A Comparative Analysis of the Tunnel-Construction Times and Costs as well as Risks Associated with the Choice of High-Speed Rail Alignment Between Los Angeles and Bakersfield

Final Report

Prepared for the

City of Palmdale

by

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EXECUTIVE SUMMARY

The California High-Speed Rail Authority (HSRA) is making a comparative evaluation of two alignment alternatives, I-5 (Grapevine) and AV (Antelope Valley), for the high-speed rail connection between Sylmar and Bakersfield.

The earlier studies of the Authority have focused on minimizing tunnel requirements and cost (Corridor Evaluation study of 1999 and QUANTM study of 2002) and minimizing potential environmental impacts (the Screening Evaluation) by avoiding sensitive zones in identifying the potentially suitable routes. However, there is a limit to these reductions due to the constraints imposed by the specific topography and tectonic setting of the region as well as the high-speed train technology. Furthermore, for the limited number of potentially suitable routes identified by the previous screening studies, and subsequently confirmed by the QUANTM analysis, the various categories of risks, especially the geological and construction risks, were not considered. In the opinion of Transmetrics and Geodata, these other risks are as important as those already considered by the Authority and its consultants; they are also critical in the final choice of the optimum alignment/route for the mega tunneling project.

The potential, typical risks that may be encountered in a mega tunneling project include risk of encountering adverse geologic conditions, constructions risks, such as choice of a wrong type of TBM, ground-squeezing behavior, and face collapses. Financial risks, such as delay in completion of the contract or cost overruns, and contractual risks such as time delays and disputes are also a typical problem.

The city of Palmdale believes that specific uncertainties in tunneling should be adequately integrated into the various studies commissioned by the Authority. Risks associated with the I-5 alignment should be adequately examined with those associated with the Antelope Valley alignment. This study is intended to continue the concept development process to an all encompassing conclusion.

Consequently, the City of Palmdale retained Transmetrics/Geodata to provide a complementary risk assessment to assist in the project development process.

The purpose of this risk analysis study is to identify the optimum alignment with respect to minimizing the capital investment and the risk of construction-cost overruns and delays, and to review specific uncertainties in the tunneling that should be adequately incorporated into the overall decision making effort.

Sufficient site-specific data was not available. Experience judgment, was used for the study model and USGS data and reports were utilized in lieu of precise, in-situ explorations and measurements. Full use was made of the information contained in the 1994 Preliminary Engineering Feasibility Study conducted for Caltrans. Relevant reports and maps were obtained from the USGS to study the geomorphological, geological, hydrogeological, and geotechnical conditions of the two alternative alignment-corridors, establishing foreseeable ground models. A preliminary model of both alignments was made to define the corresponding construction schemes based on Geodata's experience for similar projects in Europe.

The number of tunnel segments (or tunnel zones, TZ) in the I-5 and AV alternatives are 4 and 7, respectively, with the maximum anticipated grade of 2.5% or 3.5%. The geologic horizons crossed by the various tunnel zones will vary from metamorphic and igneous rocks to sedimentary rocks and gravel deposits. Numerous faults intersect the two alignments. Some of these faults have a tectonically active character and a potential for plastic slippage of the fault faces.

The construction methodology selected for the two alignments is the use of tunnel boring machines (TBMs) except in some instances, such as excavation of portals, where conventional drill and blast techniques is selected. In addition to the main, twin tunnels of 9.5m diameter, a service tunnel of 6.5m diameter and seismic chambers (in major fault zones) are the principal components of underground excavation.

The comparative analyses of the two alternative alignments were performed using the tool called DAT, or Decision Aids in Tunneling.

A unique feature of DAT is its capability for a comparative evaluation of the performance of various project alternatives. Construction schemes, alignments and methods of construction are incorporated parameters. The potential of these alternatives in managing geotechnical and construction uncertainties within prescribed, or acceptable values of time and cost is also incorporated.

A DAT run is essentially a computer simulation of several random processes. The idea of using computer simulations derives from the fact that it is not possible to find analytically resulting random functions when processes are too complicated, like the construction of tunnels. So simulating a construction process is the only solution to obtain statistical information about the total time and cost. This information gives a good estimate of the average, minimum and maximum expected values. By definition the simulation of a random process uses a random number generator.

DAT and the associated computer SIMSUPER have been developed over a period of 20 years by MIT (Massachusetts Institute of Technology) and EPFL (Ecole Polytechnique Federale de Lausanne), with the participation of Geodata for practical application of the code in various international tunneling projects.

DAT simulates the tunnel construction process cycle for TBM, with its various rounds of drilling and blasting. A simulated, probabilistically ground class profile is assembled. For each cycle or round, the program selects a cost-time pair from the cost and time distributions and the ground class associated with the particular location.

The ground class assigned to a location (or a given tunnel segment) is a function of the following parameters: behavioral category, potential instability conditions, potential problematic water, possible presence of gas, and (anomalous) abrasivity of the rock mass. The behavioral category is defined by combining the strength index of the ground with its deformation index.

The total cost and time for a particular tunnel-simulation run represents a single point in the cost-versus-time plot. By conducting a statistically significant number of runs, many points are obtained and a scattergram (or cloud) is formed, expressing explicitly the inherent variability in the estimated construction cost and time.

The construction simulation requires input regarding advance rates and costs (for various elements of construction) for different behavioral categories. Costs and advance rates are influenced by geo-events such as water inflow, and consequences related to occurrence of instability phenomena.

The results of DAT simulation for each alignment (at max grades of 2.5% and 3.5%) are given in Sec. 6 as histograms and statistics of the construction time and cost as well as the scattergram formed by 1000 points in the cost-time frame. A super-imposed comparative scattergram for the two alternative alignments, and a comparative construction time and cost table, are also provided.

Finally, the results exclude the construction risks and costs of surface structures such as bridges and surface railbed. These costs are included in the HLB Report.

The results of the analyses demonstrate the following:

- Although the amount of tunneling work involved in the I-5 and AV alignment are almost the same, be it the 2.5% grade or the 3.5% grade option, ground conditions along the AV alignments are relatively more favorable and hence involving less construction, financial or contractual risks.

- For the 3.5% max grade option, the mean construction time required for the I-5 alignment is almost twice as much as that required for the AV alignment (2218 working days against 1125 working days, see Table 6.9). Similar results were obtained for the 2.5% max grade option. A slight increase in the mean construction time for the AV alignment due to increased total length of tunneling was observed (see also Table 3.1).

- In terms of the mean construction cost for the 3.5% max grade option, the Antelope Valley alignment is about 40% less costly than the I-5 alignment. This advantage is reduced for the 2.5% maximum grade option. The 2.5% grade option is 15% less costly, due to increased total length of the tunnel. Furthermore, the increased tunnel length for the AV alignment at 2.5% max grade will reduce the costs for the corresponding external works and environmental impact.

In summary, the ground conditions along the AV alignment involve lower risks regarding construction, financing, and contracts. For both max. grades (2.5% and 3.5%), the AV alignment is clearly less costly than the I-5 alignment. Note that the DAT analyses does not simulate the financial consequences of increased duration of construction. However, it is likely that a longer duration of construction will further increase the difference in the cost of the two alternatives.

Generally speaking, the findings of this study quantifies to some extent the relative risks involved in the two alternative alignments. This should allow the Authority to make a more informed decision regarding the final alignment choice.

It is recommended that geologic uncertainties be reduced by pursuing a planned site investigations, eventually using a service tunnel as a pilot bore for an investigation. Innovative technological solutions should be incorporated in the strategy for managing the high-risk aspects of the project.

Study Team

The study Team was a joint effort of Transmetrics Inc., a civil engineering firm based in Campbell, California, and Geodata S.p.A. of Turin, Italy. Both firms have previously teamed together for work on projects of similar nature. Geodata is a geo-engineering company with particular expertise in the design of underground structures in complex and difficult ground conditions. Since its beginning in 1984, Geodata's activities have involved one or more of the various technical phases (lab and in-situ characterization, feasibility study, preliminary design, final design, performance monitoring, design optimization during construction, resident engineering, independent design checks) for over 1500 km of tunnels (for transportation, water supply, and sewage disposal).

Since 1990, Geodata has teamed with Professor H. E. Einstein of MIT in applying DAT to identify the optimum tunnel alignment relative to geologic and construction risks in various projects around the world. The more recent (1999-2002) applications of DAT involved the following projects:

1. **Guardarrama High Speed Rail Tunnel in Spain**. Geodata made an independent assessment of the basic design and the associated risks for the Minister of Public Works.

2. **PAJARAS High Speed Rail Tunnel in Spain**. Geodata made an independent design check and risk analysis. The design was prepared by the joint venture, INECO S.A. and Geoconsult Ingeneieros Consultores S.A.

3. **Torino-Lyon High Speed Railway**. For the long and deep tunnels Geodata made a risk analysis for the Authority, ALPTUNNEL (a joint organization of the French and Italian Governments).

The team of experts contributing to the present study includes:

Dr. Shulin Xu (Ph.D. in Engineering Geology from Imperial College, London, England) has performed DAT applications for Geodata since 1990. Dr. Xu is Geodata's Technical Director and is the coordinator of this study.

Eng. Piergiorgio Grasso (a Civil Engineering graduate from the Technical University of Turin, Italy) is the President and Principal Engineer of Geodata. He has 27 years of experience in design of underground works.

Prof. Sabastiano Pelizza (a Mining Engineering graduate from the Technical University of Turin, Italy) was President of International Tunneling Association during 1995-1998. He has consulted for Geodata since 1984.

Dr. Ashraf Mahtab (Ph.D. in Civil Engineering from the University of California, Berkeley) is a consultant to Geodata with particular reference to the application of DAT.

Dr. Herbert E. Einstein (Professor of Civil Engineering at MIT) is the original developer of DAT. He is an expert advisor to Geodata for this type of study.

1. INTRODUCTION

1.1 HSRA Project Description and Background

The California High-Speed Rail Authority (HSRA) has undertaken a process to develop a high speed rail ground transportation system (HSGT) to connect the cities of San Diego, Los Angeles, San Francisco, and Sacramento. The proposed HSR system would be similar to the HSR systems currently in place in Germany, France, Italy, Spain and Japan. However, the HSGT must cross the Tehachapi Mountain Range north of Los Angeles. There are several active faults in this mountain range and will require a choice of route alignment which is safe and minimizes construction related issues.

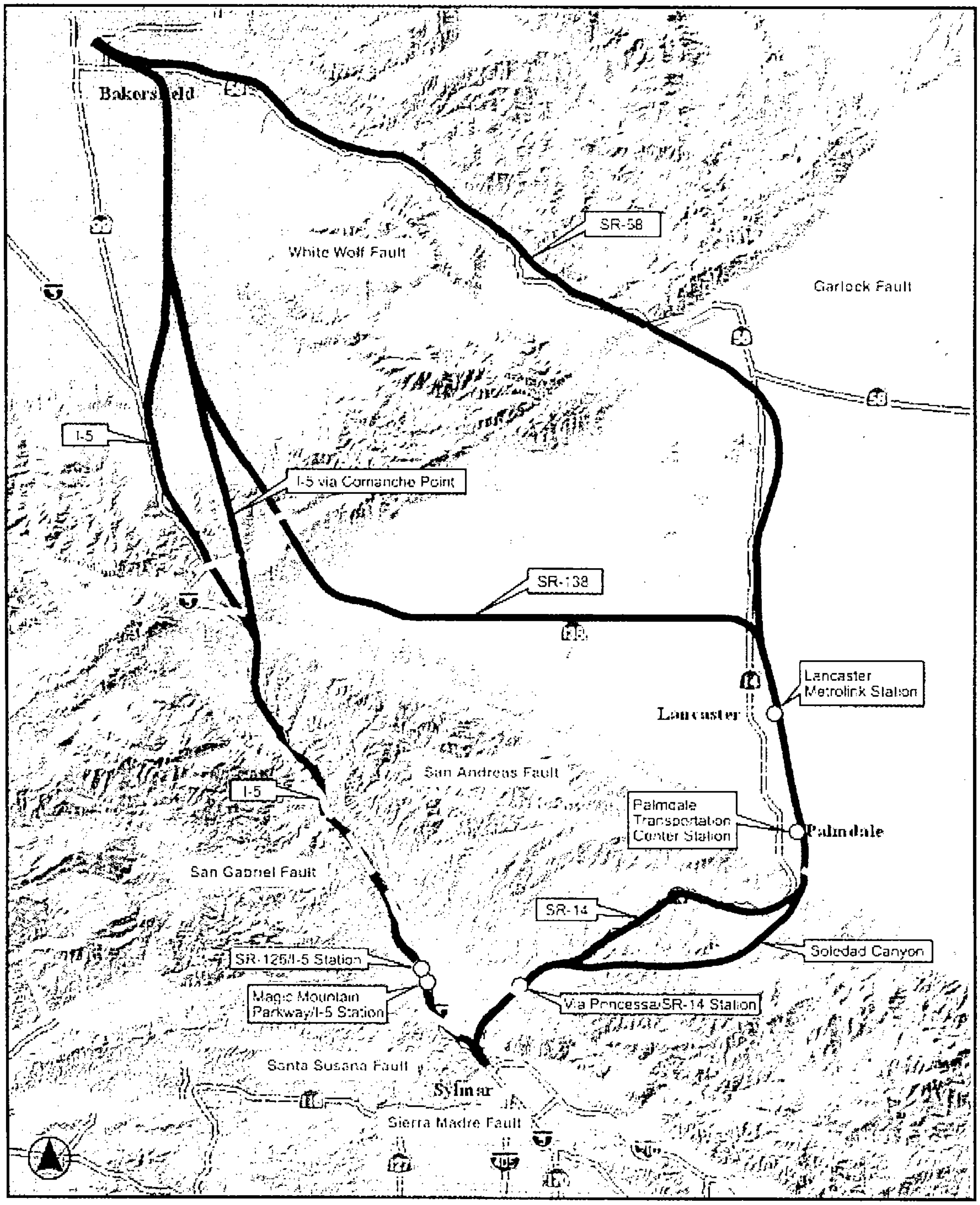
The two principal alignment options considered by the HSRA for crossing the Tehachapi Mountains between Los Angeles Union Station and Bakersfield are – the AV, or the Antelope Valley, alignment and the I-5, or the Grapevine, alignment. The two alignments differ principally in relation to length, accessibility, and construction complexity and risk (see Fig. 1.1).

For the tunnel study in this report, the tunnel portal positions have been established assuming that at least 20 meters of overburden are required above the tunnel base. This is due to the large dimension of the tunnels and the need to have a reasonable minimum cover thickness to start the excavation. This means that the position of the portals can be slightly different with respect to the position defined in the HSRA's documents (Orthophotos).

The I-5 alignment is some 65km shorter than the AV alignment and would, therefore, allow a 5 percent (6-9 minute) shorter non-stop travel time, depending on the final choice of the high speed rail technology and the train speed. In comparison, the AV alignment would offer high-speed rail service to at least 438,000 additional residents and 165,000 employees today, and to over 720,000 additional residents (and 270,000 employees) at the time of system startup in the 2015-20 period.

Finally, from a construction perspective, while the I-5 option would require the construction of a shorter track than the AV alignment, this advantage would come at the cost of more route miles of tunneling (the exact figure for the miles will depend on the choice of the grade) through a fault-ridden section of the Tehachapi Mountains, the costliest – and riskiest – type of civil construction that would be encountered in an attempt to cross the Tehachapi Mountain range.

Figure 1.1 Map of the Alternative Alignments



Legend

- Alignments to be Evaluated
- ○ Station Locations to be Evaluated
- Fault

1.2 Review of Available Information

1.2.1 Extent of available information

The analyses presented in this report have been developed by the Consultant using the available information (under the categories discussed below) and, in the absence of available information, using the appropriate assumptions based on experience.

Geology

The main source of information regarding the geology and geotechnical characteristics of the ground along the two alternative alignments was contained in the document on "Preliminary Engineering Feasibility Study – Final Geotechnical Summary Report" dated April 11, 1994, submitted to the California Department of Transportation, prepared for Parsons Brinkerhoff Quade & Douglas by MAA Engineering Consultants, Inc. of Los Angeles. On request, this document, and the maps and sections annexed to it, were supplied to Geodata by PBQD. Additional information was downloaded from the Authority's website.

Geodata also acquired relevant reports and maps from the United States Geological Survey to study the geomorphological, geological, hydrogeological, and geotechnical conditions of the two alternative alignment-corridors, aiming at identifying the corresponding risks. This information from the USGS came from their offices in Menlo Park, San Francisco and Denver.

Drawings

The only drawings available for the study where those produced for the Preliminary Engineering Feasibility Study in the period of 1993-1994 by MAA Engineering.

Boreholes

No borehole information was available to Geodata. It is understood that some boreholes were drilled recently to check the ground conditions of alternative alignments.

Tunnel Design

The Tunneling Feasibility Study made in the period of 1993-1994 for Caltrans was the only background information available on the design for either of the two alternative alignments. A judgment on certain design and construction parameters required for the analysis had to be made by the Consultant to complete the model for this study.

Construction methodology

A clear statement of the construction methodology is not found in any official documents made available to the Consultant, except in the Tunneling Conference Summary where it was mentioned that "Tunnel Boring Machines should be assumed as the excavation method for all tunnels with the exception of specific areas identified during the conference that have difficult geology."

1.2.2 Review of Previous studies

The project planning and feasibility studies, the environmental impact assessment, and the selection of the system's route alignment have been conducted primarily by the Authority's consultant, and the project development is currently at the stage of final screening evaluation of alignment options. The following two events in the long process of initial project development study should be noted.

1. During the period of 2001 to March 2002, the Authority conducted an alignment optimization and refinement study to further clarify screening decisions using the QUANTM system. The QUANTM system is a new automated alignment optimization system developed and applied in Australia. It was the intent of the authority to improve on the previous analyses based on "best practices" for conceptual engineering. The results were presented in a final report titled, "Alignment Refinement/Optimization and Evaluation of the QUANTM System" published in April 2002.

   In the beginning of December 2001, the Authority organized a two-day (December 3 and 4) Tunneling Conference to discuss major tunneling problems involved in the California HSR project. However, the documentation of this Conference is limited to only a few pages of summary placed on the Authority's website, and the proceedings of the Conference have not yet been published.

2. Great importance has been given by both the Authority and its consultant to the above two events.

   - Previous corridor evaluation studies have focused on minimizing tunnel requirements and cost;
   - Current screening evaluations focused on minimizing potential environmental impacts;
   - Influenced by the results of the Tunneling Conference, the QUANTM study attempted to minimize tunneling and capital costs. In this regard, it is more comparable to the earlier corridor evaluation study results.

The two often conflicting aspects of minimizing tunnel requirements and cost, and minimizing potential environmental impacts are interrelated. They should be treated following a systematic engineering approach.

The risks and/or critical considerations listed below have been identified in previous studies. Attempts have also been made to deal with these issues.

- Alignment crossing fault and shear zones of considerable length. The solution adopted, wherever possible, was to avoid these zones by either deviating the route or increasing the vertical grade to move the alignment to the surface.
- Alignment crossing water-saturated zones and/or zones with high groundwater pressure. The attempted solution was to deviate the route wherever possible.
- One longer versus many shorter tunnels. In general, shifting the problem of fault crossing from underground to surface may not be a an optimum choice. For the HSR project this problem will be complicated by the fact that the alignments run across active earthquake faults. The I-5 alignment is of concern because it is parallel to at least two faults. While the region is vulnerable to earthquakes, tunnels are generally more resistant to seismic events than equivalent superstructures as experienced in Kobe, Japan and in the Loma Prieta, California events. The region's faults are expected to produce large, lateral shear displacements during an earthquake and might endure a tunnel section closure.
- During operation. The time and cost involved in rehabilitating an earthquake-damaged tunnel section (compared to that of an equivalent superstructure) needs to be investigated.
- The addition of high embankments and deep trenches may also be a factor associated with vertical-grade options, considering the associated costs of trench support, embankment-slope protection, and maintenance.

However, there are also other risks which were not addressed in the previous studies. For example, the potential, typical risks to be encountered in a mega tunneling project like the California HSR project may include:

1) The risk of encountering adverse conditions due to the inherent uncertainties of ground and groundwater conditions – leading to significant cost overruns and project delay;
2) The potential for accidents during tunneling and post construction;
3) Construction risks, such as selecting the wrong type of TBM, human error, rock squeezing behavior, face collapses and production of materials causing hazardous environmental conditions;
4) Financial risks to the owner, such as delay in completion of the contract, cost overruns, or lower than projected rates of capital return;
5) Contractual risks, such as additional work not covered, time delays, disputes, claims and litigation.

It should be noted that the underground construction industry seems particularly prone to disputes – this is most likely because of the risks and uncertainties associated with subsurface conditions and costly plant and equipment required for tunneling.

It is believed that the costing (and timing) of the project would be quite different if the geological and construction risks, as well as the entailed financial risks, were included in all cost calculations.

Therefore, it is necessary to perform an alignment-specific risk analysis for each potentially suitable alignment, to complement the QUANTM analysis, considering at a minimum the following:

- the variation of construction time and cost as a function of the expected geologic conditions and the associated variations and uncertainties;
- the impact of construction duration on economic and financial issues.

The final choice of the optimum alignment can be enhanced on the basis of a multi-criteria analysis, taking into account the following key factors:

1) Environmental impacts,
2) Total construction cost and risk of cost over-runs,
3) Construction duration and the risk of delays,
4) Performance of the chosen alignment alternative in dealing with risks during operation,
5) Capital investment and the related financial risks.

Determining an optimal alignment for the HSR system is quite complex and requires a multidisciplinary approach supported by effective and efficient tools.

1.3 Purpose and Scope of the Analysis

The study presented in this report was commissioned for two main reasons, (1.) Specific uncertainties in the tunneling process were not adequately integrated into earlier studies commissioned by the Authority, and (2.) to identify the optimum alignment with respect to minimizing capitol investment and risk of construction cost overruns, and costly delays.

The objective of the study is to conduct a geo-engineering risk analysis and an economic risk analysis associated with the design and construction of tunnels for the high-speed rail project between Sylmar and Bakersfield, along two alternative alignments (see Figure 1.1):

1. *I-5 Alignment - Sylmar to Bakersfield following Interstate 5*

   ("Grapevine")

2. *Antelope Valley Alignment –*

   Segment 1 - Sylmar to Palmdale via SR-14 and Soledad Canyon

   Segment 2 - Palmdale to Mojave (level terrain)

   Segment 3 - Mojave to Bakersfield via SR-58

The tunneling duration and cost as well as the corresponding risk assessment of the two alternative alignments will be made to address the following two questions:

1. Which alignment requires the least capital investment; and
2. Which alignment presents the lowest risk of construction cost overruns and schedule delays?

[*Note that a unified benefit-cost analysis previously prepared by the Consultant, HLB Decision Economics, Inc., will be updated to include the results of the present tunneling risk analysis.*]

The specific tasks of Transmetrics Inc. and Geodata S.p.A. (to be referred to as the "CONSULTANT" will include:

1. Define Risk Assessment Model and establish the primary output paramenters such as:
   - Number, length, size, alignment, and location of tunnels, surface structures and the related surface structures;
   - General rock mass type and quality;
   - Proximity to favorable or adverse geotechnical conditions
   - Faults and fault zones (vulnerability to earthquake damage),
   - Water-saturated zones,
   - Surface instabilities,
   - Location/impact of surface facilities and structure (e.g., portals, ventilation facilities).
2. Analyze data provided by PBQD and the USGS
3. Prepare Quantitative Cost and Risk Outputs.

   Prepare central, upper, and lower values for costs and schedule impacts for each alignment and grade option.
4. Prepare General Discussion of Tunneling Risks and Risk-minimization.

   This will include a discussion of key tunneling design and cost parameters, risk factors, and other issues associated with alignment and design of long, deep tunnels based on the Consultant's international experience.
5. Prepare a Technical Working Paper.

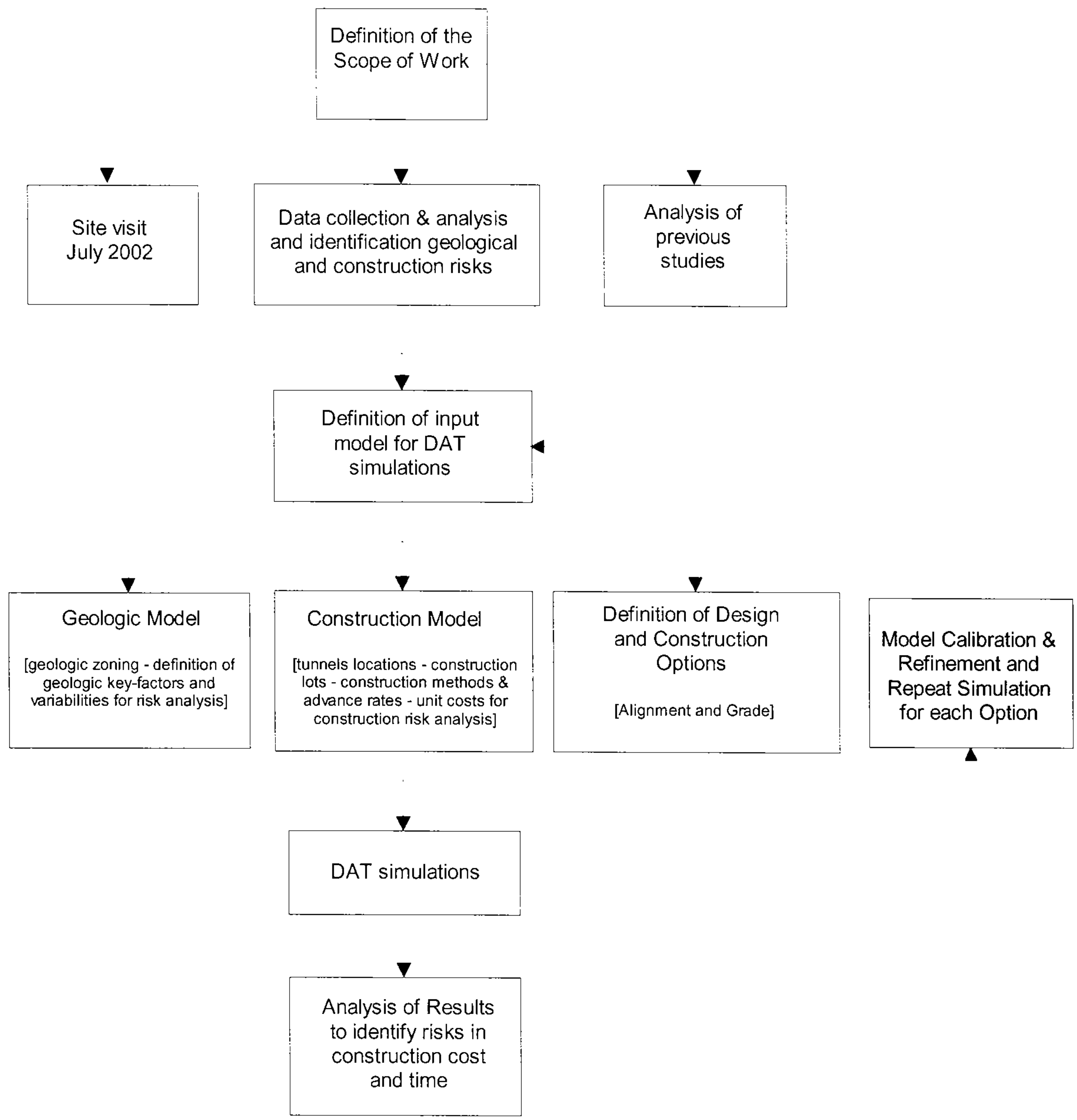
The process to fulfill the above tasks are illustrated in Figure 1.2.

1.4 List of Acronyms

CONSULTANT	Transmetrics Inc. and Geodata S.p.A.
CHSRA	California High-Speed Rail Authority
HSR	High-Speed Rail
DAT	Decision Aids in Tunneling
QUANTM	Automated Alignment Optimum System developed and applied in Australia
PBQD	Consultant to HSRA
AV	Antelope Valley (alignment)
I-5	Grapevine (alignment)
GSI	Geologic Strength Index
UCS	Unconfined Compressive Strength
TZ	Tunnel Zone
TBM	Tunnel Boring Machine

EPB	Earth Pressure Balance
CONV	Conventional Excavation (using drill-and-blast technique)

Figure 1.2 Flowchart illustrating the process for risk analysis conducted



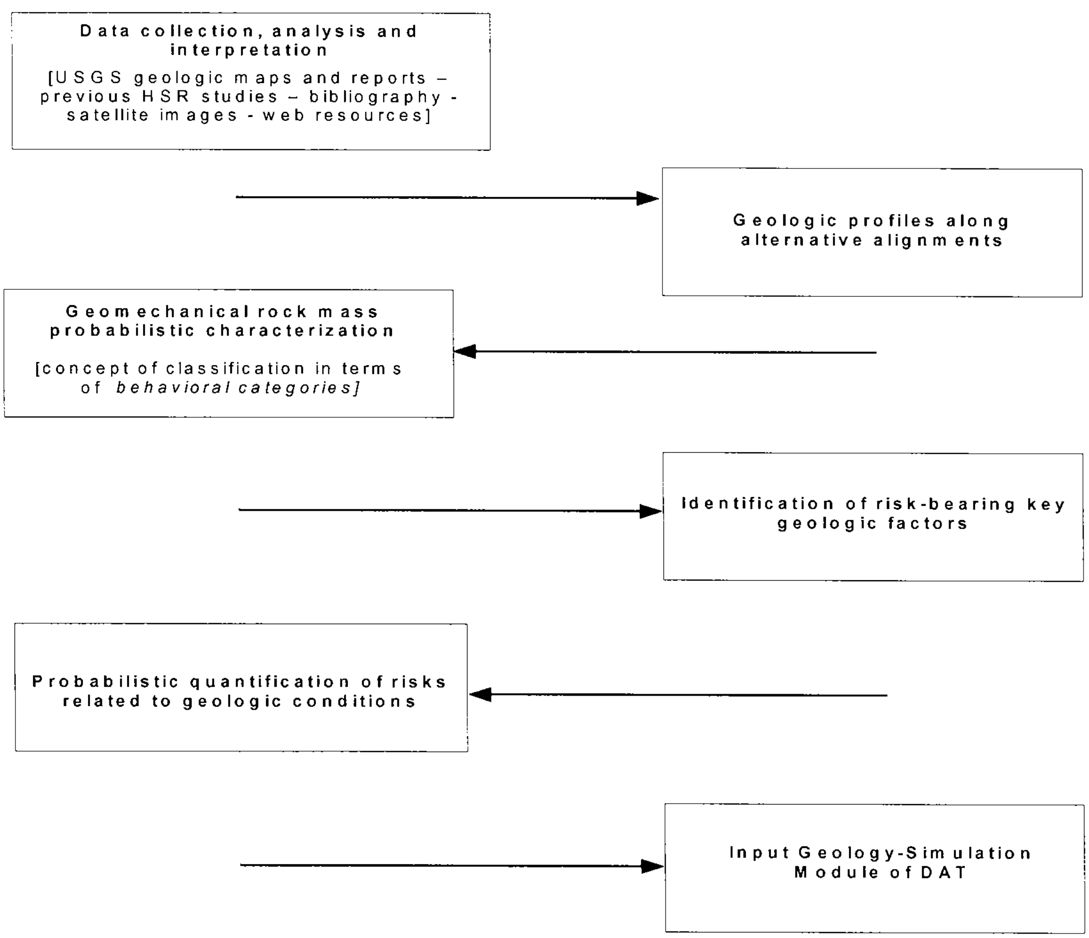
2. GEOLOGIC CONDITIONS ALONG ALTERNATIVE ALIGNMENTS

It is common experience in tunnelling that geologic conditions play an important, often critical role in determining the final success of a project in terms of meeting the planned schedule and budgeted costs. This is due to the inherent uncertainties about the prediction of the geologic key factors and their natural spatial variability, that can only be reduced but not eliminated through the execution of proper site investigations.

Bearing this in mind and considering the extent and complexity of the California HSR project, we have considered it necessary to establish an adequate geologic model aimed at defining the conditions to be encountered during tunnelling along the two alternative alignments. The model should be consistent with the current stage of development of the Project and with the available information.

The model-development process is illustrated in Figure 2.1.

Figure 2.1 Flowchart showing the geological-model development process



The following is a summary of the geologic conditions that are expected to be encountered along the I-5 and AV alignments. Details of the geologic conditions are provided in Appendix 2.

2.1 Geologic Units

The four broad geologic units expected to be crossed by the tunnel alignments are:

- (Pre-Tertiary) Metamorphic rocks, such as quartzite.
- (Pre-Tertiary) Intrusive rocks, such as granite.
- (Tertiary) Sedimentary rocks, such as sandstone, and volcanic rocks, such as basalt.
- Quaternary deposits, such as gravel.

2.2 Principal Faults

The characteristics of the principal faults that are considered to directly intersect the underground sections of the two tunnel alignments are summarized in Table 2.1. Two important aspects of the faults, which should be considered in the selection of a tunnel alignment are: the tectonically active character, and the slow, plastic slippage that may generate ground movements of several mm/year.

Table 2.1 Principal fault zones affecting the alternative alignments

Fault zone	Location (align., approx. chain.) (3)		Type	Attitude (dip/dip direction or strike direction)	Estimated width [m] (1)	Last seismic event year/magnitude] (2)	
S. Andreas	I-5	km 78+000	S, RH	Near vertical, NW-SE	800 - 1000	1857 (south branch)	8.0
Garlock	I-5 AV	km 70+250 km 79+350	S, LH	Near vertical, NE-SW	500 - 800	1992 (Mojave)	5.7
S. Gabriel	AV	km 177+950 km 178+200 km 178+850	S, RH	Near vertical, NW-SE	400 - 600	Quaternary	unknown
S. Susana	I-5 AV	? km 183+600 km 184+200	T	var., NW to NE	200 - 250	Late Quaternary 1971 (S. Fernando)	unknown. 6.5
Pleito	I-5	km 57+700	T	var., NNW	150 - 200	345-1465 years ago	unknown
Pastoria	I-5	km 67+000	R	var., SSE	300 - 400	unknown; probably non active	
Edison	AV	km 38+600 km 40+600	N	45-75°, NNW	100 - 200	unknown; probably non active	
Legend	S (strike-slip fault), T (thrust fault), N (normal fault), R (reverse fault); RH, LH (right-hand mov., left-hand mov.)						
Note	(1) The figures refer to the estimated width of the fault affected zone (2) From SCDEC (Southern California Earthquake Data Center http://www.scecdc.scec.org/faultmap.html) (3) Chainage onset is assumed in Bakersfield						

2.3 Groundwater Conditions

Groundwater in the study area is contained in three basin-fill aquifer systems: the Basin and Range aquifers, the Central Valley aquifers, and the Coastal Basins aquifers. Due to the lack of any detailed hydrogeological information, a qualitative hydrogeologic characterization was made to distinguish the potentially affected zones from the potentially unaffected zones with respect to the negative impacts of water inflow during tunneling.

2.4 Geomechanical Characterization of the Ground

The ground along the tunnel horizon was assigned "behavioral categories" **a** to **f** using the approach detailed in Appendix 2. The approach combines the Geologic Strength Index with the Deformation Index of the ground at the tunnel face and around the cavity, to define a behavioral category for the ground at a given section of the tunnel.

2.5 Anticipated Geologic Conditions Along Alternative Alignments

This section will outline the expected geologic conditions along the alternative alignments as recognized through the study of background literature (listed in Appendix 1) and visual inspection during the site visit of July 2002. Descriptions are presented for all the tunnel zones (TZ) of each alternative alignment option separately. For the sake of simplicity and completeness, reference will be made to deeper and longer, 2.5%-maximum-grade-alignment configuration. The descriptions are also valid for 3.5% max grade configuration.

I-5 (Grapevine) alignment

- TZ 1 (Grapevine to Castaic Lake)

Metamorphic to granitic rock types shall be encountered.

Tunneling shall intersect a very tectonically disturbed zone. Major regional faults are (i.e. Garlock and San Andreas systems) several hundred meterswide, while other important faults (e.g. Pleito thrust zone, Pastoria fault) and a certain number of minor shear zones will be crossed. Poor to very poor conditions can be anticipated through these zones, with a high potential for ground instability phenomena. Ground squeezing could occur in zones of low rock mass strength to lythostatic pressure ratio, while wedge-like instabilities could occur as a consequence of the blocky nature of the rock mass.

Zones bounded by successive fault zones are, on average, expected to be quite disturbed due to significant, though variable, fracture intensity. Also, the occurrence of associated potential water inflow phenomena seems to be quite probable in these zones.

The northern portal area (Grapevine) is a well recognized area subject to landsliding.

A particularly difficult geologic zone is represented by the section that extends between Garlock and San Andreas fault zones where, besides the expected very poor geomechanical conditions, groundwater can play a critical role in tunnel stability. The presence of a water body at the surface (tunneling shall be very close to Castaic lake) of this relatively low overburden zone, will constitute a very special environmental and geotechnical hazard.

- TZ 2 (Castaic Lake to Marple Canyon-Violin Canyon)

Here, sedimentary units of flysch-like character (interlayered sequence of sandstone, siltstone, claystone) are anticipated; rock properties are quite variable primarily as a consequence of the variability in rock types (reference can be made to the concept of *geotechnical complexity* or *complex rocks* as developed by the Italian Geotechnical Association since 1979).

In the northern area, intensely folded rock masses are anticipated. According to data from the USGS, the relative stiffness of the prevailing rock type (sandstone) folding could be associated with severe fracturing and blockyness of the rock mass, particularly in the fold hinge zones.

In the southern part of the tunnel zone not well lithified claystones may be encountered over a stretch of several hundred meters. Here instability phenomena is likely to occur during the excavation.

Similar to TZ1, the alignment will pass near a water body at surface (ZZZ artificial reservoir), this will be a matter of particular concern from the environmental and construction points of view.

From morphologic analysis (on both topographic maps and satellite image) the zone seems to be intersected by several minor faults that could be associated with their proximity to major fault zones (San Gabriel, San Andreas).

- TZ 3 (Santa Clara River to Lyon Canyon)

This narrow tunnel zone will intersect sedimentary units from Quaternary, unconsolidated coarse-grained grounds to Pliocene rocks. Tunneling shall be mainly in shallow conditions, except for a zone towards the center of the TZ where it will pass through a relief that appears quite densely urbanized.

While the potential for significant water inflows should not be important, the nature of the rocks could indicate the presence of gas.

- TZ 4 (Weldon Canyon to San Fernando-Sylmar)

Through this tunnel zone the alignment finally arrives at the San Fernando-Sylmar node. Again, clastic sedimentary rocks, of both marine and continental origins, will be encountered.

The entire zone, and particularly the second half towards Sylmar, is directly affected by important fault structures linked to the Santa Susana thrust system. Severe tectonization due to compressive shearing and, consequently, poor geomechanical conditions can be anticipated. Both water and gas could be present.

The tunnel will underpass a very low overburden near the I-5 freeway as well as the L.A. aqueduct.

Antelope Valley (Soledad Canyon) alignment

- TZ 1 (El Tejon to SR58-SR223-Bena Road junction)

This is the first tunnel zone that is between Bakersfield and the Tehachapi mountains.

Separated by the Edison fault, this tunnel zone encounters coarse sedimentary rocks in the first section of the tunnel, and granitic rocks until the eastern limit. With regard to the former, some uncertainty is represented by the very nature of the unit, i.e. whether it behaves more like a soil or a rock. For purposes of this study, it has been assumed that the unit is characterized by having a cohesive strength due to the presence of inter-particle bondage.

Due to its spatially variable altitude, the Edison fault could be actually intersected in different locations and possibly also in very unfavorable conditions (subparallel to the tunnel axis).

- TZ 2 (Clear Creek to Rowen)

This quite narrow tunnel zone is expected to be entirely excavated through good granitic rocks. Only minor tectonic structures have been hypothesized based on morphologic analysis.

A mainly elastic response to excavation can be anticipated.

- TZ 3 (West of Keene to West of Summit - Tehachapi)

This long tunnel zone will intersect a staggered series of dioritic and quartz-monzonitic and metamorphic rocks of probable sedimentary origin.

Through morphologic analysis and interpretation, some narrow fault zones have been introduced in the geologic model.

From the geomechanical perspective, potential instability phenomena are more likely to be associated with metamorphic rocks under high overburden and/or where rocks have been subjected to shearing.

- TZ 4 (from Proctor Lake zone to Mojave Desert)

Tehachapi mountains crossing will be carried out through this tunnel zone. The most evident feature is represented by the Garlock fault zone, which combines quartz-monzonitic rocks and Paleozoic gneiss. The latter represents a sort of tectonic slice bounded at both limits by a fault structure, and is expected to be mostly tectonically disturbed and weathered.

At the southern boundary (Mojave), quartz-monzonitic rocks disappear giving place to Quaternary coarse continental sedimentary units that progressively thicken towards the Mojave plain. For older deposits a certain cohesive strength can be hypothesized, but for more recent deposits a prevailing frictional behavior is anticipated.

Challenging geotechnical conditions shall be encountered when boring through the wide Garlock fault zone and the neighboring gneissic rocks, and particularly where the rocks are loose as a consequence of tectonic events.

- TZ 5 (from Soledad to Apple Canyon)

This long tunnel zone is south of the San Andreas Fault relief, through the Soledad Canyon region, and will intersect a variety of geologic units.

Hard and massive granitic rocks are present in the eastern border. The central portion is occupied mostly by heterogeneous rocks of the Vasquez volcano-sedimentary complex, and a tectonically bounded volume of Precambrian deeply weathered anorthosites. Finally, in the western zone, clastic sedimentary rocks appear.

On average, fair geotechnical conditions can be anticipated, with the exception of the area where anorthosites are present. Also across fault zones, most of which have also been recognized on geologic maps (e.g. the Pole Canyon fault), worse conditions are expected. Unfavorable groundwater conditions should characterize the section where the Soledad Canyon valley will be crossed with a reduced overburden.

- TZ 6 (South of SR 14 to Placerita Canyon)

This tunnel zone crosses, under relatively low overburden, sedimentary clastic rocks of various type: sandstones, siltstones, mudstones and, to a lesser extent, conglomerates (in the form of quite isolated levels or lenses). In addition, some tuff layers will be encountered in the eastern portion.

This zone also crosses in different locations some branches of the San Gabriel fault zone, which will provide a series of sub-zones with very poor geotechnical conditions. Groundwater is not expected to be a problematic issue because of the prevailing shallow conditions in which the TZ exists.

- TZ 7 (from Elsemere Canyon to San Fernando-Sylmar)

Through this tunnel zone the corridor enters the San Fernando Valley. It follows at a short distance TZ6 and shall encounter similar geologic units of sedimentary origin.

Non-marine facies, encountered at the northern margin, are described as quite loosely consolidated to poorly cemented, while marine facies in the central portion, appear as rock masses.

At the southern margin, the corridor is repeatedly crossed by different branches of the Santa Barbara thrust system, giving rise to a significant length of rock masses of very poor geotechnical condition.

Oil fields are present in the area and the potential of encountering some gas volumes particularly in the deepest sections of the TZ has to be considered.

2.6 Evaluation of Risk Arising from Adverse Geologic Conditions (Events)

For the purpose of the present study, only potentially adverse geologic conditions are considered. Other event categories, which might negatively affect the construction process, such as mechanical failures, socio-economic events, natural extreme phenomena (e.g. earthquakes, inundations, etc.) are not taken into account.

It should also be mentioned, that other factors not considered in the present study shall play an important role when a comprehensive risk analysis is implemented to help decision makers in selecting the more reliable project solution.

For example, when dealing with an alignment that passes through an area subject to landslides, one has to consider that more lengthy and costly tunneling could be a more reliable solution than increasing the grade or aerial sections. This reasoning holds true when considering the same alignment with respect to potential earthquake induced structural or functional failures.

Another important issue is represented by environmental factors. Temporary as well as permanent works or facilities above ground have different impacts on the perceived environmental value of certain areas. In this respect, a more general public consensus could be reached regarding the feasibility of some solutions instead of others. For instance, the increased costs of a longer tunnel in a territory of environmental value could represent an acceptable trade-off.

Adverse geologic conditions that can be experienced in tunnel construction have the potential of causing time delays and costs overruns. This is of particular relevance when such adverse conditions have not been sufficiently investigated before starting the construction phase.

Although the principal types of potentially adverse geologic features can be reasonably anticipated through detailed studies, uncertainties about the location still remain as an inherent risky aspect of underground construction.

The best way to effectively manage such uncertainties is to treat them in a probabilistic manner, describing the possible occurrence of each category of accident with specific probabilistic parameters as will be depicted in the description of DAT (Section 4).

For the purpose of this study, starting from the referenced geologic model, four categories of potentially adverse conditions (geo-events) have been recognized, namely:

- Tunnel instability phenomena (from local collapse to severe ground squeezing)
- Water inflows
- Presence of hazardous gas (explosive or toxic hydrocarbons)
- Anomalous abrasivity

Conceptually, the risk for each event can be defined as a function of uncertainty and damage; that is,

Risk = *f (event uncertainty, event damage)*

Through DAT simulations, a zoning of the geologic adverse conditions has been performed emphasizing for each *geo-event* two or three levels of significance. This is done combining the estimated likelihood of occurrence and the potential impact on the construction phase.

3. SCHEMES FOR CONSTRUCTION OF THE TWO ALIGNMENTS

In order to perform the proposed alignment specific risk analysis, the Consultant had to make a conceptual construction of each design construction option, making relevant assumptions for those aspects not yet defined in previous studies. This conceptual design is summarized in the following subsections.

3.1 Definition of the Alignment Alternatives

As anticipated in Section 1 - Introduction, the two alternative alignments considered by the HSRA for crossing the Tehachapi Mountains between Los Angeles Union Station and Bakersfield are:

- The AV, or the Antelope Valley Alignment, and
- The I-5, or the Grapevine Alignment.

These two alignments differ principally in relation to (1) length, (2) accessibility, and (3) construction complexity and risk.

The position of the so called "Tunnel Zones" is defined based on the position indicated in the Authority's documents (Orthophotos).

The position of each single tunnel is fixed using the following procedure:

1) Get the approximate position from the Orthophotos.
2) On the basis of Step 1, evaluate if the maximum vertical grade of the tunnel in question is consistent with the specified maximum grade option (be it 2,5% or 3,5%). If not, move the position of one or both portals, changing as a consequence slightly the length of the tunnel in order to be consistent with the maximum-grade option to be analyzed.
3) In order to have 20M of overburden above a tunnel base, portals can be adjusted to insure a reasonable cover thickness before the start of construction.
4) For those long tunnels whose lengths are greater than 6 miles (see forward to Section 3.3) a third service tunnel is required for ventilation, evacuation and construction access. In this case the portal positions are fixed in accordance with those of the corresponding main tunnels.

Applying the above procedure, the positions of the portals and the lengths of the tunnels analyzed can be slightly different with respect to those defined in the Authority's documents.

The construction scheme for each tunnel is defined according to the Consultant's experience and knowledge. The schemes adopted are detailed in the subsection 3.5 (Tables 3.3 to 3.6). Each alignment grade option has been studied independently with the intent of reducing construction risks in terms of time and cost, without neglecting the technical feasibility.

The main tunnels are configured with twin bores, each bore housing a single rail track. The distance between the two bores and therefore the length of the crosspassages, should be determined properly in a successive design phase to ensure the stability of the pillar between the twin bores.

3.2 Choice of an Excavation Technique

As technical literature and excavation experiences all over the world have shown in the last decade, long tunnel excavation by TBM is nowadays a must, not only to ensure financial return of the investment, but also to manage labor conditions and environmental impacts. When rock mass conditions exist in a wider range, TBM excavation minimizes the construction time due to the high advance rates of this technology. This technological benefit is complemented often with an almost immediate installation of the final lining in the tunnel without incurring delays.

A particular family of TBM machines, i.e., the Double Shield TBM, is known for its wide application range and high performance. This is made possible by the feature that allows the machine to advance both as an open TBM when rock conditions are good to medium and as a single shield TBM when rock conditions are poor to extremely poor. In both excavation modes, the working site is kept in a safe condition by the protection of the telescopic shield and the consequent pre-cast concrete segmental lining which is installed simultaneously with the advance of the excavation. The result is a high performance rate in both good and poor rock conditions. The main disadvantages are the high initial investment and a long period of procurement and assembly.

For the both the I-5 and the AV alignment alternative, Double Shield TBMs have been selected for the tunnel excavation.

TBM excavation is applied for all long tunnels in order to make each machine excavate as long as technically feasible, thus amortizing the initial high cost of the machine.

For short tunnels, the first option is to use a TBM previously employed to excavate a similar small section in another tunnel, taking into account the related costs of disassembling and reassembling as well as transportation from one site to the other. If the transfer of a TBM from another excavation site impacts too negatively on overall construction time, a dedicated TBM should be adopted.

Conventional excavation may be selected for all those situations where its application will significantly reduce overall construction duration.

3.3 Service Tunnel

As discussed in the Tunneling Conference (December 3-4, 2001), a service tunnel is required for tunnel lengths over 6 miles, with the aim of providing a safety access way. It is assumed that the excavation of the service tunnels will start as early as possible before to the excavation of main tunnels.

The horizontal position of the service tunnel is assumed to be central to the main twin bore tunnels, in order to provide the best geological information for the excavation of the main tunnels and thus optimize its safety role. The service tunnel also provides drainage for groundwater to avoid inflow into the main tunnels.

It should also be pointed out that the service tunnel requires a thicker pillar between the main tunnels. Therefore, the length of each cross passage must take into account this increase in the separation distance between the twin bores of the main tunnel.

3.4 Seismic Chamber

As mentioned previously in Section 1.2.2, in case the tunnel crosses a major potential earthquake inducing fault zone (the San Andreas Fault and the Garlock Fault), the construction of a 1000m long large cross-section chamber, will allow for the realignment of the rail tracks in case of a major seismic event. The basis of this conceptual design choice is that these faults are expected to produce sufficiently large, lateral shear displacements during an earthquake capable of cutting and closing the tunnel section. It should be noted that so far the enlargement of a normal tunnel section to form the required seismic chamber has been considered only in the direction of the assumed potential lateral movement, which is predicted based on the past movement records of the fault concerned. However, a very recent science discovery has revealed that "faults go backwards". This discovery was reported first in the September 2002 issue of "Science" and then in the November 2002 issue of "Geoscientist" the magazine of the Geological Society of London. The following paragraphs are extracted from the article published in "Geoscientist".

> *"The earthquake known as the Hector Mine Event (1999) has enabled seismologists to identify new forms of earthquake-related deformation.*
>
> *On October 16 1999, approximately 37 miles from Palm Springs, California, a magnitude 7.1 earthquake ripped through 28 miles of faults in the Mojave Desert. Because of the area's sparse population and development, the massive quake caused virtually no major measurable injuries or destruction.*
>
> *Yet the Hector Mine event, named after a long-abandoned mine in the area, has indeed created a mine of information about earthquakes, faults, and ruptures for scientists at Scripps Institution of Oceanography at the University of California, San Diego.*
>
> *Writing in Science (September 13), the scientists, along with a colleague at the California Institute of Technology (Caltech), reveal how they used satellite and radar technologies to uncover characteristics of faults previously unknown to science. These include the first evidence that faults move backwards, contrary to conventional observations, and indications that the material within faults is significantly different from that in its surroundings."*

This new discovery suggests there is a risk that the seismic chamber solution may not serve its intended purpose. Clearly, this is not just a design risk. On the other hand, an alternative design of the seismic chamber is out the scope of work of the Consultant.

For the proposed analysis, the seismic chamber conceived by the HSRA is analyzed, also in terms of its potential for optimization of the construction of the tunnel crossing through a fault zone. Possible scenarios have been defined and analyzed to check if construction of a seismic chamber beforehand may help to reduce the overall time of constructing the main tunnel, and to minimize at the same time, the risk exposure of the main tunnel construction.

In any case, as a design choice an at grade fault crossing is preferred for each alignment option wherever the allowable maximum grade permits in order to limit construction costs and reduce risks.

In the case of the I-5 Alignment, the excavation of the seismic chambers through the Garlock Fault, is assumed to start from the service tunnel for both the 2.5% and the 3.5% maximum grade options. Consequently, when the 9.5m diameter TBMs reach the fault zone, they can simply be pulled or pushed through the already constructed seismic chamber, and thus avoid the risks of instability and blocking of the TBM. Only for the 2.5% maximum grade option, the seismic chamber required for crossing the San Andreas Fault Zone is assumed to be realized before the arrival of the 9.5m diameter TBM excavating the main tunnel. In this case it is also assumed that the seismic chamber will be constructed during the long period of procurement and assembly of the large TBM.

In the same manner, the 2.5% maximum grade option of the AV Alignment requires the construction of a couple of seismic chambers in the Tunnel Zone no. 4 to cross the Garlock Fault. To reduce general scheduling risks and to avoid ground instabilities when constructing the main tunnels, it is assumed that these seismic chambers will be constructed *a priori* from an access shaft.

3.5 Construction Scheme of Alignment Grade Option

Given the choice of two alternative alignments (I-5 or AV) and two maximum grade (2.5% or 3.5%) options, there are in total four combined options. The construction schemes adopted for these 4 alignment maximum grade options are defined on the basis of the criteria presented in Sections 3.1 to 3.4 and are illustrated in Figures 3.1 to 3.6. In these figures the realization scheme for each portal is not represented in order to keep the figure readable.

Table 3.1 gives a legend to the graphic symbols used in Figures 3.1 to 3.6, while Table 3.2 contains a summary of the construction features of various options, detailed also separately in Tables 3.3 to 3.6.

Table 3.1 Legend to Figures 3.1 to 3.6

Tunnel Zone n° 1	Name of the Tunnel Zone considered
	Profile of the area
	Approximate position of tunnels
SHAFT	Excavation of shafts, with conventional method, is represented with black vertical arrows
Seismic Chamber	Excavation of the seismic chambers for major fault crossings (San Andreas Fault and Garlock Fault), by conventional methods, is represented with green straight arrows
TBM 9.5m EPB 9.5m	Excavation of the main tunnels is represented by black straight arrows to show the direction of advance, and with a "9.5m TBM" label if the excavation is realized by means of a 9.5m diameter TBM, or a "EPB 9.5m" label if it is realized by means of an Earth Pressure Balance Shield
TBM 5.0m	Excavation of the service tunnels (by means of a 5.0m-diameter TBM) is represented with red straight arrows
CONV	Excavation of the main tunnels using conventional methods (such as Drill & Blast or NATM) is represented with blue straight arrows
	A curved arrow represents the transportation of the same TBM in a different tunnel or in the second tube of the same twin bore tunnel
50000 60000	Chainage (i.e. Station) is given in the bottom of every figure. The chainage distance increases from Bakersfield to Los Angeles.

Fig. 3.1 I-5 Alignment with 3.5% maximum grade – Tunnel profile and construction scheme

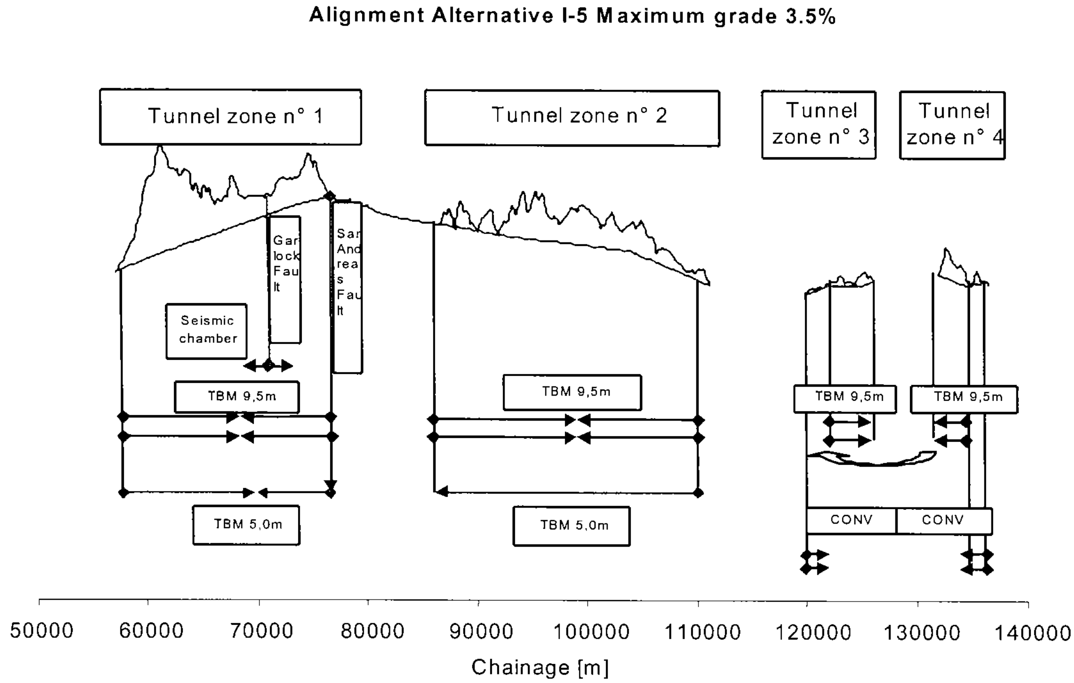


Fig. 3.2 I-5 Alignment with 2.5% maximum grade – Tunnel profile and construction scheme

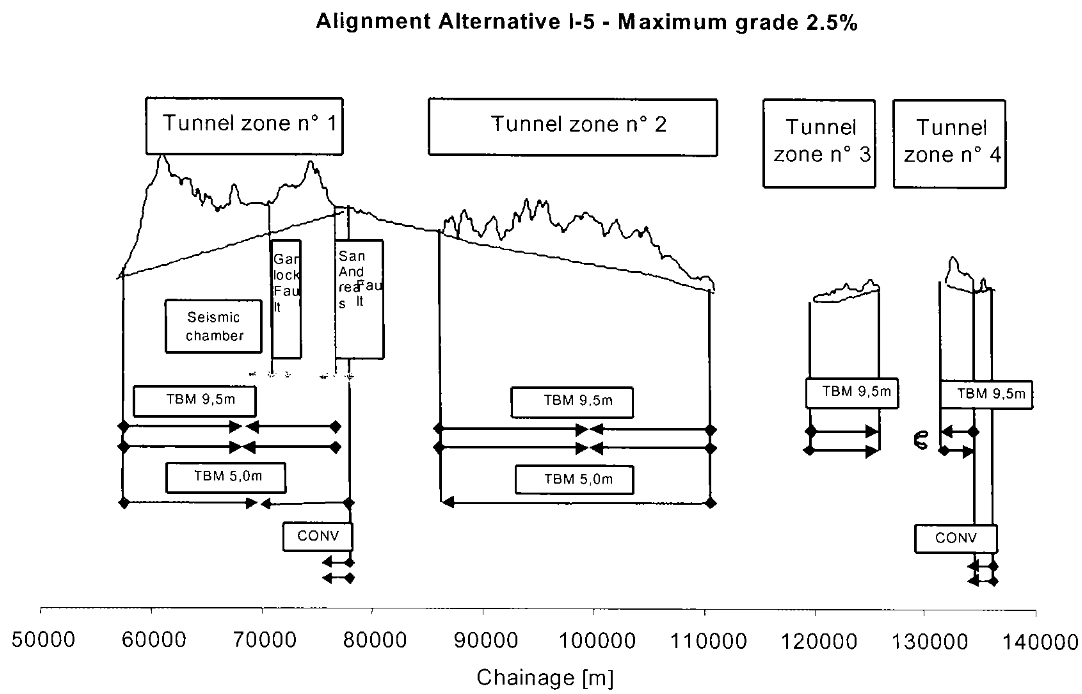


Fig. 3.3 AV Alignment with 3.5% maximum grade – Tunnel profile and construction scheme

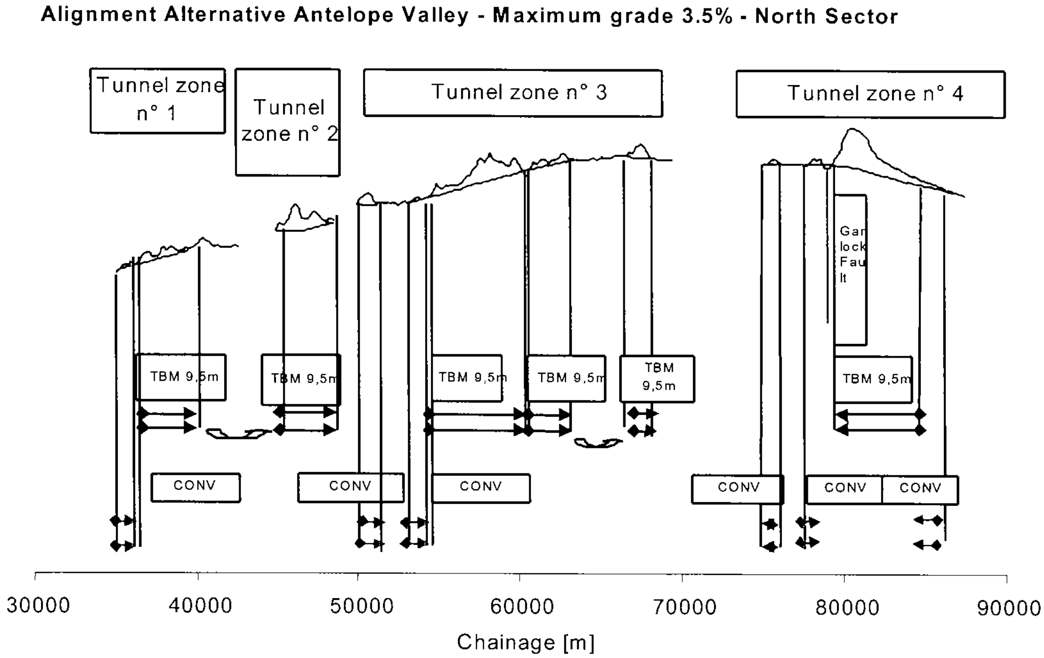


Fig. 3.4 AV Alignment with 3.5% maximum grade – Tunnel profile and construction scheme.

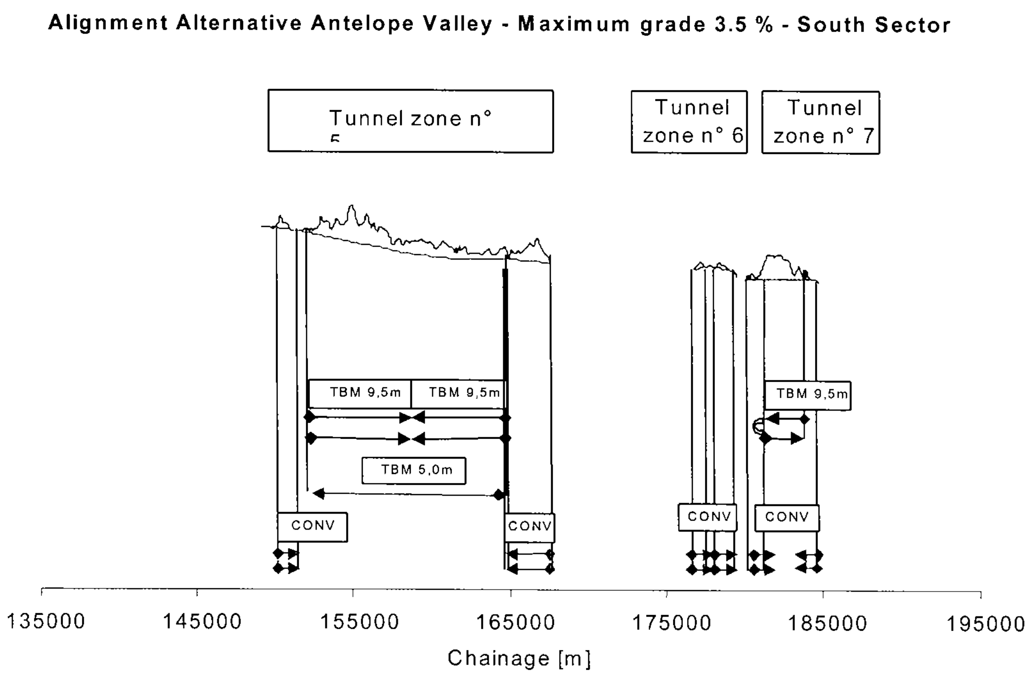


Fig. 3.5 AV Alignment with 2.5% maximum grade – Tunnel profile and construction scheme

Alignment Alternative Antelope Valley - Maximum grade 2.5% - North Sector

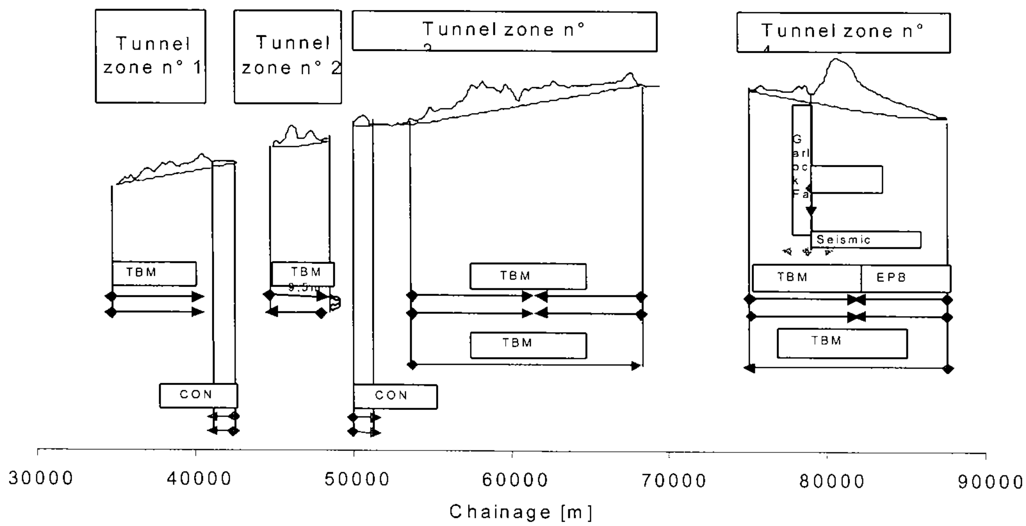


Fig. 3.6 AV Alignment with 2.5% maximum grade – Tunnel profile and construction scheme

Alignment Alternative Antelope Valley - Maximum grade 2.5% - South Sector

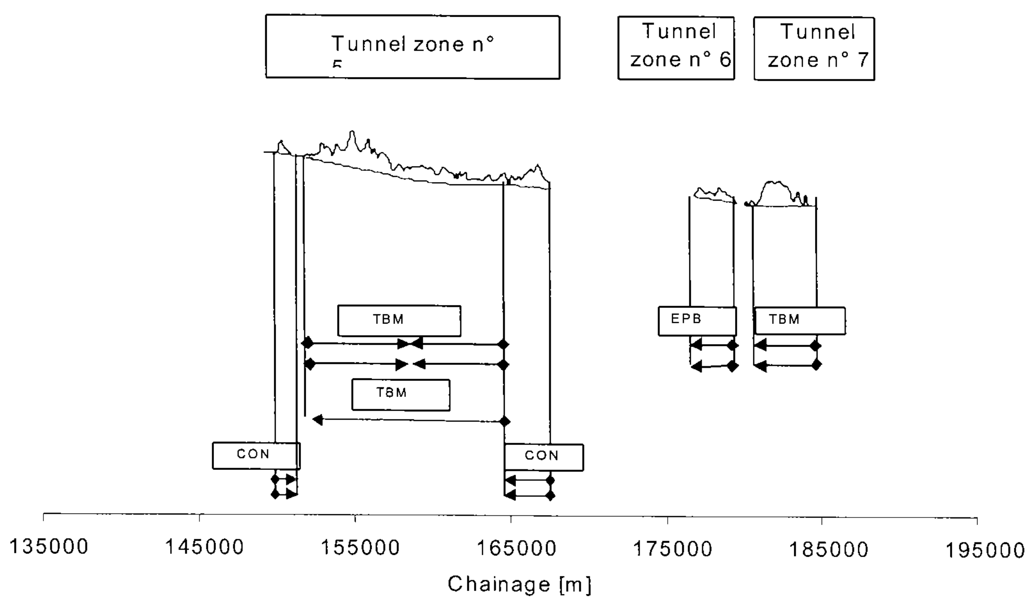


Table 3.2 Summary of construction phases

Summary of construction phases		Alignment Alternative I-5		Alignment Alternative AV	
		Max grade 3.5%	Max grade 2.5%	Max grade 3.5%	Max grade 2.5%
1) Main tunnels					
Number of Main Tunnels	[-]	8	8	36	14
Number of 9.5 m TBMs	[-]	*	*	*	*
Number of 9.5 m EPBSs	[-]	*	*	*	*
Cumulative Tunnel Length (Twin-Tunnel)	[km]	52.5	54.0	50.0	64.2
	[miles]	32.6	33.5	31.1	39.9
Total Tunneling length (counting both tubes)	[km]	104.9	107.9	99.9	128.3
	[miles]	65.2	67.0	62.1	79.7
Breakdown of Total Tunneling length according to Tunneling methods					
by TBM	[km]	100.8	103.8	78.9	114.0
	[miles]	62.6	64.5	49.0	70.8
by Cut & Cover	[km]	2.1	2.1	10.0	4.5
	[miles]	1.3	1.3	6.2	2.8
by Conventional method	[km]	2.0	2.0	11.0	9.8
	[miles]	1.2	1.2	6.8	6.1
2) Service Tunnels					
Number of Service Tunnels	[-]	2	2	1	3
Number of 5.0 m TBMs	[-]	*	*	*	*
Total length of Service Tunnels	[km]	43.5	43.5	13.0	24.9
	[miles]	27.0	27.0	8.1	15.5
3) Trenches					
Total length of Trenches due to adjustment of the Tunnels profiles	[km]	2.7	0.0	4.0	1.4
	[miles]	1.7	0.0	2.5	0.9
4) Other works					
Excavation sites/Portals	[-]	23	23	50	41
Number of shafts	[-]	1	1	0	1
Number of Major Fault Crossing Seismic Chambers	[-]	2	4	0	2
* To be defined					

Table 3.3 Construction scheme for the I-5 Alternative Alignment, 3.5% max. grade

	Alignment Alternative	**I-5**				
	Maximum grade	**3.5%**				
Tunnel zone number	**Construction features**	**From chainage [m]**	**To chainage [m]**	**9.5m TBM**	**5.0m TBM**	**Traditional Excavation Sites**
		[m]	[m]	[-]	[-]	[-]
1	Twin main tunnels	57300	76600	4		
	Service tunnel	57300	76600		2	
	Seismic chambers (from Service tunnel)	71325	70825			2
	Seismic chambers (from Service tunnel)	71325	71825			2
2	Twin main tunnels	86600	111200	4		
	Service tunnel	86600	111200		1	
3	Conventional excav.	120000	121500			2
	Twin main tunnels	121550	126000	2*		
4	Twin main tunnels	131950	134600	2*		
	Shaft (h=50m)	134600				1
	Conventional excav.	134600	135000			2
	Conventional excav.	135000	136200			2

Table 3.4 Construction scheme for the I-5 Alternative Alignment, max. 2.5% grade

	Alignment Alternative	I-5				
	Maximum grade	2.5%				
Tunnel zone number	Construction features	From chainage [m]	To chainage [m]	9.5m TBM	5.0m TBM	Traditional Excavation Sites
		[m]	[m]	[-]	[-]	[-]
1	Twin main tunnels	57300	76600	4		
	Service tunnel	57300	76600		2	
	Seismic chambers in Garlock Fault crossing (from Service tunnel)	71325	70825			2
	Seismic chambers in Garlock Fault crossing (from Service tunnel)	71325	71825			2
	Shaft (h=60m)	76200				1
	Seismic chambers in San Andrea Fault crossing (from Shaft)	75800	76200			2
	Seismic chambers in San Andrea Fault crossing (from Shaft)	76200	76800			2
2	Twin main tunnels	86600	111200	4		
	Service tunnel	86600	111200		1	
3	Twin main tunnels	120000	126000	2		
4	Twin main tunnels	131950	134600	1		
	Shaft (h=50m)	134600				1
	Conventional excavation	134600	135000			2
	Conventional excavation	135000	136400			2

Table 3.5 Construction scheme for the AV Alternative Alignment, max. 3.5% grade

	Alignment Alternative	**AV**				
	Maximum grade	**3.5%**				
Tunnel zone number	**Construction features**	**From chainage [m]**	**To chainage [m]**	**9.5m TBM**	**5.0m TBM**	**Traditional Excavation Sites**
		[m]	[m]	[-]	[-]	[-]
1	Conventional excav.	35000	36200			2
	Twin main tunnels	36250	39300	2*		
2	Twin main tunnels	44900	47850	2*		
3	Conventional excav.	50000	51350			2
	Conventional excav.	53000	54300			2
	Twin main tunnels	54300	60400	2		
	Twin main tunnels	60450	63150	2*		
	Twin main tunnels	66550	68250	2*		
4	Conventional excav.	75350	76250			2
	Conventional excav.	77750	78850			2
	Twin main tunnels	79150	85200	2		
	Conventional excav.	85200	85700			2
5	Conventional excav.	150150	151150			2
	Twin main tunnels	151950	165050	4		
	Service tunnel	151950	165050		1	
	Conventional excav.	165050	167750			2
6	Conventional excav.	176800	177600			2
	Conventional excav.	178500	179350			2
7	Conventional excav.	180600	180850			2
	Conventional excav.	181050	181650			2
	Twin main tunnels	181650	184000	1		
	Conventional excav.	184000	184700			2

Table 3.6 Construction scheme for the AV Alternative Alignment, max. 2.5% grade

	Alignment Alternative	AV				
	Maximum grade	2.5%				
Tunnel zone number	Construction features	From chainage [m]	To chainage [m]	9.5m TBM	5.0m TBM	Traditional Excavation Sites
		[m]	[m]	[-]	[-]	[-]
1	Twin main tunnels	35000	41500	2		
	Conventional excav.	41500	42950			2
2	Twin main tunnels	44900	48600	1		
3	Conventional excav.	50000	51350			2
	Twin main tunnels	53000	68200	4		
	Service tunnel	53000	68200		1	
4	Twin main tunnels	75000	87100	2+2**		
	Service tunnel	75000	87100		1	
	Shaft (h=50m)	78500				1
	Seismic chambers in Garlock Fault crossing (from Shaft)	78200	78500			2
	Seismic chambers in Garlock Fault crossing (from Shaft)	78500	79200			2
	*** EPB machine					
5	Conventional excav.	150150	151150			2
	Twin main tunnels	151950	165050	4		
	Service tunnel	151950	165050		1	
	Conventional excav.	165050	167750			2
6	Twin main tunnels	176800	179600	2**		
	** EPB machine					
7	Twin main tunnels	180000	184800	2		

4 DESCRIPTION OF DAT (DECISION AIDS IN TUNNELING)

In view of the number of alternatives under analysis and the potential for considerable risks associated with the selection of one alignment over the other, the use of the software /system DAT (Decision Aids in Tunneling) was used by the project study team. DAT is a tool for making probabilistic estimates of the time and cost of constructing a tunnel, or network of tunnels, taking into account the uncertainties in the geologic and construction variables. DAT also functions as a value adding tool for making an assessment of the risk of exceeding the thresholds of cost and time for projects.

A DAT run is essentially a computer simulation of several random processes. The idea of using computer simulations comes with the fact it is not possible to find analytically resulting random functions when processes are too complicated like the construction of tunnels. So simulating a construction process is the only solution to obtain statistical information about the total time and cost. This information gives a good idea on the average, minimum and maximum expected values. By definition, the simulation of a random process uses a random number generator.

DAT and the associated computer code SIMSUPER have been developed over a period of 20 years by MIT (Massachusetts Institute of Technology) and EPFL (École Polytéchnique Fédérale de Lausanne), with the participation of the US National Science Foundation, the Swiss Federal Office for Transportation, the Swiss Science Foundation, and Geodata SpA.

A unique feature of DAT is its capability for a comparative evaluation of the performance of project alternatives with respect to the potential of these alternatives in managing geotechnical and construction uncertainties within prescribed or acceptable values of time and cost.

DAT consists of two interrelated simulation modules: Geology and Construction.

In the Geology module the geotechnical conditions are organized in the various input matrices following an approach similar to that of defining a geotechnical profile, i.e., defining, chainage by chainage, all the geological and geomechanical conditions that have an impact on the tunnel construction practice. The user's task is to identify and define which are those parameters and what are their possible states. Uncertainty in this definition is either entered by indicating the variability in the assigned value of the parameter, and/or in its state probability (e.g., see Table 5.3). In addition, variability of conditions along a segment is modeled using a Markov process. In a manner similar to defining the geomechanics classification, different parameter states are combined to define homogeneous ground classes that are subsequently associated with the construction methods. For example, if problematic water inflows and squeezing conditions are identified as impacting parameters, their possible states have to be defined, as well as the influence of their possible state combinations on every excavation phase modeled in the subsequent construction module.

The Construction module consists of two principal components:

- The first refers to the construction methods where the construction cycle can be simulated activity by activity. In this case variability is introduced into the model by statistical distributions of basic construction indices, e.g., advance rate and unit cost, usually derived practical case histories and price analysis.
- The second module, which is referred to as *tunnel network,* permits the definition of the sequence of realization of a tunnel and a project, e.g., two opposite fronts for a tunnel, or excavation of a pilot bore by a TBM, followed by the enlargement by traditional (or conventional) methods.

In both the geology and the construction modules, variability of the parameters is described through a user-defined distribution function that can be chosen from among Uniform, Triangular, and Bounded Triangular distributions. In the Uniform distribution, the variable always has the same probability of taking on any value. In the Triangular distribution, a minimum value, a most likely value (the mode), and a maximum value have to be provided, recognizing that the total area under the triangle must equal one (as the total probability of occurrence of the parameter must be 100%). In the Bounded Triangular distribution, the probabilities on the minimum and maximum boundaries of the triangle are greater than zero. Where this last distribution has been used in this study, the minimum and maximum probabilities are indicated in the input tables.

5 DAT SIMULATIONS INPUT

5.1 Determination of the Geomechanical Parameters

As part of the input to the DAT analysis, geological and geomechanical longitudinal profiles were defined based on maps of the USGS. Also, based on USGS reports, the essential geomechanical parameters were defined for each homogeneous geological zone.

In addition to the behavioral categories, the range of "geo-events" (see Sec. 2.6) that could cause delays and extra costs were considered, particularly when a tunnel was to be excavated by a TBM. A TBM is a relatively rigid method of excavation that cannot easily be adapted to changing ground conditions. The events that have been considered are:

- Potential instability conditions (excavation face, cavity, or both);
- Potential problematic water inflows (large quantities in short time);
- Possible presence of gas
- Anomalous abrasivity of the rocks to be excavated.

The combination of the behavioral categories and the first three of the above mentioned geo-events determines in an unambiguous way the so-called "Ground Parameter Set". A Ground Parameter Set includes the probability of occurrence of each parameter state and is not yet associated with a segment of tunnel. In other words, a few combinations of the parameters can be applied to a zone characterized by a unique Ground Parameter Set, as each parameter state is still expressed as a probability of occurrence. The univocal association of the unit segment to a homogeneous set of parameters brings it to the following stages: (a) combination of the Ground Parameter Set and the Anomalous Abrasivity parameter to define a Combined Ground Class, and (b) the Geological simulation that is repeated at every global simulation. The combination of the parameters that determine the values of cost and average advance rates, and/or the cost and duration of interventions in case of "accidents" associated with each meter of tunnel or each unit segment is the output of the Geological simulation. This output in turn becomes an input to the Construction simulation. This feature, which can be considered as the simulation of the geological uncertainty, makes one simulation different from another with respect to the geological aspect. It is not possible to show the detailed zoning of each parameter as it is different for each of the 1000 simulations. Instead, the following sections will define the meaning and the determination process of each Ground Parameter Set, as well as its zoning and the formation of the Anomalous Abrasivity zones that constitute the highest detail information that can be given without entering into each simulation run. Further details are given in Section 5.2.

Table 5.1 Schematic generation of the Ground Parameter Set corresponding to each homogeneous zone in DAT's Geo Module, results from the combination of behavioral categories and "geo-events". Colors refer to different states and/or combination of the parameter and express the importance of this combination. Values and combinations are given as an example of the method of determination of any Ground Parameter Set. For a detailed screening of possible parameter states, see Sections 5.1.1 to 5.1.5. The significance of brackets around the parameter "Anomalous abrasivity" is explained in paragraph 5.1.5.

Zone number → / **Parameter name** ↓	1	2	3	etc.
Behavioral category	90% a/b 10% c	50% c 50% d	100% fault	...
+ **Potential instability conditions**	100% no	1% yes 99% no	[redacted]	...
+ **Potential problematic water**	1% yes 99% no	100% no	[redacted]	...
+ **Possible presence of gas**	1% yes 99% no	100% no	100% no	...
+ ***(Anomalous abrasivity)***	*100% no*	*100% yes*	*100% no*	...
= **Ground parameter set**	GPS X	GPS Y	GPS Z	...

The following sections show the details of each parameter, and the resulting Ground Parameter Set for each homogeneous zone.

5.1.1 Behavioral categories

For a description of the assumed classification, reference may be made to Section 2.4 Geomechanical characterization of the ground. In the present analysis, behavioral classes have been grouped in a slightly different way to fit the specific conditions of the specific project area characterized by an important number of major fault zones. In order to associate the most suitable construction parameters to those very special zones, a behavioral category named "fault" has been created because its characteristics actually duplicate those of the "f" category discussed in Section 2.4. The possible states of the "Behavioral category" parameter are shown in Table 5.2.

Table 5.2 The possible states of the "Behavioral category" parameter

Parameter	Possible states
Behavioral category	a/b
	c
	d
	e/f
	fault

In the definition of the Ground Parameter Sets, assignment of the parameter state is obtained with probabilistic assumptions, for example, a particular zone may be defined with a 50% probability of state "c" and a 50% probability of state "d". Several combinations have been assumed, presenting ratios of 10/90, 50/50 and 90/10 between two contiguous classes. The result is a probabilistic distribution of the behavioral classes, modeled in every simulation-run.

5.1.2 Potential instability conditions

Instability conditions have been grouped into three main categories: No Instability Zones, Minor Instability Zones and Major Instability Zones.

The three possible states of the parameter are associated with a probability of occurrence that allows the program to create the parameter zoning in a probabilistic way. The possible states of the "Potential Instability Condition" parameter, with their associated probabilities, are shown in Table 5.3.

Table 5.3 "Potential Instability Condition" parameter possible states and assumed probabilities of occurrence

<table>
<tr><th rowspan="2">Parameter</th><th rowspan="2">Possible states</th><th>Probability of occurrence</th><th>Probability of occurrence</th></tr>
<tr><th>Instability</th><th>No Instability</th></tr>
<tr><td rowspan="3">Potential Instability Condition</td><td>No instability zones</td><td>0%</td><td>100%</td></tr>
<tr><td>Minor instability zones</td><td>1%</td><td>99%</td></tr>
<tr><td>Major instability zones</td><td>10%</td><td>90%</td></tr>
</table>

5.1.3 Potential problematic water inflow

Two principal scenarios have been hypothesized. In the first, no significant water inflows or minor water inflows (that do not impact on the construction process) can be anticipated. In the second, the water inflow phenomenon is severe enough to cause a construction delay (the excavation must be stopped in order to adopt the necessary countermeasures).
The two possible states of the parameter, are associated with a probability of occurrence that allows the program to create the parameter zoning in a probabilistic way. The possible states of the "Potential Problematic Water Inflow" parameter, with their associated probabilities, are shown in Table 5.4.

Table 5.4 "Potential Problematic Water Inflow" parameter possible states and assumed probabilities of occurrence in fault-free zones

Parameter	Possible states	Probability of occurrence	Probability of occurrence
		Water Inflow	No Water Inflow
Problematic Water Inflow	No/Minor Water Inflow	0%	100%
	Severe Water Inflow	1%	99%

When associated to Fault Zones, the probabilities of occurrence have been modified in order to consider the particular conditions and the higher risks of encountering problematic water inflows. In those particular zones, the two states of the parameter are shown in Table 5.5.

Table 5.5 The possible states of the "Potential Problematic Water Inflow" parameter and assumed probabilities of occurrence in Fault zones

Parameter	Possible states	Probability of occurrence	Probability of occurrence
		Water Inflow	No Water Inflow
Problematic Water Inflow	Minor Water Inflow	10%	90%
	Severe Water Inflow	20%	80%

5.1.4 Possible presence of gas

Two principal scenarios have been hypothesized. In the first case, no gas (mainly potentially explosive hydrocarbon-type) shall be encountered during construction, while in the second case it will be encountered without prior warning and thus force the excavation to be stopped in order to allow the gas to dissipate.

The two possible states of the parameter are associated with a probability of occurrence that allows the program to create the parameter zoning in a probabilistic way. The possible states of the "Possible presence of gas" parameter, with their associated probabilities, are shown in Table 5.6.

Table 5.6 The possible states of the "Possible presence of gas" parameter and assumed probabilities of occurrence.

Parameter	Possible states	Probability of occurrence	Probability of occurrence
		Gas detected	No Gas detected
Possible presence of gas	No Gas zone	0%	100%
	Probable Gas zone	1%	99%

As for the "Potential Problematic Water Inflow" parameter, in Fault zones characterized by a high risk of gas presence, the probability of occurrence has been raised as showed in Table 5.7.

Table 5.7 The possible states of the "Possible presence of gas" parameter and assumed probabilities of occurrence in Fault zones

Parameter	Possible states	Probability of occurrence	Probability of occurrence
		Gas detected	No Gas detected
Possible presence of gas	Minor Gas zone	10%	90%
	Probable Gas zone	20%	80%

5.1.5 Anomalous abrasivity

Two conditions are anticipated. In the first, normal abrasion conditions can be anticipated, while in the second, the presence of quartz-feldspar-rich massive rocks can cause delays during the TBM construction phase due to abrasivity. This condition will lead to additional costs because excavation tools are changed more often. Like the other parameters, the "Anomalous abrasivity" parameter has also two states with different assumed probabilities of occurrence that permit the creation of the parameter state distribution profile along a tunnel alignment in a probabilistic way. Unlike the other parameters, the abrasivity doesn't really take part in the definition of the Ground Parameter Set (that is why its name has been enclosed in brackets in Table 5.1), but acts at the same level as the Ground Parameter Set. This increases the cost and reduces the advance rate in the successive construction phase. This option, especially included in the DAT program, allows for the number of Ground Parameter Sets to be kept relatively low otherwise it would be doubled by the presence of this double state additional parameter, thus increasing the data-input time and the possibility of errors. The combination of Ground Parameter Set and Abrasivity class leads to the definition of the so-called "Combined Ground Class" that is finally used to define the most appropriate method of construction for each of the Combined Ground Classes. By the way, the effect of this device over the simulation results is minimal as it works as a mere user facility.

For this reason abrasivity will henceforth be considered as a "normal" parameter in order to maintain a higher readability of the report.

Table 5.8 The possible states of the "Anomalous abrasivity" parameter and assumed probabilities of occurrence

Parameter	Possible states	Probability of occurrence	Probability of occurrence
		Anomalous abrasivity	Normal abrasivity
Anomalous abrasivity	Non abrasive	0%	100%
	Abrasive	100%	0%

5.1.6 Ground parameter set

The result of the combination of considered parameters is the subdivision of both the Alignment Alternative corridors in homogeneous zones, defined either position wise or length wise and characterized by an assigned Ground Parameter Set. In Table 5.9a an example of a particular tunnel zone is given (Tunnel zone n°2 of the I-5 Alternative Alignment), with reference to the univocal determination of the Ground Parameter Set in each homogeneous zone. In Table 5.9b a detailed example is given for a typical Ground Parameter Set in order to show how the concepts shown previously are realized in the geomechanical input phase.

Note that a zone can be considered as homogeneous only when the key geologic factors, characteristic of that particular zone, can be reasonably assumed to be constant or variable in accordance with a certain "probabilistic rule" (the concept of Markov process).

Furthermore, the zoning of an alignment according to the established geologic conditions is modeled in DAT allowing the boundaries between adjacent homogeneous zones to vary in each simulation run with a predefined range. For example, the position of a fault zone at the tunnel level cannot be defined precisely until construction approaches the approximate position and the variability can be considered in the geological model and modeled statistically by DAT. This method of simulating geological parameter variations or uncertainties represents actually a sensitivity analysis.

Finally, it should be noted that the negative effects of tunnel instability on construction time and cost are generally greater with increasingly worse ground conditions or when the ground falls in unfavorable behavioral categories (e, f and fault zones).

Table 5.9a Example of the zoning of Tunnel zone n°2 in the I-5 Alternative with reference to the determination of the Ground Parameter Set (GPS)

			BEHAVIORAL CATEGORIES					POTENTIAL INSTABILITY CONDITIONS		POTENTIAL PROBLEMATIC WATER INFLOW		POSSIBLE PRESENCE OF GAS		GPS
Zone number	Mode start position	Mode end position	a/b	c	d	e/f	Fault	Instability	No instability	Water inflow	No water inflow	Gas detected	No gas detected	
T2_1	86600	86700			50%	50%		1%	99%		100%	0%	100%	41
T2_2	86700	87900	10%	90%					100%		100%	10%	90%	21
T2_3 f	87900	87950					100%	1%	99%	10%	90%	10%	90%	4
T2_4	87950	90100	10%	90%					100%		100%	10%	90%	21
T2_5 f	90100	90150					100%	1%	99%	10%	90%	10%	90%	4
T2_6	90150	91900		90%	10%			1%	99%		100%	10%	90%	27
T2_7 f	91900	91950					100%	1%	99%	10%	90%	10%	90%	4
T2_8	91950	93600		50%	50%			1%	99%	1%	99%	10%	90%	34
T2_9 f	93600	93650					100%	1%	99%	10%	90%	10%	90%	4
T2_10	93650	94600		50%	50%			1%	99%	1%	99%	10%	90%	34
T2_11 f	94600	94650					100%	1%	99%	10%	90%	10%	90%	4
T2_12	94650	97400		50%	50%			1%	99%	1%	99%	10%	90%	34
T2_13 f	97400	97450					100%	1%	99%	10%	90%	10%	90%	4
T2_14	97450	101300		90%	10%			1%	99%	1%	99%	10%	90%	26
T2_15 f	101300	101350					100%	1%	99%	10%	90%	10%	90%	4
T2_16	101350	103200		90%	10%			1%	99%	1%	99%	10%	90%	26
T2_17 f	103200	103250					100%	1%	99%	10%	90%	10%	90%	4
T2_18	103250	104550		50%	50%			1%	99%	1%	99%	10%	90%	34
T2_19	104550	106350			50%	50%		1%	99%		100%	10%	90%	43
T2_20 f	106350	106400					100%	1%	99%	10%	90%	10%	90%	4
T2_21	106400	109850			50%	50%		1%	99%		100%	10%	90%	43
T2_22 f	109850	109900					100%	1%	99%	10%	90%	10%	90%	4
T2_23	109900	120000			50%	50%		1%	99%		100%	10%	90%	43

As can be seen in Table 5.9a, each homogeneous zone of Tunnel n°2 is defined by a particular set of parameters and its code is given in the last column. That particular value is the result of the combination of behavioral category and the range of "geo-events". For example, the Ground Parameter Set n°26 can be found in Table 4.9a at Chainage 97450-101300 and 101350-103200, with the corresponding parameter probabilities. As it is shown in that table, those two zones contain a Fault zone (Chainage 101300–101350, characterized by an "f" suffix in the zone name, Ground Parameter Set 4), that is characterized by a 100% probability of "fault" behavioral category, a 1% probability of instability conditions, 10% probability of problematic water inflow and 10% of gas presence. Other fault zones can be found in the same tunnel zone, as well as in poor condition zones.

Table 5.9b Example of characterization of a Ground Parameter Set for a given zone

<table>
<tr><td colspan="3" rowspan="2">Ground Parameter Set number</td><td colspan="2" rowspan="2">26</td><td colspan="4">Zones in which the GPS is present in Alignment Alternative AV</td><td colspan="2">T5_16, T5_20</td></tr>
<tr><td colspan="4">Zones in which the GPS is present in Alignment Alternative I-5</td><td colspan="2">T2_14, T2_16, T4_6</td></tr>
<tr><td colspan="5">BEHAVIORAL CATEGORIES</td><td colspan="2">POTENTIAL INSTABILITY CONDITIONS</td><td colspan="2">POTENTIAL PROBLEMATIC WATER INFLOW</td><td colspan="2">POSSIBLE PRESENCE OF GAS</td></tr>
<tr><td>a/b</td><td>c</td><td>d</td><td>e/f</td><td>Fault</td><td>Instability</td><td>No instability</td><td>Water inflow</td><td>No water inflow</td><td>Gas detected</td><td>No gas detected</td></tr>
<tr><td></td><td>90%</td><td>10%</td><td></td><td></td><td>1%</td><td>99%</td><td>1%</td><td>99%</td><td>10%</td><td>90%</td></tr>
<tr><td colspan="5">Notes</td><td colspan="2">Notes</td><td colspan="2">Notes</td><td colspan="2">Notes</td></tr>
<tr><td colspan="5">In the zones characterized by the GPS 26, DAT assigns to each unit length a behavioral category that is determined with the Monte Carlo method assuming a probabilistic distribution of 90% of "c" group and a 10% of "d" group.</td><td colspan="2">In the same zones, the presence of instability conditions has a probabilistic distribution of 1% of occurrence, and 99% of no occurrence</td><td colspan="2">The presence of problematic water inflows has a probabilistic distribution of 1% of occurrence, and 99% of no occurrence</td><td colspan="2">In the same manner, the presence of gas has a probabilistic distribution of 10% of occurrence, and 90% of no occurrence</td></tr>
</table>

The Ground Parameter Set n°26 is shown with its characteristics in Table 5.9b; the meaning of the given probabilities is expressed in the last-row notes. For each unit length (whose value gives the distance between two successive parameters typically 10 m), the Monte Carlo method is applied to determine the state of each parameter following the distribution of probabilities defined in the corresponding Ground Parameter Set. With reference to the same Ground Parameter Set n°26, shown as an example, it can be pointed out that each unit segment can be assigned a "c" or a "d" behavioral category following respective probabilities of 90% and 10%. In the same way, instability or no instability can be assigned with a 1%/99% ratio, as well as water inflow or no water inflow and gas detected and no gas detected with their relative probabilities. This leads to the fact that each unit segment characterized with a Ground Parameter Set n°26 may be assigned to a combination of parameters that is different in every simulation run. (See Table 5.9c):

Table 5.9c Example of the combinations of Behavioral category, Instability conditions, Problematic water inflow and Presence of Gas that can be assigned to a unit segment characterized by a defined Ground Parameter Set (in this example, set n° 26).

GROUND PARAMETER SET N° 26			
BEHAVIORAL CATEGORIES	POTENTIAL INSTABILITY CONDITIONS	POTENTIAL PROBLEMATIC WATER INFLOW	POSSIBLE PRESENCE OF GAS
c (90%)	Instability (1%)	Water inflow (1%)	Gas detected (10%)
			No gas detected (90%)
		No water inflow (99%)	Gas detected (10%)
			No gas detected (90%)
	No instability (99%)	Water inflow (1%)	Gas detected (10%)
			No gas detected (90%)
		No water inflow (99%)	Gas detected (10%)
			No gas detected (90%)
d (10%)	Instability (1%)	Water inflow (1%)	Gas detected (10%)
			No gas detected (90%)
		No water inflow (99%)	Gas detected (10%)
			No gas detected (90%)
	No instability (99%)	Water inflow (1%)	Gas detected (10%)
			No gas detected (90%)
		No water inflow (99%)	Gas detected (10%)
			No gas detected (90%)

As explained in Section 5.1, it is not possible to show the detailed zoning of each segment, as it varies in each simulation run and its single run report would not bring any further useful information. The zoning of both the Alignment Alternatives is thus given in Tables 5.10 to 5.17, showing both the probabilistic positioning of zones and the probabilistic assignment of the parameters by means of the Ground Parameter Set zoning. In Tables 5.18 and 5.19 the zoning of the parameter "Anomalous abrasivity" is shown. The zonings with little error are valid for both max grade options 2.5% and 3.5%.

Finally, it should be pointed out that the estimation of the probability of occurrence of adverse geologic conditions is partly based on engineering judgement and past experiences gained from tunneling in similar geologic environments, in addition to maximizing the usage of the available information. This approach is appropriate considering the limited quality and the extent of the available geologic knowledge about the specific area of interest, as mentioned earlier in Section 1.2.1. In the future when additional new information (from direct investigations and from records of past tunneling experiences in the project region) becomes available one can use the new information to check the adequacy of currently assumed figures and to re-calibrate the occurrence assumptions of adverse conditions, thus arriving at a more objective model.