemented in the Monte Ceneri tunnel. After the Monte Ceneri tunnel (and extension of Belllinzona tunnel), the extension of this north-South connection through the new Gothard and Zimmerberg basis tunnels could be envisioned as already mentioned here-above, in order to have a complete link between Italy and Germany through Switzerland.

1.3.1.5. Channel tunnel between England and France

This submarine tunnel of 50 km length presents all a required feasibility conditions to install a new electricity transmission link from the technical, reliability and economic points of view.

The twin tube tunnel of 7.6 m internal diameter with the service gallery is presented on figure 1.15.

Such opportunity has already been studied.

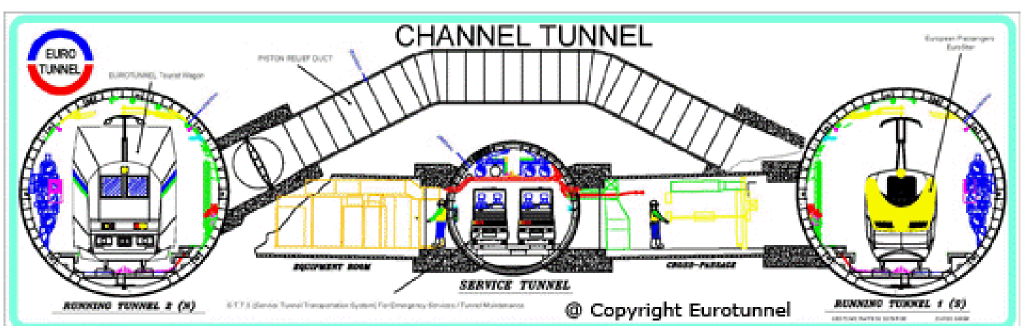


Figure 1.15.
Typical cross-section of the main galleries and the safety gallery of the Eurotunnel (source Eurotunnel)

1.3.1.6. Somport tunnel in the Pyrenees

The 8.6 km length motorway Somport tunnel is a monotube tunnel with a horse shoe section. This tube has links with the disaffected railway tunnel (7.9 km) used as safety gallery (see figure 1.16.).

Figure 1.16.
Visualisation of the Motorway Somport Tunnel linked with old railway tunnel in France Section (source DDE Pyrénées-Atlantiques)

The Somport tunnel presents the characteristic of:

- being in the middle of the central Pyrenees what constitute an important electricity priority axis (EL 3 project) in the long terme;
- difficulty to add HV line into the road tunnel due to the road traffic and the equipment (see figure 1.17.).
- offering the possibility of using the existing disaffected rail tunnel for installing a transmission link without any interference with the road traffic.

The horse shoe section of the rails tunnel has a width of 4.4 m as seen on figure 1.18.

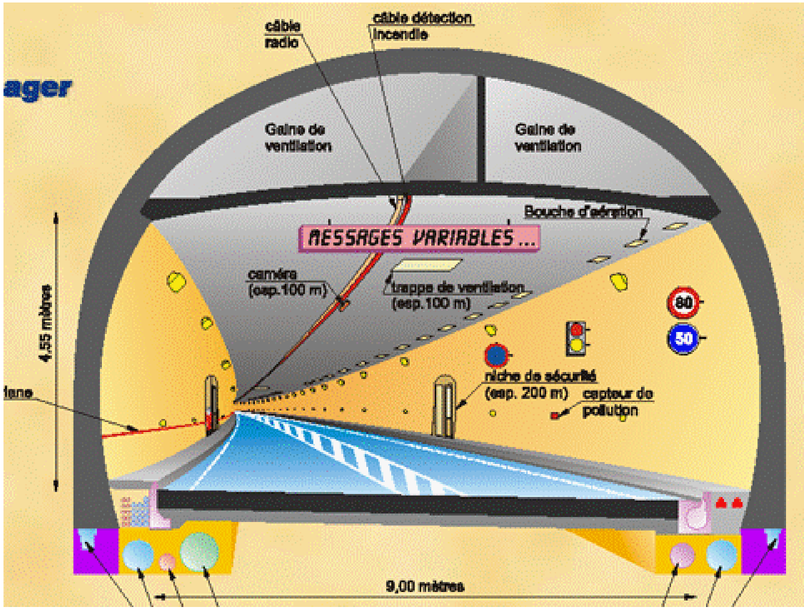


Figure 1.17.
Cross section of the Motorway Somport Tunnel
(source DDE Pyrénées-Atlantiques)

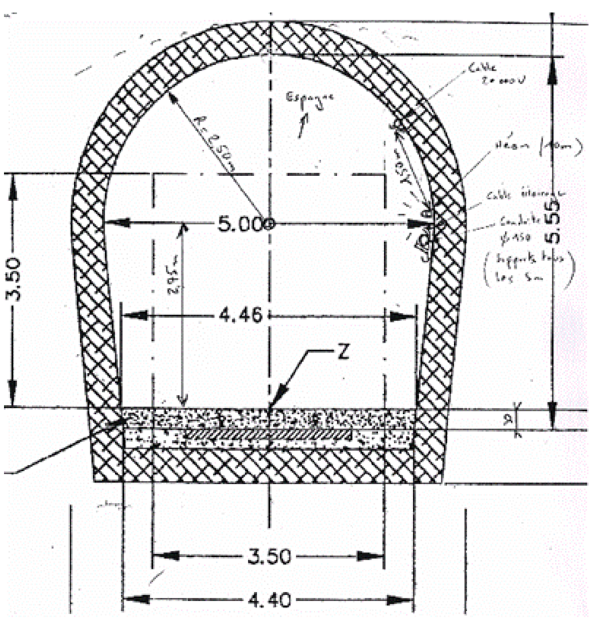


Figure 1.18.
Horse shoe section of the railway tunnel

However, the distance from the entries of this tunnel and the neighbouring 400 kV or 220 kV HV grids is significant.

Up to now in the central part of the Pyrenees, RTE says it has achieved a first enquiry about environmental sensitivities, but has not carried out accurate feasibility studies relating to electric interconnections. They will examine the possibilities of using the transmission infrastructures in project in the frame of the search of a new cross-border link, but this kind of project, according to RTE, has not yet been clearly identified.

As far as the region of Andorra is concerned, RTE confirms that the two networks supplying today Andorra from France and from Spain do not enable to contribute to an electric interconnection between France and Spain.

1.3.1.7. Tunnel Perpignan - Figueras

In the frame of the new Baixas-Bescano 400 kV cross-border line project, RTE has already examined, jointly with the LVG Perpignan-Figueras, the possibilities of installing an electricity transmission link in the Perpignan- Figueras tunnel (8.3 km). The conclusions of these studies were negative because the construction design of this twin tube tunnel without safety gallery does not permit the implementation of such link.

1.3.1.8. Frejus Tunnel: safety gallery

Presently, there is an interesting project consisting in building a new safety gallery for use along the existing Frejus road tunnel between Italy and France. This safety gallery would be 13 km long and provides a great opportunity of synergy between electricity transmission and an existing road tunnel: indeed, the section of road tunnels most generally do not permit the addition of additional electricity transmission equipment due to a lack of place and only safety galleries offer such opportunity. In the Frejus tunnel the safety gallery is still a project waiting for approval. This is an ideal situation from which one could take profit.

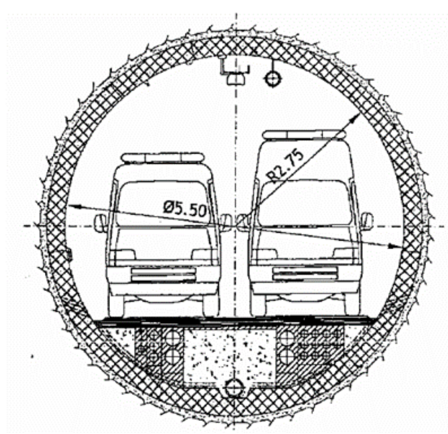


Figure 1.19.
Cross section (TBM) of the planned safety gallery of the Frejus Tunnel
(source article A. Chabert - AFTES Congress Chambery Oct. 2005)

1.3.1.9. The Oresund Tunnel

This project includes a direct rail and road connection through the straights between Denmark and Sweden.

It includes a main road (with 4 bands) going above a double track railway link.

It is composed of a 4 km tunnel under the sea, coupled with a 7.5 km bridge.

Additional studies should be necessary to compare the cost of the installation of an electric AC transmission link through this scheme with the cost of a possible new submarine DC link between the two countries. It is to mention that other DC submarine cables already exist or are in project across these straights.

1.4. Tunnel selection for a more detailed analysis

From the priority list of rail/road tunnels (in Table 3, Table 4 and Table 5) for which a possible synergy with electric priority axes has been identified, the considerations presented here-above lead to select the following rail/road tunnels for further analysis:

- the future Brenner basis tunnel (Austria - Italy);
- the future Lyon - Turin basis tunnel (France - Italy);
- the future Monte Ceneri basis tunnel associated with the Gothard and Zimmerberg basis tunnels in more internal Swiss territory (Germany-Italy through Switzerland);
- the submarine railway tunnel existing between France and England (Eurotunnel).

Additional opportunities:

- the Somport tunnel between Spain and France (disaffected railway tunnel re-used as safety gallery for road tunnel);
- the Frejus tunnel, safety gallery between Italy and France for the road tunnel.

These tunnels can be compared focusing on the most important requirements for acceptable feasibility, i.e.:

- a long distance compulsory to obtain acceptable investment and operation costs per km of tunnel length. This generally can only be achieved with basis rail tunnels;
- the presence of pilot or service gallery to introduce the transmission cables;
- an easy access to the electrical grid;
- the matching with highest electricity congestion in the future;
- the highest environmental impact avoided cost.

This is the aim of the following multi-criteria analysis summarized in the decision matrix.

1.5. Multi-criteria analysis - Decision matrix

	Weighing from 5 to 1 (5 = excellent, 1 = worst)		Brenner Tunnel Rail base	Lyon - Turin Rail base	Monte Ceneri, Gothard + Zimmer-berg Rail base	Euro-tunnel Rail base	Simplon + Lôtsch-berg Rail base	Somport Tunnel Road	Frejus Tunnel Road	Perthus Tunnel Rail base
Technical	Priority of Interconnection axis	5: EL2 4: EL3 3: EL5/6 2: EL7 1: EL8	5	5	5	3	5	4	5	4
	Total length of tunnel	5: l > 50 km 4: 30 < l < 50 km 3: 20 < l < 30 km 2: 20 < l < 10 km 1: l < 10 km	5	5	5	5	5	1	2	1
	Distance tunnel – HV grid	5: d < 10 km 4: 10 km < d < 20 km 3: 20 km < d < 30 km 2: 30 km < d <40 km 1: 40 km < d	3	5	1	5	2	1	4	3
	Access to HV grid	5: low altitude base tunnel 1: higher altitude road tunnel	5	5	5	5	5	1	1	5
	Type of tunnel	5: Rail 2 tubes with service gallery 4: Road with service gallery 3: Rail 2 tubes without service gallery 2: Road without service gallery 1: Rail 1 tube without service gallery	5	3	3	5	3	4	4	3
	State of the project	5: Planned with service gallery > 2010 or existing but disaffected 4: Planned without service gallery 2007-2009 3: In construction with service gallery 2: In construction without service gallery 1: Existing	5	4	2	1	2	1	5	2
	Security aspect	5: Rail 2 tubes with service gallery or existing tunnel but disaffected 4: Road with service gallery 3: Rail 2 tubes without service gallery 2: Road without service gallery 1: Rail 1 tube without service gallery	5	3	3	5	3	5	4	3
	Space and facilities inside the tunnel	Available space and ease of access for installation 5: service/pilot gallery of road tunnel 4: service/pilot gallery of rail tunnel 2: main tunnel gallery	4	2	2	4	2	5	5	2
Total technical			**37**	**32**	**26**	**33**	**27**	**22**	**30**	**23**

In this decision matrix, weights (from 5 to 1; where 5 = excellent and 1 = worst) are attached to the different criteria considered, for each pre-selected tunnel project. The criteria taken into account relate notably to:

- The fact of belonging to a priority interconnection axis: for example, taking into account the analysis made in section 1.2.4, the electric axis EL2 (borders of Italy with France, Austria, Slovenia and Switzerland) receives the highest priority.
- The total length of the tunnel: a minimum length is compulsory for acceptable investment and O&M costs distributed per km.
- The distance from the HV grids: a smaller distance from the HV grids of both countries increases the economic feasibility of an electric link through the tunnel. It is worth mentioning the possible synergies with end-substations required for railway power supply, the possible synergies with necessary re-organization of local transmission grids near the border (voltage upgrade in Austria and Italy) or the possible synergies with existing hydro plants connection (located in the mountains near the border).
- The access to the HV grid: low altitude railway base tunnels make the connection to the HV grid easier, while higher altitude road tunnels are less favourable.
- The type of tunnel: a greater number of tubes and the presence of pilot or service gallery are favourable to the technical feasibility of implementing electricity transmission in the tunnel.
- The state of the project: planned tunnels are more favourable than tunnels under construction or existing tunnels, for which additional modifications are difficult to implement. Also, tunnels planned with service gallery are more likely to permit electricity transmission.
- The security aspects: here also, the number of tubes, the presence of service galleries, the presence of existing but disaffected tube or the type of tunnel play a role in the tunnel security.
- The space and facilities inside the tunnel: the required space and access for installation depend on the tunnel configuration.

For each tunnel analysed in the decision matrix the sum of the weights assessed for the different criteria has been calculated.

The tunnel selection proposed her-above for a more detailed analysis corresponds to the results of ranking the tunnels by decreasing total weight in the decision matrix.

Conclusion:

Based on the “Multi-criteria analysis decision matrix” giving the total weight for each of the tunnels, the tunnels are ranked by priority as shown in the list below:

1. Brenner Tunnel- Rail base -pilot gallery (37);
2. Euro-Tunnel (33);
3. Lyon-Turin Tunnel- Rail base (32);
4. Frejus Tunnel - Road Tunnel - safety gallery (30);
5. Simplon + Lôtschberg Tunnel - Rail base (27);
6. Monte Ceneri, Gothard + Zimmerberg Tunnels - Rail base (26);
7. Perthus or Perpignan-Figueras Tunnel - Rail base (23);
8. Somport Tunnel - Road+ Rail tunnels (22);

Of this list we will select for a deeper analysis the five following tunnels:

1. **Brenner Tunnel** : undoubtedly this is one of the priority tunnels in terms of the interconnection and of grid access, but also and especially as its structure : rail base + pilot gallery is very favourable as regards the safety aspect.
2. **Euro-tunnel** : this offers a very sensible alternative to a link with submarine cables between France and England and is very interesting considering the differential between these two countries in terms of cost of the kWh. .

3. **Lyon-Turin Tunnel** : because this is one of the important connection axes between France and Italy, plus it permits a very easy grid connection and, furthermore, the present progress status of the design still permits making a number of adaptations needed to accommodate the link.
4. **Monte Ceneri,Gothard + Zimmerberg tunnels**: this chain of basis tunnels is unique because it will shorten the distance between Germany and Italy and hence it could provide an excellent link between these two countries.
5. **Somport tunnel**: although ranked lower, this is so far the only tunnel that would permit an interconnection between France and Spain, through the disused rail tunnel that has now been rehabilitated into a “safety gallery” for the road tunnel. The only other tunnel that could permit a France – Spain interconnection is the Perpignan-Figueras or Perthus tunnel. This tunnel has been investigated already by RTE and the conclusion indicated it was impossible to install a VHV link in it.

The possible future safety gallery of the Frejus Road Tunnel will not be investigated at this stage for the following reasons:

1. This tunnel is situated not far from the future Lyon - Turin tunnel. For this last tunnel the feasibility study indicates that it is possible to install a VHV DC link of substantial transit capacity and with maximum safety.
2. It was deemed more judicious to examine the possibility of a connection between France and Spain (Somport Tunnel) instead of investigating two possibilities between France and Italy;
3. That Safety Gallery is being considered/studied, and it is uncertain that it will be built one day. In turn, the Somport exists.
4. That Safety Gallery is comparatively short. It may be able to accommodate an AC link at either 220 or 400 kV with a relatively poor connection to the grid compared to the Lyon-Turin link's connection to the grid.

The Simplon+ Lôtschberg tunnels present the same characteristics as the string of the Monte Ceneri, Gothard + Zimmerberg tunnels and will therefore not be studied in details hereafter. Moreover, the Simplon tunnel already exists, what would make design modification more difficult to achieve.

The location of the "best choice" tunnels in the Alps i.e. of Brenner, Lyon-Turin, Monte Ceneri + St Gothard and Simplon + Lötschberg is illustrated in figure 1.20.

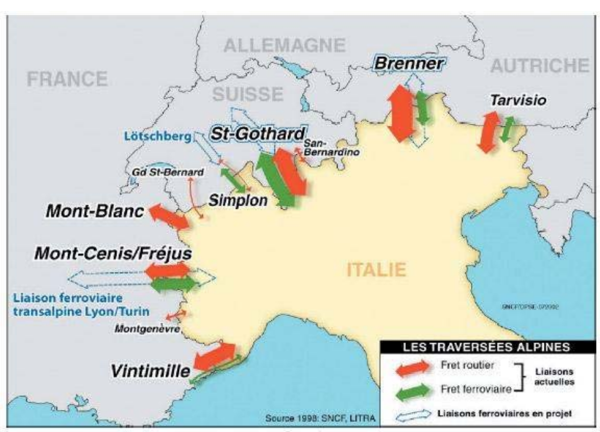


Figure 1.20.
Alpine rail/road existing and projected tunnels

2. Feasibility study of installation of HV links in the tunnel

2.1. Brenner tunnel

Problem statement

- Analysis of the technical feasibility of integrating into the Brenner tunnel:
  - HV link;
  - possible locations;
  - type of link with consequences on the thermal behaviour, electromagnetic impact.

Methodology

- Research amongst the railway manager(s) concerning:
  - the current status of the studies and design, construction;
  - the current status of the studies/design, research already performed on this type of project;
  - detailed cross-section of this tunnel.

Major results

- This tunnel project has the major advantage that prior to building the two railway tunnels, a pilot tunnel will be built for the purpose of the soil and rock analysis.
- This pilot tunnel is perfectly suitable to install a VHV link in it.
- The recommended type of link is the GIL technology.
- Thermal behaviour should be thoroughly investigated in function of the power to be transited.
- Electromagnetic impact: in principle compatible with the values stipulated by the WHO.
- Electromagnetic interference with railway: should be investigated further. The first analyses performed by R. Benato as discussed in his paper on "Gas Insulated Transmission Lines in Railway Galleries - part II" show that there is not necessarily an incompatibility.

2.1.1. General information on the tunnel

The Brenner tunnel is a future b-tube railway tunnel that links Innsbruck in Austria to Franzensteste (Fortezza) in Italy.

Figure 2.1-1 shows the geographical location of the projected tunnel.

Figure 2.1-2 shows the geographical location of the tunnel in the European HV network (Austria - Italy).

This map clearly indicates that network adaptations/extensions will be necessary both on the Austrian and the Italian side.

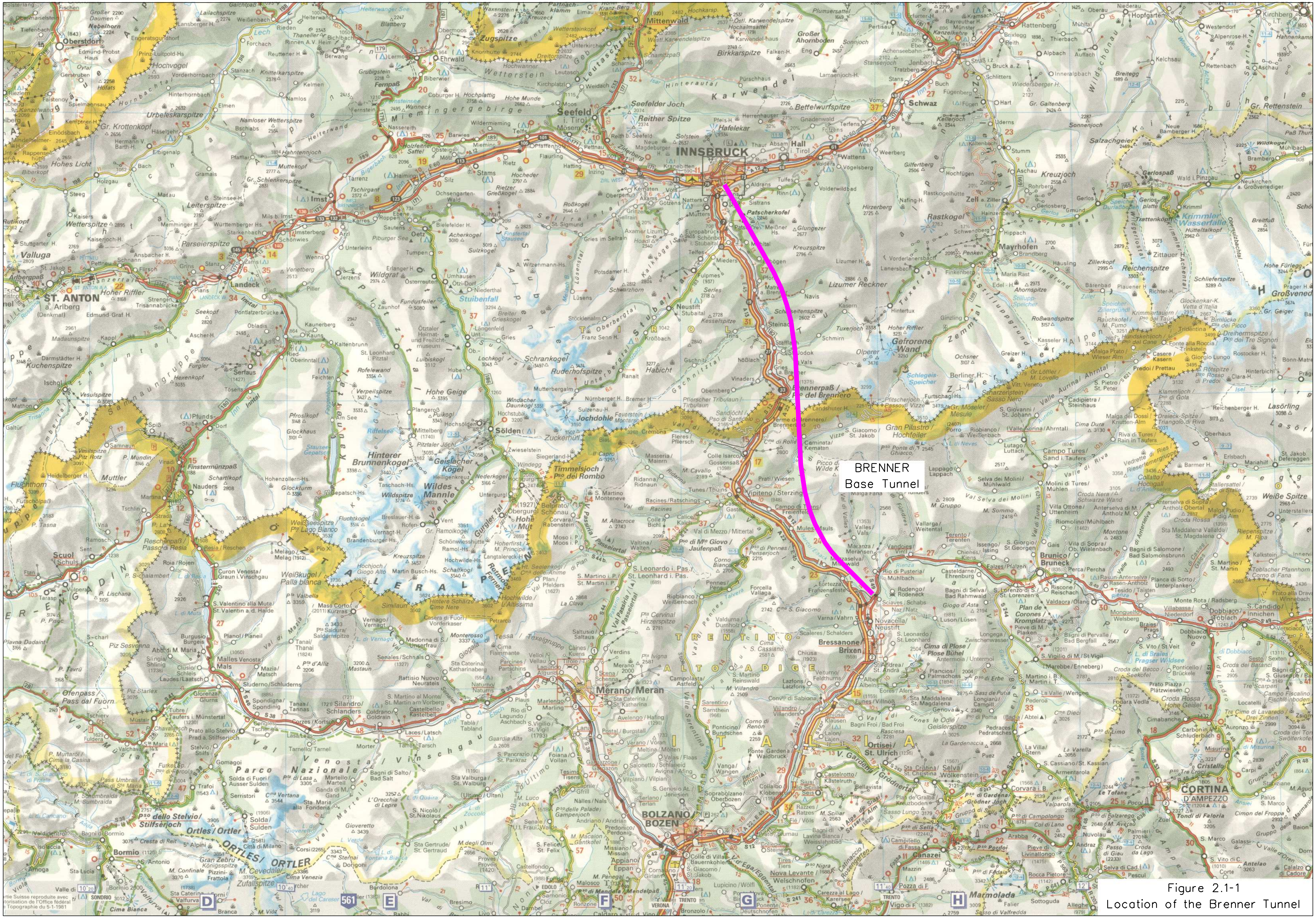


Figure 2.1-1
Location of the Brenner Tunnel


Westtirol
Imst
Thaur
Zell/Ziller
Tauern
Gerlos
Siz
Mayrhofen
Kühtai
INNSBRUCK
Roßhag
Häusling
Innerfragrant
Außerfragrant
Kaunertal
Pradella
Amlach
FRANZENSFESTE
FORTEZZA
BRENNER
TUNNEL
Etsch
Lana
Cardano
Premadio
Edolo
Floriano
Somplag
S. Fiorano
Lavis
Soverzene
Fadalto

Figure 2.1-2

The length of the tunnel is 56 km. The tunnel is currently under design and its construction is planned by 2015.

One of the particularities of the tunnel is that a pilot tunnel will be excavated between the tunnel's two railway tubes.

Figure 2.2. below gives a cross-section of the two railway tunnels and the pilot tunnel.

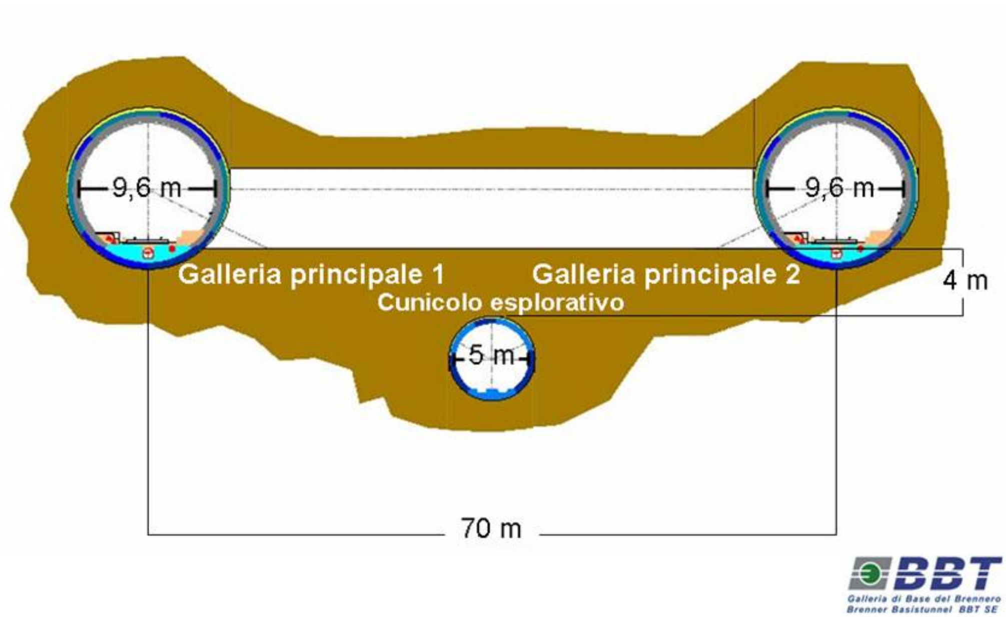


Figure 2.2.
(source BBT SE)

Two separate tunnels will constitute the railway galleries (one for each railway track) and a pilot tunnel will precede the main tunneling in order to detect the geologic situation of the rock stratigraphy, to drain water away and to convey the mucking during the main tunnel construction.

One the whole work will be over, the pilot tunnel will be used as a service gallery (4,3 m diameter).

2.1.2. Possible location in the tunnel- Type of link

- **Location**

  The pilot tunnel length is about 65 km. This tunnel will be efficiently used to install a high voltage transmission line.

  The figure 2.3. shows the pilot tunnel section during the excavation of main railway tunnels.

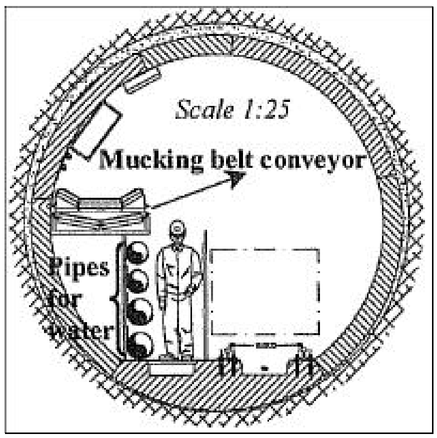


Figure 2.3.

When the main tunnel excavation will be definitively over, the pilot tunnel will have to foresee a suitable room for a HV line.

- **Type of link**

  In that space the installed can be envisaged of any of the three technologies discussed in above chapter 2.

  Comments and recommended technology.

  a. <u>Voltage level</u>

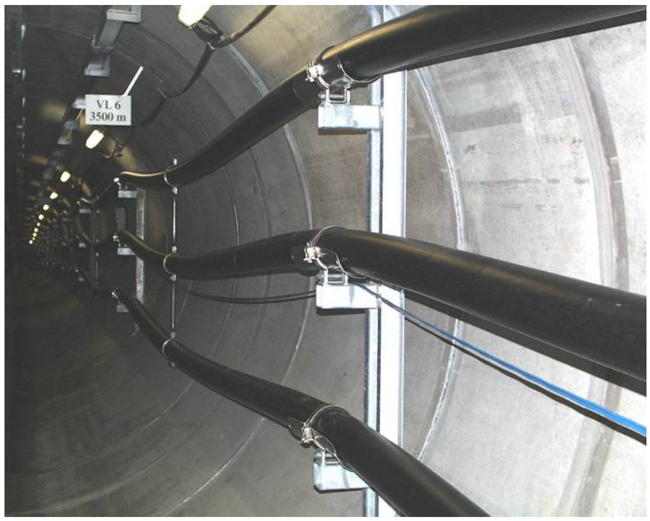
  Considering the considerable cost of this installation, a technical option has to be examined that really brings a solution to network congestion. In this respect, links have to be considered that make an important transit possible, which can be achieved realistically only with voltage levels of 400 kV (AC) or 500 kV (DC).

b. <u>Type of link</u>

1) AC cable - XLPE insulation

Since the service (or pilot) tunnel is in principle to be accessed only by tunnel management personnel (not open to the public) an AC solution may be considered.

The position of the cables could be as shown in the figures 2.4. below.



Figures 2.4.

However, this technology is limited by the restrictions concerning its admissible length. For a link at 400 kV - with 2500 sq. mm Copper cable, if the length exceeds 50 km it becomes necessary to install shunt reactors.

There is not enough space available in the pilot tunnel to install that type of installation, because a shunt reactor unit requires an important free space, see sketch hereafter "shunt reactor 400 kV - one phase".

Shunt reactors

2) DC cable - XLPE insulation

Idem same as for 1); this type of link is perfectly acceptable in the pilot tunnel and, since in principle there is no limitation on the length, the link could consist of two dry insulation DC cables or multiples of these.

However, the only draw2back with this type of link is its cost, mainly due to the cost of the converter stations that have to be provided at either ends of the tunnel (cf. above paragraph 3.9.).

As in this case the pilot tunnel is quite spacious, there is no pressing reason to opt for this costly type of link which is reasonable only for tunnels in which the available space is much more limited.

3) GIL technology

GIL technology (which is relatively space-consuming) seems to be more appropriate for this tunnel, where space is less scarce.

Also, as this pilot tunnel will be easily accessible for inspections, monitoring of the link in this tunnel should not be a problem.

Figure 2.5. shows the pilot tunnel with one circuit GIL.

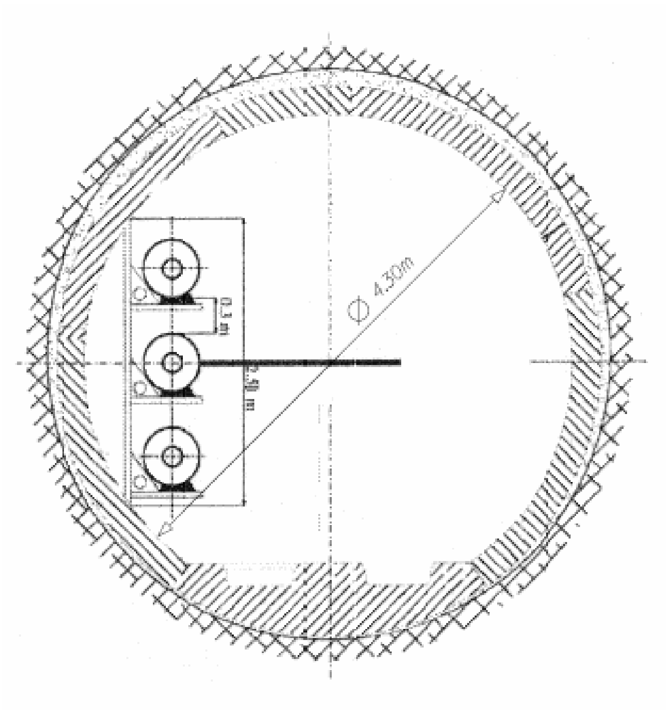


Figure 2.5.

Possible arrangement with a double-circuit GIL is shown in figure 2.6.

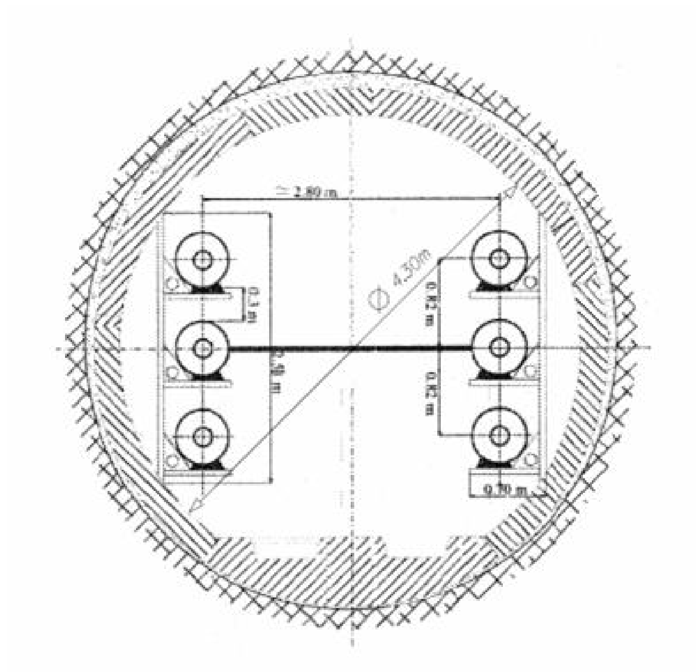


Figure 2.6.

As during the excavation (figure 2.3.) a service rail track would be provided it could be very well used to bring the various components of the GIL to the place of installation, facilitating the construction of the link.

Once the supports and the components of the link are transported to the place of installation, the elements can be assembled either by welding or with bolted flanges.

It is also possible to opt for a GIL composed of three pipes that have the following characteristics:

- Dimensions of enclosures
  - . 12 to 18 m enclosure section
  - . Internal diameter of enclosures : 500 mm
  - . Enclosure thickness (Aluminium) : 10 mm
  - . Typical external diameter of conductor (Aluminium Alloy tube) : 180 mm
  - . Typical thickness of conductor tube : 11 mm

- Electrical performances

. Service voltage	:	400 - 420 kV
. Power frequency withstand voltage	:	630 kV
. Lightning impulse withstand voltage	:	1425 kVρ
. Switching impulse withstand voltage	:	1050 kVρ
. Transmission capability (depending on installation and ambient conditions)	:	2000 to 5000 mm
. Short-time withstand current	:	63 kA/1 sec

Figure 2.7. below shows a double GIL-type link in a 3 m diameter tunnel.

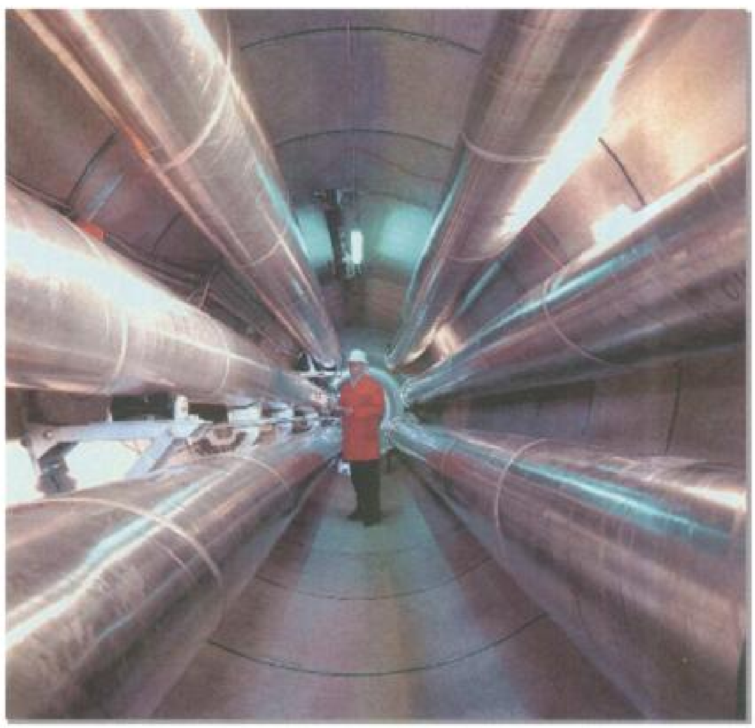


Figure 2.7.

2.1.3. Thermal behavior

The thermal behavior of a GIL circuit inside the pilot gallery deserves a careful consideration.

It should be noted that IEC 61640 recommends that the maximum allowable temperature for the enclosure shall not exceed 70° C.

The Joule power losses W/m can be precisely evaluated.

For example for a transmissible power of 2000 MVA - 3000 A the total losses are 255 W/m (255 kW/km link).

Moreover, a deeper study must be undertaken in order to evaluate the gallery ventilation, so a future work will surely deal with a more detailed study of the thermal behavior.

Please also note that in case of a GIL installed in an area accessible to the public, safety features shall be required (IEC 61640).

2.1.4. Power flow and short-circuit studies

The adding of a GIL line in the EHV European network, constituted almost exclusively by OHL, makes it necessary to examine deeply the GIL influence on power flows, short-circuit levels and voltage stability.

It should be noted that the interface between GIL - OHL does not give any problem as regards re-closure cycles so that normally no change is needed in relay schemes.

2.1.5. Electromagnetic impact

2.1.5.1. Electrostatic fields

The earthed, conducting enclosure of a GIL will provide complete screening against the power frequency electrostatic filed of the conductor at high voltage.

The screening will remain effective under transient conditions.

2.1.5.2. Magnetic fields

Where a GIL is of the single-phase enclosed design (which is the case) and the enclosures are solidly bonded at each end and at different points of the line, enclosure currents will circulate tending to reduce the magnetic filed external to the GIL.

However, due to the spatial disposition of the three phases, screening is not complete.

GIL installation allows a very effective magnetic shielding, due to the enclosure current phasors, which have almost the same magnitude and are almost perfectly opposite to corresponding phase current phasors: it ensures a high electromagnetic compatibility with other neighbouring systems inside the tunnel. A precise study of magnetic fields generated by GIL has to be computed in order to evaluate the magnetic levels inside and outside the tunnel.

The magnetic field can be calculated using a numerical method, such as the finite element method.

As an example for a 2000 MW (2 x 1000 MW) transmitted power, the magnetic filed at 1 m above ground should be of:

- maximum **5 μT** for a flat configuration of GIL compared to ≈ 100 μT for an XLPE cable 1 cable/phase in flat configuration (trefoil configuration should be better);
- **3 μT** for a double circuit 1000/1000 MW at the distance more than 3 m from gallery axis;
- **50 μT** maximum inside the pilot tunnel with 2 circuits (1000 - 1000 MW).

It means that the value of 100 μT (maximum value recommended by OMS) is never exceeded [*].

2.1.5.3. Electromagnetic interference with railway supply system [**]

The electromagnetic induction phenomenon produced by a power line (or railway supply) on a neighbouring line can be easily understood from the effects produced by a single conductor line with ground return on another single wire line parallel to the first one.

The inducing line (or killer) and the ground constitute a coil; circulation of current in the coil creates a magnetic field H and a magnetic induction B that produce a magnetic induction flux.

A part of the flux passes through the loop formed by induced circuit and the ground. If the flux is time-variable, an induced longitudinal electromotive force (e.m.f.) U_0 appears in the parallel circuit (which is usually termed as victim).

If the inducing current I_0 is an alternating current with a frequency f, the induced voltage is in principle obtained by the product of it and the mutual (between killer and victim) per unit length impedance $\underline{Z}_M$:

$$\underline{U}_0 = \underline{Z}_M \, \underline{I}_0$$

where $\underline{Z}_M$ is the mutual per unit length impedance with earth return between inducing and induced circuits. In order to compute this impedance, first the conservative distance d_{ij} has to be calculated as the minimum distance between the pilot tunnel and the main railway gallery centers:

---

* "Magnetic Filed computation for Gas insulated Lines installed in Gallery"
R. Benato - L. Fellin

** Gas Insulated Transmission Lines in Railway Galleries - Part II
Roberto Benato - Enrico Maria Carlini - Claudio Di Mario - Lorenzo Fellin - Gerald Knollseisen, Markus Laussegger - Michael Muhr, Hubert Wörle, Rudolf Woschitz

$$d_{ij} = \sqrt{\left(20^2 + 10^2\right)} \cong 22.4\ m$$

→ 20 = 40/2 = min. horizontal distance between main tunnels

→ 10 m = vertical distance between horizontal axis between main tunnels and axis of the pilot tunnel

and then, by applying the simplified Carson-Clem formula, the mutual impedance arises:

$$\underline{Z}_M = 0.99 \,.\, 10^{-3} \,.\, 50 + j\, 4\, \pi \,.\, 50 \,.\, 10^{-4}\ In \left(\frac{9333}{22.4}\right) = 0.0495 + j \,.\, 0.379 \left[\Omega/km\right]$$

whose magnitude is $\left|\underline{Z}_M\right| = 0.382 \left[\Omega/km\right]$.

In general, two different scenarios can be hypothesized:

- the inducing system is the GIL and the induced one is the railway supply system;
- the inducing system is the railway supply system and the induced one is the GIL.

With regard to the former one, the stray current due to power line is almost null either in steady-state or in faulty condition so that the magnetic interferences due to GIL towards the railway supply system are wholly negligible.

For short-circuit regime the stray currents depend upon several features (a typical curve of section, fault location, etc.); with the aim of a possible order of magnitude, figure 2.8. shows the stray current when a short-circuit occurs between the contact line and the rails of the same track.

It is worth noting that the spacing between the two tracks hypothesized is much closer that that foreseeable for the Brenner tunnels, but the short-circuit occurs in one track only so that the presence of the other one gives slight differences.

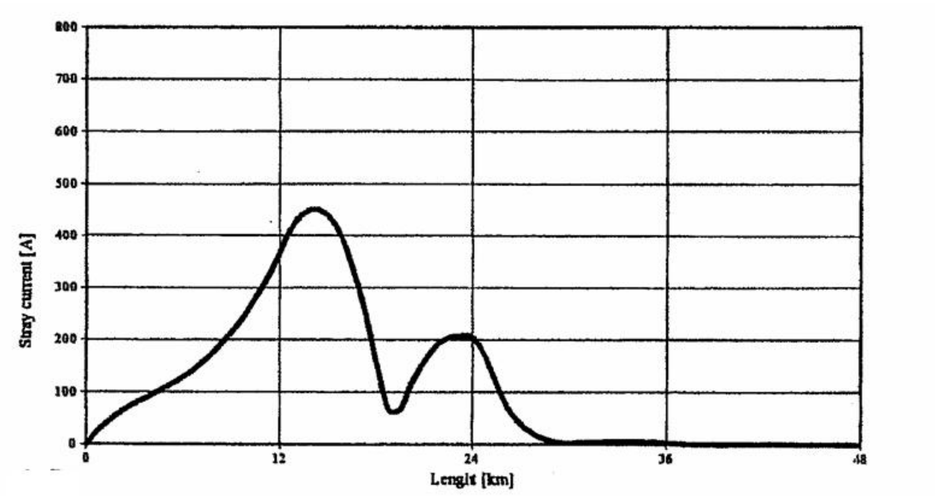


Figure 2.8.
Stray currents in the earth for short circuit between contact line and rails in a high speed railway supply

Assuming an average value of stray current magnitude $I_0 = 200\ A$ the induced voltage magnitude can be roughly evaluated:

$$U_0 = Z_M I_0 \cong 200\ .\ 0.382 = 76.4\ V/km$$

which considering a parallel length of 65 km would yield a total induced voltage equal to:

$$U_0 = 96\ .\ 55 = 6.24\ kV$$

This kind of "overvoltage" will last only the fault clearance time. Moreover it should be remembered that the enclosures provide a very effective shielding also for magnetic disturbances coming from external source.

2.1.6. GIL Gas Monitoring System

The installation must be completed with electronic monitoring and diagnostic system.

Following systems can be mentioned:

- The insulating gas pressure with density sensors in fibre-optic (new technology).
- Continuous monitoring of partial discharge activity in order to detect arising faults as early as possible. If the partial discharge activity increases, the system gives an alarm.

- Arc Location System can also be installed to locate a possible insulation fault. The principle for operation is the following:
  - an internal flashover produces high frequency traveling waves which are moving from the origin towards ends with the speed of light;
  - detectors collect these signals under registration of the exact time of occurrence.

2.1.7. Highest compatibility of GIL with tunnel

In the following some GIL features are highlighted in order to show the fully compatibility with gallery installation:

- The environmental impact (visual and "magnetic") of a traditional overhead line (single or double circuit) is already considered undesirable. GIL solution zeroes the visual impact.
- High safety

  In case of an insulation failure, an AC-XLPE insulation cable in operation explodes and there is a risk of fire and damages, to adjacent cables, other nearby installations and persons. On the contrary, GIL manufacturers have to guarantee, for internal fault, a rated short-time withstand current of 60 kA. 1 sec without burn-through of the enclosure.
- High reliability

  The GIL technology has proven its reliability since 25 years in service without any failure up to now. The main reasons are: the dielectric stress in the material is very low (GIL: 3 ÷ 4 kV/mm, cables: 10 ÷ 13 kV/mm), and GIL has no special joints, which are critical elements in a cable.
- No ageing

  Cables are thermally and electrically ageing. The higher the temperature and the electrical field, the higher the ageing effect. The cable insulation becomes weaker under the influence of electrical stress, temperature and time, so that the possibility for failures increases with the service time. Gases are not ageing, neither thermal nor electrical.
- SF_6/N_2 gas mixtures

  These mixtures are long-time experienced insulating gases and used worldwide in high voltage technology.
- Long-term tests

  GILs have passed successfully long duration tests. Some tests allow to simulate 50 years of service lift under full load conditions.

2.2. Lyon - Turin tunnel

Problem statement

- Analysis of the technical feasibility of integration into the Turin - Lyon tunnel:
  - a HV link;
  - possible locations;
  - type of link;
  - impact of the HV link project on the studies.

Methodology

- Collection of information from the tunnel manager in order to obtain:
  - the current progress of the studies/design and possibly the construction already started;
  - the detailed, typical cross-sections of the tunnels.

Major results

- This tunnel consists of two railway tunnels, without pilot and/or service tunnel.
- The studies are already well advanced, so that we were able to obtained detailed cross-sections.
- The recommended type of link is a DC link with two cables per tunnel, permitting a bipolar link in each tunnel (the advantage being that in case of the loss of one link in one tunnel, the link is still operable with the link of the other tunnel).
- This implies that a number of adaptations should be made, including as regards the sheaths for
  LV cables and sheaths for signalling cables, as well as to the drainage tube maintenance chambers. These adaptations are perfectly feasible at this stage of the studies and design.
- The impacts of such a link have been analysed:
  - temperature rise → 2 - 2.5 MW: to be evacuated;
  - electromagnetic effects:
    - ⇒ magnetic fields: at 1 m above the soil level the value would be 39.6 µT;
    - ⇒ electromagnetic effects on the galvanic links: it is certain the impact can be controlled, but more in-depth analysis is necessary.

2.2.1. General information regarding this tunnel

The Lyon - Turin is a bi-tube railway tunnel linking St. jean-de-Maurienne in France to Bruzolo in Italy.

The length of the basic tunnel is 53.1 km and that of the Bussoleno tunnel is 12.2 km, the two being connected by a viaduct (spanning Val Cenischia). The structure has a plain profile (the so-called basic tunnel).

Two separate tunnels will constitute the railway galleries (one for each railway trench).

There will be no service tunnel or pilot tunnel. The basic structure will consist of two parallel tunnels. Its construction is planned by 2020. The studies and design are currently ongoing.

Figure 2.9-1 shows the geographical position of the projected tunnel.

Figures 2.9-2 and 2.9-3 show the position of the future tunnel in Europe's HV network (220/400 kV level).

On the figure 2.9-3, in red we have the HV network in the area of the tunnel with the corresponding substations.

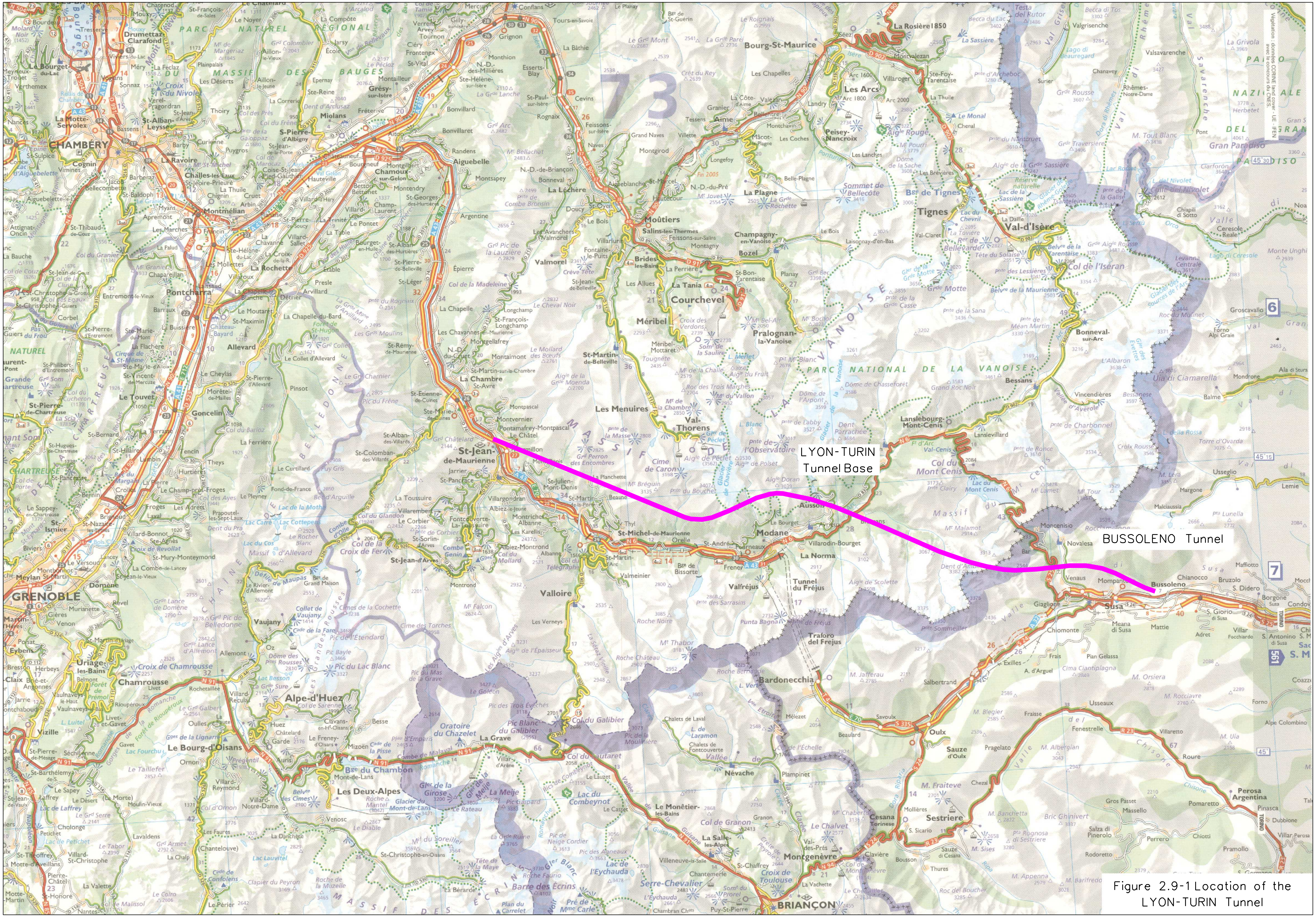


Figure 2.9-1 Location of the LYON-TURIN Tunnel

Aoste
Albertville
Randens
Malgovert
Grande-Ile
Le Cheylas
Les Brevieres
La Coche
Villarodin
Crolles
Froges
Longefan
Praz
Leyni
Villarodin
Lancey
Vaujany
Saussaz
Venaus
S.Bissorte
St.Guillerme
Cordeac
Le Sautet
Piossasco
Italian
Tunnels
Saint-Jean-de-Maurienne
Bruzolo
Tunnels
Future
French
Tunnels

Figure 2.9-2

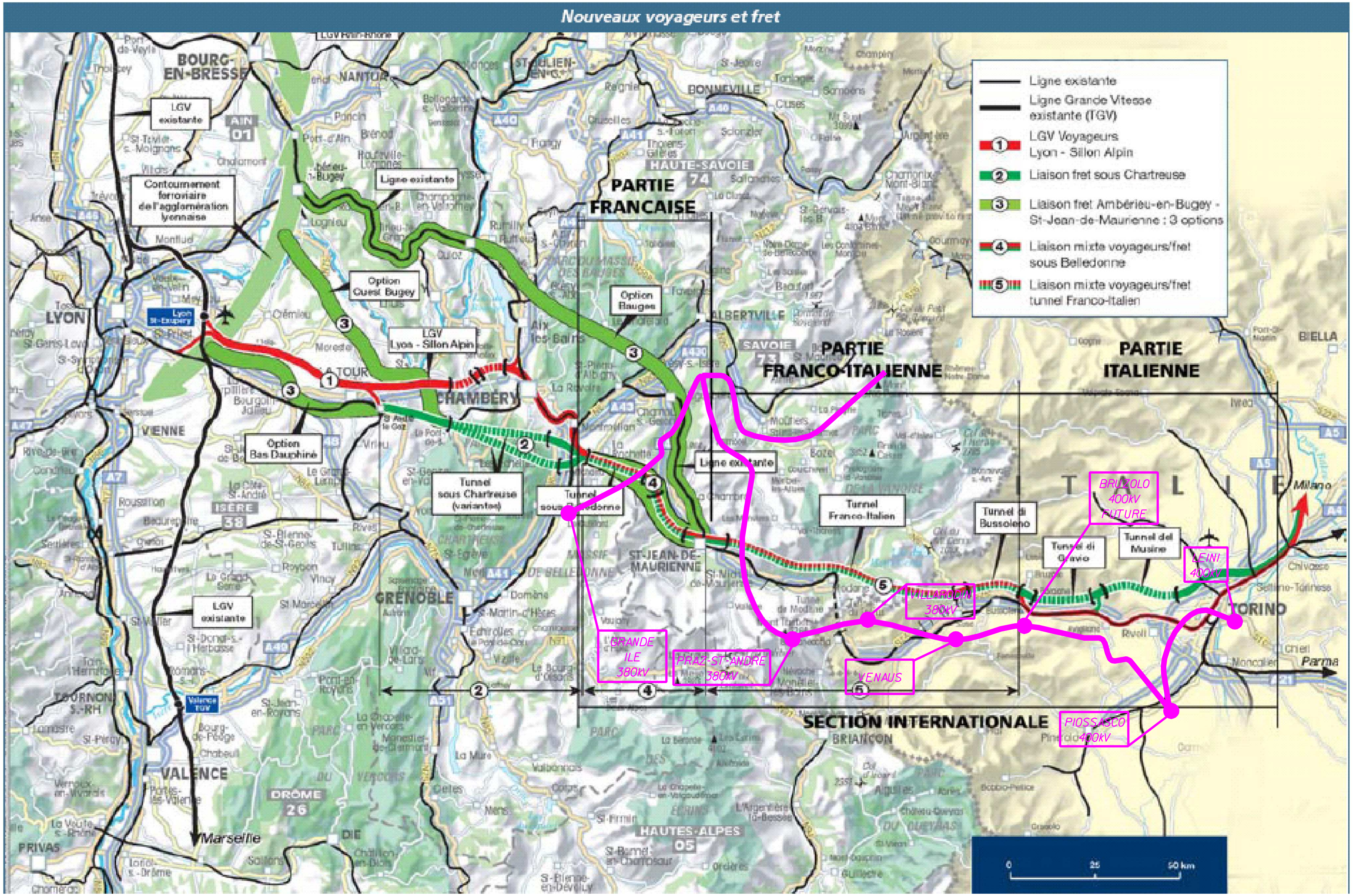


Fig 2.9-3 Position of the tunnel in the HV network area (in red = HV network)

Figures 2.10. and 2.11. show, respectively:

→ The plane view of the tunnel from St. Jean-de-Maurienne up to Bruzolo (fig. 2.10.).

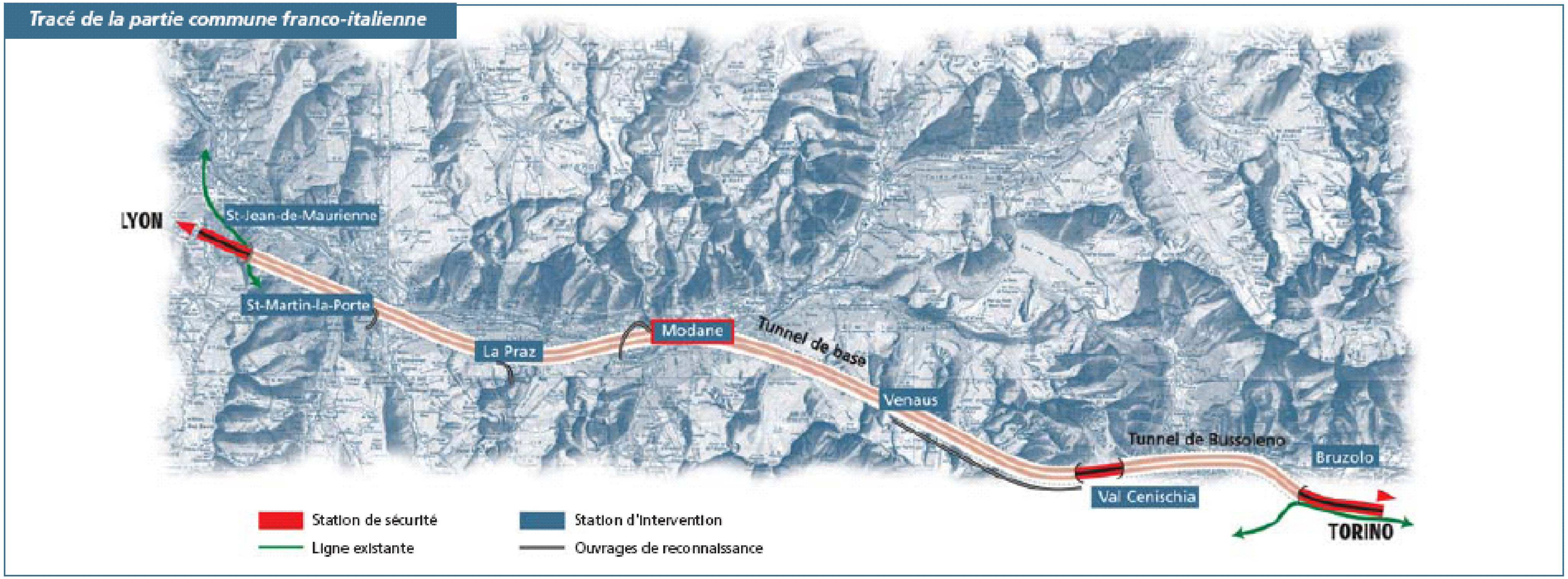


Figure 2.10
Plan view of the tunnel

→ The longitudinal profiles of the basic tunnels and the Bussoleno tunnel (fig. 2.11.).

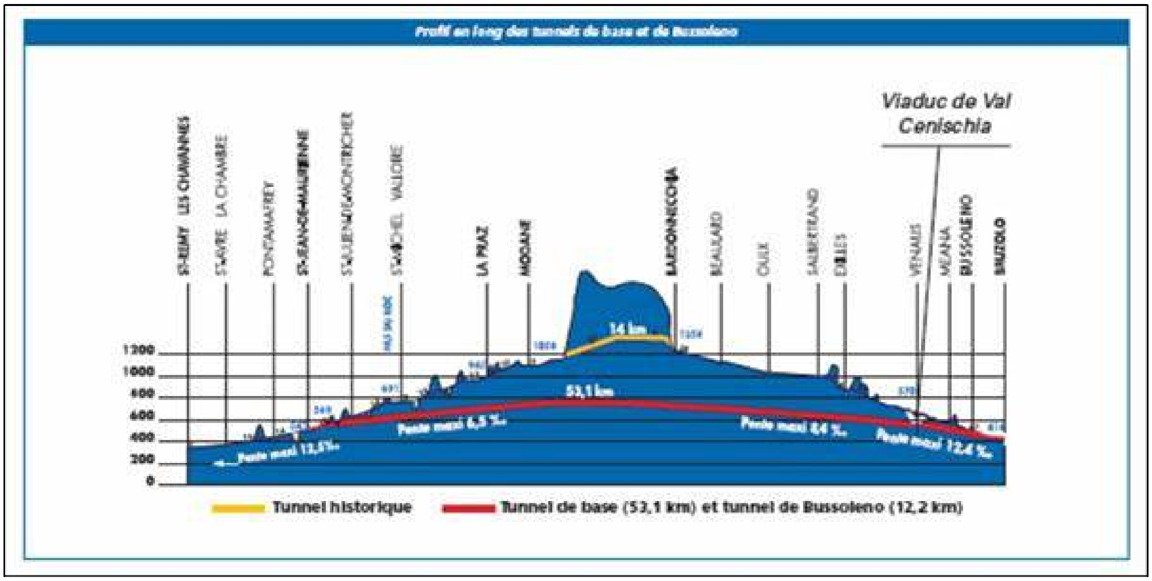


Figure 2.11.
(source website LTF)

Figure 2.12-1 shows the typical cross-section of one of the two railway tunnels.

Figure 2.12-2 shows the basic concept of the tunnel.

Figure 2.12-3 shows a cross-section of the two tunnels with the "Connecting gallery" every 400 m.

Figure 2.12-4 shows a cross-section of the two tunnels at a "Communication branch" every 1.6 km.

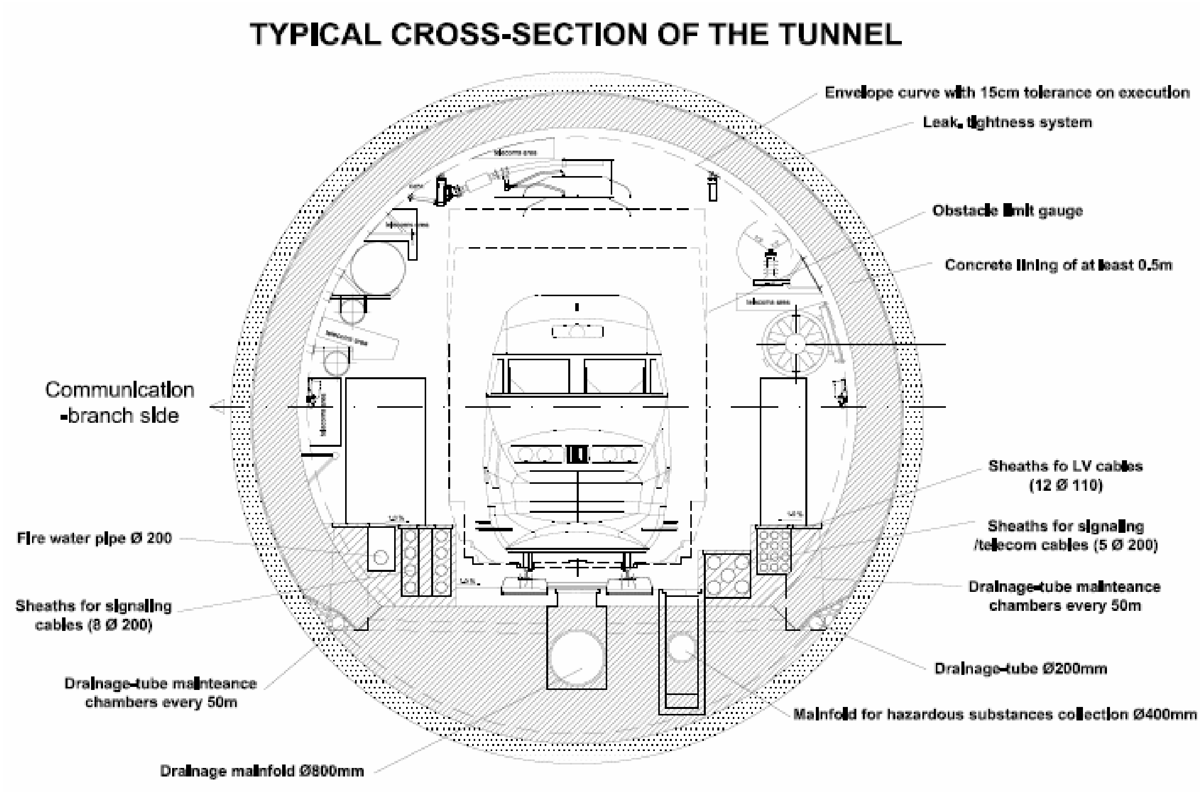


Figure 2.12-1
Typical cross-section of the railway tunnel

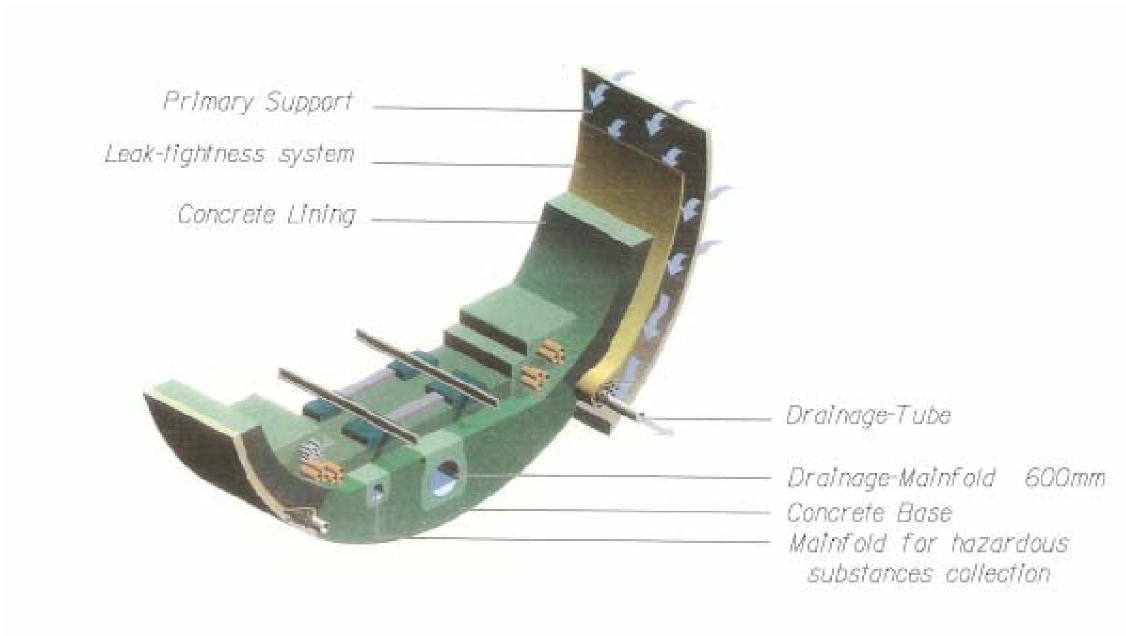

Primary Support
Leak-tightness system
Concrete Lining
Drainage-Tube
Drainage-Mainfold 600mm
Concrete Base
Mainfold for hazardous
substances collection

Figure 2.12-2

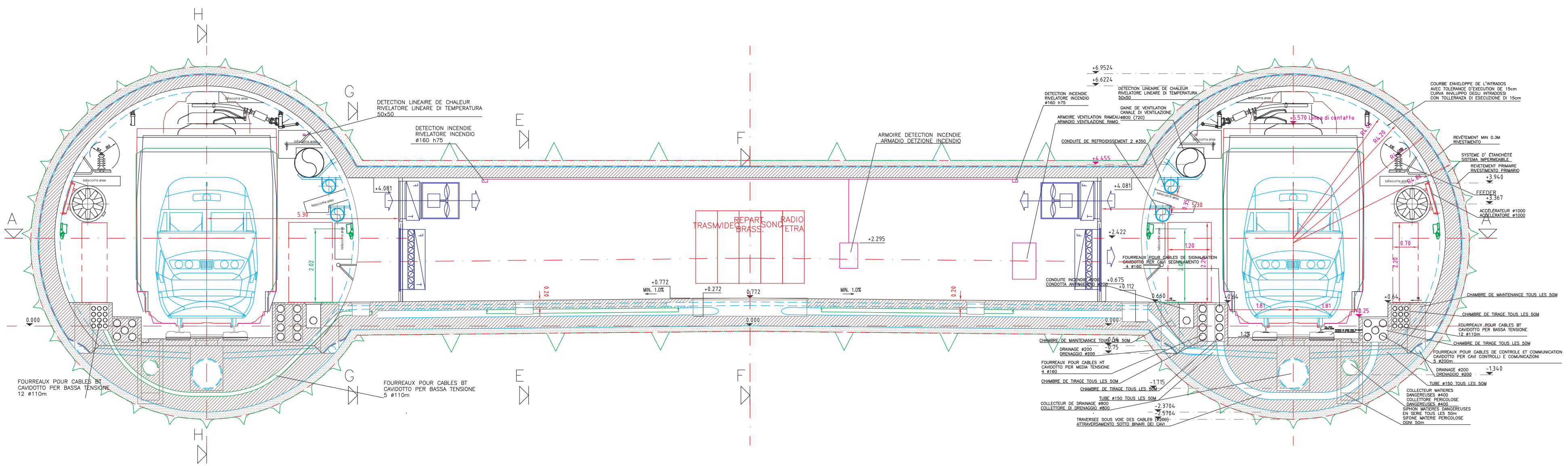


Fig 2.12-3
Cross-section of the tunnels with connecting gallery

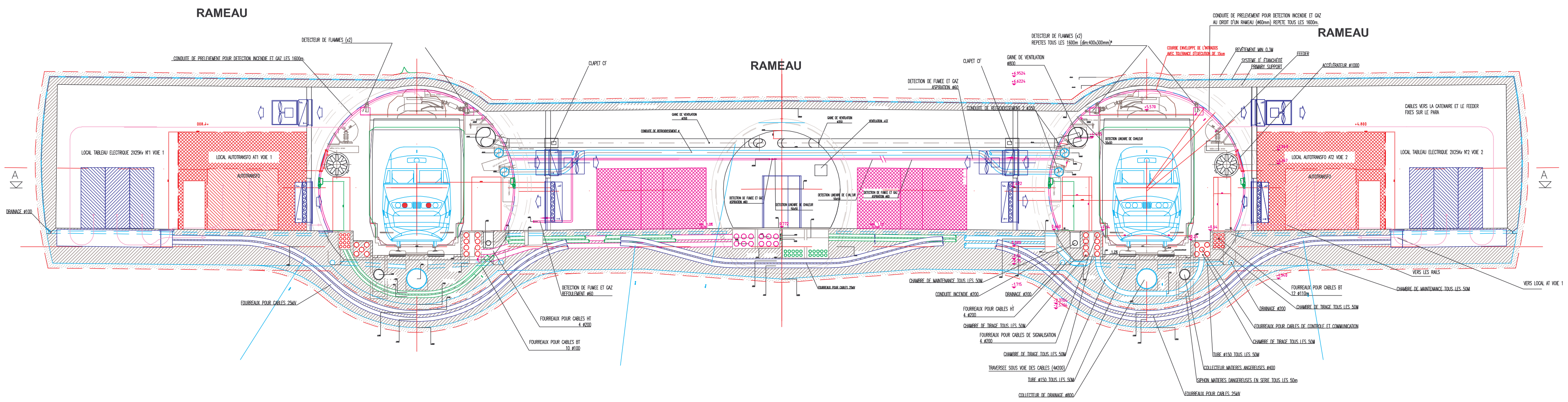


Fig 2.12-4
Cross-section of the tunnels
with communication branch every 1.6km

2.2.2. Possible location in the tunnel - Type of link

2.2.2.1. General - Examined areas

An examination of the typical cross-section of the railway tunnels makes it obvious that the available space for a VHV link is very limited.

In these tunnels, some areas are more or less suitable to install a VHV link.

Figure 2.13-2 below shows to zones that are best avoided, mainly for reasons of safety and operation.

The first of these zones is that in which every 400 m there is a communication branch between the tunnels - see figure 2.13-1. Moreover, that is the side of the tunnel where the fire water piping is installed.

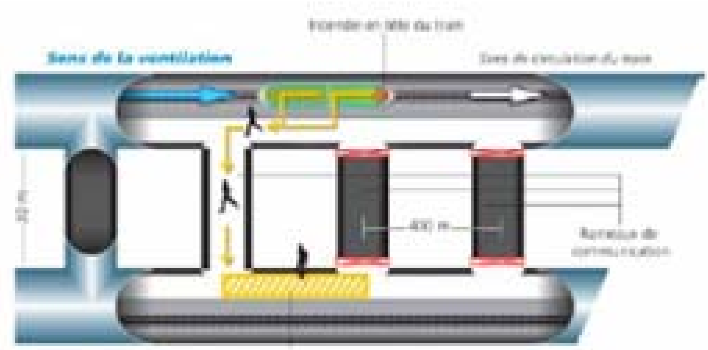


Figure 2.13-1

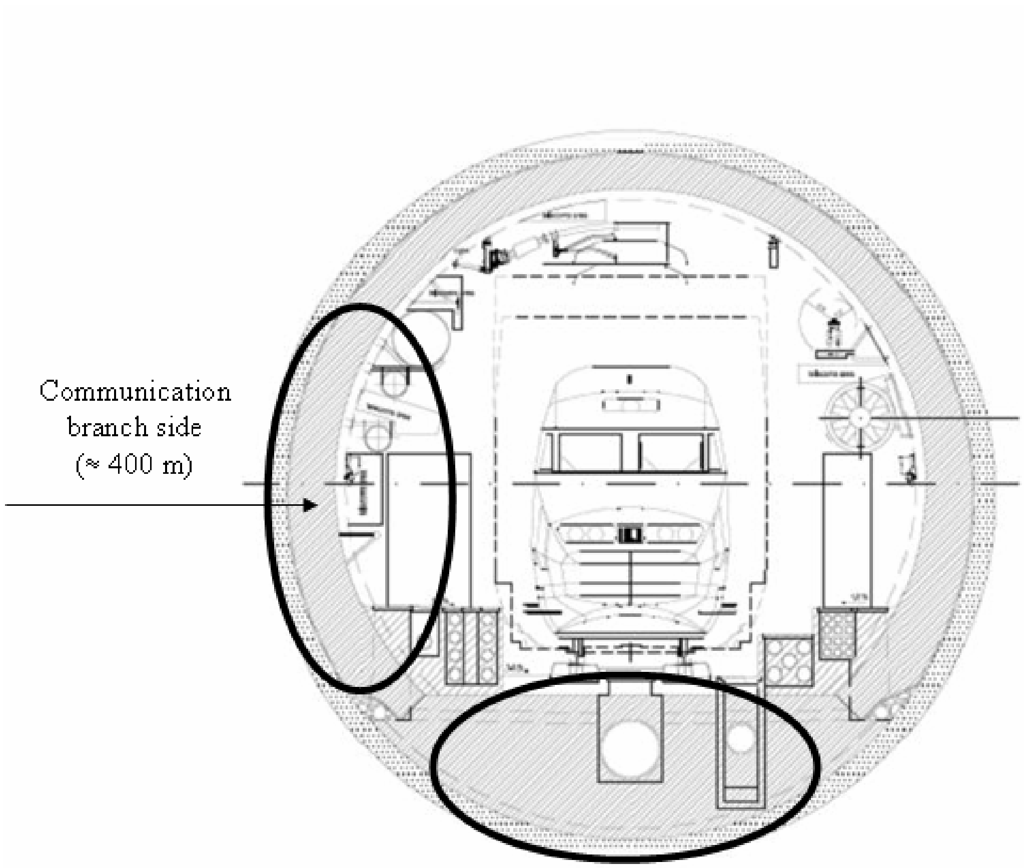


Figure 2.13-2
Tunnel cross-section - Non recommended zones

The second zone is that situated under the tracks. This zone is relatively spacious and could accommodate the VHV links, However, access is a major problem:

- not only for the installation work, but above all as concerns maintenance;
- how can this zone be accessed when the tunnel is in operation and the frequency of passage is high, as can be expected;
- embedding the cables definitively in the concrete without having easy access to them in some way remains a problem with such links;
- security aspect.

This leaves for consideration the far side of the two tunnels (the zones opposite the communication branch side).

Provided some arrangements are made regarding the lay-out of the tubes housing the LV and telecommunication cables, there are a number of possibilities to install VHV cables.

2.2.2.2. Types of link

2.2.2.2.1. General

Considering the relatively limited space allocated, we consider for this tunnel either an AC or a DC link.

2.2.2.2.2. Principles of these two types of link

a) AC transmission

Management of the reactive power: any transmission component (line, cable) is characterized by a distributed series impedance (resistance + inductance) and a distributed shunt admittance (capacity). The series impedance causes the voltage differences that appear between the extremities of the link and which are proportional to the transited current. The shunt admittance generates a capacitive current that superposes onto the transmitted useful current. This superposition is done in quadrature, but still limits the transmissible power. Furthermore, this reactive power has to be transmitted and managed in the two networks beyond the link (i.e. the networks connected at the link's extremities), which also causes problems. When the length of the link is such that the capacitive current at half-length of the link gets close to the nominal current of the link, an AC solution becomes impossible.

In the case of AC transmission, a simplified Load Flow calculation would give:

1. The calculation has been made considering only the "STATIC" operation of the installation.

2. In order to absorb locally the reactive (capacitive) power generated by the cable, both a load and at no load, shunt reactances have to be installed.

   At first sight it would not be necessary to install shunt reactances half-way the link, but anyway, if these were necessary it would not be technically feasible to install them.

   The reactances, in particular those installed at the receiving end of the link, both at load and at no load contribute to a substantial reduction of the capacitive current that circulates in the cable, with as a direct result a reduction in the cross-section of the conductor core of the cables as well as a reduction of the active power losses.

3. In case of outage of the shunt reactances at the receiving end of the link, the steady operation would not be jeopardized, but the transit over the link then has to be reduced to a level compatible with the thermal withstand ability of the cable. Similarly, in the case of outage of shunt reactances at one or the other end of the link, the supply network shall have to be able to absorb the excess reactive power.

b) <u>DC transmission</u>

The direct current links are classified into three types (figure 2.14.):

- monopolar link;
- bipolar link;
- homopolar link.

1. Monopolar link

   In this case there is only one conductor the return being provided by the earth/sea.

   Normally the link operates with negative polarity.

2. Bipolar link

   The bipolar link has two conductors, one operating with positive polarity, the other with negative polarity.

   The junction between the two converters may be earthed at one or the other end of the link.

   The earth/sea does not normally transit any current. However, if both ends of the link are earthed, each of the two conductors could operate independently should the necessity arise.

3. Homopolar link

   Homopolar links are composed of two or more conductors having the same polarity (normally negative) and which are operated with a return via the earth(sea).

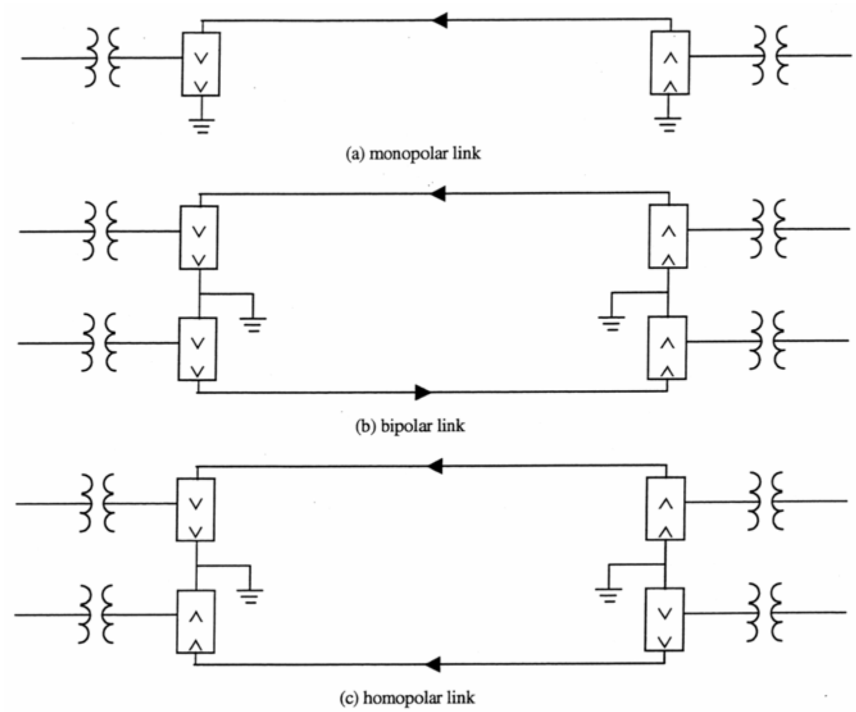


Figure 2.14.

2.2.2.2.3. Recommended type of link

The choice shall be based on the following criteria:

→ Priority No. 1 - Safety

From this point of view it is obvious that a DC solution with dry insulation is the safest, especially in the event of a defect (cf. above paragraph 3.9.).

→ Priority No. 2 - Space consumption

Here again the DC solution is more advantageous, with 2 cables in the bipolar solution instead of 3 in the AC solution.

Furthermore, a DC doesn't require shunt reactances, unlike and AC link that may need them from a certain length of link.

→ Priority No. 3 - Maintenance

The two types of link have a roughly similar reliability level, and in both cases maintenance should be very little.

At similar transit capacity, one of the differences may reside in the fact that since a DC link could operate at more or less 500 kV, the minimal cross-section required in DC is less than in AC, resulting in a slightly lesser number of junctions being required in DC. Knowing that junctions are always a weak point in these links, the reliability in DC would be slightly better than in AC.

→ Priority No. 4 - Price

As regards the supply of cables and the construction of an AC link compared to a DC link, the DC solution will at all times be less costly (2 cables instead of 3).

The only drawback, which is a substantial one in terms of overall cost, resides in the need to install very costly AC/DC - DC/AC converter stations at either ends of the tunnel, whose price is directly proportional to the kW to be converted.

Hence the interest in a DC solution to have an as long as possible link in order to justify and absorb to some extent the expenditure of conversion.

2.2.2.2.4. Selection of the link

At this stage we recommend a bipolar DC link, since it is safer, permits a link in excess of 50 km and requires less arrangements in the tunnel, its only drawback being an overall cost that is much higher than an AC solution.

The proposal would be either 1 pole per tunnel in the case of one cable/pole, or 2poles/tunnel in the case of 2 cables/pole.

In the 1st case each pole would consist of a 2000 sq.mm Copper cable.

In the 2nd case each pole would consist of two 1000 sq.mm Copper cables.

Solution: one 2000 sq.mm Copper cable/pole

For one 2000 sq.mm Copper cable placed in a 300 mm outside diameter PE tube embedded in concrete, the transit capacity would be 1500 MW at a voltage of + 500 kV/-500 kV.

→ Main characteristics of the link

- Nominal voltage 500 kV
- Lightning surge withstand 1000 kV
- Switching surge withstand 900 kV

→ Dimensional characteristics

- Approximate diameter of the copper conductor core: 53.8 mm
- Insulation: thickness ≈ 20 mm
- Mass of the cable: 27.8 kg/m (approx.)
- Overall outside diameter of the cable: 115 mm

→ Construction conditions

- Ambient temperature: 35° C
- Thermal resistivity of the soil (concrete): 0.7 K.m./W
- Depth of embedding: 0.3 m

→ Electrical characteristics

- Screen earthed at either ends of the link
- Max. temperature of the conductor: 63° C
- Losses per cable and per pole: 23.7 W/m

→ Mechanical characteristics

- Bending radius under max. traction: 3.4 m

Solution: two 1000 sq.mm Copper cables per pole

This solution, although more costly and more space consuming, presents the following advantages:

→ Permits a greater transit capacity than 1 x 2000 sq/mm Copper.

→ Is easier to install; manipulating 1 cable weighing 17 kg/m is easier than one weighing 23.7 kg/m.

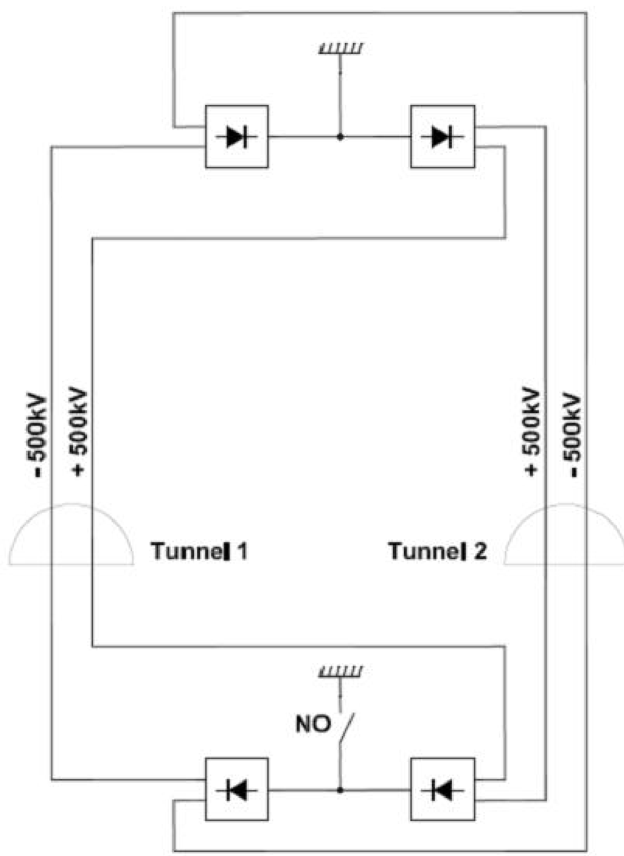
→ Most likely permits to install greater lengths, resulting in less junctions being needed.

→ Characteristics

- Transit capacity
    . 1000 A/cable and therefore 2000 MW at ± 500 kV
    . Max. conductor temperature: 63° C
- Weight of the cable: 16.9 kg/m (approx.)
- Overall outside diameter ≈ 97 mm

- Conductor core diameter ≈ 38.5 mm
- Insulation thickness = 20 mm
- Overall losses
  . Losses per cable : 20.6 W/m
  . Losses per pole : 41.2 W/m
- Bending radius: 2.9 m

In this case the system operation would be:



Location of the pole in the tunnel

Figures 2.15. (1, 2 and 3) here after show the zone that could be suitable to accommodate this type of link.

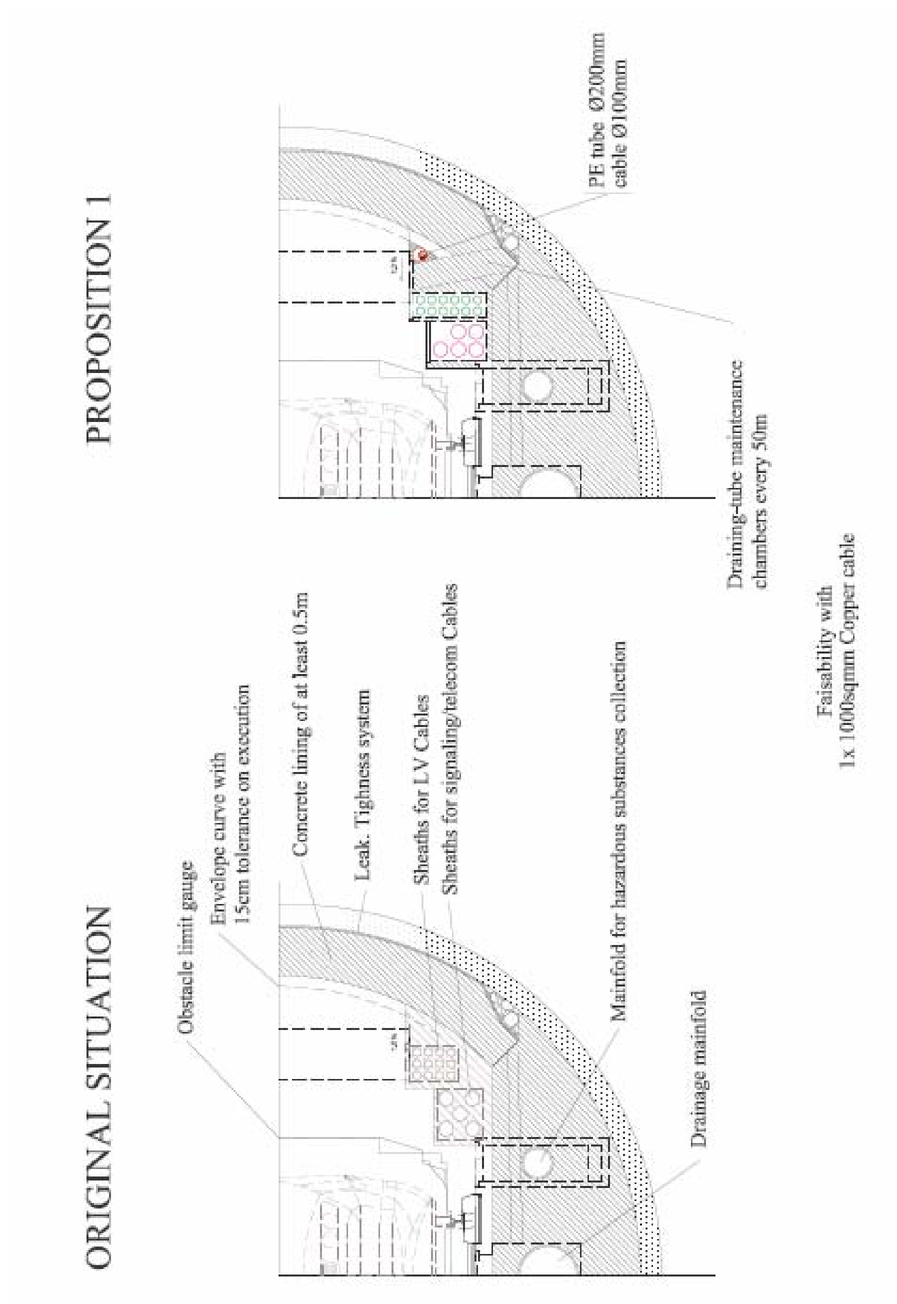


Figure 2.15-1
1 câble 1000 sqmm/pôle

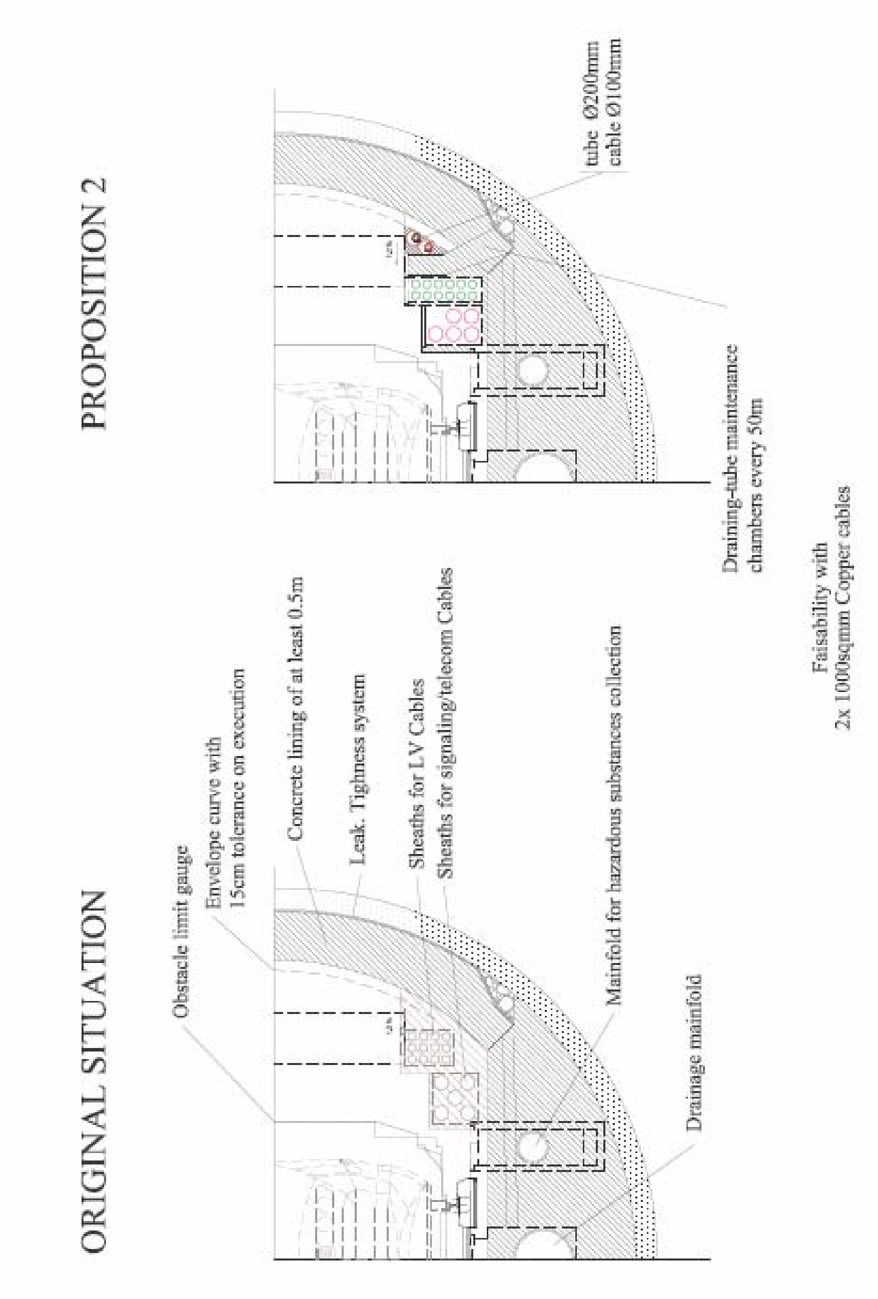


Figure 2.15-2
2 câbles 1000 sqmm

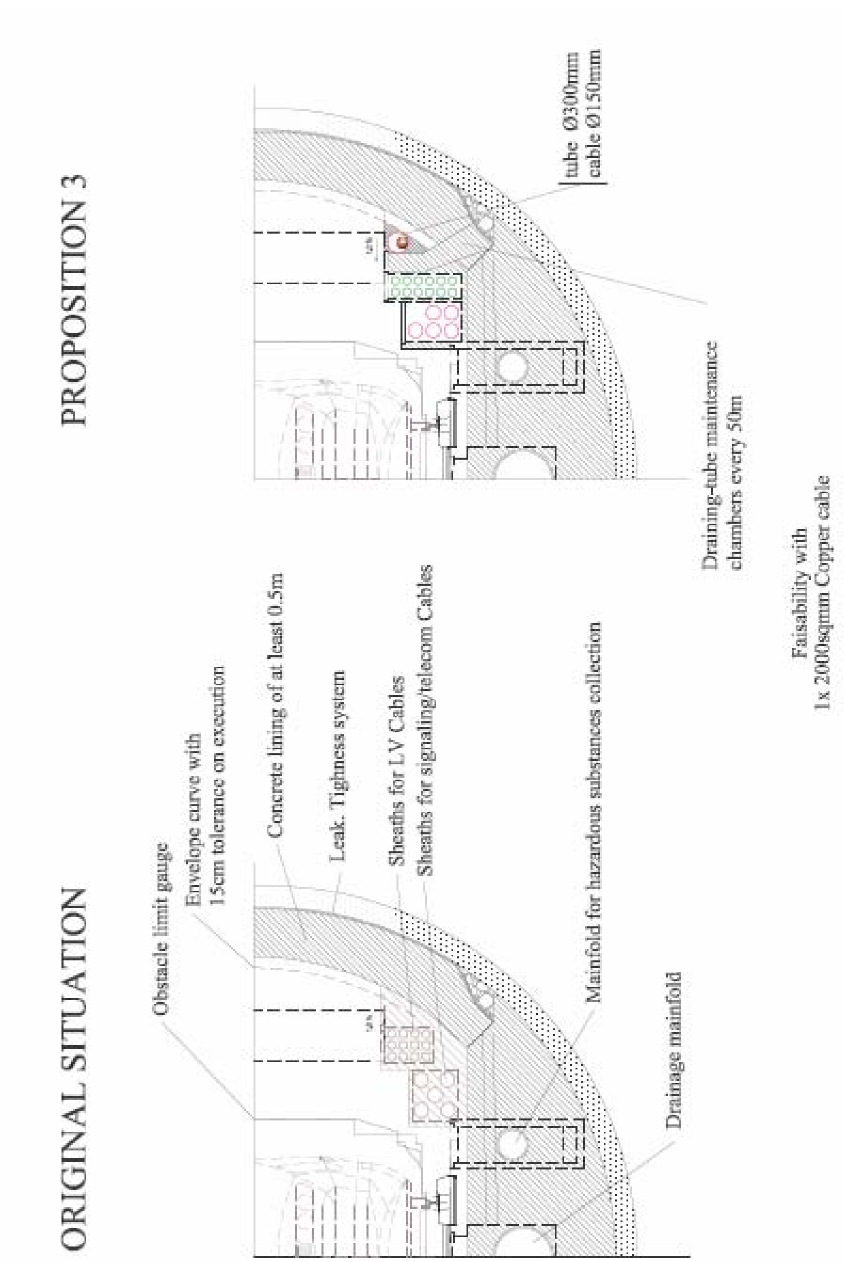


Figure 2.15-3
1 câble 2000 sqmm/pôle

This zone requires some rearrangement of the tubes in the concrete in order to accommodate the LV and telecommunication cables.

Each of the figures below shows:

- the present situation (the proposal as it is today);
- the situation as could be in order to win space in order to install the PE tube(s).

Also included are inspection chambers (every 50 m) in order to get access to the drainage manifold, which inspection chambers also require some rearrangements.

2.2.2.2.5. Zone for junctions

The overall dimensions of a typical junction DC - 1000 sq.mm Copper are given below (figures 2.16-1 and 2.16-2).

Figure 2.16-1

Figure 2.16-2

Figure 2.16-3 shows the overall dimensions of a junction chamber.

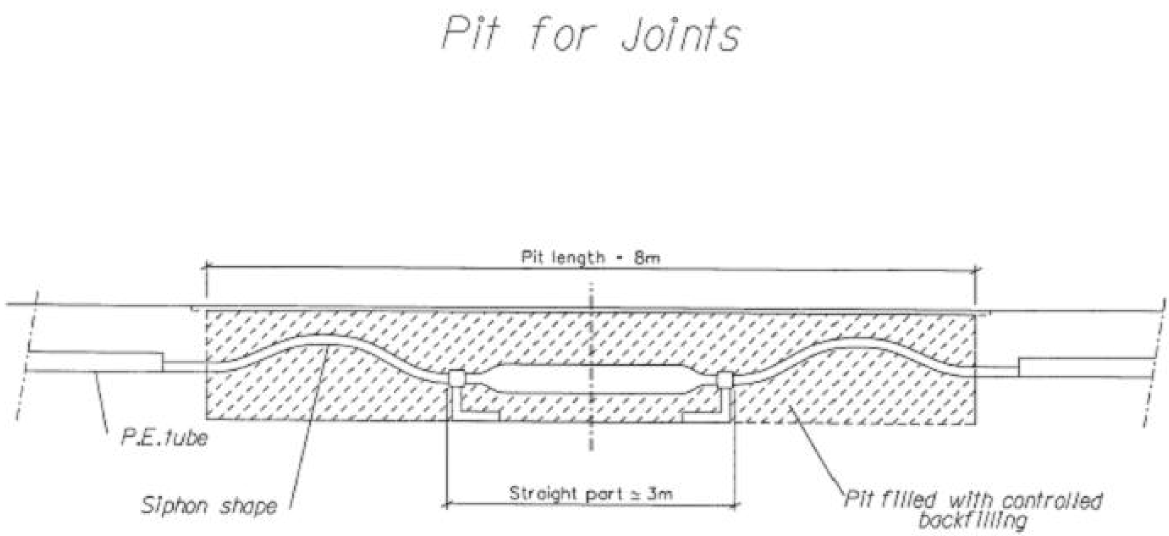


Figure 2.16-3

Generally it is estimated that for a cable with an outside diameter of about 100 mm the outside diameter of the junction will be about **300 mm** and the junction length will be 2 m.

Inside the junction chamber the junction is kept in place by two steel supports. On either sides of the junction the cable is shaped in a siphon so as to prevent any traction arising on the junction following the variations in cable length. These siphons may be vertical or horizontal.

Figure 2.17. shows the position of a junction in the cross-section of the tunnel.

Needless to say that the junctions will be located not to coincide with the locations of:

- branch R2 (room for the auto-transformer + 2 x 25 kV switchboard);
- maintenance chambers of the drainage manifold.

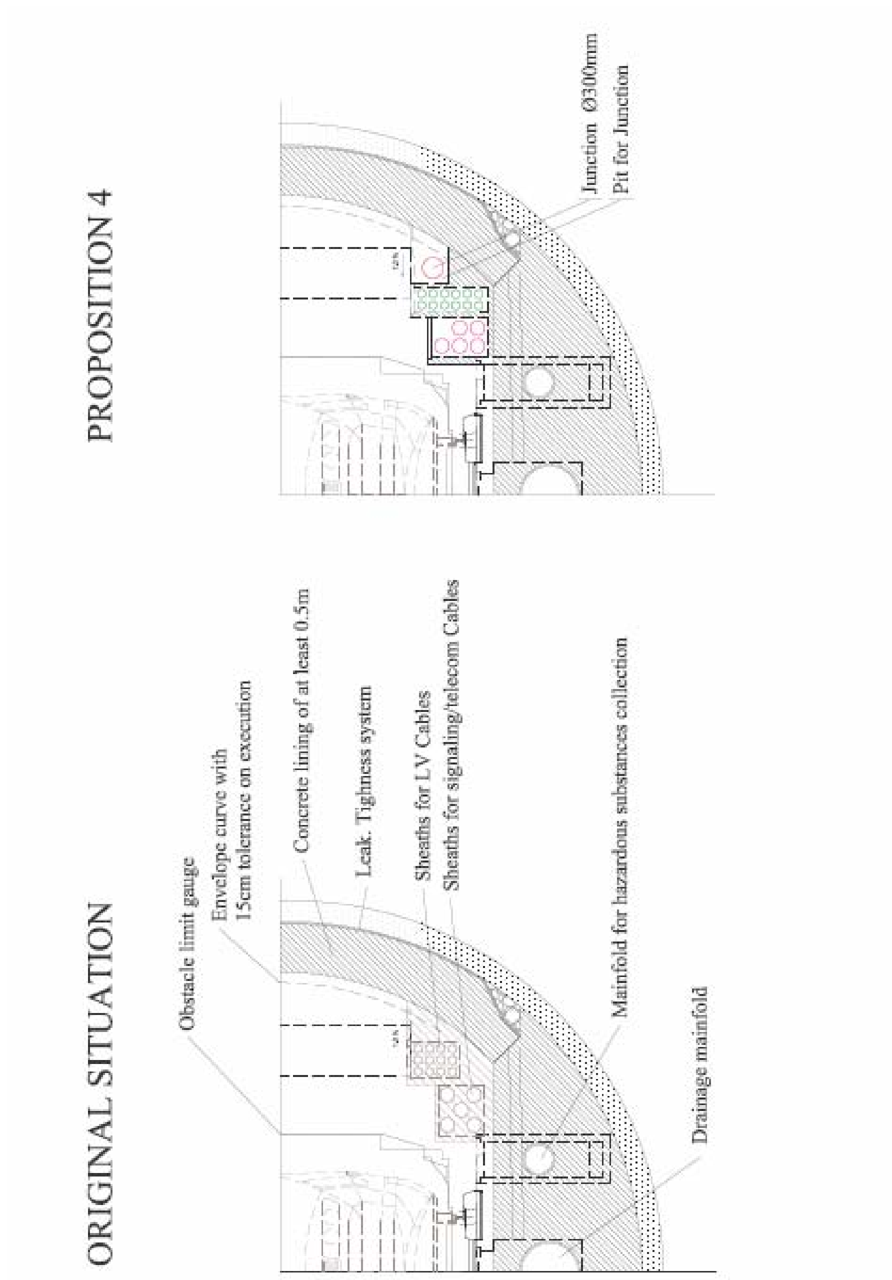

ORIGINAL SITUATION
Obstacle limit gauge
Envelope curve with
15cm tolerance on execution
Concrete lining of at least 0.5m
Leak. Tighness system
Sheaths for LV Cables
Sheaths for signaling/telecom Cables
Mainfold for hazardous substances collection
Drainage mainfold
PROPOSITION 4
Junction Ø300mm
Pit for Junction

Figure 2.17.

2.2.3. Heat rise

For a link:

- U = 500 kV (2 poles);
- cross-section: 2 x 1000 mm^2 Copper;

the losses are some 21 W/m/cable, making them 42 W/m for the two cables together, which results in 2 - 2.5 MW to be evacuated for the entire link in the tunnel.

In the case of the two cables (2 x 1000 sq.mm Copper) in sheaths and embedded in concrete:

- maximum temperature of the conductor: 63° C
- outside temperature of the cable ≈ 53° C
- outside temperature of the sheath ≈ 45° C

2.2.4. Electromagnetic impact

2.2.4.1. Electrical field

As the electric field is confined inside the cable (metal screen), there are no outside electric fields.

2.2.4.2. Magnetic fields

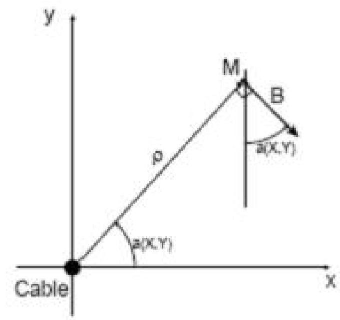
The magnetic fields have been calculated for the option of 2 cables 1000 sq.mm Copper.

The nominal current is 1000 A for each cable.

The magnetic fields at 0,5 m and at 1 m above the cable's centre line are shown hereafter.

ELECTRO-MAGNETIC FIELD

$\mu o := 4 \cdot \pi \cdot 10^{-7} \frac{henry}{m}$

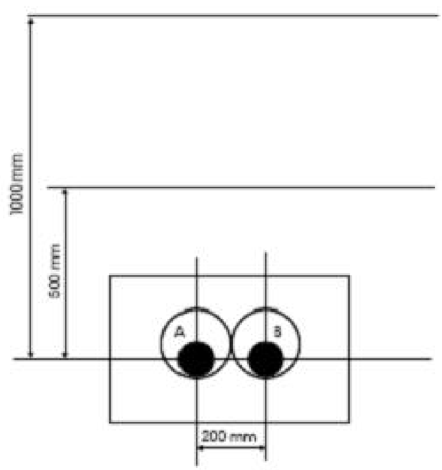


$B(I,\rho) := \frac{\mu o \cdot I}{2 \cdot \pi \cdot \rho}$ ρ : distance between field emission cable to current point

Constant $\alpha := -1$

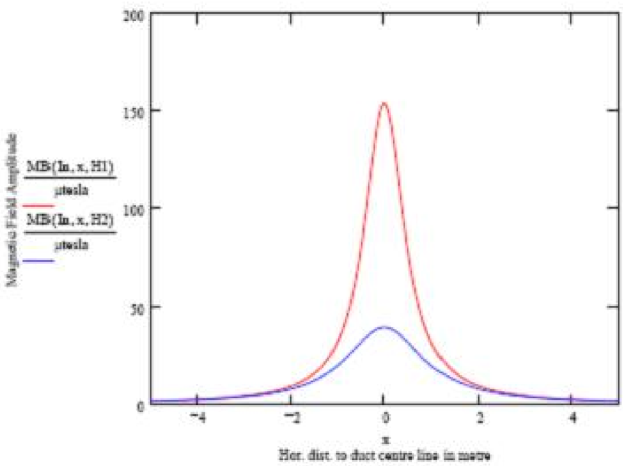
Laying conditions

Two 1000 mm² copper cables



Calculation of the magnetic field at H1 := 500 mm and H2 := 1000 mm above the cables centre line

d = (m)	MB(In, d, H1) = (µtesla)	MB(In, d, H2) = (µtesla)
-5	1.585	1.539
-4.5	1.962	1.863
-4	2.463	2.354
-3.5	3.202	3.021
-3	4.329	4.003
-2.5	6.163	5.523
-2	9.431	8.01
-1.5	16.051	12.322
-1	32.154	20
-0.5	79.984	31.846
0	153.846	39.604
0.5	79.984	31.846
1	32.154	20
1.5	16.051	12.322
2	9.431	8.01
2.5	6.163	5.523

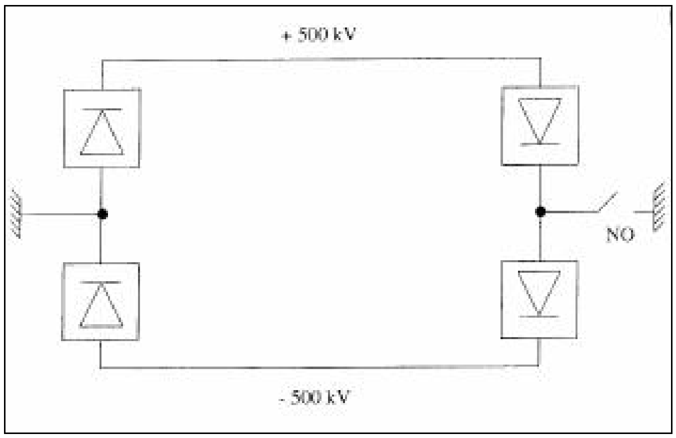


2.2.5. Electromagnetic effects

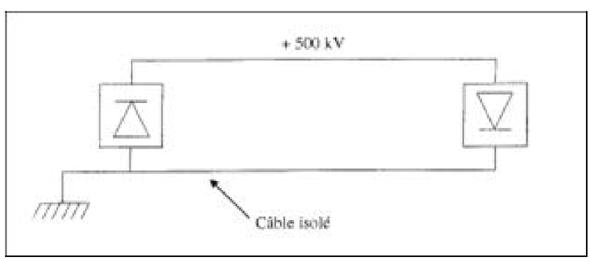
2.2.5.1. Characteristics of the VHV DC link

Here we have a VHV DC installation with two cables in which two identical currents circulate in opposite directions.

It is either a bipolar link without intentional return of current by the earth, or a monopolar link with a metallic return, see figure 2.18.



Bipolar without return by the earth per tunnel



Monopolar with metallic return

Figures 2.18.

The electromagnetic effects concern the galvanic links (of the I&C system, signalling and telecom).

For the VHV DC circuit we consider two cables per tunnel, each cable being a pole of the circuit, with a screen and placed in a PE tube embedded in concrete. In both cases a possible insulation defect results in a return current flowing only via the cable screen to the source.

2.2.5.2. Influence phenomena - General

The influences on the I&C circuits are due almost exclusively to inductive phenomena, as all capacitive effects are neutralized through the presence of screens around the power cables.

Inductive effects are distinguished between:

- Common mode

  A longitudinal potential is created (identical in all the conductors of the I&C circuit). The effect depends on the influence zone, including the length of parallel-running between the VHV DC cables and the I&C circuits. This phenomenon mainly loads the insulation of the I&C circuits with respect to the mass. Due to the asymmetrics of the I&C circuits the common mode also generates a certain differential signal (see definition later).

- Differential mode

  Creation of a potential between the conductors of the I&C circuit. This effect is also proportional to the length of the influence zone. The differential mode possibly loads the insulation between the I&C system conductors but, above all, it puts at risk the functioning of the I&C system proper, whose information is also transmitted by the differential mode.

2.2.5.3. Circuits concerned

For the I&C or telephone cables the direct induction effect in differential mode is small. However, the induction in common mode always remains possible.

2.2.5.4. "Inductor" phenomenon in the VHV DC circuit

→ <u>Steady currents</u>

The current in a VHV DC link is composed mainly of the continuous component on which are superposed multiple harmonic components of 100 Hz and especially of 300 Hz.

The amplitude of these harmonics is not constant all along the cable and may be strongly reduced by the filter circuits at the entrance of the VHV DC cable.

The induction phenomena are by principle related to the inductive current variations.

Induction can therefore be generated by a steady current variation or its inversion and the (sinoid) harmonic components.

It can be estimated that an harmonic current at 300 Hz of 1 % (of 1500 A) would give rise to some 0.35 V/km of common mode voltage in the I & C cables.

→ <u>Transient currents</u>

The "quick" transients are related to the (exceptionally) arising of failures in the VHV DC cable, with quick cancellation of the net inductive current (core + screen) of the cable affected.

Typically, a current of 1500 A that is cancelled in ± 10 ms (according a semi-period cosine curve) gives rise to flow change and a common mode induction (Mo ≈ 0.8 μH/m) of 190 V/km, of an impulse nature.

2.2.5.5. Evaluation

The voltages induced in differential mode and in common mode remain relatively weak compared to the values encountered in similar situations with AC transmission cables.

Prior to construction of the link, a more detailed check will be required of the behaviour of the signalling/telecom cables present in this tunnel.

Note that the I&C cables will have to be operated in an environment that is already strongly polluted by the electromagnetic fields generated by the loops between the traction overhead contact wires and the rails.

2.2.6. Connection to the grid - Tunnel exit on the Italian side

From the map, given in figure 2.19-1, it can be seen how interesting it would be to prolong the installation of the in-tunnel HV link into the tunnels on the Italian side.

These would be the "di Gravio" and the "del Musino" tunnels.

Extending the link through these two tunnels would provide a much easier access to the Italian grid by arriving at Leini substation and, further down, at the (very important) substation of Rondissone.

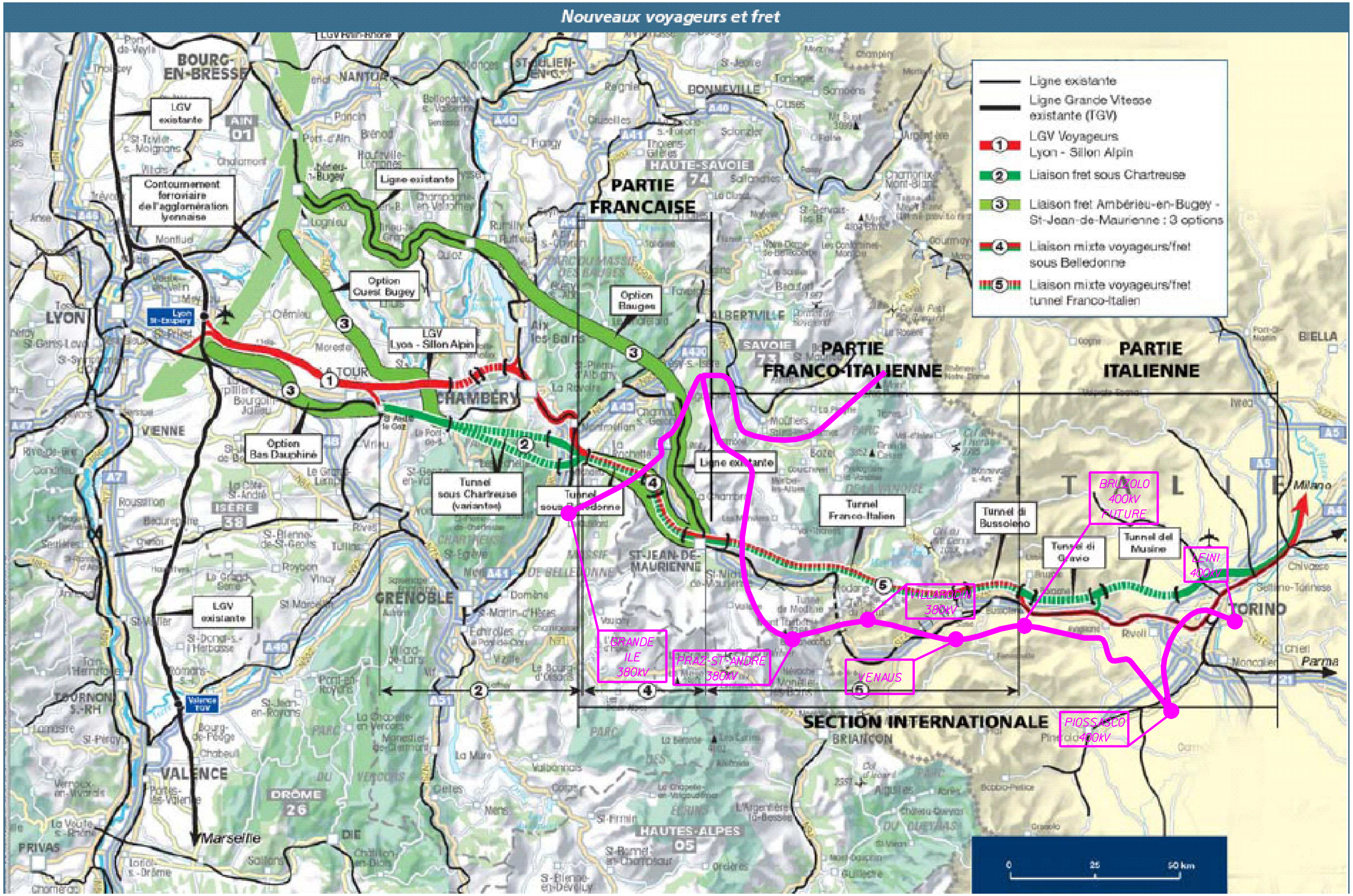

Nouveaux voyageurs et fret
Ligne existante
Ligne Grande Vitesse existante (TGV)
LGV Voyageurs Lyon - Sillon Alpin
Liaison fret sous Chartreuse
Liaison fret Ambérieu-en-Bugey - St-Jean-de-Maurienne : 3 options
Liaison mixte voyageurs/fret sous Belledonne
Liaison mixte voyageurs/fret tunnel Franco-Italien
PARTIE FRANCAISE
PARTIE FRANCO-ITALIENNE
PARTIE ITALIENNE
SECTION INTERNATIONALE
GRANDE ILE 380kV
PRAZ-ST-ANDRE 380kV
VILLARODIN 380kV
VENAUS
BRUZOLO 400kV FUTURE
LEINI 400kV
PIOSSASCO 400kV
LYON
CHAMBERY
GRENOBLE
TORINO
VALENCE
Tunnel Franco-Italien
Tunnel di Bussoleno
Tunnel del Musine
Tunnel sous Chartreuse (variantes)
Option Bas Dauphiné
Option Quest Bugey
Option Bauges
LGV Lyon - Sillon Alpin
Contournement ferroviaire de l'agglomération lyonnaise

Fig 2.19-1

Figures 2.19-2 and 2.19-3 give an overall cross-section of these tunnels.

These cross-sections are those of the preliminary project. They are note compatible with the gauge of the truck-on-rail design. Therefore they shall have to be modified at the time of the next design stage, which is planned for 2007. The aim should be for the gauge to be more similar to that of the Lyon - Turin base tunnel.

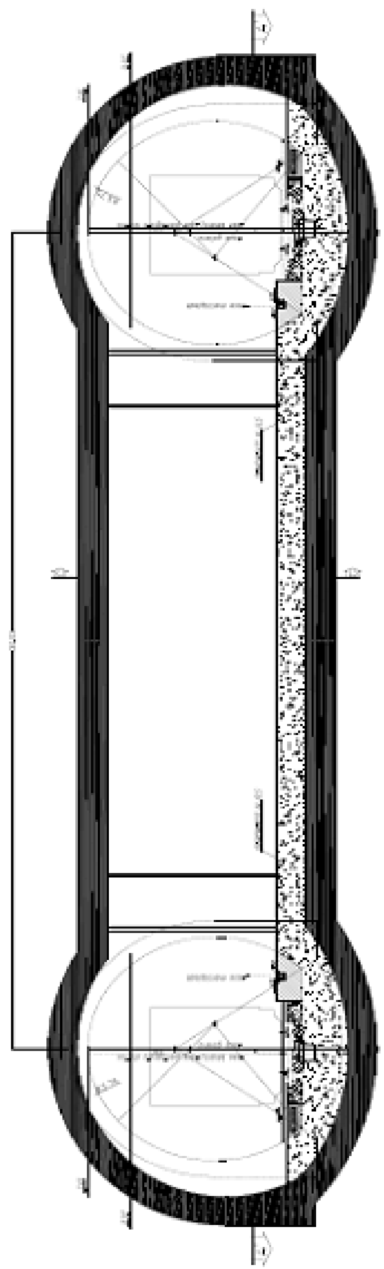


Figure 2.19-2

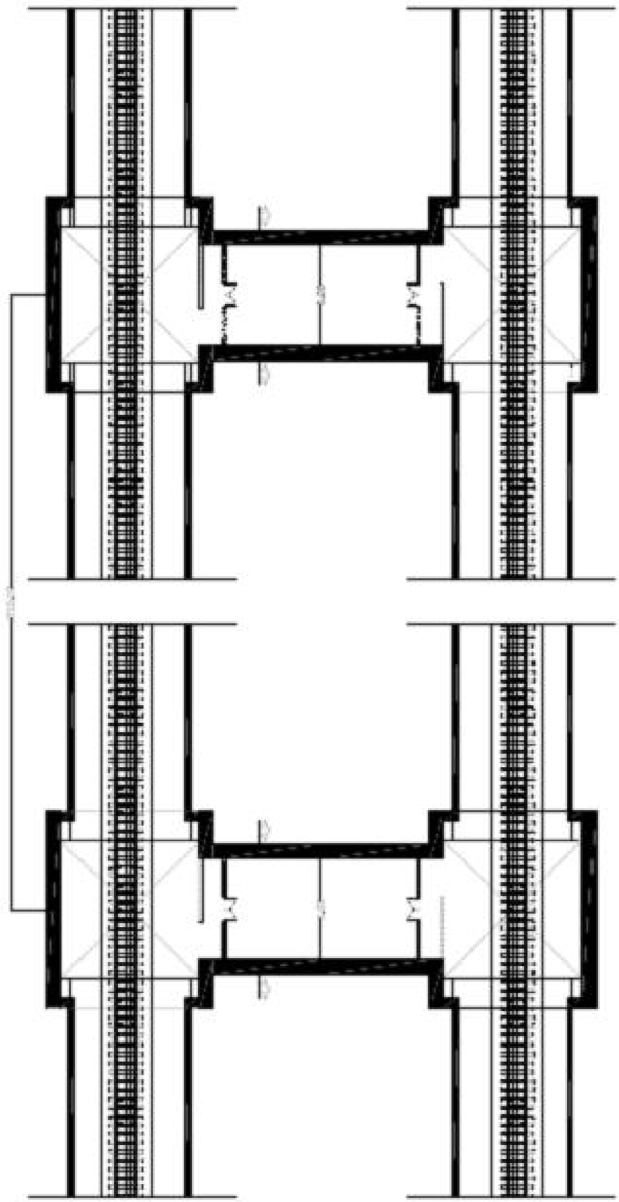


Figure 2.19-3

2.2.7. Connection to the grid - Tunnel exit on the French side

The link will exit the tunnel at the St. Jean-de-Maurienne station.

Figures 2.20-1 and 2.20-2 below give overall view of the future station.

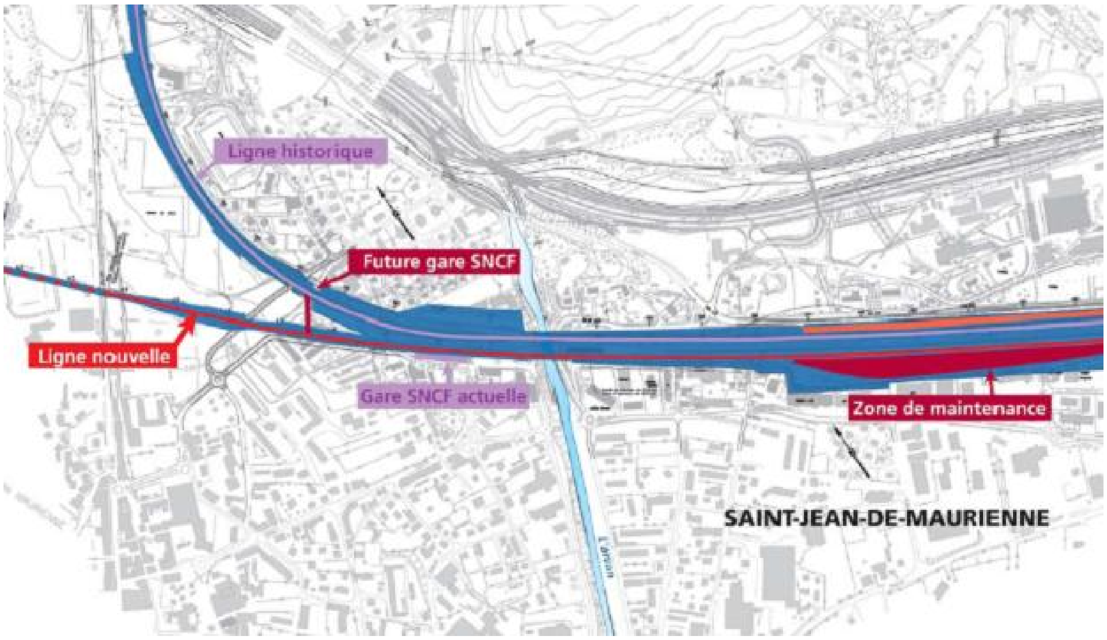


Figure 2.20-1

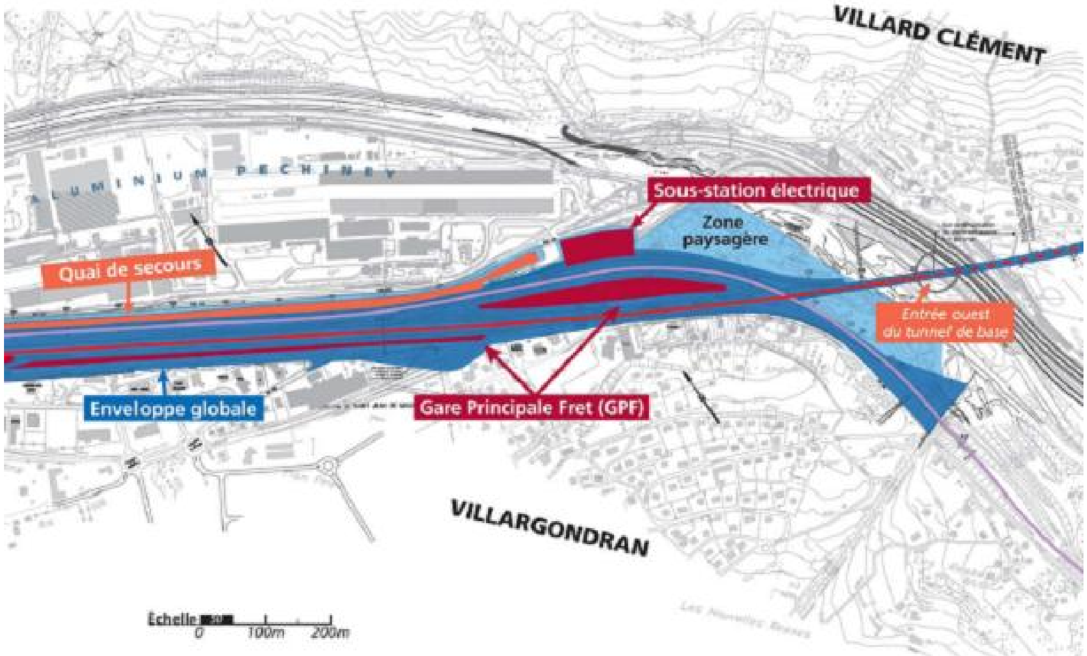


Figure 2.20-2

Note also that next to it, redevelopments and extensions of tunnels are planned (date as yet unknown).

These tunnel extensions will permit also an easier connection to the VHV 400 kV network (cf. map in above paragraph 2.2.7.).

Extending the link through extended tunnel would provide a much easier access to the French grid arriving at Grande Ile substation.

2.3. Eurotunnel

Problem statement

- Analysis of the technical feasibility of installation into the Eurotunnel:
  - a HV link;
  - possible location;
  - type of link;
  - impact of the HV link on the existing installation.

Methodology

- Collection from Eurotunnel of:
  - the various cross-sections (railway tunnel + service tunnel);
  - requirements of Eurotunnel regarding safety, access, ...

Major results

- Type of link: only a DC link is acceptable, due to the problem of synchronizing the UK and the European networks.
- Tractebel performed an extensive study on this for Eurotunnel in 2003.
- Tractebel performed that study under a contract that included a secrecy clause between Tractebel and Eurotunnel. Tractebel asked Eurotunnel to lift the confidentiality of that study, but Eurotunnel refused.

2.3.1. General information on the tunnel

Figure 2.21-1 gives the geographical location of the Channel Tunnel.

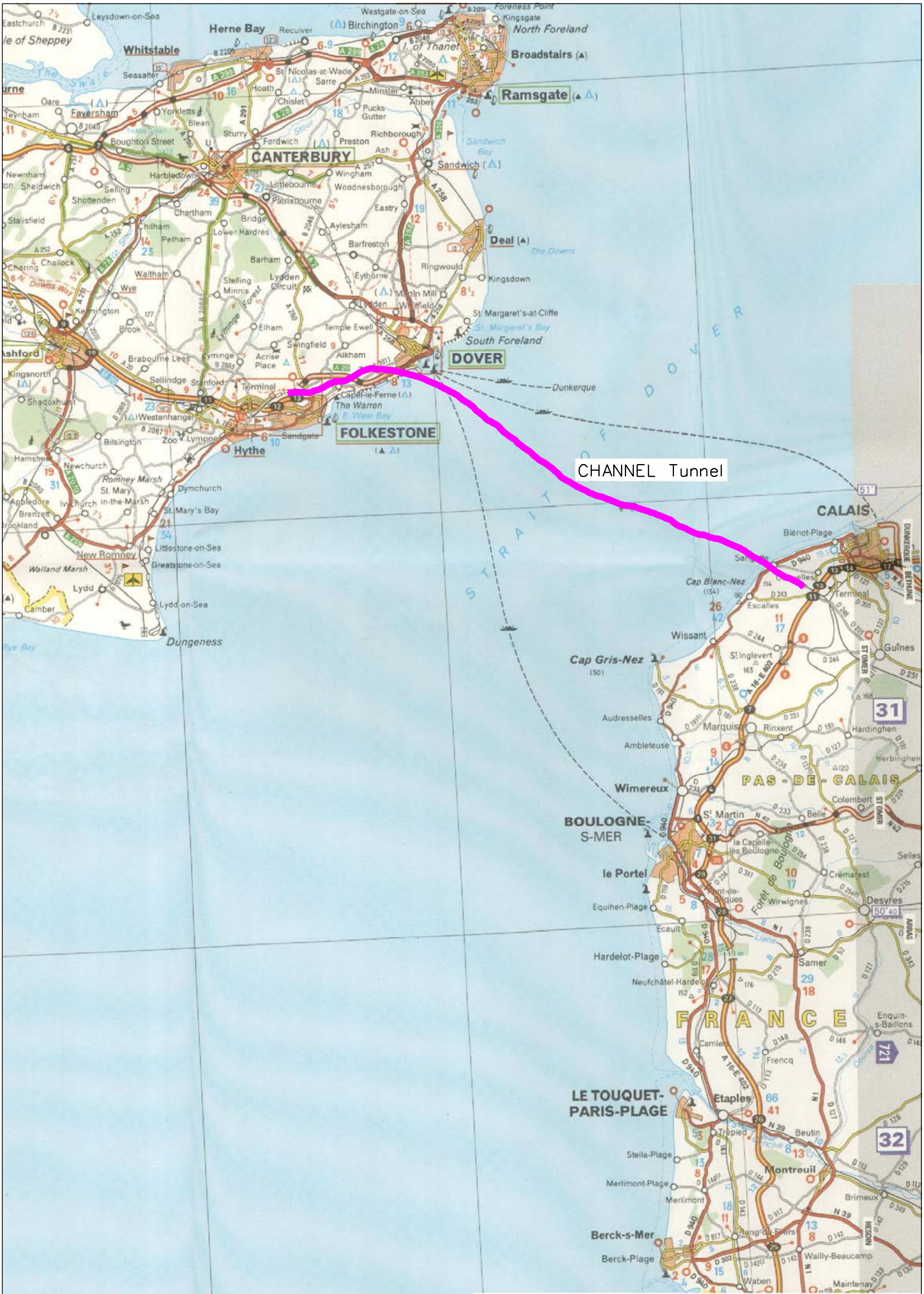


Figure 2.11-1 Geographical location of the tunnel

Figure 2-21-2 hereafter shows the position of the tunnel with respect to the European HV grid.

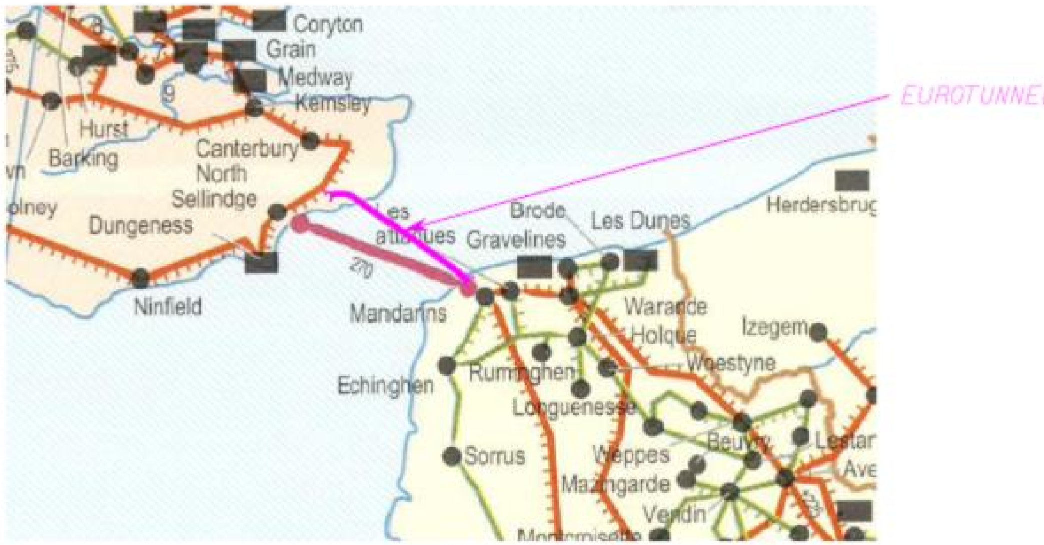


Figure 2.21-2

Note the IFA2000 submarine link of 2000 MW between France and England.

ϖ Information on IFA 2000

This 2000 MW link comprises two bi-pole links of 1000 MW each, operated at a DC voltage of ± 270 kV.

This link is connected on one side to "Les Mandarins" substation in France and on the other side to the "Sellindge" substation in England.

The submarine cables have a 900 mm^2 Copper conductor cross-section and are of the mass impregnated paper insulation type.

The land cables, 7 km in France and 17 km in UK, have a conductor cross-section of 900 mm^2 and are oil-filled paper insulated.

Figure 2.22. below gives a cross-section of the tunnels.

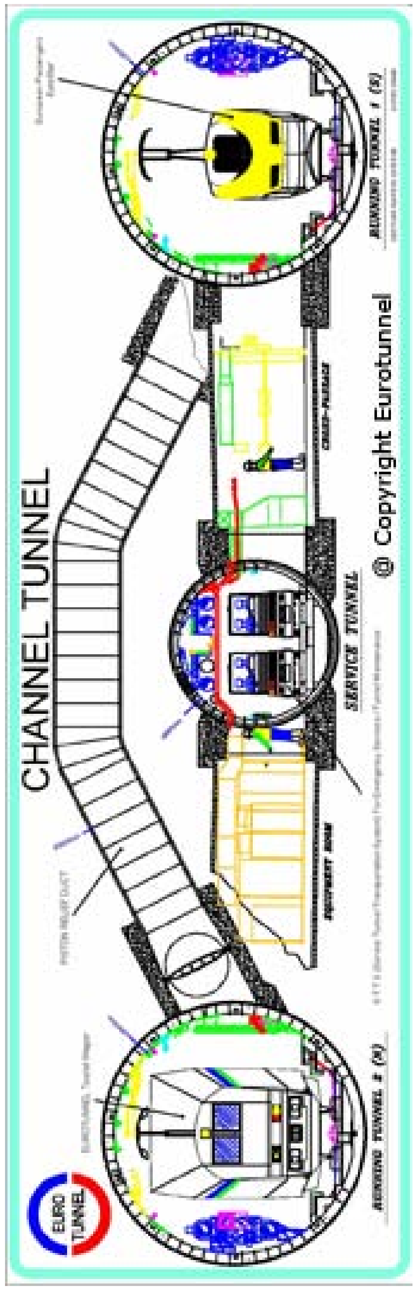


Figure 2.22.

This project is composed of 3 tunnels:

- 2 railways tunnels (Eurostar or shuttle train) of 7,5 m diameter;
- 1 service tunnel of 4,8 m diameter.

The service tunnel is a road tunnel used by purpose-built, narrow, vehicles for maintenance and emergency access.

The railway tunnels are linked to the service tunnel by cross-passages every 375 m for emergency access and egress.

During normal operations, where it meets the railway tunnels, each end of each cross-passage is sealed by a heavy door.

The railway tunnels themselves are linked directly by pressure relief ducts to reduce air pressure that builds up in front of moving trains.

About 15 km from each tunnel portal, trains pass through large crossover caverns. As the name implies, their purpose is to permit trains to pass from one tunnel to the other.

The total length of the tunnel is about 50 km.

2.3.2. Particularity of a HV link between France and England

The particularity between the two grids, the UK and France (Europe) resides in the two grids not being "SYNCHRONOUS".

2.3.2.1. Synchronous and non-synchronous grids

An alternating current link between two grids transmits a current that is only function of the two voltages at the ends of the link. The series impedance being essentially inductive it can be admitted that the reactive power transmitted is proportional to the amplitude differential, while the active power is given by the formula $\frac{V.E}{Z} \sin \Theta$, where Z is the series reactance of the link and Θ is the phase angle between the two extremities of the link.

In fact the operation of a link between two grids is governed by a vector diagram that may be presented as follows:

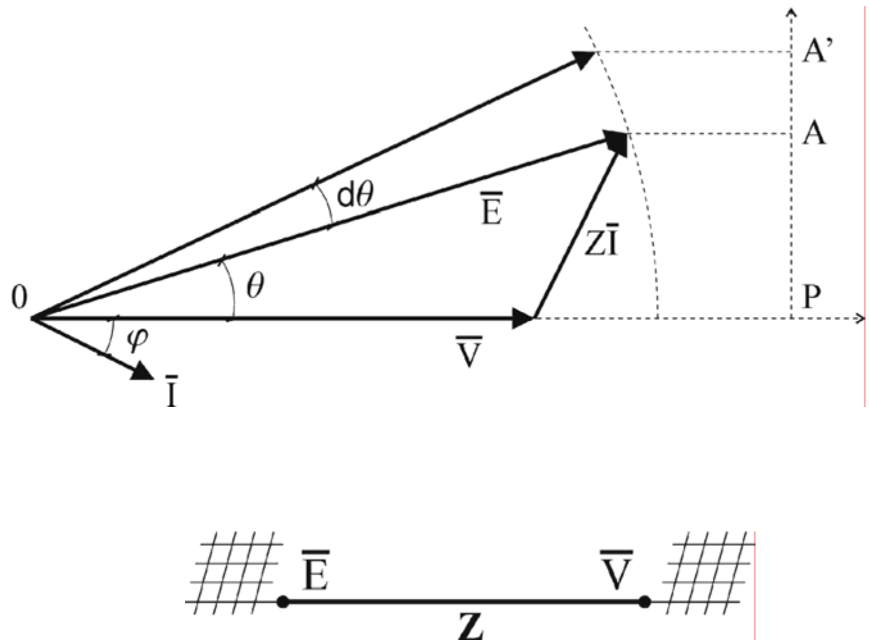


Figure 2.23.

(considering only an inductive voltage drop, and neglecting the resistive voltage drop).

The power delivered per phase $P = VI \, . \cos \varphi$.

$$PA = Z\ \bar{I}\ \sin(90° - \varphi) = Z\ \bar{I}\ \cos\varphi$$

$$I \cos\varphi = \frac{PA}{Z}$$

$$P = V \, . \, \frac{PA}{Z} = \frac{V.E}{Z} \, . \sin\Theta$$

From this finding we can derive that the theoretic maximum power arises at $\Theta = 90$ degrees (the value generally admitted at full load is 30°). Beyond 90 degrees the power no longer increases with the angle, and the link (or more precisely) the transmission through the link becomes unstable.

If the two grids connected at the extremities are sufficiently interconnected, the phase angle between the two extremities is not likely to diverge much. This is usually the case of all the connections within an AC grid.

In the case of the Eurotunnel the two grids have no other interconnection in AC. The Eurotunnel link, if the decision is made to build it, therefore has to be capable on itself of maintaining the synchronism between the two grids. This leads us to the following point.

Figure 2.24. shows the European continent with the zones that are synchronized with each other.

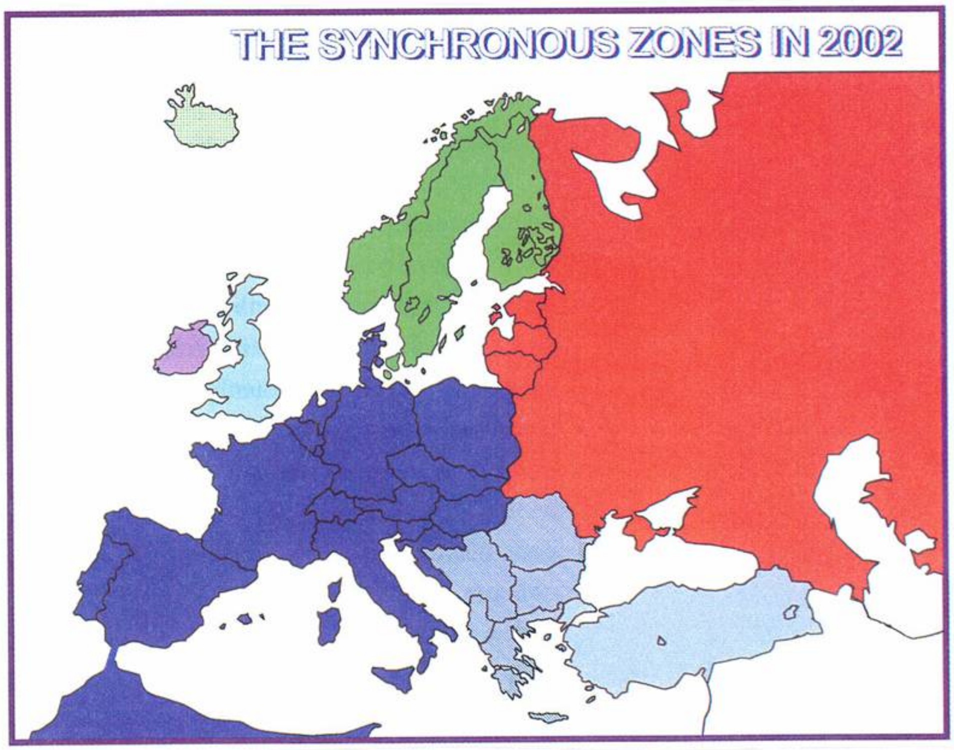


Figure 2.24.

2.3.2.2. Size of the grids with respect to the considered link

A link between two powerful grids (each having their generation and loads) can be affected by any unbalance that may arise in one of the grids.

Referring to what happens on European level, figure 2.25. hereafter shows how the exchanges are made between countries under normal conditions and how these evolve when 1000 MW of generation is lost.

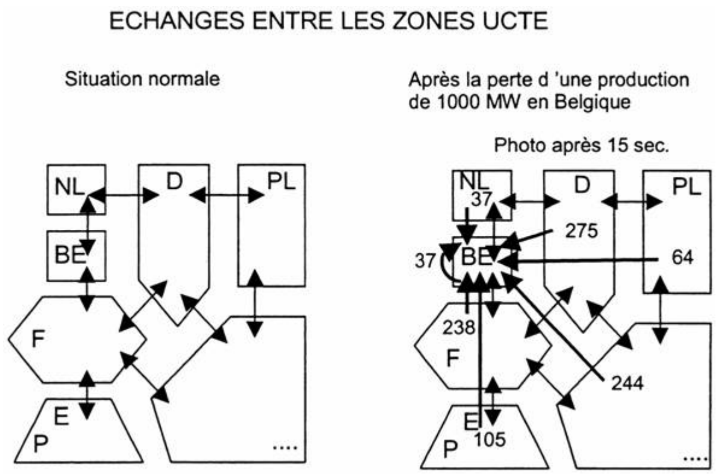


Figure 2.25.

In the case that interests us, since our link would be the only link with Europe, a 1000 MW loss of generation would mean that that power would have to transit in our link, which would trip out due to overload an instability.

If these unbalances are of the same order of size as the nominal capacity of the link, there will be overloads on the link if not instabilities. In other words the synchronizing power of the link is not commensurate with the size of the grids that have to be synchronized. In turn, if a small size grid is connected to a powerful grid by a link that is also powerful, the problem is a different one. In this case the link has sufficient synchronizing power to offset the unbalances in the smaller grid.

In the case of the Eurotunnel we are talking of grids that have to be interconnected that each have an installed power of several tens of GW. A single link of ~ 1 GW is obviously insufficient to synchronize such grids, both in terms of transmission capacity and ability to ensure stability.

Also note that to this day the only existing link between France and England is the IFA2000 project, this link being a DC one for the reasons mentioned above.

2.3.2.3. Possibility of Back-To-Back uncoupling

As discussed before, an AC solution can be considered only if provided with a Back-to-Back conversion station either at the Source side or at the Receiving side, the rectifier and the inverter being located on the same site (figure 2.26.).

Accordingly, it is composed essentially of:

- a 400/40 kV transformer (for example);
- a rectifier;
- a DC link of 40 kV, which is a substantial current, but with a very short link;
- an inverter;
- a 40/400 kV transformer.

The DC link directs the energy.

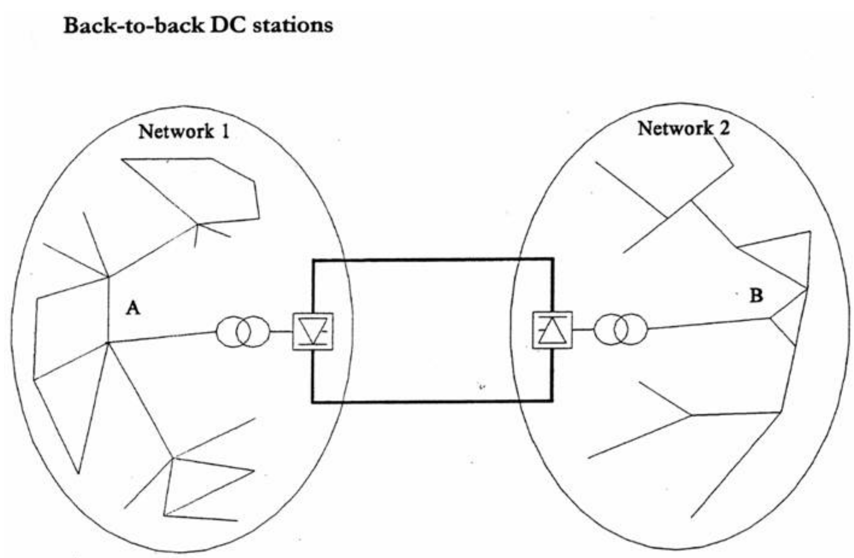


Figure 2.26.

2.3.2.4. Summary about the functional suitability of an AC solution

An alternating current solution is excluded because of the functional problems it poses. A mixed solution in AC with a Back-to-Back station is still technically possible, but it combines the disadvantages of the cost of the cable for AC and the cost of conversion into DC.

2.3.3. Possible location in the tunnel - Type of link

In 2003 Tractebel was entrusted by Eurotunnel with a feasibility study regarding installation of a VHV link in one of the channel tunnels.

This study was completed end 2003 and was covered by a secrecy agreement between Tractebel and Eurotunnel.

We have made a request to Eurotunnel for them to agree to lifting this secrecy so that we may disclose to you our conclusions of that feasibility study.

Eurotunnel have informed us it does not want that information regarding the feasibility study regarding the installation of a VHV link in a tunnel to be disclosed. This study had been performed by Tractebel for Eurotunnel. Below is Eurotunnel's reply:

> **"Further to your request, please be informed that we do not wish to communicate information concerning the feasibility study on the possible installation of a VHC cable in a tunnel.**
>
> **Best regards,**
>
> **Jean-Pierre Dupont"**

2.4. Monte Ceneri tunnel

Problem statement

- Analysis of the technical feasibility of integration into the Monte Ceneri base tunnel:
  - a HV link;
  - possible location;
  - type of link;
  - impact on the environment (magnetic, heat, ...).

Methodology

- Collection of information form the tunnel manager concerning:
  - the current status of the design/construction of the Monte Ceneri as well as the Gotthard and Zimmerberg;
  - detailed cross-sections of the Gotthard and Monte Ceneri tunnels.

Major results

- Zimmerberg/Gotthard/Ceneri base tunnels are railway tunnels and have no service tunnels.
- The optimal solution would be if the Zimmerberg - Gotthard and Monte Ceneri could be combined for the link.
- In this respect a DC link may be envisaged (same as Lyon - Turin).
- However, the physical progress of construction made so far has a great impact on the installation of a DC link particularly as concerns the Gotthard tunnel where the base raft is already placed in a number of areas.
- The only option remaining would be fix the link's cables on the tunnel wall, but this gives rise to a problem at the locations where there are linking or evacuation galleries.
- The only tunnel that could still accommodate a HV link is the Monte Ceneri tunnel, provided a decision can be taken rapidly as construction is already starting.
- Should the link be envisaged only in the Monte Ceneri (i.e. not combined with the other tunnels mentioned above), the DC option has to be abandoned (due to the length of the Ceneri tunnel: 16 km).
- Conclusion: at this stage we feel it is excluded to imagine an HV link in this set of tunnels.

2.4.1. General information on the Monte Ceneri/Gotthard tunnels

The Monte Ceneri base tunnel (15 km length) is a tunnel which is part of a rail link between Zürich to Lugano in Switzerland.

The rail link includes also the Zimmberberg tunnel (20 km length) and the Gotthard tunnel (57 km length).

Figure 2.27-1 shows the geographical location of the Zimmerberg/Gotthard and Monte Ceneri tunnels.

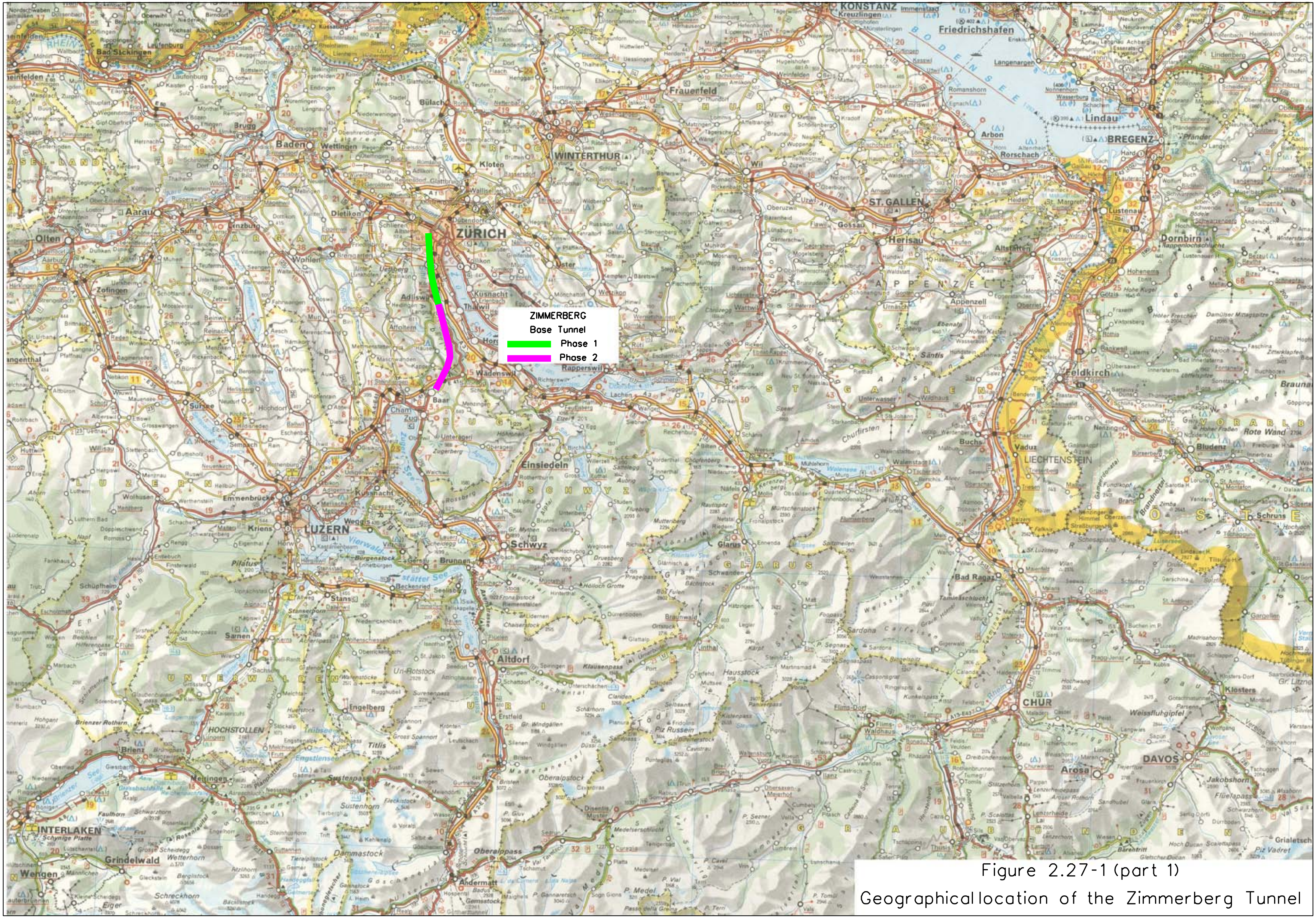


Figure 2.27-1 (part 1)
Geographical location of the Zimmerberg Tunnel

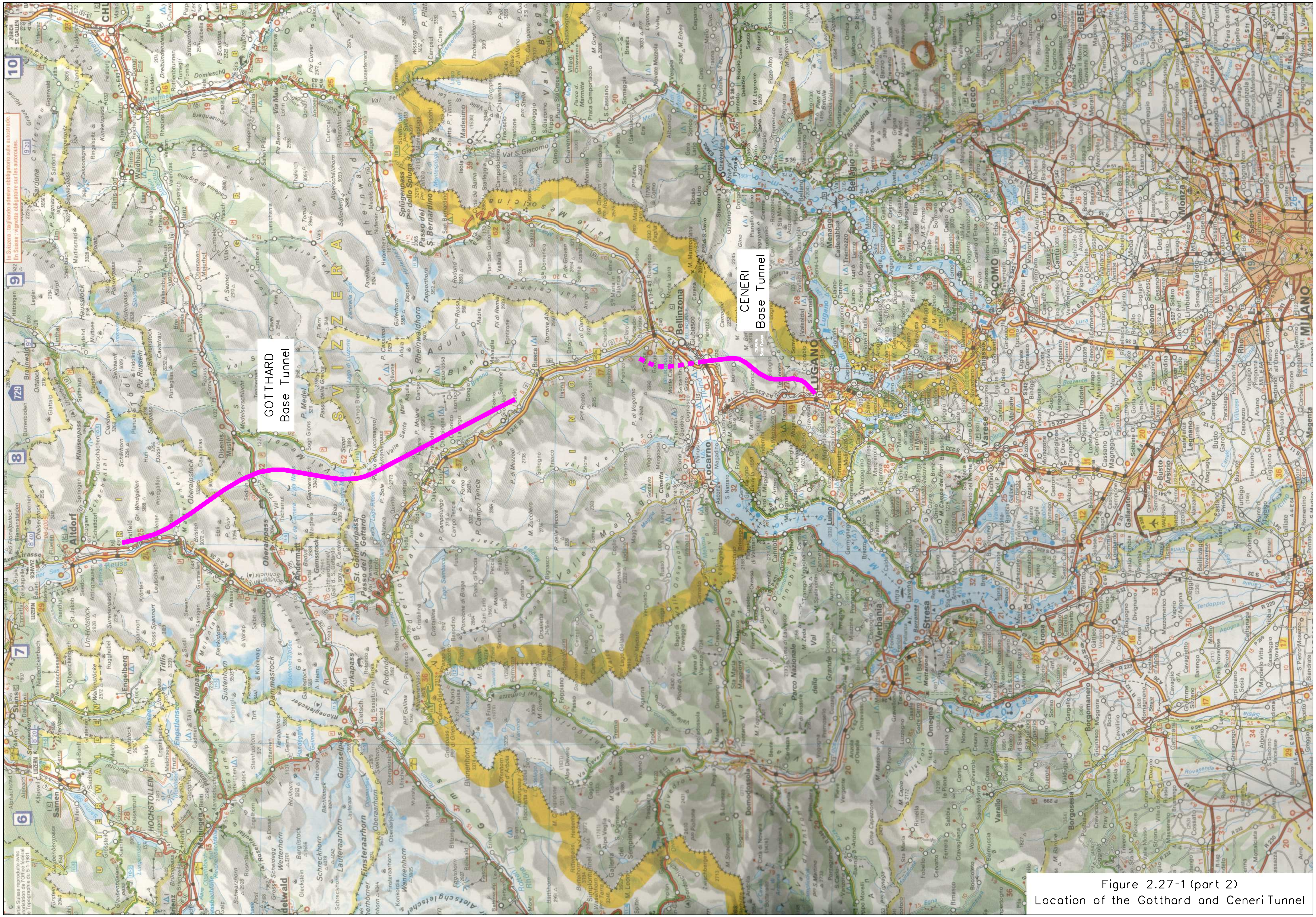


Figure 2.27-1 (part 2)
Location of the Gotthard and Ceneri Tunnel

Figure 2.27-2 shows the road of this rail link and the length profile.

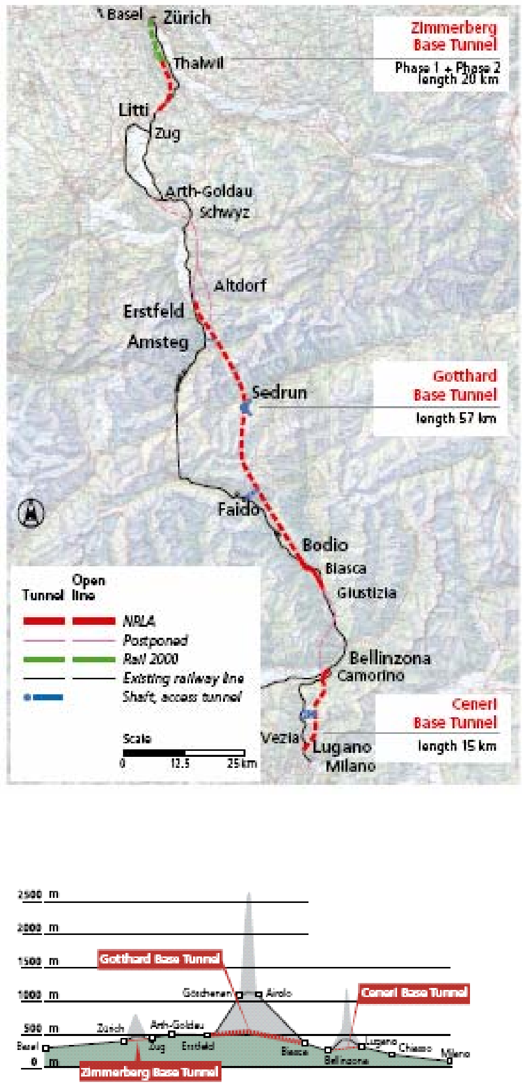
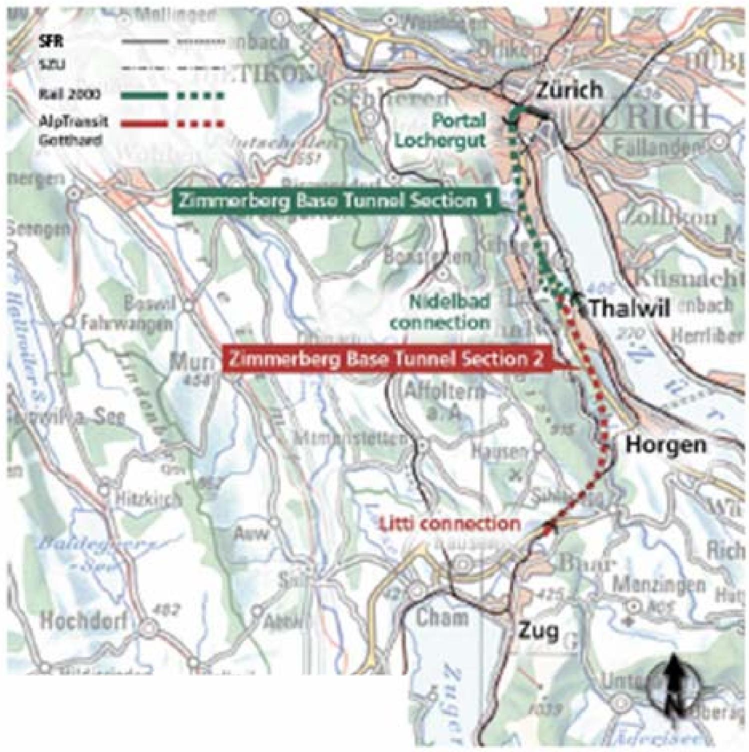


Figure 2.27-2
(source AlpTransit)

a) Zimmerberg base tunnel complements the new Gotthard link to the north (see figure 2.28.).



The Zimmerberg Base Tunnel in the north

Figure 2.28.

b) Gotthard base tunnel of a length of 57 km (figure 2.29.).

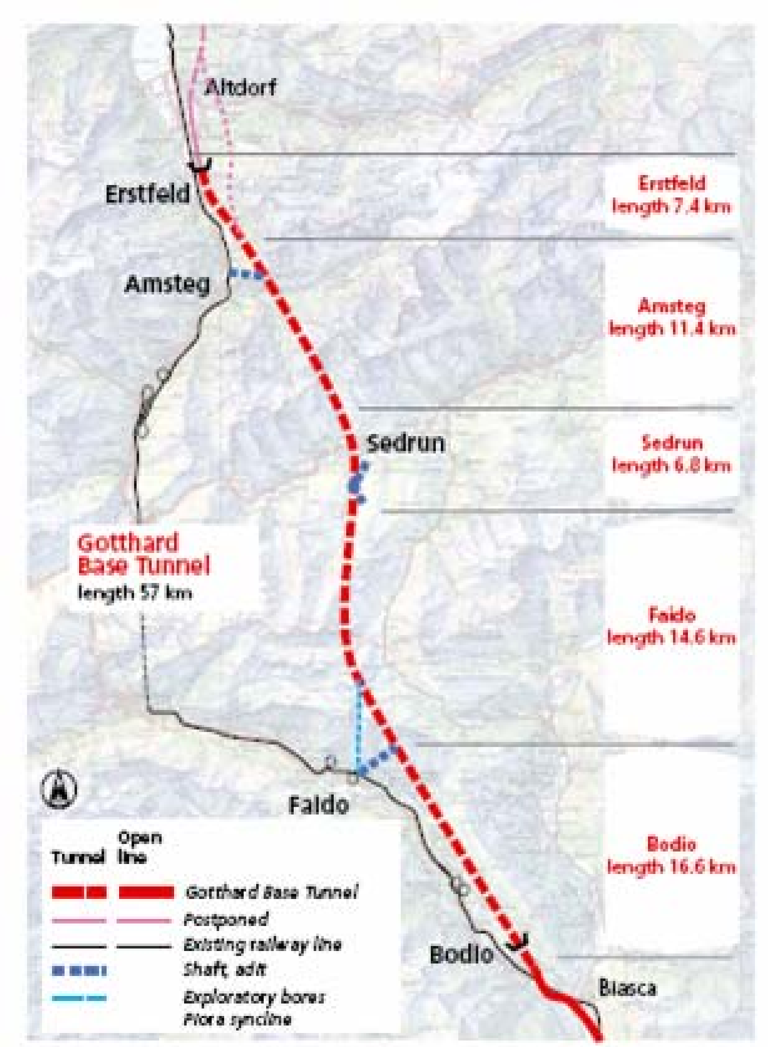


Figure 2.29.

c) The Ceneri base tunnel (15,4 km) which completes the new Gotthard link to the south (figure 2.30.).

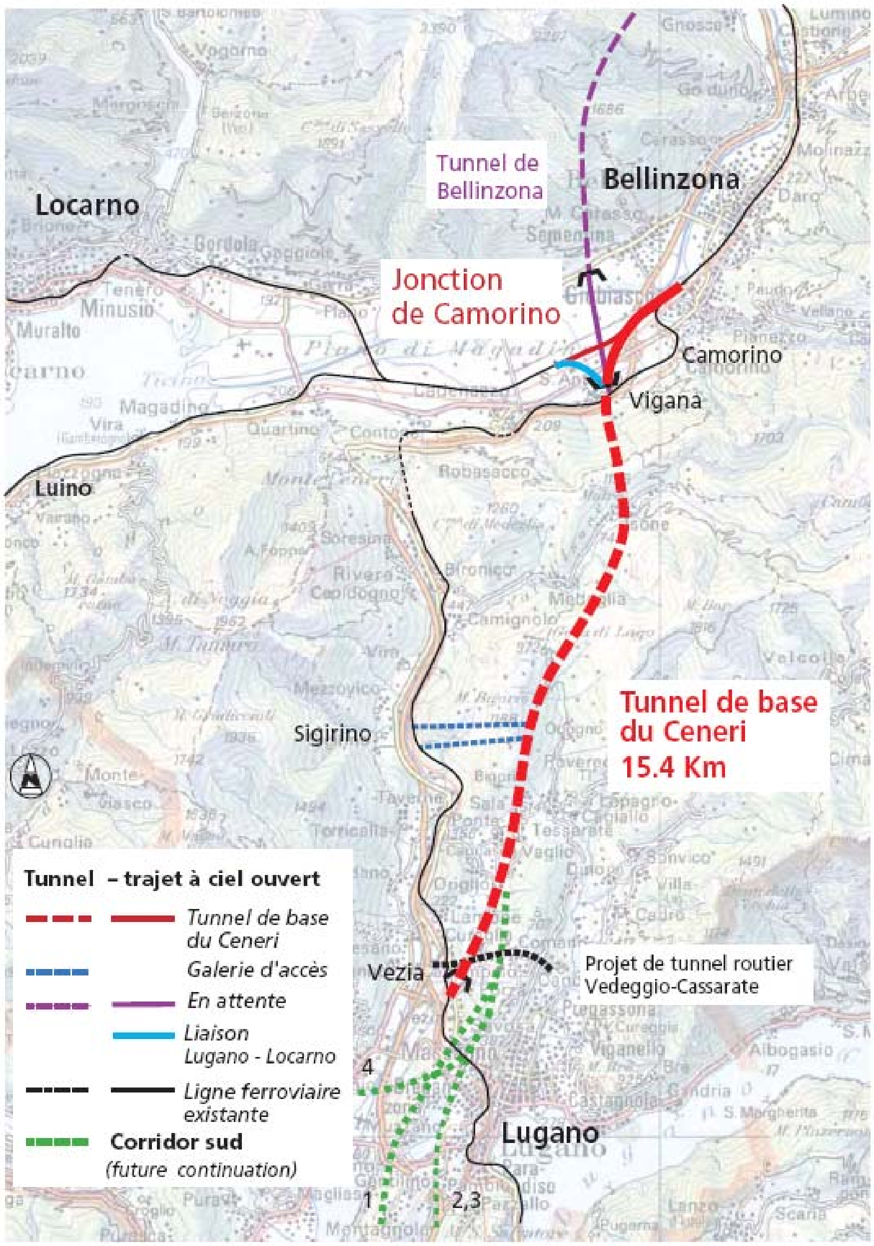


Figure 2.30.

d) Additional tunnel

Referring to the figure 2.30, additional tunnels between Zimmerberg/Gotthard/Ceneri should be done later. The actual state is that the project is postponed.

One of these projects is the Bellinzona tunnel which will connect the Ceneri base tunnel to the Gotthard base tunnel.

2.4.2. Zimmerberg - Gotthard - Ceneri base tunnels in the HV network

The figure 2.31. shows the tunnels in the HV European network.

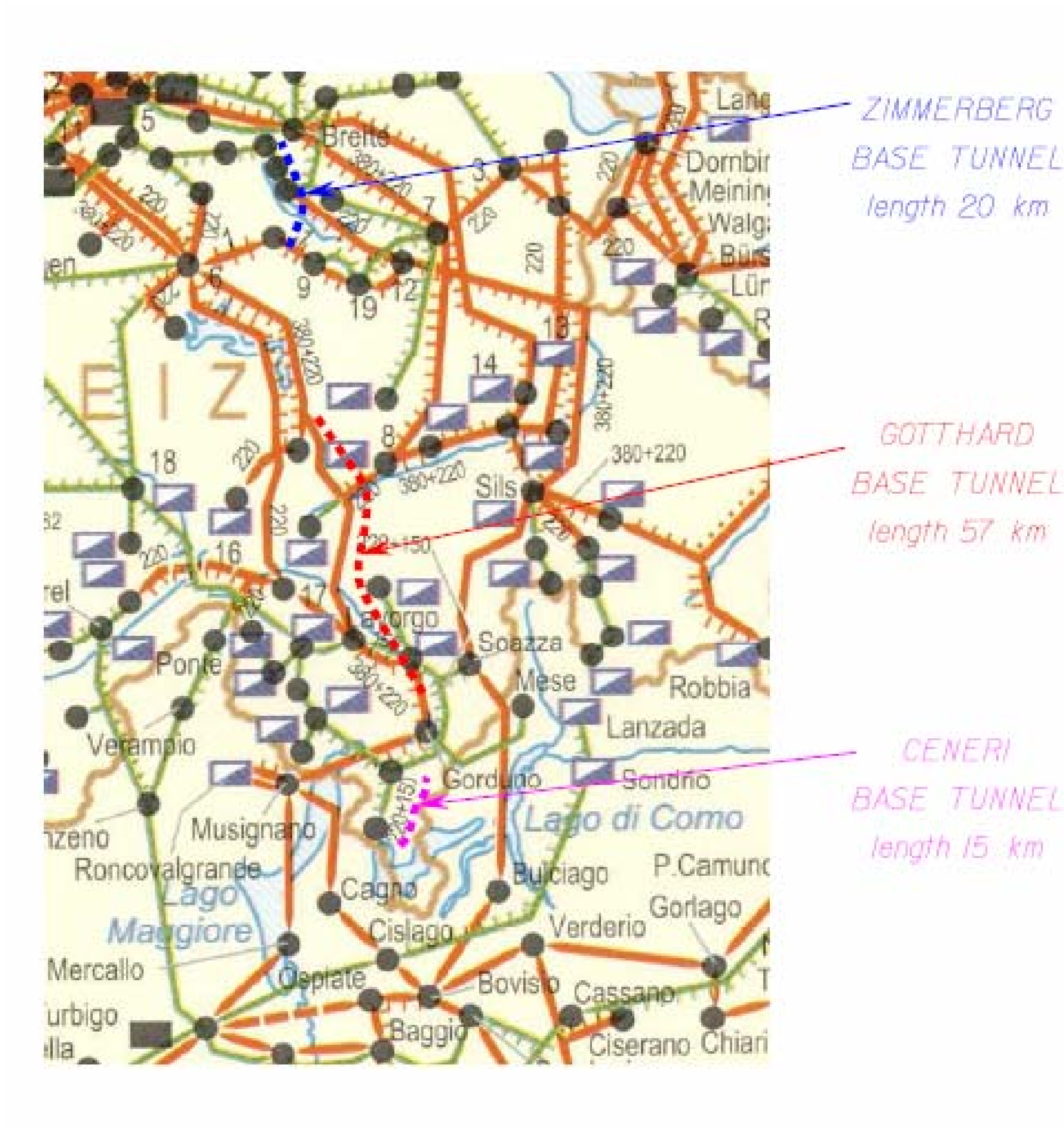


Figure 2.31.

2.4.3. Situation of the work

Figures 2.32. and 2.33. show the state of excavation for the Gotthard tunnel and for the Ceneri tunnel.

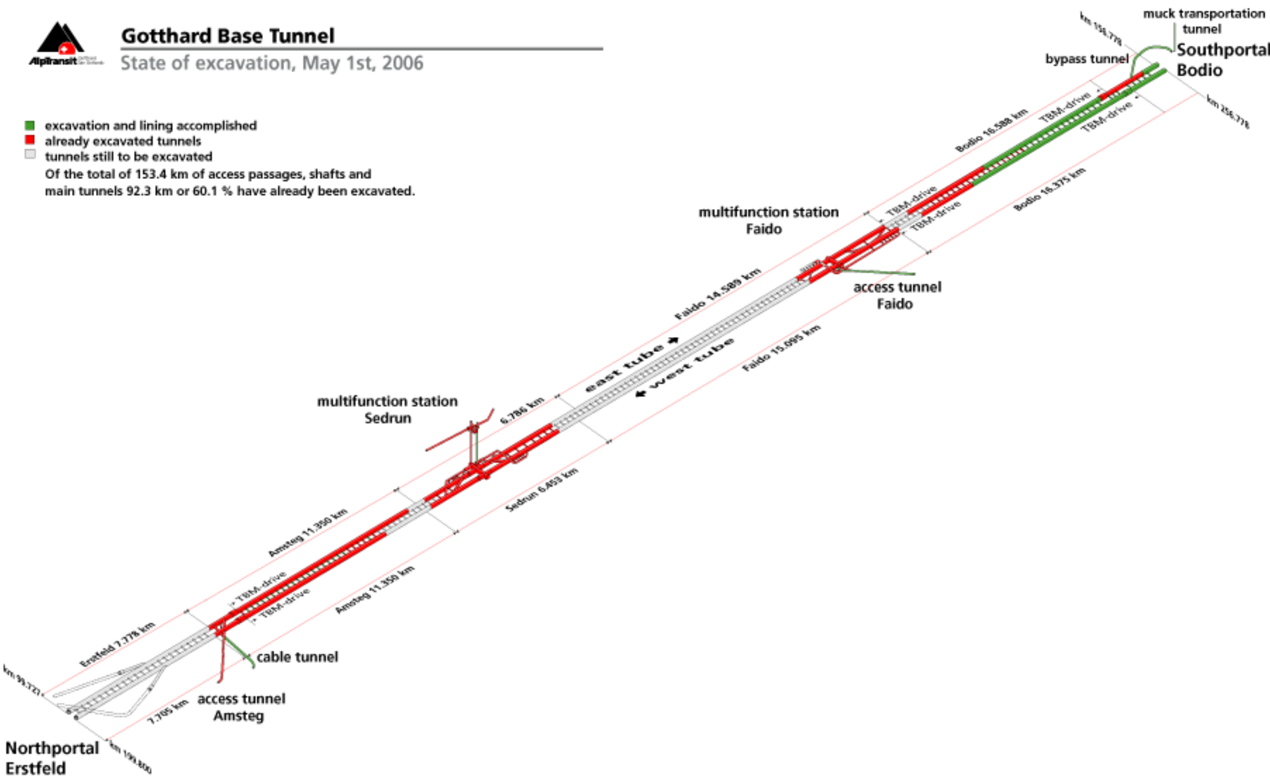


Figure 2.32.
Gotthard tunnel - State of excavation

On May 1, 2006, of the total of 153,5 km of tunnels, galleries and passages of the Gotthard base tunnel, 92,3 km or 60,1 % had been excavated.

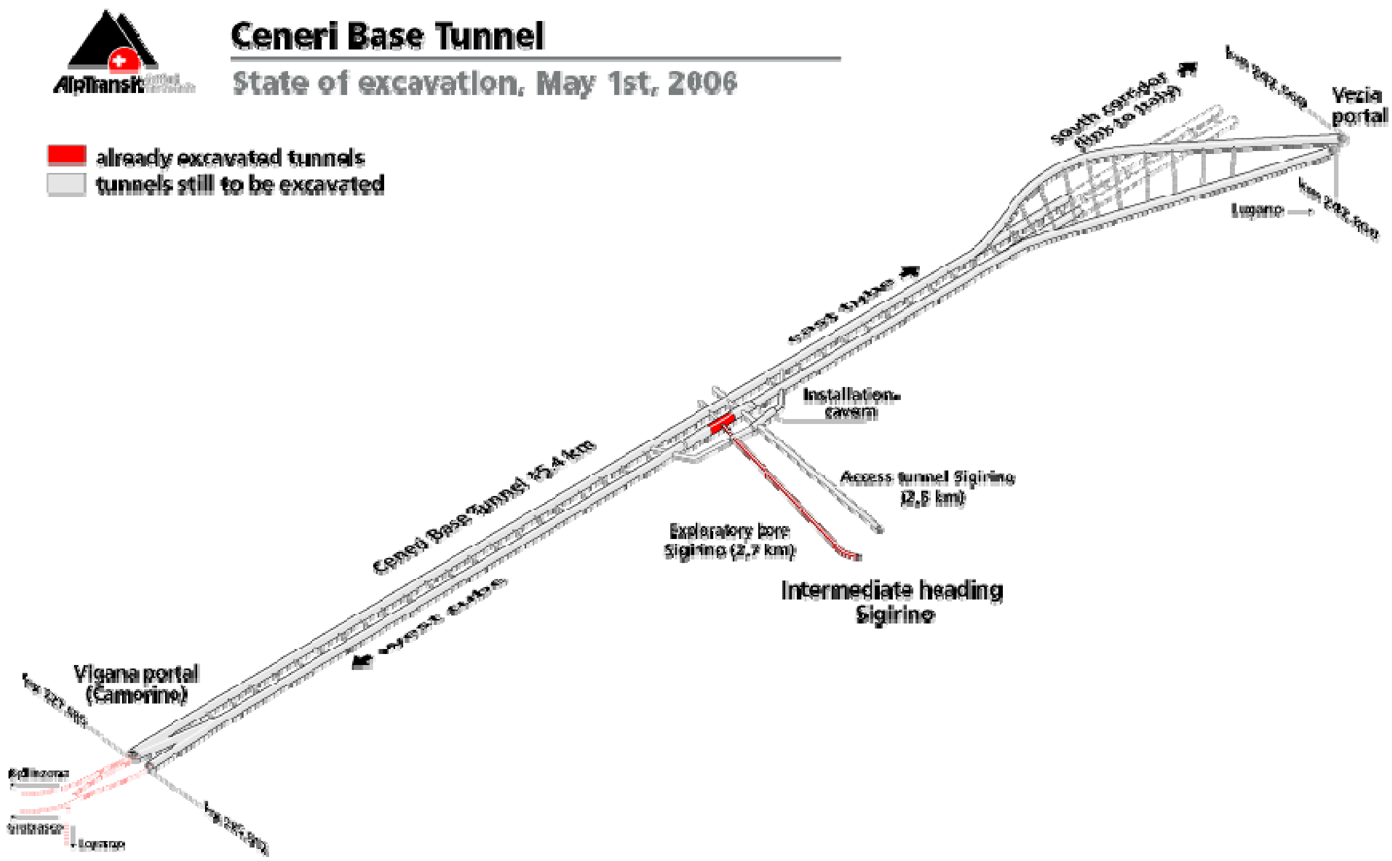


Figure 2.33.
Ceneri tunnel - State of excavation

The construction of the two single-track tunnels will start in 2006. Opening of the tunnel is scheduled for 2016.

Zimmerberg base tunnel

For the Zimmerberg tunnel: except for the connection at Nidelbad, which was already completed by Swiss Federal Railways as part of the Rail 2000 project, all work has been suspensed.

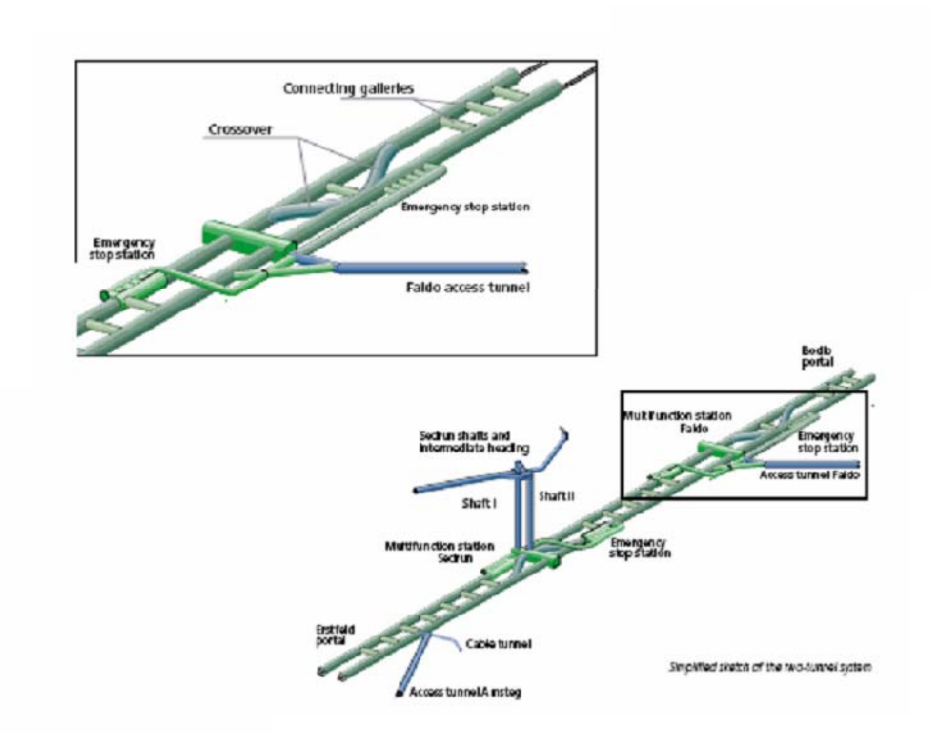
It was planned to start construction of the Zimmerbeg base tunnel (phase 2: Nidelbad - Litti) in 2006. Opening of the tunnel was scheduled for 2013.

In the meantime, the Swiss Federal Council has announced that in 2007/2008 it will conduct a full review of public transportation projects financed from the FinöV fund on which construction has not yet begun. This includes the Zimmerberg base tunnel. Consequently, work on publication of the Zimmerberg base tunnel phase 2 project will only be resumed when a revised order is received from the Swiss Federal Council.

2.4.4. Type of tunnel and tunnel cross-section

The concept of the Ceneri tunnel is the same as the Gotthard tunnel. It means that the type of link is a two single track tunnel with connecting galleries.

A simplified sketch of the two-tunnel system is shown at the figure 2.34.



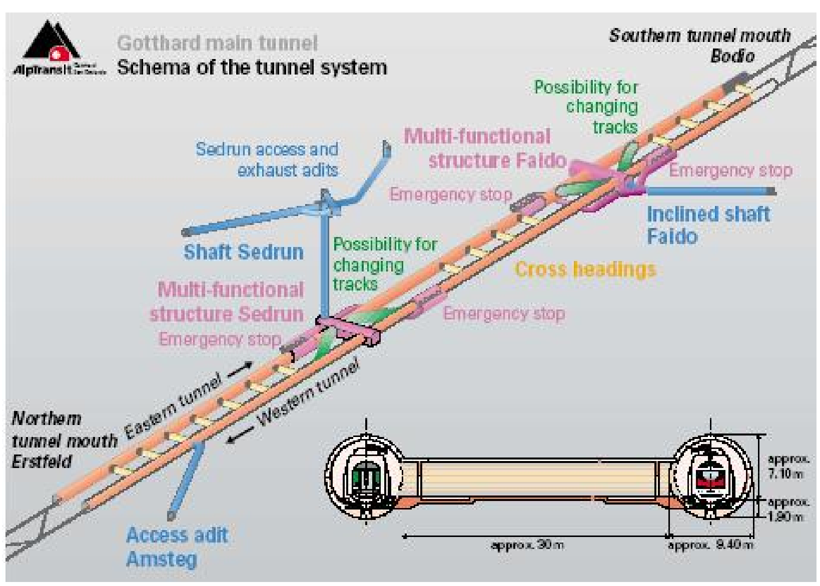


Figure 2.34.

Two types of driving are used (see figure 2.35.):

→ driving with a tunnel boring machine;

→ driving with drill and blasting.

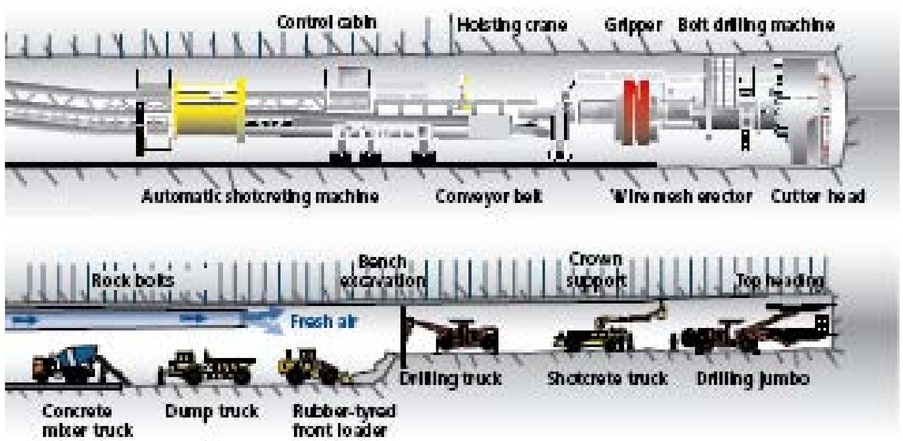
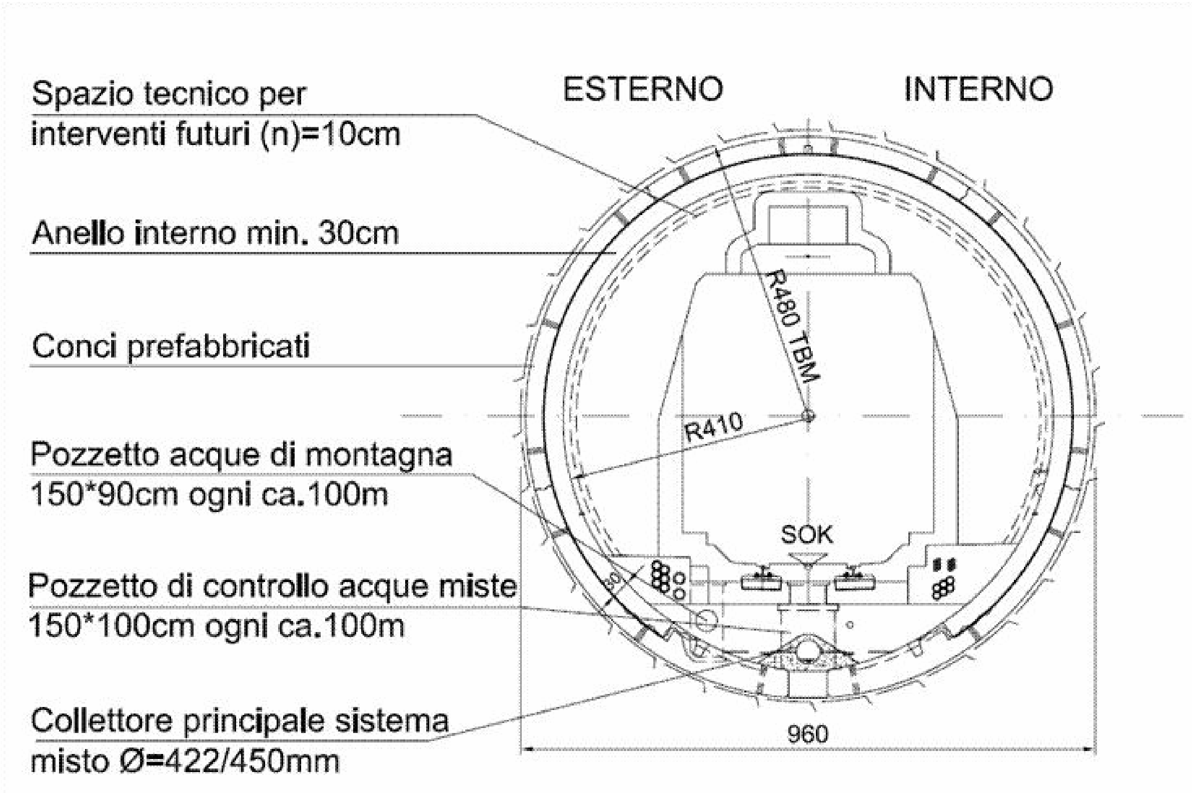


Figure 2.35.

Due to the system of driving, two types of tunnel cross-section are used.



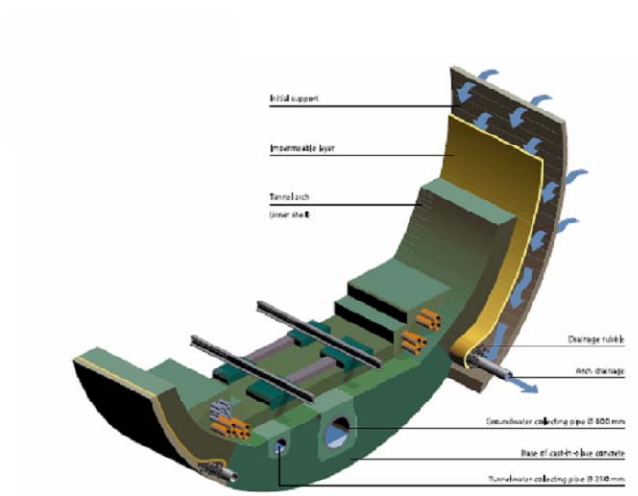


Figure 2.36-1
Tunnel cross-section with a boring machine
(source AlpTransit)

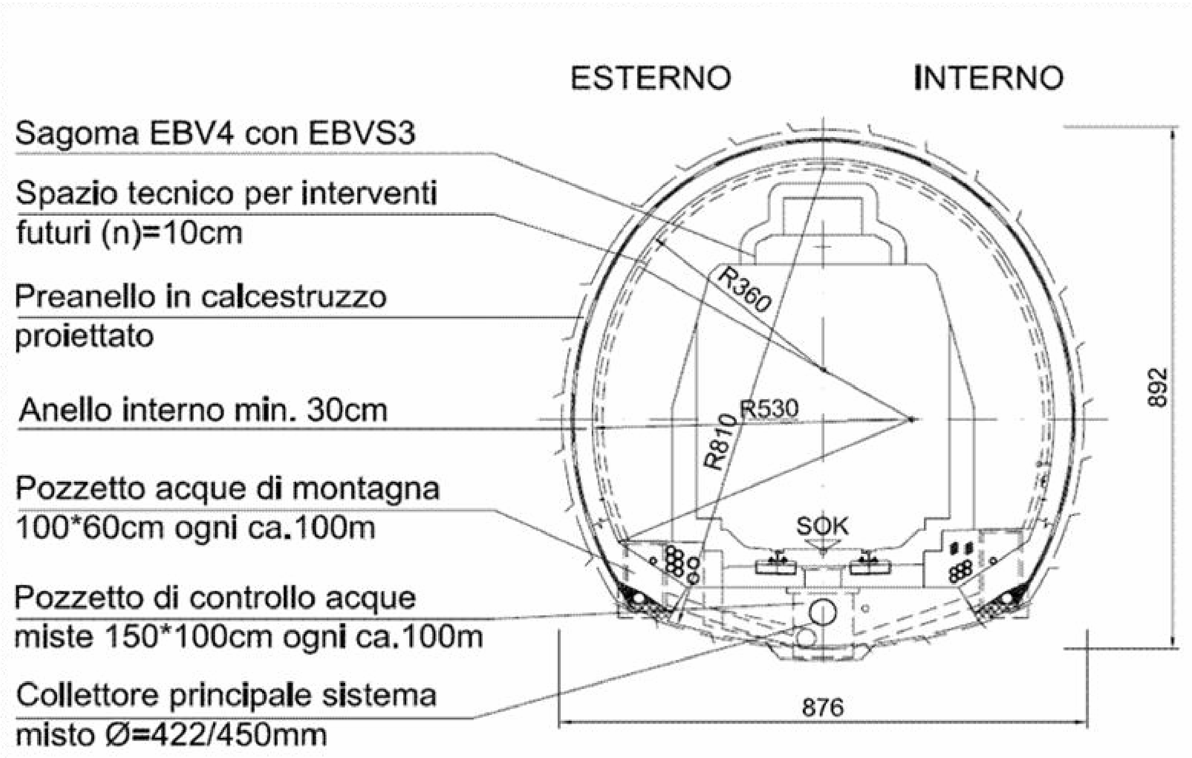


Figure 2.36-2
Tunnel cross-section with drilling and blasting method

2.4.5. Type of link

2.4.5.1. General

According to the information received, including the cross-sections of the tunnels, the case is quite similar to that described in the above chapter 2.2. (relating to the Lyon - Turin tunnel).

In fact in this type of infrastructure we systematically find the same basic principles.

At this stage we don't have an as detailed cross-section as that which we received for the Lyon - Turin tunnel, but we can imagine that the difficulties we will encounter will be roughly the same, such as:

- the available space;
- zones not to be recommended, such as under the tracks or on the side of the tunnel where the connecting galleries are.

Also, it seems obvious that these tunnels become interesting only if they can be linked to each other, so providing a VHV link from Zurich → Milan (for example).

2.4.5.2. State of the excavation work

The above paragraph 2.4. gave the status of excavation as at May 1st, 2006.

→ For the Gotthard tunnel

More than 60 % of excavation complete.

→ For the Zimmerberg tunnel

- Work postponed for phase 2.
- Phase 1 completed as part of the Rail 2000 project.

→ For the Ceneri tunnel

The work started end March 2006/beginning April 2006: preparatory work, road access.

2.4.5.3. Proposal

The physical progress of the excavation leads us to examine this feasibility in a different way than our approach for the Lyon - Turin tunnel.

Indeed, in the present case it is excluded to imagine making arrangements/adaptations for the position of the LV/telecom cables, because in certain locations pouring of the base concrete has started already (for example in the Gotthard tunnel).

Under those circumstances we could propose:

⇒ A DC link, for the same reasons as explained concerning the Lyon - Turin tunnel.

Brief reminder of the reasons:

- safety concerns;
- power to be transmitted much greater and over a greater length than in a usual AC solution;
- drawback: cost of the converter stations;
- GIL link: excluded, mainly for reasons of lack of space.

⇒ Location in the tunnels?

Here again it appears that a zone like the one selected for the Lyon - Turin would be the most advisable option, i.e. the zone in the tunnel opposed to the connecting galleries.

If we consider a tunnel cross-section similar to that of the Lyon - Turin tunnel (to be confirmed), a solution could be imagined that is similar to that shown in figure 2.37. below, comprising:

- two 1000 sq. mm Copper cables in 2 PE tubes of ∅ 200 mm;
- tubes fixed with supports to the wall;
- all protected by a perforated stainless steel plate permitting heat removal.

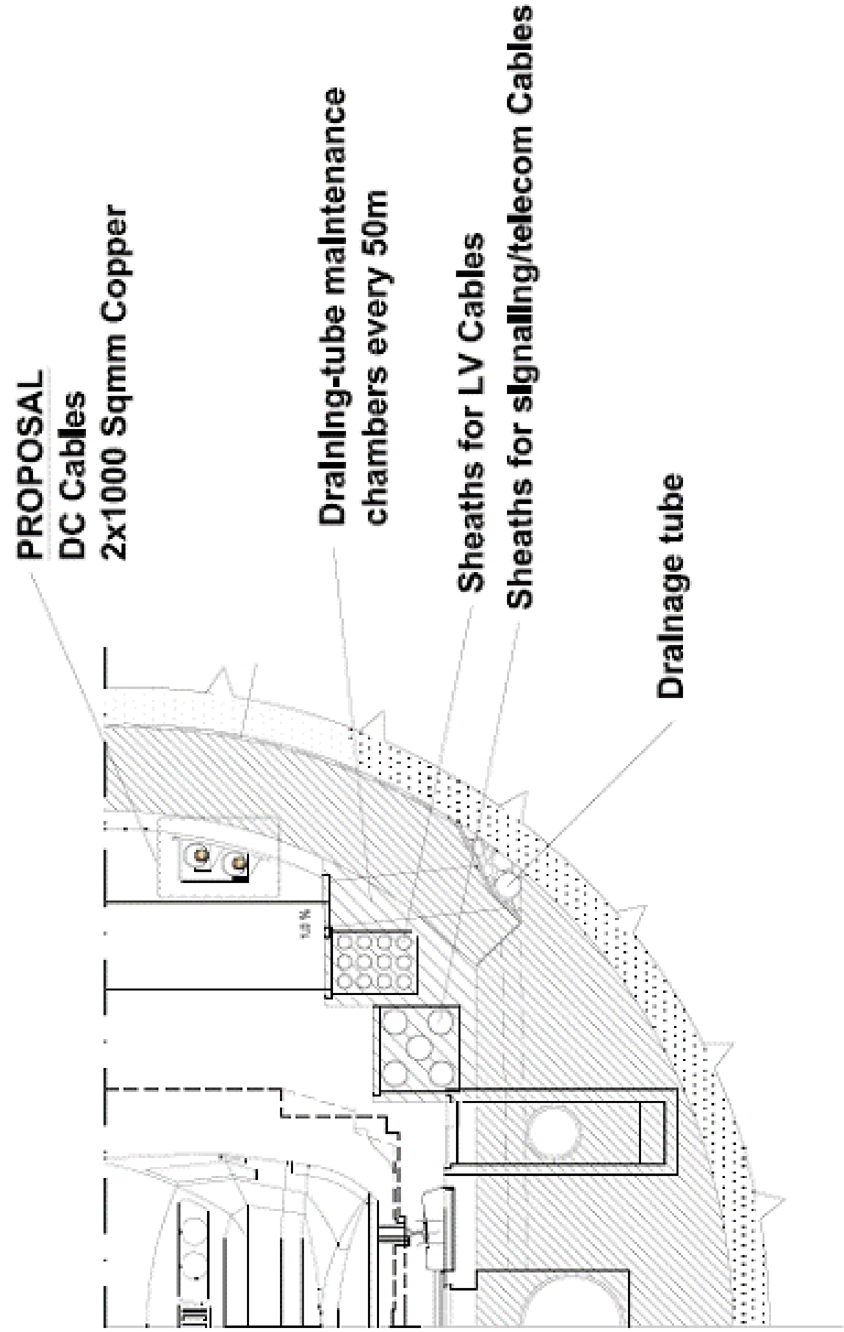

PROPOSAL
DC Cables
2x1000 Sqmm Copper
Draining-tube maintenance
chambers every 50m
Sheaths for LV Cables
Sheaths for signalling/telecom Cables
Drainage tube

Figure 2.37.

This can only be imagined conditional to not encountering on the side of the tunnel on which it is intended to place the link a number of obstacles such as access zones to emergency galleries or, like for the Lyon - Turin tunnel, areas to house the transformers and MV cells.

Should such zones be planned, and this is likely to be so, as illustrated by the above figure 2.34. which clearly shows an "emergency stop station", the conclusion would be that it becomes difficult to install a VHV link in these tunnels, and especially in the Gotthard tunnel, without having to make substantial rearrangements or modifications to a structure of which the construction is already in progress, and therefore calls for an as early as possible decision whether or not to install a VHV link (before construction is too far advanced and renders link installation impossible).

As regards the Ceneri tunnel, installing a link in it may still be possible, taking into account that construction is about to start and that it may still be possible to adapt the drawings, again requiring a very urgent decision and quick response.

However, should only the Ceneri tunnel be capable of accommodating a VHV link, having this link in DC would no longer be justified and should therefore be replaced by a three-phase AC link with XLPE insulation.

This solution would entail even further problems, because in that case:

a) space would have to found for 3 phases;

b) the safety/security level would be less in the event of a defect;

c) this type of link could cause serious disturbances to the LV/telecom links and to the traction power supply to the overhead contact wires.

2.4.6. Conclusions

Considering the information as presently available to us, we feel it is most unlikely that a VHV link could be installed in the chain of tunnels composed of Zimmerberg/Gotthard/Ceneri.

2.5. Somport tunnel - Additional tunnel

Problem statement

- Analysis of the technical feasibility of integration into the (disused) Somport railway tunnel:
  - a HV link;
  - possible location;
  - type of link;
  - impact on the environment, magnetic field.

Methodology

- Collection of information from the tunnel managers:
  - cross-section of the tunnel;
  - present situation of the tunnel.

Major results

- The Somport (railway) tunnel has become an emergency tunnel for the new road tunnel. 17 evacuation galleries are built between the new road tunnel and the disused railway tunnel.
- The old railway tunnel could accommodate a 220 kV link (this voltage level being that of the transmission network situated nearest the tunnel).
- The type of link would be AC, three-phase, 220 kV.
- The magnetic field values depend on the current transited via the link and remain within the acceptable limits specified by the WHO.

2.5.1. Situation map

The railway tunnel of Somport is situated some 88 km from Pau.

It is 7.875 km long, of which 4.012 km in France.

Figure 2.38-1 gives the geographical position of the tunnel.

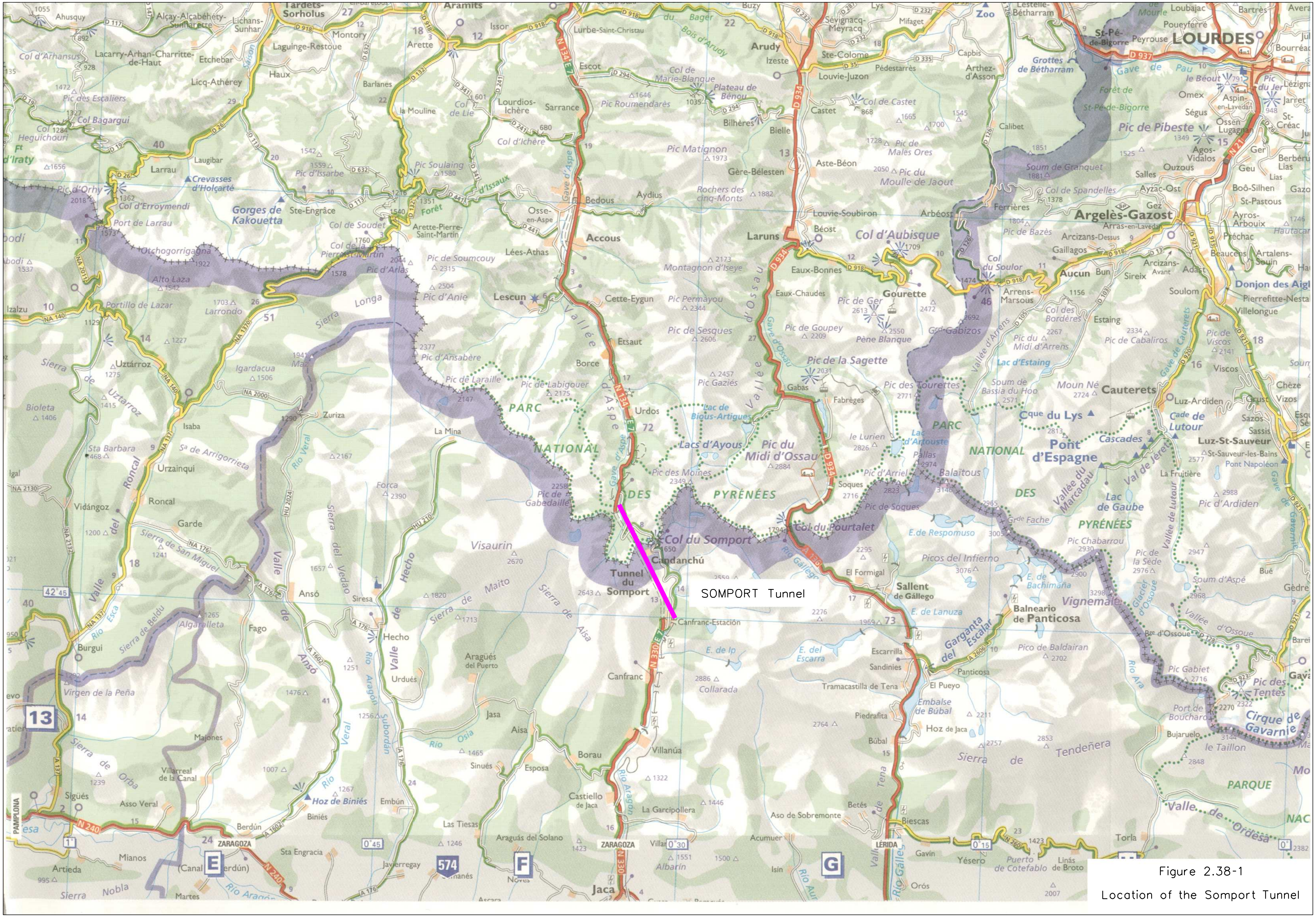


Figure 2.38-1

Location of the Somport Tunnel

Figure 2.38-2 below shows the position of this tunnel with respect to the French and Spanish VHV grids.

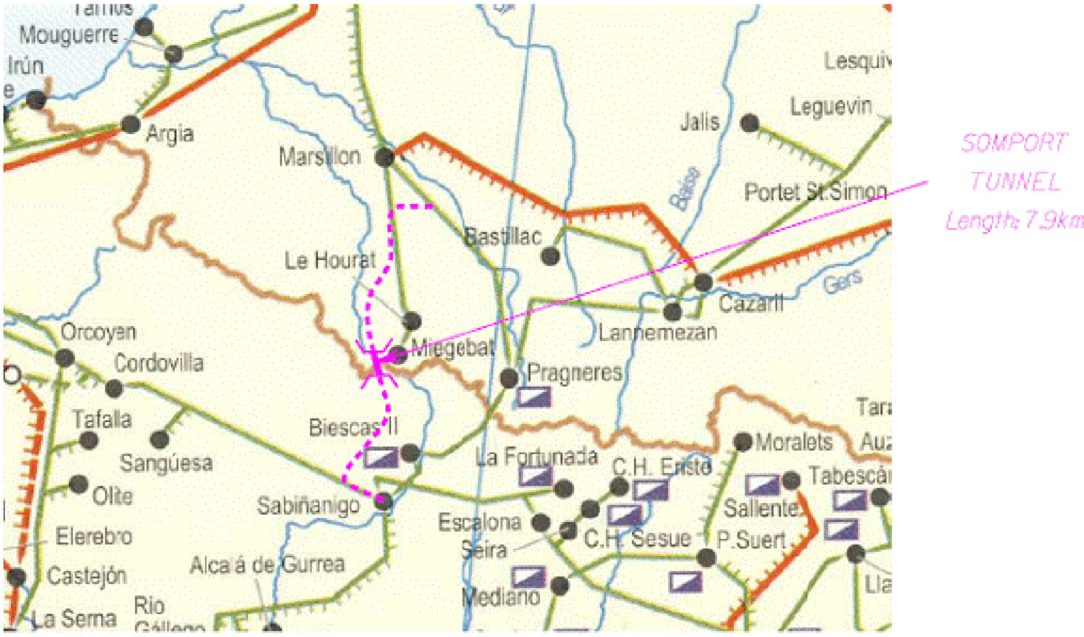


Figure 2.38-2

2.5.2. Present situation of the railway tunnel

The tunnel dates from 1928. In 1970 a goods train destroyed the bridge of l'Estanguet between Bedous and Lescun - Cette-Eygun (French side).

Figure 2.39.

SNCF (French Railways) refused to re-build the bridge (the line was loss-making).

The Oloron - Canfranc railway line is completely neutralised in 1985 and even the overhead contact system was dismantled.

In 2003, inauguration of a new road tunnel, 8.6 km long, of which 5.75 km in Spain and 2.8 km in France.

Figure 2.40. shows a cross-section of this road tunnel.

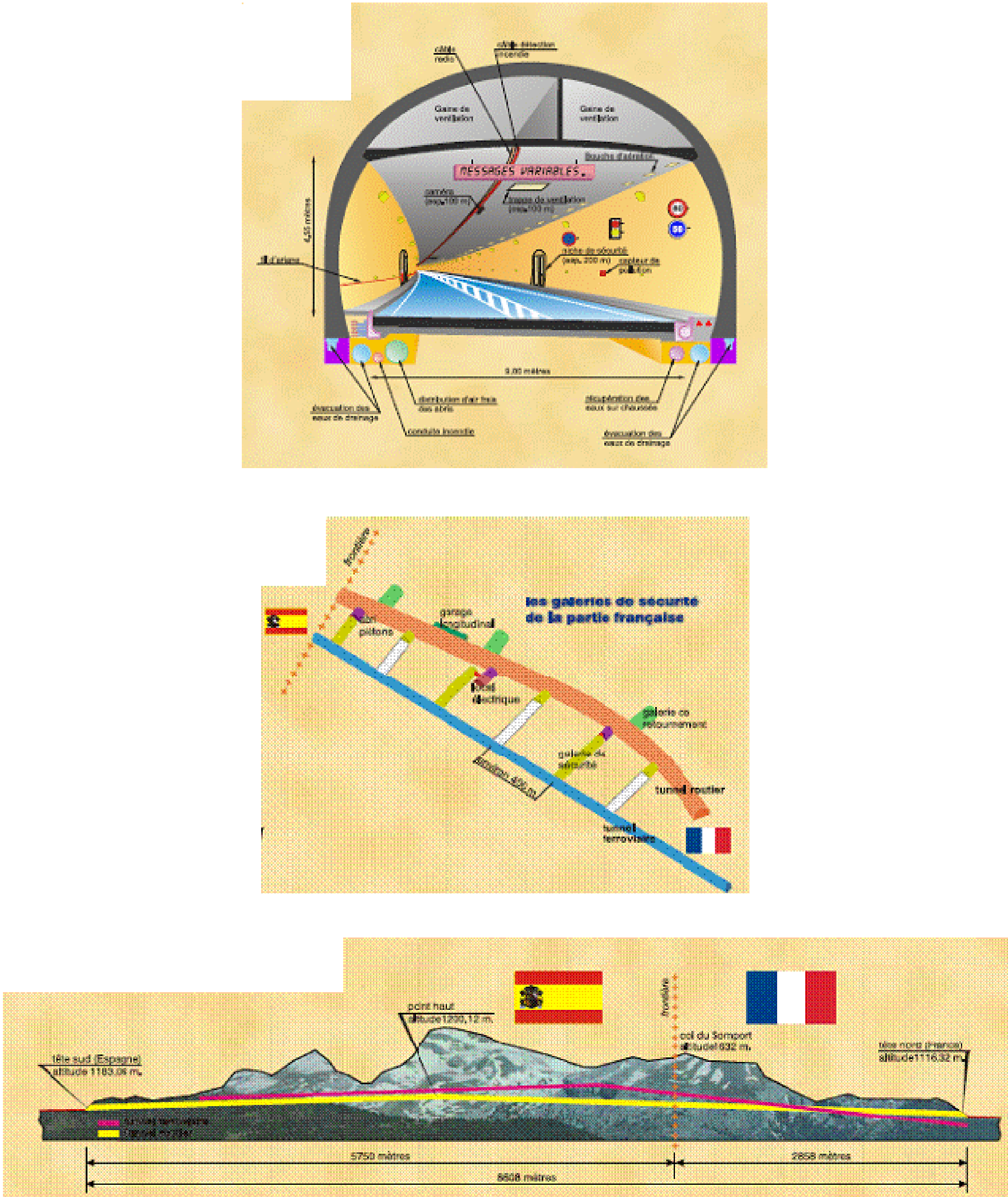


Figure 2.40.
(source http - pyrénées - atlantique)

After this, road and rail agree to cooperate with each other: the railway tunnel becomes the emergency tunnel for the road tunnel.

Evacuation galleries are built between the new road tunnel and the disused rail tunnel. The evacuation galleries, 17 in all, are spaced about every 400 m. There are six such galleries on the French side, 11 on the Spanish side.

The railway tunnel has been restored with a backfill of 0/31.5 materials.

2.5.3. Cross-section of the railway tunnel

Figure 2.41. gives a typical cross-section of the railway tunnel. The tunnel has a horse-shoe gauge.

The railway track has been backfilled with an 0/31.5 material, forming a 30 cm thick cover.

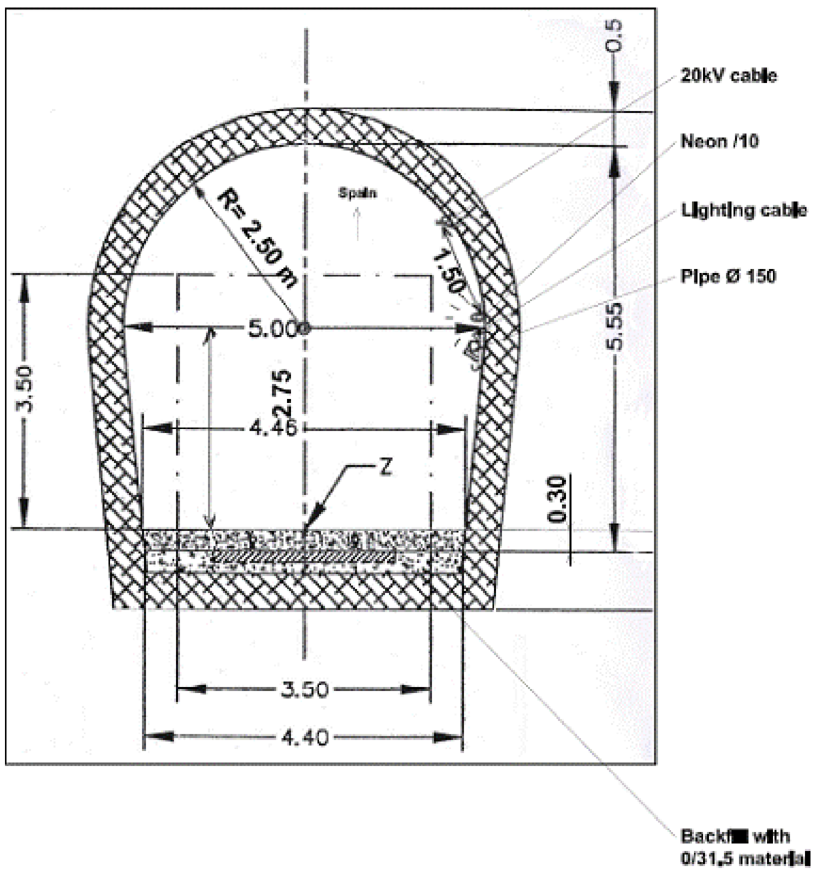


Figure 2.41.
Cross-section of the Somport railway tunnel

2.5.4. Possible location in the tunnel - Type of link

2.5.4.1. Type of link

Taking into account the length (≈ 8 km) we would propose an AC link with XLPE insulation.

The voltage level could be either 220 kV (grid nearest the tunnel) or 400 kV to be connected at the greater distance.

At this stage we propose to opt for the 220 kV level, which permits a transit of 500 MW (sheaths embedded in concrete) or 1300 A (Copper conductors).

2.5.4.2. Location in the tunnel

The figures 2.42-1 and 2.42-2 show the possible positions of the link:

→ either in the tunnel base (cables in horizontal configuration placed in 200 mm outside diameter PE tubes embedded in concrete); or

→ in vertical configuration on cable trays on a side wall; fixed on a tilting cradle and protected by a perforated stainless steel plate.

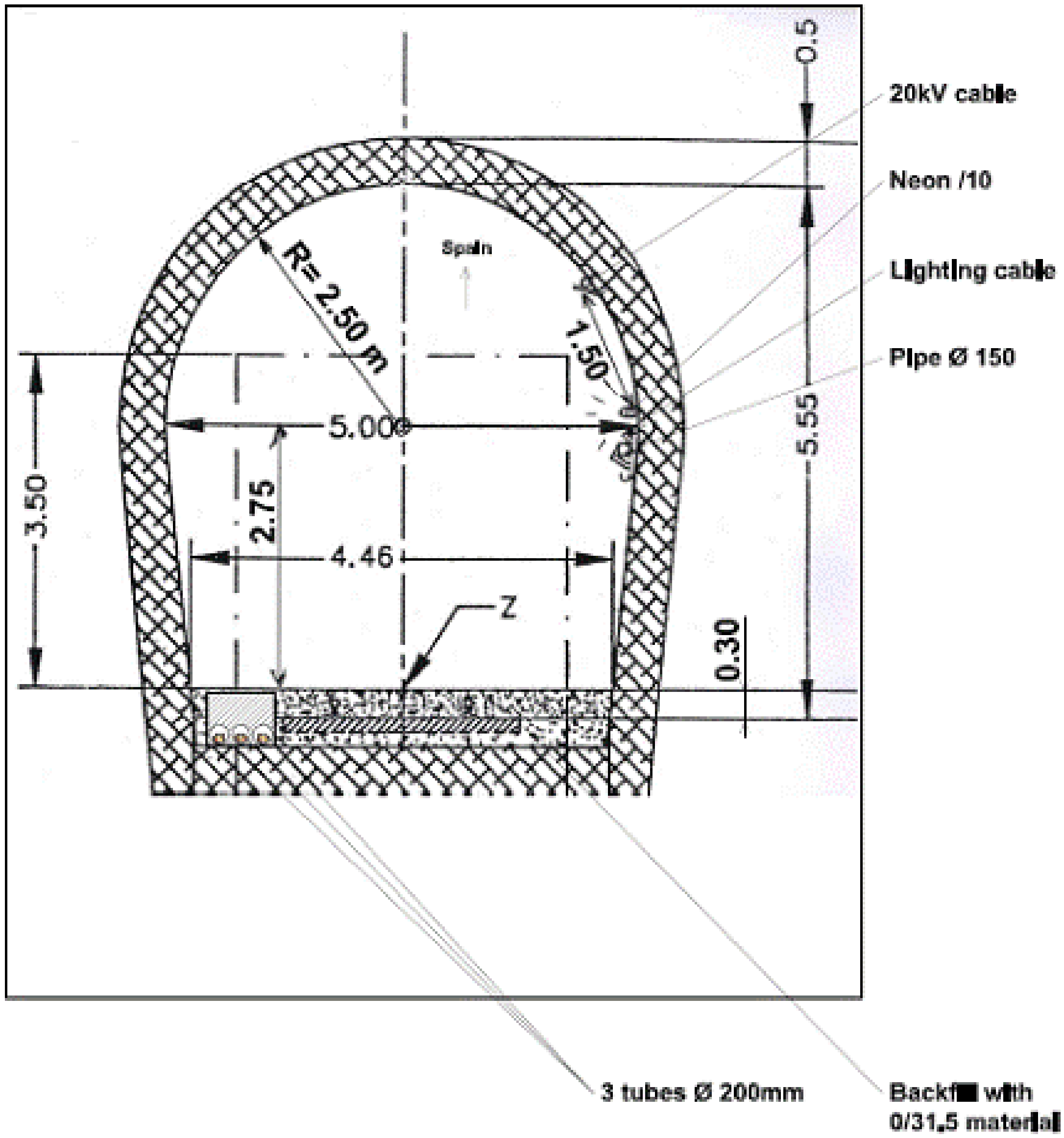

0.5
20kV cable
Neon /10
Lighting cable
Pipe Ø 150
Spain
R= 2.50 m
1.50
5.00
5.55
3.50
2.75
4.46
Z
0.30
3 tubes Ø 200mm
Backfill with
0/31,5 material

Figure 2.42-1

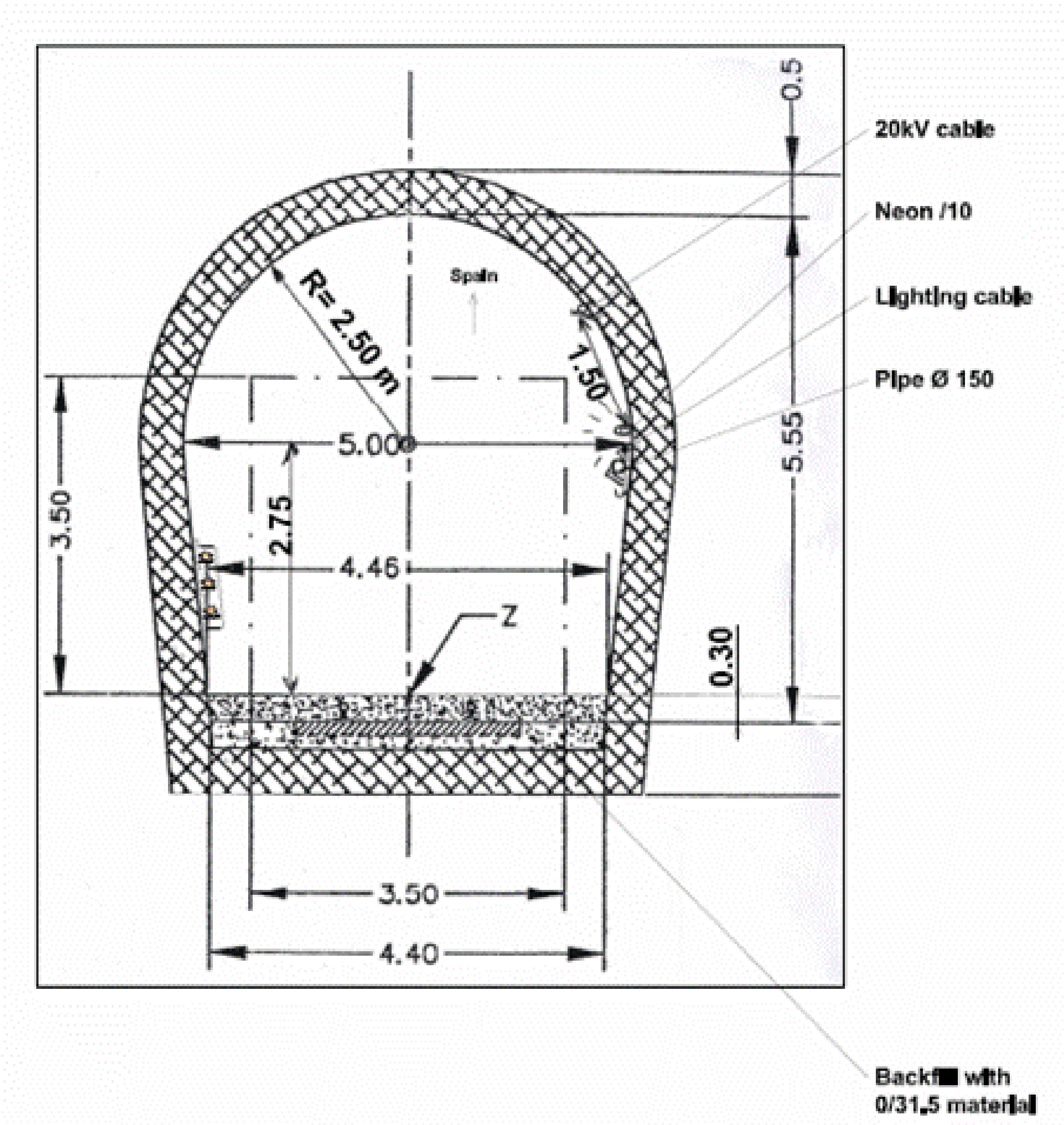

0.5
20kV cable
Neon /10
Lighting cable
Pipe Ø 150
Spain
R= 2.50 m
1.50
5.00
3.50
2.75
4.46
Z
0.30
5.55
3.50
4.40
Backfill with
0/31.5 material

Figure 2.42-2

2.5.5. Magnetic field

A calculation of the magnetic fields has been done for I = 1300 A in horizontal configuration and covered by concrete (depth of the centre line of the cables: - 0.5 m).

The magnetic field calculated is situated 1.5 m above the soil level.

Figure 2.43. below indicates the curve of the magnetic field.

At 1.5 m above the central cable the magnetic field is 19.5 µT.

At 2 m from the centre: E = 10.15 µT.

At 3 m from the centre: E = 6.24 µT.

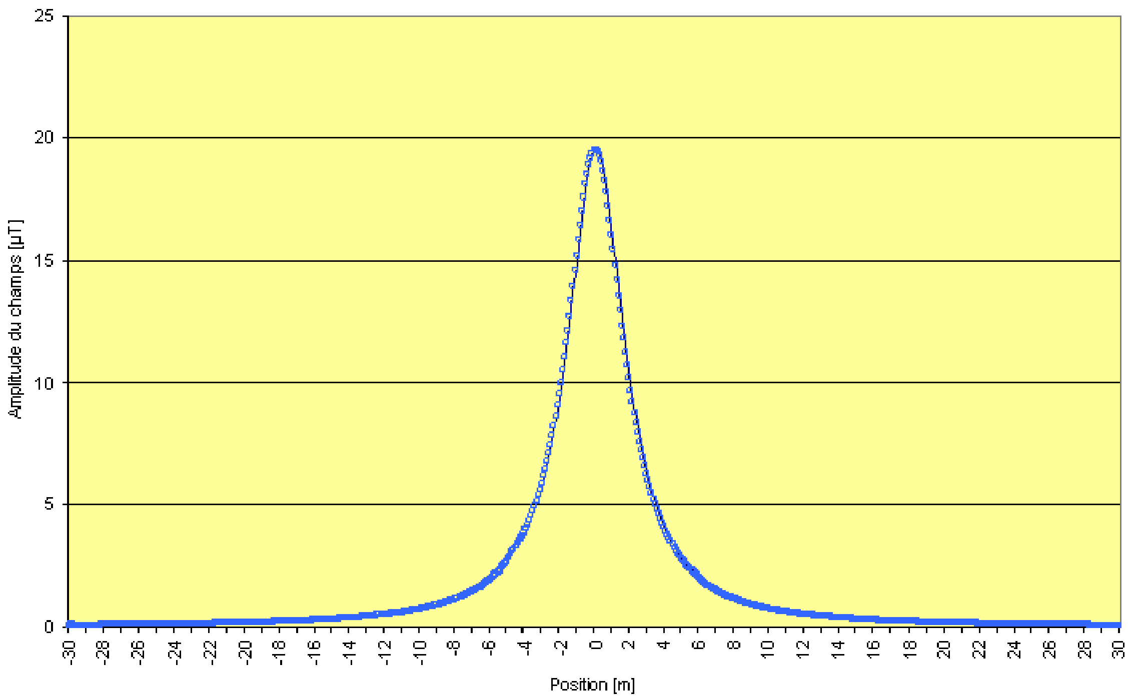


Figure 2.43.

3. Cables technology

Problem statement

- Analysis of the new technologies in AC/DC links compatible with the requirements for installation in a tunnel.

Methodology

- Consulting/discussions with suppliers of underground cable.
- Examination and comments on the technologies for cable types:
  - AC - XLPE insulation;
  - DC - Dry insulation;
  - GIL.
- Investigation of the cable behaviour in the event of failure - environmental impact.
- Investigation of the reliability level of the various technologies.

Major results

- AC - XLPE insulation

  This technology is well under control for voltage levels up to 400 kV and even higher. Development work has been done with a view to achieving a better transit capacity with a same cable cross-section.
- DC - Dry insulation

  This technology is fairly recent and is now under control. Long-term type-tests are underway on cables of ± 500 kV level.
- GIL technology

  This technology is an extension of the GIS technology. It is well under control, but the experience until now with operational installations relates to links that are of relatively short length. This technology permits very high capacity transit.
- Environmental impact
  - AC - XLPE insulation

    Important risk of explosion and subsequent fire; requires particular precautions.

Major results (cont'd)

- DC - Dry insulation

  In case of failure the risk is similar to that expected in case of a failure of a 20 kV AC cable.

- GIL

  The test performed demonstrates no burn-through of the enclosure.

➢ Reliability

- AC - XLPE insulation

  Very high, less than 0.2 failures/year/100 km terrain.

- DC

  No experience feedback. One may imagine reliability to be close to that of AC - XLPE cable.

- GIL

  No real experience feedback on GIL. The experience is derived mostly form that of GIS.

➢ Space consumption

- AC - XLPE

  3 cables to be installed in PE tubes (for protection in case of failure) (order of size: 3 ∅ 250 to 300 mm tubes).

- DC - Dry insulation

  2 cables (two poles). Recommendation: "inside PE tubes".

- GIL

  3 tubes of outside ∅ 500 to 600 mm (these consume considerable space).

This study includes:

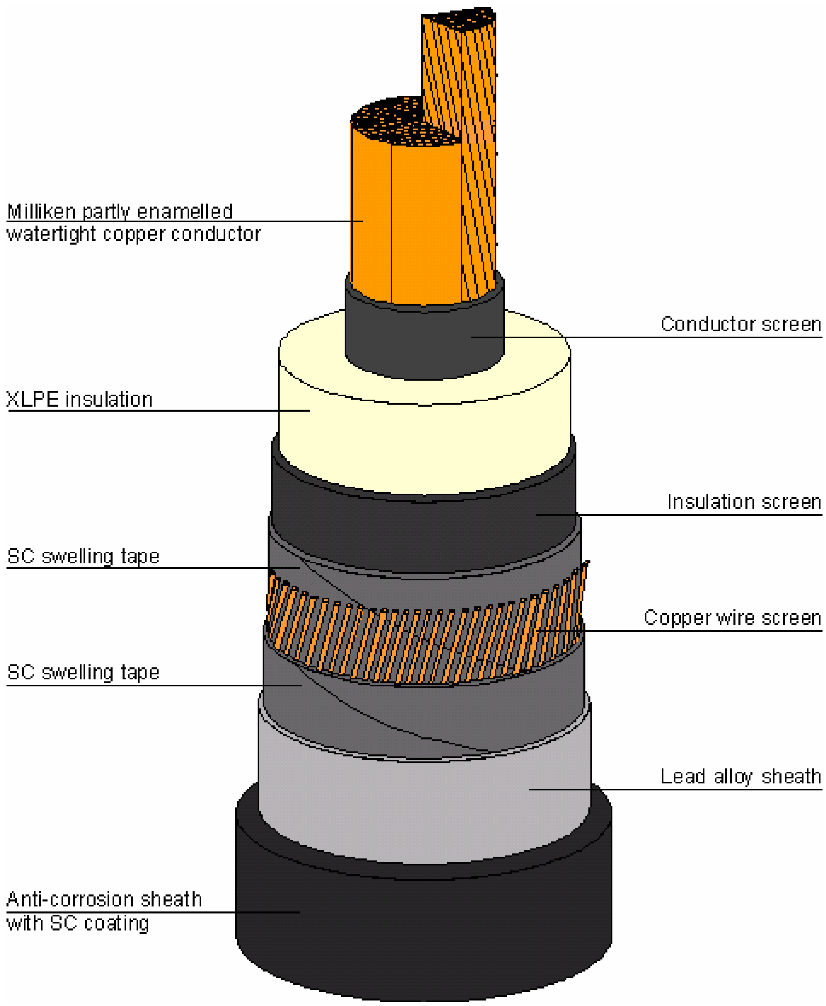
- type and level of AC/DC voltage;
- type of cable:
  - dry insulated cable (XLPE or PR insulation);
  - gas insulated cable - GIL type.

3.1. Cable technology - AC (U = 400 kV)

3.1.1. Cable technology

The structure of AC high voltage cable with synthetic cross-linked polyethylene insulation will always involve the following items.

A cross-section of a typical cable 400 kV - 2500 sqmm is shown in figure 3.1.



Dimensions are subject to manufacturing tolerances

NOT TO SCALE

		Diameter approx. mm	
Conductor		65	**2500mm² copper XLPE cable Copper wires + lead screen**
Insulation		123	
Copper wire screen (nominal section in mm²)		131	
Lead alloy sheath		138	**EeXeCLWgr 230/400(420)kV 1x2500/138**
PE outer sheath		151	
Weight (approx.)	51 kg/m		

Figure 3.1.

- **Conductor core**

The aluminium or copper conductor carries the electrical current.

The conductor behaviour is characterized by two particularly noteworthy phenomena: the skin effect and the proximity effect.

The skin effect is the concentration of electric current flow around the periphery of the conductors. It increases in proportion to the cross-section of conductor used. The short distance separating the phases in the same circuit generates the proximity effect. When the conductor diameter is relatively large in relation to the distance separating the three phases, the electric current tends to concentrate on the surfaces facing the conductors.

The wires of the facing surfaces indeed have a lower inductance than wires that are further away (the inductance of a circuit increases in proportion to the surface carried by the circuit). The current tends to circulate in the wires with the lowest inductance. In practice, the proximity effect is weaker than the skin effect and rapidly diminishes when the cables are moved away from each other.

The proximity effect is negligible when the distance between two cables in the same circuit or in two adjacent circuits is at least 8 times the outside diameter of the cable conductor.

There are two designs of conductor compact round stranded and segmental "Milliken" stranded.

→ <u>Compact round conductors, composed of several layers of concentric spiral-wound wires.</u>

In round stranded compact conductors, due to the low resistance electrical contacts between the wires, the skin and proximity effects are virtually identical to those of solid plain conductor.

→ <u>Segmental conductors, also known as "Milliken" conductors are composed of several segment-shaped conductors assembled together to form a cylindrical core.</u>

The large cross-section conductor is divided into several segment-shaped conductors. There are from 4 to 7 of these conductors, which are known as segments or sectors. They are insulated from each other by means of semi-conductive or insulating tape.

The spiral assembly of the segments prevents the same conductor wires from constantly being opposite the other conductors in the circuit, thus reducing the proximity effect.

This structure is reserved for large cross-sections greater than 1200 mm^2 for aluminium and at leas 1000 mm^2 for copper. The Milliken type structure reduces the highly unfavourable skin effect and proximity effect.

→ Enamelled copper wire

For copper conductors with a cross- section greater than 1600 mm^2, enamelled wires (around two thirds of the wires) are included in the structure of the Milliken type segmental conductor.

→ The proximity effect is a mast completely eliminated as each conducting wire follows a path alternating between areas that are far away from and areas close to the other phases conductors.

- **Reduction of the skin effect**

AC_{90} resistance / DC_{90} resistance	Conductor structure		
Cross-section (mm^2)	Compact round stranded	Milliken segmental stranded	Milliken enamelled stranded
1600	1.33	1.24	1.03
2000	1.46	1.35	1.04
2500	1.62	≈ 1.56	1.05
3000	1.78	≈ 1.73	1.06

The skin effect is reduced owing to the small cross-section of the wires used, each insulated from the others. In practice, a structure containing enamelled wires adds roughly a whole conductor cross-section.

For example, a 2000 mm^2 enamelled copper cables is equivalent to a 2500 mm^2 non-enamelled copper cable.

- **Semi-conductor screen on conductor**

To prevent electric field concentration, there is an interface of u ultra-smooth XLPE between the conductor and the insulation.

- **XLPE insulation**

As its name suggests, the insulation insulates the conductor when working at high voltage from the screen working at earthing potential. The insulation must be able to withstand the electric field under rated and transient operating conditions.

- **Semi-conductor screen on insulation**

This layer has the same function as the conductor screen: progressive transition from on insulating medium, where the electric field is non- null, to a conductive medium (here the metal cable screen) in which the electric field is null.

- **Metallic screen**

  When the voltage reaches tens or even hundreds of kV a metallic screen is necessary.

  Its main function is to nullify the electric field outside the cable. It acts as the second electrode of the capacitor formed by the cable.

  Use of metallic screen implies:

  - The need to connect it to earth at least at one point along the route.
  - Draining the capacitive current that passes through the insulation.
  - Draining the zero-sequence short-circuit currents, or part of them. This function is used to determine the size o the metallic screen.
  - The circulation of the currents induced by the magnetic fields from other cables in the vicinity. These circulating currents cause further energy loss in the cables and have to be taken into account when assessing the transmission capacity of a cable system.
  - The need to electrically insulate the metallic screen from earth over the greater part of the length of cable installed.
  - The need to protect the metallic screen from chemical or electrochemical corrosion.

  The second function of the metallic screen is to form a radial barrier to prevent humidity from penetrating the cable, particularly its insulation system.

  The synthetic insulation system should not be exposed to humidity. When humidity and a strong electric field are present together, the insulation deteriorates by what is called watertreeing, which can eventually cause the insulation to fail.

- **Different types of metallic screen**

  → <u>Extruded lead alloy sheath</u>

  - Advantages
    - . Waterproofing guaranteed by the manufacturing process
    - . High resistance therefore minimum energy loss in continuous earthing links
    - . Excellent corrosion resistance
  - Drawbacks
    - . Heavy and expensive
    - . Lead is a toxic metal whose use is being restricted to a minimum following European directives
    - . Limited capacity to expel zero-sequence short-circuit currents

→ Concentric copper wire screen with aluminium tape bonded to a polyethylene or PVC jacket

- Advantages
  - . Lightweight and cost effective design
  - . High short-circuit capacity
- Drawbacks
  - . Low resistance necessitating special screen connections (earthing at one point or cross-bonding) in order to limit circulating current asses

→ Aluminium screen welded longitudinally and bonded to a polyethylene jacket

- Advantages
  - . Lightweight structure
  - . High short-circuit capacity
  - . Impervious to moisture guaranteed by the manufacturing process
- Drawbacks
  - . Low resistance necessitating special screen connections (earthing at one point or cross-bonding) in order to limit circulating current losses
  - . Higher Eddy Current losses than with the previous screen types

→ Copper wire screen with extruded lead sheath

This is a combination of the above designs. It combines the advantages of the lead sheath and concentric copper wire screen.

Its main drawbacks lie in its cost and the lead content.

The copper wire screen is placed under the lead sheath thus enabling it to share the anti-corrosion properties of the latter.

- **Anti-corrosion protective jacket**

The jacket has a dual function:

- it insulates the metallic screen from ground (particularly for lines with special screen connections);
- it protects the metal components of the screen from humidity and corrosion.

The outer jacket must also withstand the mechanical stresses encountered during installation and service as well other risks such as termites, hydrocarbons, etc.

The most suitable material for this is polyethylene.

PVC is still used but increasingly less so. Indeed one of the advantages of PVC is its fire-retardant properties, although the toxic and corrosive fumes released are prohibited by many users.

If "fire-retardant" is specified in accordance with IEC standards 332, HFFR (Halogen-Free Fire Retardant) materials will be used in preference to PVC.

These materials however have mechanical properties that are inferior to those of polyethylene and are more costly. They should be reserved for installations or carts of installations where fire protection is required.

To verify the integrity of the outer jacket, a semi-conducting layer is often applied to this jacket.

This layer can either be a graphite paint or a layer of semi-conducting polymer co-extruded with the outer jacket.

- **Summary**

Item	Function	Composition
Conductor	- To carry current . Under normal operating conditions . Under overload operating conditions . Under short-circuit operating conditions - To withstand pulling stresses during cable laying	$S \leq 1000\ mm^2$ (copper) or (aluminium) Compact round stranded cable with copper or aluminium wires $S \geq 1000\ mm^2$ (copper) segmental $S \geq 1200\ mm^2$ (aluminium) segmental
Internal semi-conductor	- To prevent concentration of electric field at the interface between the insulation and the internal semi-conductor - To ensure close contact with the insulation - To smooth the electric field at the conductor	XLPE semi-conducting shield
Insulation	To withstand the various voltage field stresses during the cable service life: - rated voltage - lightening overvoltage - switching overvoltage	XLPE insulation The internal and external semi-conducting layers and the insulation are co-extruded within the same head
External semi-conductor	- To ensure close contact between the insulation and the screen. - To prevent concentration of electric field at the interface between the insulation and the external semi-conductor.	XLPE semi-conducting shield
Metallic screen	To provide: - An electric screen (no electric field outside the cable) - Radial waterproofing (to avoid contact between the insulation and water) - An active conductor for the capacitive and zero-sequence short-circuit current - A contribution to mechanical protection	- Extruded lead alloy, or - Copper wire screen with aluminium bonded to a PE jacket - Welded aluminium screen bonded to a PE jacket - Combination of copper wires and lead sheath
Outer protective sheath	- To insulate the metallic screen from he surrounding medium - To protect the metallic screen from corrosion - To contribute to mechanical protection - To reduce the contribution of cables to fire propagation	Insulating sheath - Possibility of semi-conducting layer for dielectric tests - Polyethylene jacket - HFFR jacket

3.1.2. Additional information - Insulation thickness

For this type of cable with XLPE insulation and taking into account the thickness of the insulation used, the dielectric stress would be:

- cable core : ± 13 kV/mm
- on the insulation: ± 6 kV/mm

These values are perfectly acceptable.

Additional information:

- In 1996, cables were manufactured with stresses of 13 and 6 kV/mm.
- In 2000, these same stresses increased respectively to 15 and 7 kV/mm.

Currently, certain manufacturers produce cables with an insulation that allows maximum stresses to reach 18-20 kV/mm

This is linked to cable manufacturers' skills as regards the quality of the insulation used (e.g. tests, controls) and the implementation process itself.

3.1.3. Voltage

The maximum voltage is foreseen for going up to 500 kV.

Actually the manufacturers produce XLPE cables and accessories up to 400 kV.

3.1.4. Dimensions - size of the sections (for information)

The following is required to transit 1,000 MW - 400 kV AC, i.e. I = 1,550 A:

1) <u>In the air</u>

- Cables in close horizontal formation

  1,600 mm^2 copper (I = 1,415 A) or 980 MW

- Cable in vertical configuration with 25-cm spacing

  1,600 mm^2 copper (I = 1321 A) or 915 MW

- In close trefoil formation

  1,600 mm^2 copper (I = 1589 A)

Only cables in close trefoil configuration - 1,600 mm^2 copper are suitable for transit of 1,000 MW.

2) In concrete
(in a 10-mm thick HDPE sheath)

A 2500 mm2 copper allows a maximum transit of 820 MVA (I = 1182 A).

3.1.5. Current development work and technological changes

- Cable with insulated wire conductor, with low shin and proximity effects, for less energy loss and increasingly higher unitary carrying capacity.
- Cable with welded aluminium screen bonded or not bonded to the outer synthetic jacket.
- Cable with integrated optical fibre (which serves to control the temperature along the whole cable length offering better grid efficiency). A Nexans mainly development for the Benelux countries (Belgium, Netherlands and Luxemburg).
- Joint with integrated mechanical electrical and anti-corrosion (HOP type) protection for minimum volume, robust design and restricted number of on site manual operations.
- Sealing ends with explosion-proof device for increased sub-station safety.
- Fully synthetic sealing ends, for minimum maintenance.
- Composite sealing ends, for greater safety and shorter procurement times.
- Joint and sealing end with integrated partial sensors for early PD detection.
- Dry GIS sealing end oil maintenance free.
- Dry outdoor sealing end, fluid (gas or oil) maintenance free.

3.2. Technology currently used in high-voltage cables for direct current - extruded synthetic insulation cable

3.2.1. State of the technology

Since the 1970s, many studies have been carried out to identify suitable types of insulation for high-voltage direct current cables with extruded synthetic insulation.

It should be noted that although XLPE or PR insulations are fully compatible with alternating current connections they are much less suitable for direct current connections due to the accumulation of space charge in the insulating material.

The following section provides a brief summary of the type of physical phenomena involved and the impact they have on the way in which the cables function.

When direct current is passed through an insulation via two metallic electrodes, the problem of the distribution of the electric field in the material is simple if the dielectric medium is perfect.

However, actual scenarios are quite different because the problem is much more complicated in real insulations due to the free charges in the dielectric medium.

There are two types of free charges.

Each type has its own characteristic and moves about in the insulation to form areas of different density.

They are produced by the insulation (intrinsic charges) and the electrodes, which in this case are the installed semiconductors at both ends of the insulator (these are doped charges).

These doped charges can also result from contact between the dielectric surface and a group of charged particles.

Moreover, inside each insulation there are what are known as traps which are actually empty spaces or interfaces.

Due to the fixed DC polarisation, these free charges are attracted to or repelled from these traps (depending on their polarity).

Once these free charges are caught in the traps they create areas of space charge that change the stability of the material. These space charges create areas of different electric fields that change the constant conduction current.

This change can go as far as the disruptive gradient of the insulation.

Moreover, as noted above, the dielectric terminals (capacitors) are semiconductors.

Due to their function, these semiconductors are highly charged.

Consequently, if care is not taken, these charges are injected into the insulation which aggravates the problem further.

Hence the need to develop semiconductors with a low tendency to inject charges into the insulator but remain semiconductive.

Moreover, in order to prevent thermal runaway, insulation with high resistivity need to be used to limit the leakage current (conduction) in the insulator.

Summary: high-voltage cables for direct current are affected by electrical and thermal stresses.

The resistivity of insulation materials used for these cables therefore depends on the temperature and/or electric field; this results in the accumulation of space charges in the insulation which cause structural changes to the material.

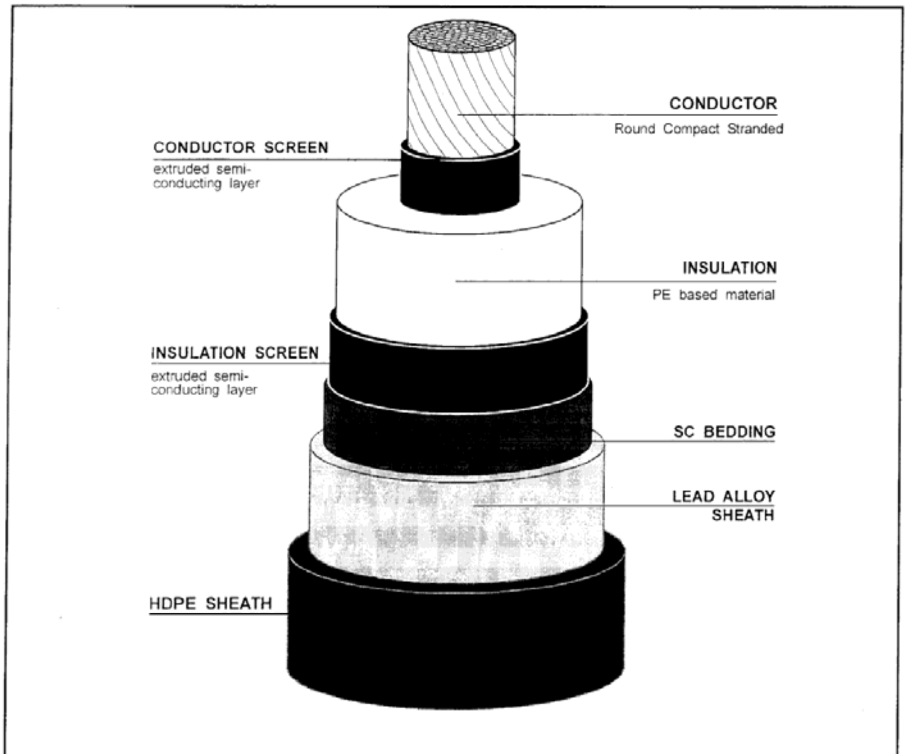
Several types of insulation using polyethylene as the base element have already been tested. Long-term tests are currently being carried out on extruded DC cables at a voltage of approximately 500 kV.

Extruded synthetic insulation cables are primarily made of:

- a conducting core of copper or aluminium;
- insulation screen;
- extruded synthetic insulating sheath made from a polyethylene base, polyethylene alloy or modified cross-linked polyethylene;
- insulation screen;
- metallic shield made of either an extruded lead sheath, strip of aluminium soldered with copper wires or a combination;
- external protective sheath.

A cross-section of a typical cable can be found in figure 3.2.

The maximum operating temperature depends on the type of insulation used and is between 70° C and 80° C.



Dimensions are subject to manufacturing tolerances

NOT TO SCALE

	Nominal thickness mm	Diameter approx. mm	
Conductor, 1000 mm² Copper		39.9	
Conductor screen, SC PE	1.5	43.4	
Insulation, PE based material	19.7	82.8	**HVDC Qualification Cable**
Insulation screen, SC PE	1.5	85.8	
SC Swelling tape	0.5	87.2	
Lead Alloy Sheath	2.5	92.2	**1000 mm² Copper cable for DC application**
Anticorrosion sheath, HDPE	3.0	99	
Weight	22.3 kg/m approx		
Date	23/03/2006		

Figure 3.2.

3.2.2. Main criteria for establishing the dimensions of DC cables

The main criteria are:

- maximum permissible temperature for the conductor;
- voltage stress in the conductor with zero load;
- voltage stress in the external sheath at full load.

To understand the third criterion, it must be reiterated that:

1. with AC voltage the electrical stress depends on the permittivity of the material which is independent of the temperature;

2. with direct current the distribution of the stress in the dielectric medium depends on the resistivity of the material (leakage current) which is dependent on the temperature.

Therefore, at zero load, and when temperature in the cable insulation is uniform, stress distribution follows a curve similar to that for AC where the stress at each point is inversely proportional to the distance between the point concerned and the centre of the cable.

The increase in the charge causes temperature to increase through the insulation and stress decreases close to the conductor and increases gradually. This is known as stress inversion.

The general objective is to achieve a dielectric stress on the insulator shield at full load similar to the dielectric stress on the conductor shield at zero load, which in certain cases determines the maximum load in the cable rather than the maximum temperature permissible on the conductor.

The diagram below shows the electric stress in the insulation of a DC cable.

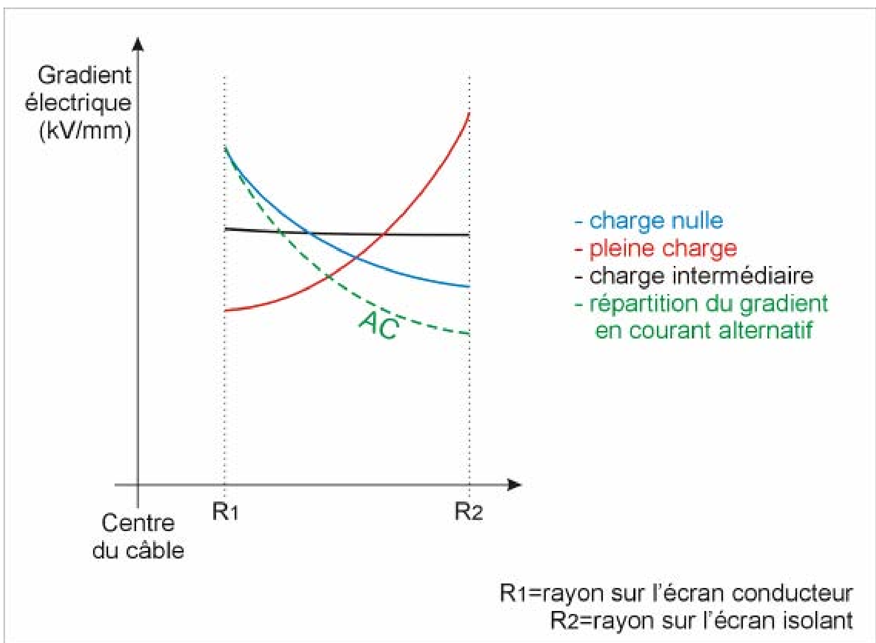


Figure 3.3.
Electric stress in the insulation of a DC cable

Gradient électrique	=	*electric stress*
Charge nulle	=	*zero load*
Pleine charge	=	*full load*
Charge intermédiaire	=	*intermediate load*
Répartition du gradient en courant alternatif	=	*electric stress in AC*
R_1	=	*radius on the screen of the conductor*
R_2	=	*radius on the screen of the insulator*

- Transient voltage (during polarity reversal).
- Internal pressure during heating-cooling cycles.

Calculations for DC section where P = 1,000 MW with dry insulation:

- in the air:
  - 500 kV/DC → 630 mm^2 copper;
- in sheaths covered with concrete:
  - 500 kV/DC → 630 mm^2 copper;
  - 400 kV/DC → 1,000 mm^2 copper.

3.3. "GIL" (Gas Insulated Line) - technology

3.3.1. Introduction

The first generation of GIL has been developed with purely GIS technology. It has been directly used inside or in relation with gas insulated substations and is well adapted to connection lengths up to several hundreds of metres. The total world-wide experience, all manufacturers and voltage cumulated from 72.5 kV to 550 kV, is estimated to be more than 300 km single phase circuit (mainly outgoings of power plants).

A second generation of GIL technology is now emerging.

Application to transmission networks from 145 kV to 550 kV is now possible with the best economical performances probably for 400 kV and 550 kV networks.

This chapter describes a typical 400 kV GIL. Different aspects of the technology are presented:

- basic performance and main technical features;
- type testing;
- manufacturing and factory testing;
- erection and testing on site;
- monitoring, maintenance and reparation.

GIL has an intrinsic very high transmission capability. Typically, in open-air conditions, it allows up to 5000 A (~ 3500 MVA at 400 kV) with a short time current of 63 kA.

Numerous different arrangements such as above ground arrangement, trenches with or without cover, tunnels and directly buried arrangement are possible. The permissible transmission capability is of course depending on arrangement and on conditions such as ambient temperature and ventilation.

In addition to evident advantages over overhead lines like insensitivity to weather conditions and reduced visual impact, GIL has a higher current rating, lower emitted electromagnetic field and lower capacitance than conventional cables.

3.3.2. Basic performance and main technical features

3.3.2.1. Basic performance

For a typical use on a 420 kV network, the rated performance according to IEC standards [1] are:

- service voltage: 420 kV;
- power frequency withstand voltage: 630 kV;

- lightning impulse withstand voltage: 1425 kV peak;
- switching impulse withstand voltage: 1050 kV peak;
- transmission capability up to 4500 A depending on installation and ambient conditions;
- short-time (1 s) withstand current: 63 kA.

3.3.2.2. Main technical features

Large quantities of SF6 present obvious concerns on environmental grounds. The second generation of GIL introduces two main technical features which address the need to prevent the release of SF6 to the atmosphere:

- Use of an insulation mixture of nitrogen and SF6 (10% to 20%) instead of pure SF6, which entails more complicated gas handling operations but allows for a major reduction in the quantity of SF6 gas.

  Note that in this assumption the weight of SF6 is 3.7 tonnes/km for the three phases. With a compartmenting of 150 m this would result in the order of 180 kg of SF6 per phase.

  The relative pressure is 9.3 bar for the filling pressure and 8bar for the minimum pressure. This technology has been in use for many years in high voltage switchgear for application in extreme low temperature regions, N2/SF6 mixtures are now well known. Their dielectric behaviour has been widely investigated. Equipment for all handling operations (mixing-filling, quality, checking, recovering-recycling-separation) is now commercially available.

- Connection between enclosures by welding on site: This technology requires a perfect mastering of welding process in any situation which could be encountered on site and a more specialised site organisation. This practically eliminates the risk of leakage occurrence during the life of the equipment, and thus allows a much lower leakage rate than IEC requirement. The aluminium enceinte has an internal diameter of 500 mm. The wall thickness of the enclosure is dependent upon the continuous current, ambient temperature and arrangement. Typically wall thickness between 6 and 10 mm are used.

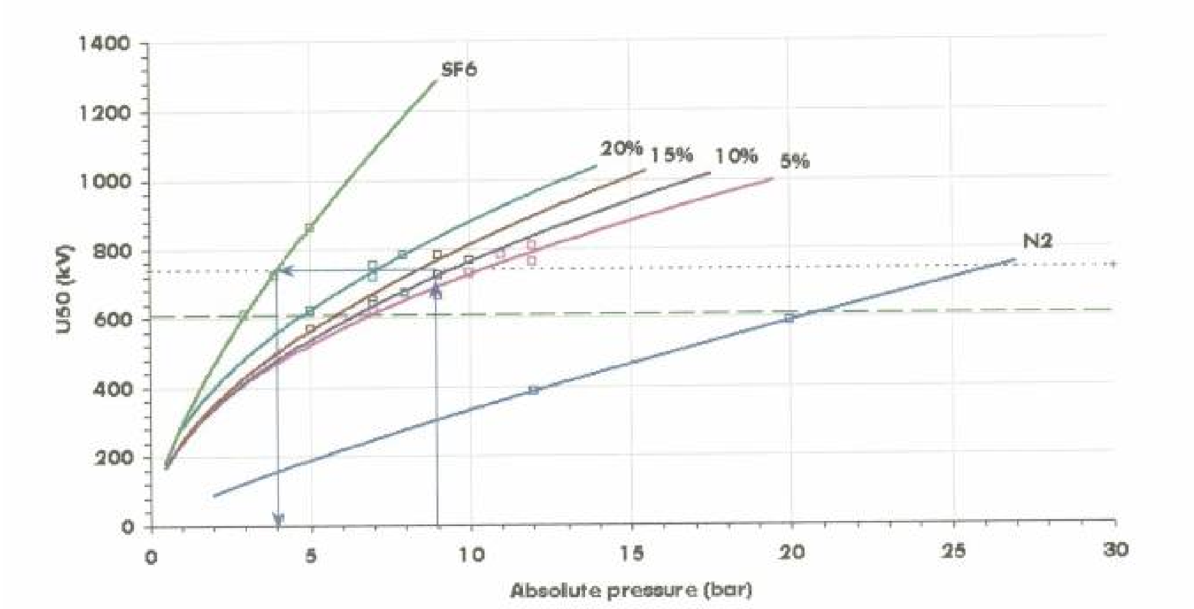


Figure 3.4.

- Gas mixture

  Studies have shown that using mixtures of N2/SF6 at low SF6 content permits achieving dielectric performances equivalent to those with pure SF6. For example, a dielectric strength achieved at 4 bar with pure SF6 can also be achieved by a mixture at 9.4 bar with only 10% of SF6. Such a mixture would also help preserve the environment..

  However, the mixture has its limits.. Indeed the dielectric strength increases to 11 bar with a mixture that is 5 % SF6/95 % N_2 and to 27 bar with 100 % $N_{2,}$ which is technically not realistic.

  Furthermore it becomes extremely difficult to achieve a good stability of the dielectric strength if the proportion of SF6 drops below 10 %.

  At present the proportion of 20/80 is the best compromise mainly due to the partial discharges analysis.

Basic design principles have been chosen in order to provide the highest possible availability for the transmission system for a lifetime of 40 years or more:

- use of materials for which long term behaviour is well known with metal enclosed substations, the oldest of which are still in service after more than 30 years;
- large safety margin for dielectric, thermal and mechanical stresses;

- special care to the cleanliness during the life time of the equipment by using:
  - low wear contacts;
  - fixed parts where possible;
  - particle traps both on the side of the contacts of the conductors and on the side of the enclosure.

The resulting design (see fig. 3.5. and 3.6.) is characterised by:

- Special conductors formed from aluminium alloy tube. Large cross section (typically outside diameter of 180 mm and thickness of 11 mm) allows for low resistance (< 4.9 mΩ/km). Length of the conductors is typically in the range from 12 to 18m depending on the project. A maximum length of 18 m has been type tested. The conductor is pre-formed with a curved profile to compensate for gravitational sag.

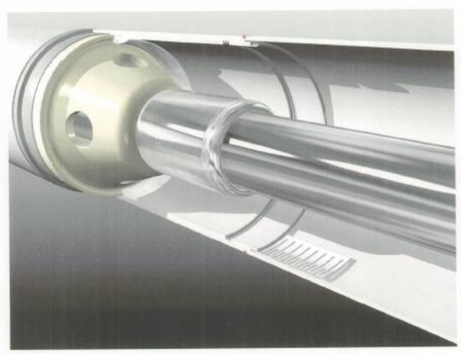


Figure 3.5.
Internal configuration of GIL

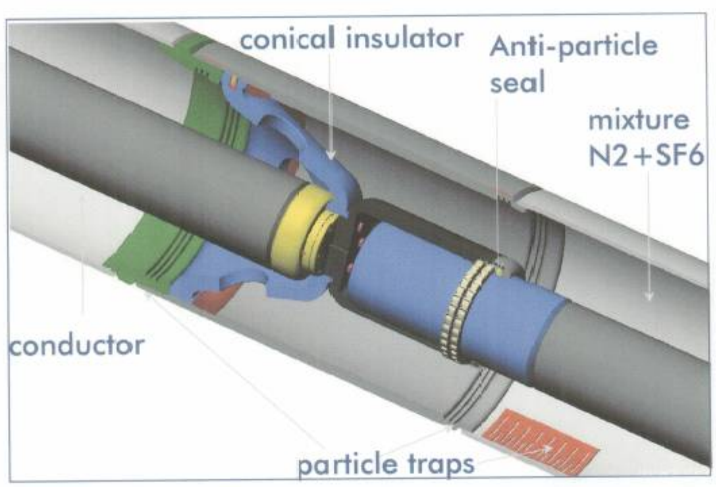


Figure 3.6.

- Conical support insulators of filled epoxy resin with long creepage distance and limited electrical stress.

  This type of support insulator is specific for GIL; the special GIL insulators are made up of mixture of high temperature epoxy resin and wollastonite. The glass transition temperature is 130° C, which provides a large margin to the maximum working temperature, which is 105° C in the most stringent conditions.

- GIS type silver-plated contacts. The sliding contacts allow the thermal expansion between the enclosure and the conductor to be absorbed. These contacts are the same as those used in GIS. Contact wearing test have been performed with more than 20,000 operating cycles with the maximum possible stroke which in practice corresponds to an higher wear than the one resulting from the whole equipment life.

  Very low wear and "non generation" of particle behaviour has been proved. However, any particles that are accidentally generated are trapped by a seal, which prevents them from entering into the enclosure (see Fig. 3.5. and 3.6.).

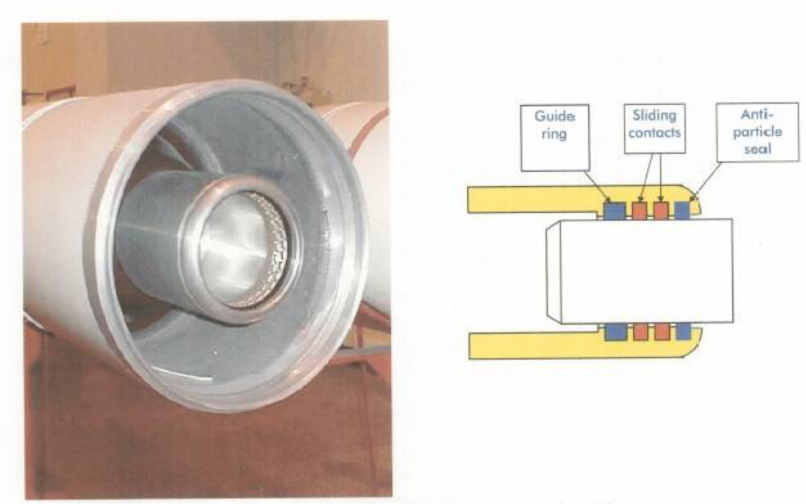


Figure 3.7.
Configuration of internal contacts

- Inside the enclosures, particle traps deal with the presence of contamination which may have been introduced at the time of assembly.

3.3.2.3. Thermal expansion - Insulation co-ordination

Ambient temperature variations, solar radiation in case of open air arrangement and the current flowing in conductors and enclosures result in thermal expansion of the conductors and enclosures.

Differential thermal expansion between conductor and enclosure is compensated for each conductor length by the sliding contacts shown in Fig. 3.7.

The solutions adopted to compensate for thermal expansion of enclosures are much dependant on the current rating, the extreme atmospheric conditions which can be encountered and, the length, the route and the arrangement of the GIL.

Several solutions are available like natural bending of GIL, radial bellows in the corners, axial bellows in the straight portions with sliding/guiding supports and withstand of pressure efforts by reinforced structures and civil works.

Any particular situation requires study in order to optimise the solutions.

Insulation co-ordination also requires study taking into account the particular situation of the GIL in the network, as is usually done for large GIS substations. The long lengths of GIL may reinforce the effects of travelling wave reflections on the ends due to changes in characteristic impedances (connection to overhead lines or cables) and may need protection by lightning arresters fitted at the ends of the GIL, on line side or on GIL itself.

3.3.3. Manufacturing and factory routine testing

Shipping units comprising basic sections (maximum length 12 to 18 m) including the enclosure, the conductor and a support insulator are manufactured, assembled and routine tested in the factory.

- The section of enclosure is made of two different parts welded together using a TIG process (tungsten inert gas) supplied with dc pulsed current.
- Routine tests are performed on all shipping units including:
    - gas-tightness of the enclosures according to the standard vacuum test with helium;
    - tests on welded joints either by hydraulic pressure test or by non-destructive control (ultrasonic process or X-ray).

3.3.4. Erection and testing on site

Erection and testing of this new GIL technology requires strong and rigorous site organisation and procedures in order to ensure a high level of reliability.

The shipping units are assembled on site according to the following process:

- Inspection of the cleanliness of the different components after transportation using a video camera moved inside the enclosure by a robot.
- On site assembly of conductors is a simple process of plugging the elements together.
- Two types of assemblies
    → Orbital welding of the enclosures of the different sections with special generator of de-pulsed current. A special ring prevents against pollution entering daring welding.

GIL elements are welded in their final location, even in limited space. This can be done in any route and situation using adapted tools and processes.

→ Bolted assembly with bolts and flange.

- Inspection of the welded joint by ultrasonic process.
- Gas-tightness of the enclosures according to the accumulation method with SF6.
- Pneumatic. pressure test on complete compartment at 1.1 times the design pressure (or greater depending on local regulations). This test may require specific organisation and precautions in order to meet safety rules.
- Drying of the gas compartments by vacuum.
- Filling with gas mixture.
- Dielectric test (ac test) with a partial discharge detection using Ultra High Frequency method performed on sections of 200 m to 1 km depending on test generator.

3.3.5. Earthing system

The earthing circuit has been designed in order to achieve a maximum touch voltage much lower than 70 V.

Figure 3.8.
Connection of GIL enclosure to the earth

The GIL enclosures are solidly bonded and earthed at both ends of the line, below the gas to air bushings, and at a different point of the line. The steel supports of the above ground section are earthed. The GIL enclosures are earthed in the proximity of every two supports. In the trench section, the supports are connected to the GIL enclosures.

3.3.6. Partitioning, monitoring, maintenance and repair

The choice of the compartments dimension is the result of an optimisation between various conflicting constraints like GIL length and route, cost, availability of gas handling and storage facilities, etc. In practice the length of gas compartments can reach about 100 m/150 m.

Monitoring allows checking for:

- Gas tightness (density monitoring).
- Internal arc location by measurement of an overpressure wave. This measurement is done by the density monitoring sensors which detects the fast transient overpressure.
- Partial discharges by UHF method (permanent or periodic).
- Density analysis

  Two systems can be proposed for analysing the SF6 gas density:

  The system comprises density sensors connected to each gas-tight department and linked by 4-20 mA connections to an acquisition unit that permanently displays the gas density and indicates (the reaching of) the alarm levels by means of LEDs.

  The display further permits to generate advanced alarms, compute leakage rates, locate an internal arc and, also, to analyse the evolution of pressures inside the compartments.

  The 4-20 mA links permit to achieve high transmission speeds and an excellent electromagnetic compatibility of the entire system as well as a permanent self-diagnosis of the monitoring system.

- Analysis of the partial discharges

  In order to prevent any insulation defect that could put the equipment at risk, metal-clad links can be equipped with UHF sensors that detect the partial discharges. The start of a failure results in the emission of high-frequency electromagnetic waves inside the cavity formed by the metal-clad bus bars. The frequency of these waves may reach 1 GHZ and can be sensed by capacitive coupling sensors.

  The sensors are positioned in a way as to avoid any protrusion inside the envelope.

  The signal generated by the sensor can be relayed to a broadband amplifier, the latter connected directly to a spectrum analyser.

  Signal analysis permits to prevent and locate possible defects and identify the causes.

The density sensors are linked, by digital serial connections, to electronic acquisition units positioned at regular intervals (about 1 km), which carry out pre-processing of collected data. These acquisition units are themselves connected to a supervision PC via a redundant telephone line (modem and twisted pairs), defined by a redundant architecture, which minimises common mode faults.

Maintenance is limited to periodic inspection mainly of the monitoring system and possible additional filling of the compartment in case of leakage (the gas tightness of the system corresponds to an interval between gas completion of much more than the 10 years required by IEC, in fact around 50 years).

- Repair

  In the unlikely event of failure in a GIL the dimension of the compartments (except very specific small compartments, if any, which would be equipped with a pressure relief device) are such that no external effect is to be feared but the faulty compartment is immediately identified by internal arc location monitoring system and the compartment is open (cut with special tools). Depending on duration and movement of the arc, it can be necessary to change the whole compartment.

  The repair is made with the same process as for the initial assembly with the exception that the last element to be inserted in the GIL is a special telescopic element.

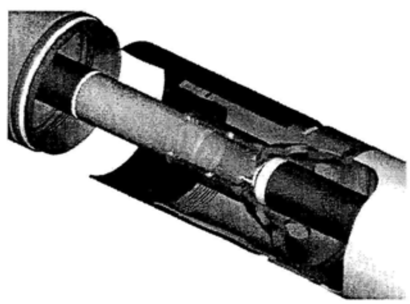


Figure 3.9.
Telescopic element for repair

3.3.7. Leakage rate

At present the leakage rate is less than 0.1 % per year. In other words it represents 3.7 kg of SF_6 emitted to atmosphere per km three-phase per year."

3.4. Environmental impact in the event of AC/DC faults

3.4.1. Power cut times in the event of a fault

- For 400 kV AC

  The duration of the minimal cut (first stage) for 400 kV AC is 120 msec. However, if the first stage fails, and there is a dual main protection circuit, this cut time can last as long as 240 msec if there is a two-phase short-circuit and 600 msec if there is a single-phase short-circuit.

- For DC

  The duration of the cut is 1.5 and 2 periods (30-40 msec). In this case the current turns itself off; all that remains is for the capacity of the cable to be discharged.

3.4.2. Energy released at the area of the fault

3.4.2.1. For AC

For 400 kV AC, short-circuit currents examined in this study were those observed on the RTE grid, i.e. 40 kA or 63 kA; 0.5 seconds.

Energy released during a breakdown on a line is calculated using the following formula:

$$E = I_{cc} \text{ x } U_{cc} \text{ x } t$$

where	I_{cc}	=	short-circuit current
	U_{cc}	=	peak ark voltage
	t	=	duration of short-circuit
taking	I_{cc}	=	40 kA/63 kA
	U_{cc}	=	1 kV
	t	=	0.25 seconds
Energy		=	10 megajoules/15,8 megajoul

In practice, U_{cc} is often greater than 1 kV. On several occasions, EDF recorded values of 1.5 kV, 1.7 kV and even over 2 kV which give energy values of 15-20/23,7-31,6 megajoules.

Under these conditions, the environmental impact is significant with an AC - XLPE cable.

Example

- 400 kV Bewag cable cast in thin mortar - energy released: 35 MJ

  Results:

  . very violent impact;

  . mortar destroyed;

  . more than 50 m away maximum pressure recorded of over 140 dB - RMS noise of 130 dB.

- Cable in the air - power released: 27 MJ

  Results:

  . violent impact;

  . cable catches fire;

  . thick smoke given off;

  . more than 50 m away, maximum pressure of 146 dB recorded and RMS noise of over 130 dB.

  Results are very similar for energy released of 16-20 MJ.

3.4.2.2. For AC with a GIL technology

A breakdown can be produced:

- by particles inside the gas mixture (for example during the installation of the tubes) which should be a preferential way for breakdown;
- by the gas mixture pressure drop.

The energy release heats the gas mixture.

During the breakdown: "no explosion".

Type test shows that for an internal arc I_{eff} = 63 ka, t = 0,5 sec: no burn-through of the enclosure.

3.4.2.3. For DC

For DC, the energy released is that of a capacitor discharging itself.

This energy is 1/2 $C.U^2$.

For a 50 km line with cable capacity of 0.2 μF/km, energy released is calculated as follows:

$$1/2 \times 0.2\ 10^{-6} \times 50 \times (500\ .\ 10^{+3})^2 = 1{,}25 \text{ MJ (Megajoules)}$$

or 20-30 times lower than for alternating current (for 70 km the value would be 1.75 MJ).

For purposes of comparison, a 21 kV cable, as currently installed in a tunnel, can be taken as an example.

For this type of cable, it can be assumed that the single-phase short-circuit current is 2 kA with a power cut lasting 1.7 seconds. If the peak ark voltage is taken to be 500 V, energy released is calculated as 2 x 0.5 x 1.7 = 1.7 MJ.

Results for tests on DC cables are not currently available. However, it can be expected that the environmental impact would be much more lower that that of AC cables.

3.5. Protection

Given the energy that needs to be confined, there is good reason to protect the cables or rather to place a barrier between the cable and the surrounding environment.

3.5.1. For AC - XLPE insulation

For AC - XLPE cables a strong protection is recommended and also to place cables in HDPE tubes covered with concrete.

Installing cables within a tube allows energy to be released inside the tubes (space between the cable and the tube) and to thus spread the impact over an extremely long distance.

3.5.2. For AC - GIL technology

Due to the technology itself, this type of cable does not need any special protection.

Also it is recommended that this cable should be installed in the air for the monitoring and access of the cables.

3.5.3. For DC links

We should recommend same type of protection as the one proposed for AC links (= in HDPE tube covered with concrete).

If we would install this type of cable in the air, it would be advisable to install cables with a mechanical protection (tube made of steel).

For DC, this type of protection does not pose any problems.

Typical installation with AC - XLPE links - Figure 3.10.

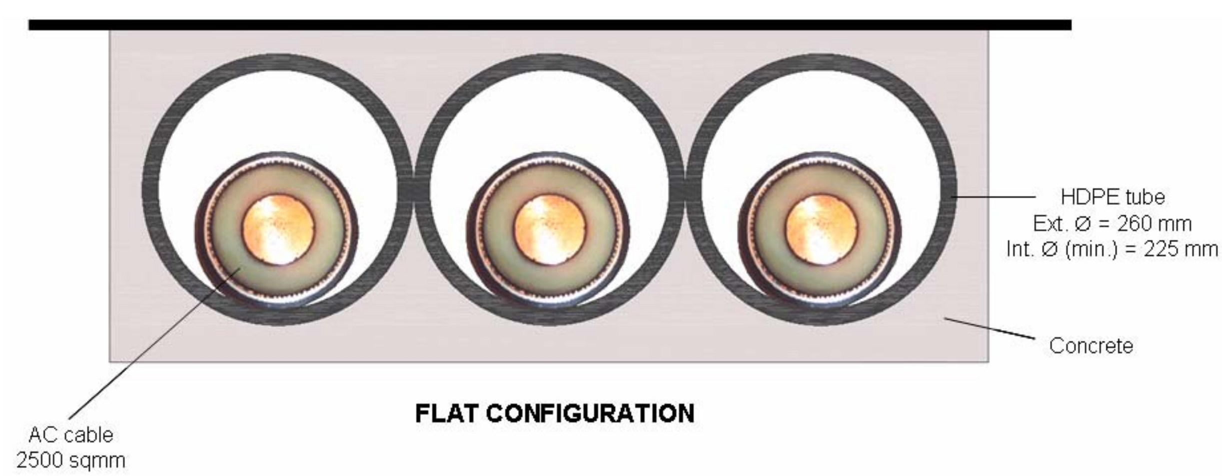


Figure 3.10.

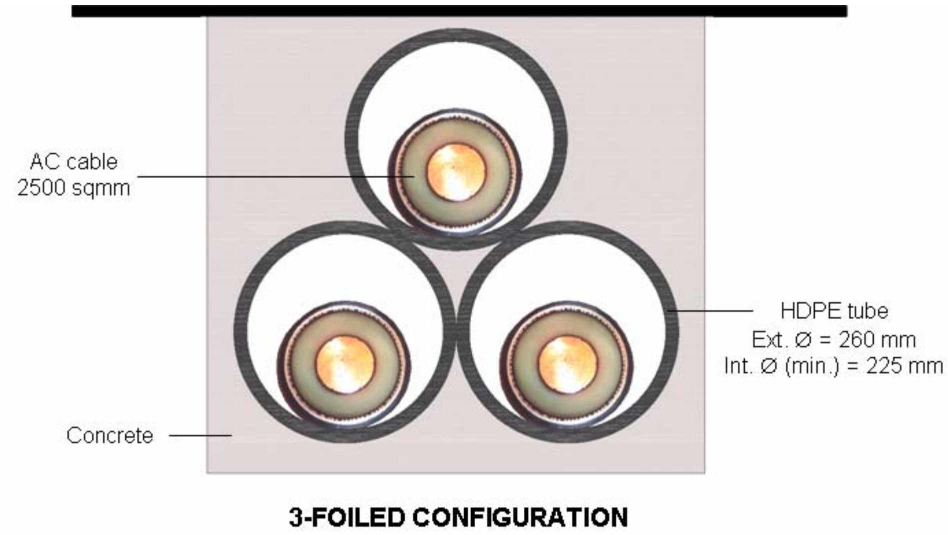


Figure 3.10.-bis

Typical installation of DC - XLPE links - Figure 3.11.

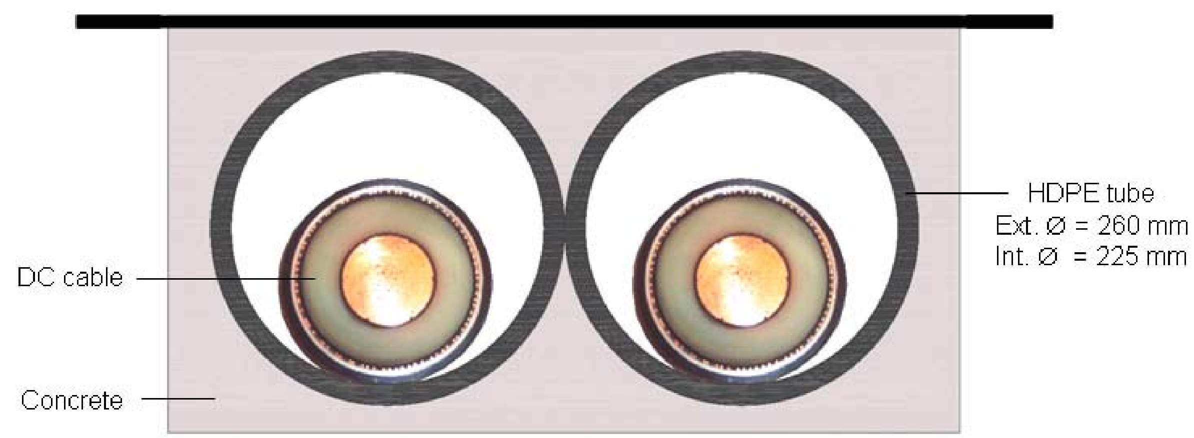


Figure 3.11.

Typical installation of DC - XLPE links in open air in the tunnel (2 phases instead of 3).

Figure 3.11.-bis

Typical installation with GIL links

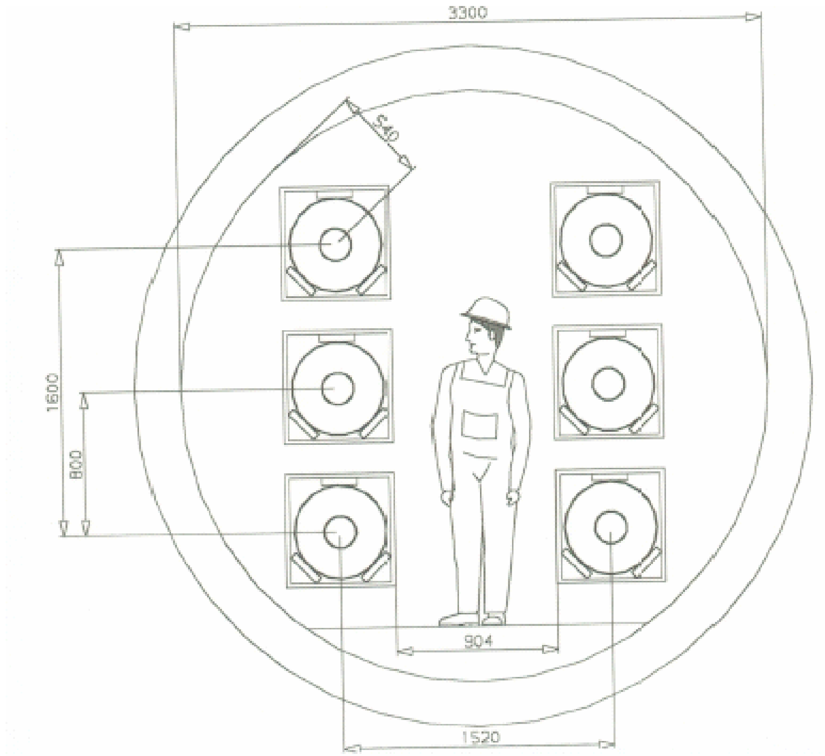


Figure 3.12.

Figure 3.12.-bis

3.6. Reliability of each type of links

3.6.1. Reliability of the XLPE-insulated underground AC links

This reliability or the fault rate is expressed for 100 km/year.

Statistically, at present, this rate is 0.2 failures/year/100km terrain.

In reality this ratio is 0.02.

This is related to the facts that:

- the qualification tests, and amongst them the type-tests, are extremely stringent:

  → example

  Ten years ago certain type-tests were performed on 10 cycles, while these days they are performed on 100 cycles; similarly, at a number of manufacturers the routine gradient tests are performed at 26 kV/mm, which is extremely strict and does not tolerate any internal defect of the insulation.

- the cable has been shop tested, during and after manufacture, applying extremely stringent procedures;
- the fittings, including the junctions, are now pre-moulded and therefore are also shop tested;
- the cables are tested on site, after laying each portion and when the link is complete (tests of the outer sheath);
- the complete link is tested on site, including the fittings, with AC tests (2 Uo);
- all is compliant to the IEC recommendations.

This concerns the internal defects and for a supply and construction as performed in Belgium consistent with the procedures developed in Belgium.

Also, note that this technology does not require any monitoring.

It is recommended to test each other sheath on a yearly basis, especially if this type of link is installed in an area open to the public.

3.6.2. XLPE-insulated DC links

For this type of link the design qualification tests shall have to be complied with.

Same for the routine tests.

We would then be in a scenario similar to that of AC XLPE-insulated cable.

It can be assumed that the same results would be achieved provided the necessary arrangements are made with the relevant cable manufacturers.

In any case, the cable manufacturers possibly selected for the supply of DC cable are the same that are candidates for supply of the AC cable.

3.6.3. GIL-type AC-AC links

Here again we deal with suppliers who have been supplying and installing this type of equipment for decades, for instance for GIS.

Furthermore, similar procedures are applied during the shop tests as well as during the on-site tests after construction.

Moreover, this system is monitored permanently using a very complete monitoring system.

Here probably resides it's drawback: constant care will be required in order to make sure that the monitoring system remains fully reliable, which calls for very strict maintenance of the system.

3.7. Maximum allowable length for AC/DC links

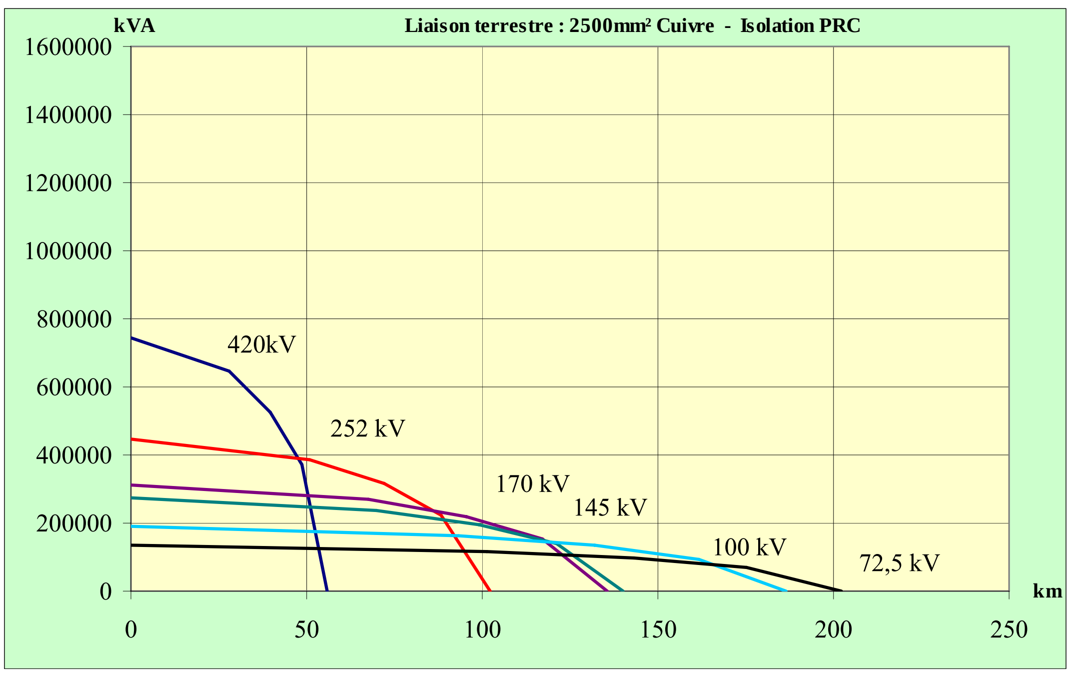
3.7.1. Links with AC - XLPE insulation cables

The figure 3.13. hereafter shows the maximum length for underground cables with a cross-section of 2500 mm^2 Copper for different voltages.

This graph indicates that the max. acceptable length is about 50 km.

In excess of this length the link becomes too capacitive and calls for installation shunt reactors, which cannot be installed in the tunnel due to the amount of space they require.

Limitation de la longueur des câbles terrestres
2500mm² Cu à isolation PRC (50Hz)



fréquence (Hz)	50	50	50	50	50	50
Tension composée (V)	400.000	220.000	150.000	132.000	90.000	63.000
C (F/km)	2,65E-07	2,87E-07	3,25E-07	3,60E-07	4,00E-07	5,35E-07
S (kVA)	746.000	446.000	311.000	276.000	190.000	135.000
I (A)	1.077	1.170	1.197	1.207	1.219	1.237
Lc (km)	56	102	135	140	187	202

Figure 3.13.

3.7.2. Links with DC - XLPE insulation cables

As far as we are aware, there are no limitations in DC.

Therefore it would permit us to position as appropriately as possible the converter stations beyond the tunnel zones.

A limit regarding the length of the link has to do mainly with the DC screen, because in the event of a short-cut, it is the screen's strength in DC that will be the defining element with respect to the max. acceptable length of the link.

3.7.3. Links with AC - GIL technology

For this type of links, as a rule, there are no limitations in terms of length.

Also due to the low capacitive load for this type of links, no compensation (shunt reactors) is required for long lengths.

3.8. Joints

- **Joints**

These accessories are used to join together two cables.

For AC cables - XLPE insulation.

There are currently two different technologies:

- taped joint used up to 110 kV voltages;
- premoulded joint used up to 500 kV voltages.

It is essential to know the type of cable and installation conditions for defining the most appropriate model.

There are currently three models of joint:

- straight joint, earthed or not earthed;
- joint with screen interruption (or screen separation).

→ Straight joint without earthing

This contains the same components as the cable and ensures physical and electrical continuity.

It is used in the case of a short power line or in sections of long circuits when the induction current in the screens is low.

→ Straight joint with earthing

In the case of a earthed out, the connection of the screen to the earth is made by an insulated cable of the rigid industrial type.

It is used n short-circuits or in sections of a long power circuit.

→ Joint without screen separation and joint with screen separation

The difference between those two above is the design of the outer screen.

In joints with screen separation, the screen "separation" part provides a physical discontinuity of the semi conductor screens and the metallic screens.

When combined with phase switching and/or cross-bonding, these materials allow the cable cross-section and transmission power to be optimised, and energy loss to be minimized.

Cross-bonding involves creating the interruptions in the screen circuits and making connections between the circuits of different phases to cancel out the induced voltages.

It is used in the case of power circuits containing at least 3 sections of an equal length for each phase.

All types of screen or outer sheath can be connected using a joint. With regards to the cable conductors, it is necessary to know the type of metal used in each cable, its cross section and dimensions.

Among the models described above, there are also transition joints. They serve to connect two cables of different types or different cross section.

- **The technology**

→ Taped joint

The technology of the taped joint, which has been around the longest, involves the reconstituting on site an insulation that equals that of connected cables.

→ Synthetic tapes

With good dielectric properties is used in this case. The taping operation can be done manually or mechanically, although the latter method is less common.

Characteristics:

- Economic

  Owing to the low cost components involved, this joint is very economical.

- Technical

  The tapes used have good physical and dielectric properties. Their physical properties ensure a tight interface between the cable and the taped joint. Their dielectric properties ensure good electric resistance under alternating current to lightening and switching overvoltages.

  When made manually, the efficiency of the joint is directly related to the skill of the electrician.

→ Premoulded joint

The more recent technology of joints consists of a premoulded elastomer body with one electrode and two stress cones made of semi-conducting elastomer. This single-piece joint, manufactured and pre-tested in the factory, is pushed over the prepared cable.

The quality of the joint is less dependent on the fitters skill than for taped joints.

The joint is attached mechanically. The joint dimensions chosen in relation to those of the cable ensure that the interface with the cable is tight enough.

→ Mounting premoulded joints

Two alternative techniques may be used:

- The slip-over technique

The joint is first expanded on a temporary support tube that is temporarily positioned at one side of the cable while the conductor is being connected. When the support tube is removed the joint fits around the cable.

- The slip-on technique

  The joint is pushed over the cable and temporarily put to one side while the conductor is being connected. The joint is then positioned in its location.

  This type of joint is used at all network voltages, the maximum voltage being 290/500 (550) kV.

Characteristics:

The routine test (or pre-test) in the factory allows any flaws in the joint to be detected and any defective parts to be eliminated.

The properties of the joint material and the quality of the cable preparation ensure that the interface between the cable and the premoulded joint remains right throughout the cable's service life.

The dielectric properties of the material offer good electric resistance under alternating current to lightening and switching overvoltages.

→ Prefabricated joint

These are composed of several parts assembled together on site. Whenever a joint involves assembling several components, its performance is directly related to the fitters dexterity.

The electric function of a joint is to ensure the continuity and insulation of the metallic screens either to ground or between each other.

- **Joint space**

The actual joint requires space. The exterior ∅ for a 400 kV connection is approximately 40 - 50 cm for a length of 1.5 - 2 m.

The figures 3.14. and 3.15. below show a cross-section of this type of joint and a joint on a 400 kV line in Berlin.

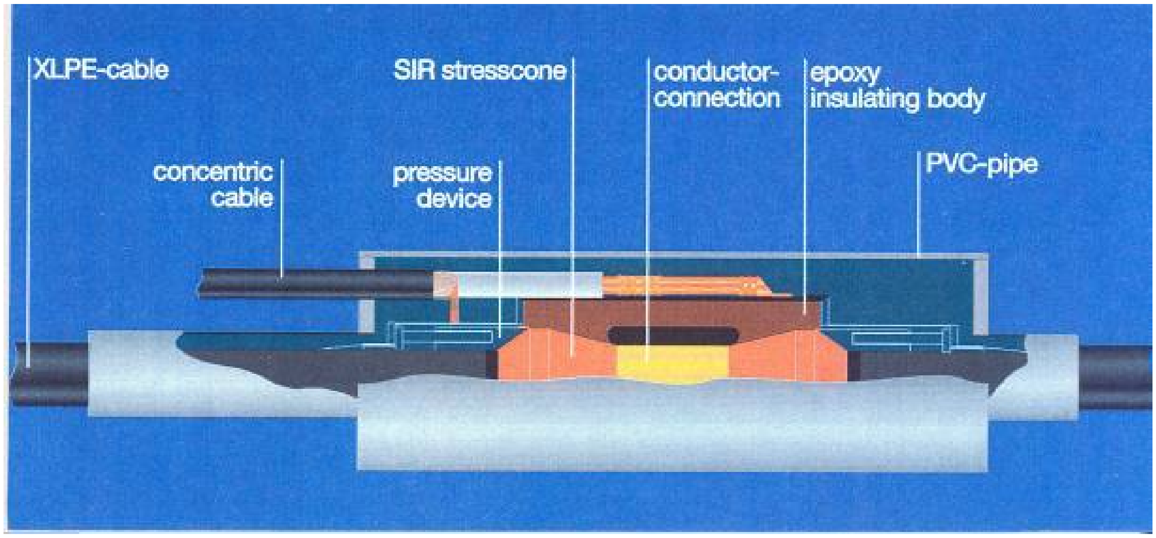


Figure 3.14.

Figure 3.15.

For DC, technology is quite the same.

The pre-moulded joint for an extruded DC cable is very similar to the pre-moulded used for an AC cable.

For GIL technology of course no special joints are required, each element of 12 to 15 m are assembled together.

3.9. Cost comparison

It is not very easy to make a comparison between the different technologies, mainly due to the installation prices which can strongly vary depending of the type of installation in a new tunnel, in an existing tunnel, ...

3.9.1. AC - XLPE insulation

For a 2500 sqmm Copper, one circuit, the prices per km are:

→ 2.65 M€/km

assuming the installation cost is the same as the costs of the equipments supplied;

→ 2.00 M€/km

assuming the installation cost is 50 % of the costs of the equipments supplied;

→ 1.75 M€/km

assuming the installation cost is 30 % of the costs of the equipments supplied.

3.9.2. DC - XLPE insulation

The prices for DC links are depending mainly on the price of the AC/DC convertors.

The roughly estimated price of an AC/DC - DC/AC convertor is 0.165 M€/MW (100 U$/KW single convertion).

For a double AC/DC - DC/AC convertor with a capacity of 1000 MW, the total price is **165 M€.**

Based on the same argument as the one taken for an AC link (100 % - 50 % and 30 % for the installation costs); the prices per km are:

- For a 30 km total length of the link

  → Installation costs = supply costs

  7.16 M€/km

  → Installation costs = 50 % of the supply costs

  6.75 M€/km

  → Installation costs = 30 % of the supply costs

  6.58 M€/km

- For a 50 km total length of the link

  → Installation costs = supply costs

  4.96 M€/km

  → Installation costs = 50 % of the supply costs

  4.55 M€/km

  → Installation costs = 30 % of the supply costs

  4.38 M€/km

- For a 75 km total length of the link

  → Installation costs = supply costs

  3.86 M€/km

  → Installation costs = 50 % of the supply costs

  3.45 M€/km

  → Installation costs = 30 % of the supply costs

  3.28 M€/km

3.9.3. GIL link

A gas insulated link (GIL) can be considered only if there is sufficient space from the start to install that type of link.

Bear in mind that, at 400 kV, the main sizes concerning the pipes would be:

- pipe outside diameter : 600 mm
- outside diameter of the pipe assembly flanges : 700 mm

Also, in the version placed inside a tunnel in the open (not embedded or in ducts) the pipes are usually placed on rollers permitting them to contract/expand freely under thermal variations. These rolls would be fixed directly onto a steel structure. The minimum space between each pipe is about the diameter of a pipe, i.e. 600 mm.

Assuming there is sufficient free space and that the installation work is limited to placing the supports and assembling the pipes, the cost per km would be around 3 M€/km including the monitoring.

Note also that for a power of 1000 MW which is the option selected for AC and DC, the GIL concept as developed is in fact oversized.

Indeed, under the same conditions, between 2000 and 2500 MW could be transited, which would then call for a double 400 kV AC link.

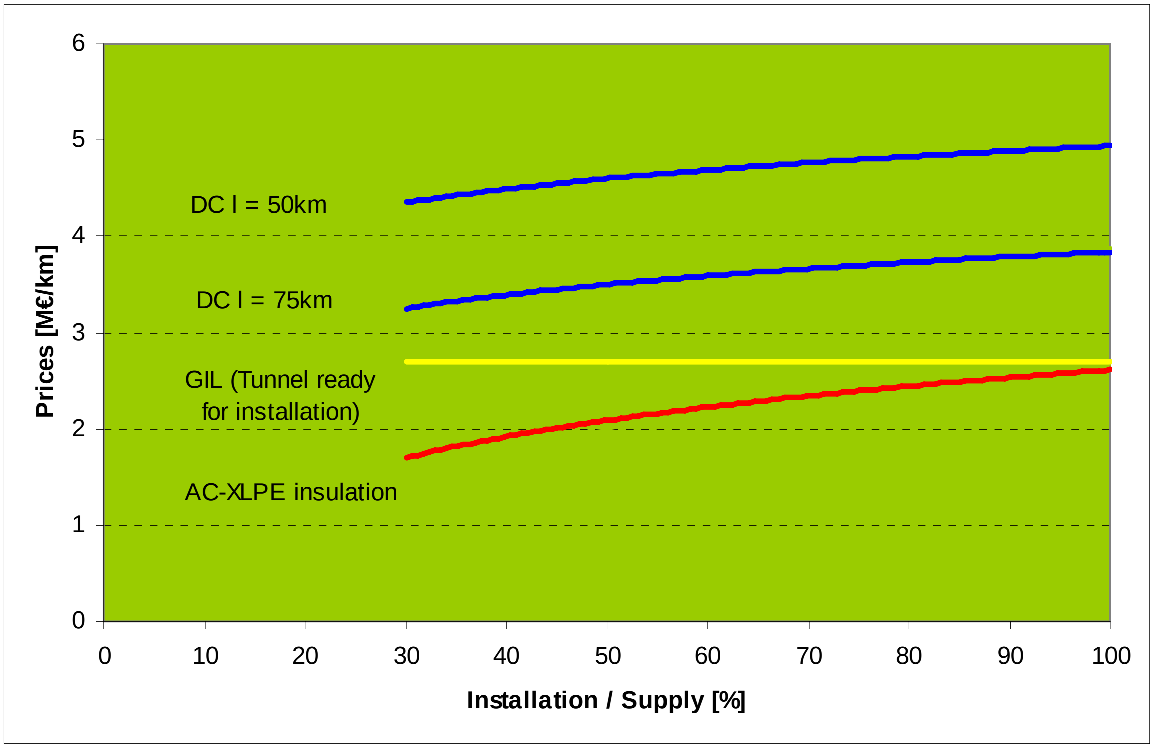


Figure 3.16.
Cost comparison for a 1000 MW load