AL063-04

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

Summary Report

Prepared for the

City of Palmdale, California

Prepared by

TRANSMETRICS Inc.
Campbell, California

GEODATA S.p.A.
Turin, ITALY

and

HLB Decision Economics, Inc.
Silver Spring, Maryland

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California High-Speed Rail Project – Background and Context

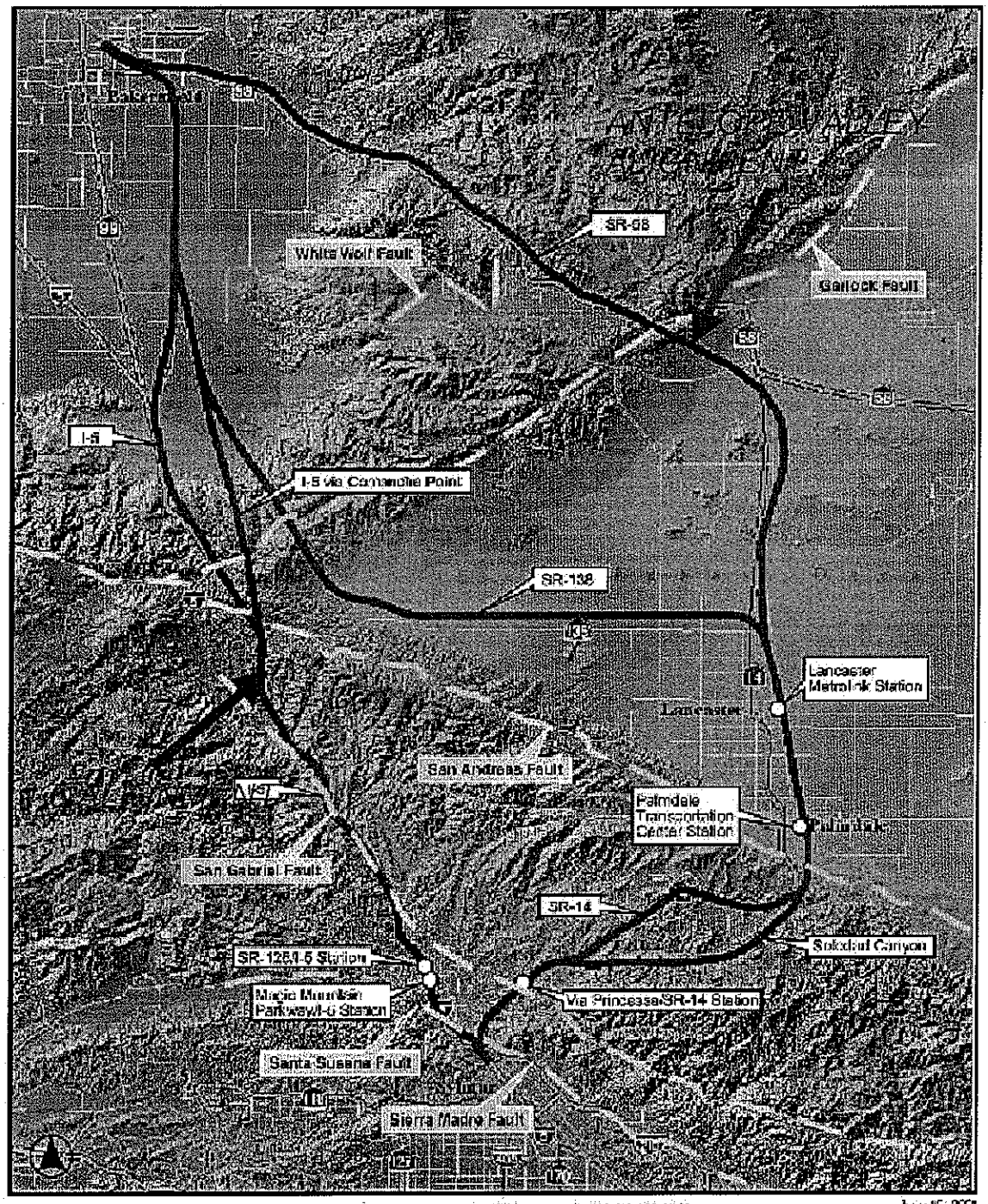
The California High-Speed Rail Authority (the "Authority") has been authorized by the state of California to pursue development of a high-speed rail system to connect the cities of San Diego, Los Angeles, San Francisco, and Sacramento. The proposed HSR system would be similar to those currently in place in Germany, France, Italy, Spain, and Japan.

In order to connect southern and northern California, the HSR system must pass the Tehachapi Mountain Range north of Los Angeles, an area of steep terrain and complex geology that is crossed by several active earthquake faults. The choice of route alignment through this region is a complex task, and must take into account, among other things, length, grade (steepness), ground conditions, ventilation, surface access, and the aforementioned earthquake faults. Any route would require extensive use of tunnels, structures, and major sections of cut and fill.

Over the past several years, the Authority and its predecessor agency (California High-Speed Rail Commission) have considered two principal corridors for crossing the Tehachapi Mountains between Sylmar (north of downtown Los Angeles) and Bakersfield – an alignment generally following I-5 freeway over the Grapevine ("I-5 alignment"), and one through the Antelope Valley ("Antelope Valley alignment"), generally following (going north from Union Station) I-5, SR-14, and SR-58. The two alignments differ principally in terms of length, accessibility, and construction complexity and risk (see Figure 1, below).

To date, the Authority has not formally adopted a preferred alignment. However, several Authority members and staff – including the Authority Chair and the Executive Director – have frequently expressed support for the I-5 alignment in both open public forums and in written communications. The stated reasoning for this position is principally tied to their perception that the shorter I-5 alignment, with a 6-9 minute travel time advantage, would significantly increase ridership in what they consider to be their key market – that between San Francisco and Los Angeles.

Figure 1



Legend

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

It is the collective view of local governments and stakeholder groups in the Los Angeles Basin that this stated bias for the I-5 alignment by key Authority members and staff ignores numerous important considerations.[1] One of these is the fact that the Antelope Valley alignment would provide high-speed rail service to at least 440,000 additional residents and 165,000 employees today (the entire length of the I-5 alignment between Sylmar and Bakersfield is virtually unpopulated), thereby generating significant additional ridership and associated economic benefits to the region and the state. Even more critically, the Antelope Valley alignment would significantly reduce the need for construction of costly, high-risk tunnels and structures, and thereby improve the financial feasibility of the project and help garner essential public support.

Purpose and Scope of this Study

The City of Palmdale, in expression of the concerns raised by numerous government agencies and private stakeholders, commissioned this study to (1) investigate tunneling-related risks and their potential effect on high-speed rail project cost and schedule; and (2) identify the best route alignment through the Tehachapi Mountains with respect to minimizing capital cost, risk of construction cost overrun, and project delay. Specific study tasks were:

1. Define risk assessment model and establish primary output measures:
   - Number, length, size, and location of tunnels, and related surface structures;
   - General rock mass type and quality;
   - Proximity to favorable or adverse geotechnical conditions, including faults and fault zones, water-saturated zones, and surface instabilities; and
   - Location/impact of surface facilities and structure (e.g., portals, ventilation facilities).
2. Analyze geologic and project engineering data.
3. Estimate costs and risk assessment values.
4. Prepare a general discussion of tunneling risks and risk minimization strategies.
5. Prepare a technical report.

Alternatives Considered

Consistent with alternatives development and analysis conducted by the Authority, the analysis conducted in this study considered four alignment alternatives in total, defined by location and maximum permitted grade, as shown in the following figure.

[1] Local governments expressing support on the record for the Antelope Valley alignment include Los Angeles County Board of Supervisors, Kern County Board of Supervisors, Los Angeles City Council, Mayor of Los Angeles, Los Angeles World Airports, and the Southern California Association of Governments (SCAG).

Alternatives Considered

I-5/Grapevine – 2.5% maximum grade	Antelope Valley – 2.5% maximum grade
I-5/Grapevine – 3.5% maximum grade	Antelope Valley – 3.5% maximum grade

The maximum grades were defined by currently available and potentially available technology (2.5% and 3.5%, respectively). Also, while the Antelope Valley alignment actually consists of two independent tunneling sections separated by the Antelope Valley itself, the two sections were analyzed as though they were joined consecutively in order to simplify the presentation of results.

Assessment of Previous Analysis and Approach to Risk Minimization

California High-Speed Rail Project planning and feasibility studies, environmental impact assessment, and selection of the system's route alignment are currently at the stage of final screening evaluation of alignment options. While there has been considerable investigation of ridership and potential environmental impact, to date, detailed technical consideration of the costs and risks associated with the two alignment alternatives between Los Angeles and Bakersfield has been limited to two activities:

- In late 2001, the Authority engaged the developer of a newly-designed, automated alignment optimization system ("QUANTM") to refine and optimize, on a very fast-track basis, previous alignment studies that employed standard "best practices" methods for conceptual engineering, using only readily available geologic information from secondary sources. The results of that analysis were released in April 2002.
- Also in late 2001, the Authority convened a two-day workshop of mostly American tunneling contractors and engineers to discuss tunneling issues associated with the California High-speed Rail Project. While the Authority has expressed satisfaction with the usefulness of this exercise, documentation of the workshop to date has been limited to a brief summary.

Recent Authority screening evaluations for alignment alternatives have focused on minimizing potential environmental impacts, while the QUANTM study and workshop attempted to minimize tunneling length and computed capital costs. In general, the Authority has chosen to avoid known fault and shear zones and water-saturated zones wherever possible by deviating horizontally or by shifting the alignment from underground to surface. However, this might not be an optimum choice, as tunnels can actually be more resistant to seismic events than surface structures, as demonstrated in the Kobe, Japan, and Loma Prieta, California earthquake events.

There are, however, other important tunneling risks and potential costs that have not been explicitly addressed in previous Authority studies and analyses including, but not limited to:

- Risk of encountering unknown adverse ground and groundwater conditions, leading to significant cost overruns and project delay;

- Construction risks, including design errors (such as selecting the wrong type of tunnel boring machine[2]), other human error, rock squeezing behavior, face collapses, water intrusion, and production of materials causing hazardous environmental conditions;
- Costs associated with use of high embankments and deep trenches (instead of tunnels) including trench support, embankment-slope protection, and maintenance.
- Financial risks to the owner, such as delay in contract completion, cost overruns, or lower than projected rates of capital return;
- Contractual risks, such as additional work not covered, time delays, disputes, claims and litigation; and
- Operation risks, including time and cost involved in rehabilitating an earthquake-damaged surface structures versus tunnel sections, including loss of revenue while service is suspended.

Critically, the approach followed in this study to comprehensive cost and risk analysis included:

1. Estimation of most likely values and possible variation of construction time and cost as a function of expected geologic conditions and associated uncertainties; and
2. Estimation of impact of construction duration on economic and financial issues.

The comparison of alignments was further detailed by utilizing a multi-criteria analysis process, taking into account the following key factors:

- Total construction cost and risk of cost overruns;
- Construction duration and the risk of delays;
- Performance of alignment alternative in dealing with risks during operation;
- Environmental impact; and
- Capital investment and the related financial risks.

Engineering Assumptions, Analysis, and Findings

Conceptual Design and Construction Schemes

The I-5 and Antelope Valley alignments differ principally in relation to (1) length, (2) accessibility, and (3) construction complexity and risk. In order to perform the proposed alignment-specific risk analyses, it was necessary to prepare a conceptual design and construction scheme for each alignment alternative, making relevant assumptions for those aspects not yet defined in previous studies.

The position of each single tunnel was fixed using orthophotos and adjusted to conform to maximum permitted grades (2.5% and 3.5%). The main tunnels were assumed to be twin bores, with each bore housing a single rail track. For long tunnels whose lengths

[2] Each tunnel boring machine (TBM) is unique, individually designed to accommodate expected conditions at a tunnel site. These complex and expensive machines take up to 12 months to build and deliver to a job site; a major error in specification can delay a project by a year or more and cost tens of millions of dollars.

were greater than 6 miles, a third ("service") tunnel for ventilation, evacuation and construction access was assumed, which would be located between the two main tunnel bores.

The construction scheme for each tunnel was defined according to recent industry practice and experience. Each maximum grade option was studied independently, with the intent of reducing construction risk without neglecting technical feasibility. However, the use of double-shield tunnel boring machines (TBMs) was assumed for all major tunnel sections. For short tunnels, conventional excavation was assumed in those situations where its application would significantly reduce overall construction duration.

Where a tunnel would cross a major potential earthquake inducing fault zone (e.g., the San Andreas Fault and the Garlock Fault), an at-grade is preferred wherever the allowable maximum grade permits in order to limit construction costs and reduce risks. Alternatively, construction of a large chamber would allow for restoration of the rail tracks in case of a major lateral shift at the fault location. For this analysis, the seismic chamber design conceived by the Authority was analyzed.[3]

Description Of DAT (Decision Aids In Tunneling) Model

The Decision Aids in Tunneling modeling system ("DAT") was used to define and assess the potential risks and costs of the two alignment alternatives.[4] 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 (the tunneling consultant for this study).

DAT consists of two interrelated simulation modules, Geology and Construction. In the Geology module, the geotechnical conditions are organized in an approach similar to that of defining a geotechnical profile. The user's task is to identify and define parameters and their possible states. The Construction module consists of two principal components: (1) construction methods, and (2) tunnel network, which defines the sequence of construction activities.

[3] To date, Authority studies have considered seismic chambers oriented only in the direction of the potential lateral movement predicted based on the past movement records of the fault concerned. However, recent scientific discoveries have revealed that "faults go backwards." 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, this suggests there is a risk that the seismic chamber solution may not serve its intended purpose.

[4] 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. The DAT model allows simulation of several random processes simultaneously. Given that it is not possible to find analytically determinate results for processes involved in the construction of tunnels, 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.

DAT Model Input Data

Geological profiles and essential geo-mechanical parameters were defined based on US Geological Survey (USGS) maps of the corridor areas. A range of "geo-events" that could cause delays and extra costs were considered as well, particularly where a tunnel would be excavated by a TBM. The events considered were:

- Unstable conditions;
- Problematic water inflows;
- Presence of gas; and
- Unusual rock abrasiveness.

Construction-related information used average rates of advance (progress per day) and costs per linear foot of tunnel for each construction method employed (e.g., TBM, conventional drill and blast). The rates of advance for excavation by TBMs were based on the Colorado School of Mines Model (Clark, 1987 and Howart, 1987). Rates of advance and costs per foot for other excavation techniques were based on other recent tunnel projects. Cost values included overhead and profit rates. All conditions that could negatively affect the tunnel construction were quantified in terms of their economic impact. Financial costs (e.g., interest, carrying costs) were not included.

A maximum number of simultaneous working sites was not fixed, nor were limitations in the TBM fabrication market considered. It was assumed that delivery times would run to approximately 12 months for 9.5 meter TBMs, and 8 months for 5.0 meter TBMs.

DAT Model Analysis and Results

Prior to running the DAT model simulations, several pre-modeling activities were undertaken:

- A deterministic (manual) estimate of minimum, total construction cost and duration was made for each alignment-and-maximum grade option. These served as a guide for checking the output of the DAT model.
- A limited number of DAT model simulations were compared with the manual estimates, in order to calibrate the DAT process.
- The sensitivity of the DAT model simulations to the number of simulation iterations was tested. It was observed that there was practically no further benefit to increasing the number of simulation iterations to more than 1000. As a result, the number of simulation iterations was fixed at 1000.

Following completion of the DAT model analysis, a number of general relationships were observed. First, considering the variation in the total construction costs amongst the options considered, it was observed that, for both the I-5 and Antelope Valley alternatives, there is a clear relationship between the increase in average cost and the total length of tunneling, as would normally be expected.

Second, both of the grade options (2.5% and 3.5%) of the I-5 alignment show higher potential variation (uncertainty) than those of the corresponding Antelope Valley

alignment, which can be attributed to the anticipated, more adverse, geologic conditions along the I-5 alignment.

Third, the extended tunneling length for the 2.5% maximum grade Antelope Valley alignment implies an increase in the variation of results, which is consistent with an increase in uncertainty associated with a longer tunnel stretch. For the I-5 alignment, the opposite trend resulted, as the actual tunnels configurations do not differ significantly between the 2.5% and 3.5% maximum grade options.

Fourth and last, there was a reduced average total construction time for the 2.5% maximum grade configurations, despite approximately 1.5 miles of more tunneling than the 3.5% configuration, due to the different construction scheme adopted.

In addition, a number of specific results were observed:

1. With respect to mean (average) construction cost, the 3.5% maximum grade option of the Antelope Valley alignment is about 40% less expensive than that of the corresponding I-5 alignment, and about 15% less expensive in the case of the 2.5% maximum grade option. The differences vary between the two grade options due to the total length of tunneling involved with the flatter (2.5%) option. Despite the smaller difference between I-5 and Antelope Valley at the 2.5% grade, it should be noted that the longer tunnel length at the 2.5% maximum grade means savings in costs for construction of the external (surface) works and associated mitigation of environmental impacts.
2. The cost and time (delay) variations for the Antelope Valley alignment are more constrained than those of the I-5 alignment (at both 3.5% and 2.5% grades), implying that uncertainty associated with I-5 alignment is much higher than with the Antelope Valley alignment.
3. For both grade options, the Antelope Valley alignment has an extremely "slim" variation in potential cost, with quite small differences between the projected 95% maximum value and minimum value ($76 million for the 3.5% maximum grade option and $137 million for the 2.5% maximum grade option). The results are much more uncertain for the I-5 alignment, with very large differences between the 95% and minimum values ($500 million and $400 million for the 3.5% and 2.5% maximum grade options, respectively.)
4. Analysis of the 2.5% maximum grade option for the Antelope Valley alignment produced a consistently lower range of variation in the total construction time (a difference of 990 working days between the 95% value and the minimum value) than did the I-5 alignment alternative at the same grade (1608 days). The Antelope Valley 3.5% maximum grade option yielded an even lower range of variation (288 working days) as compared with 1430 days for the equivalent I-5 option. These differences between the Antelope Valley and the I-5 alignments derive from the differences in the total length of tunneling and the number of short tunnels involved. (Shorter and shallower tunnels are generally associated with fewer geological difficulties and thus present a lower degree of uncertainty.)
5. Mean construction time required for the I-5 3.5% maximum grade option was almost twice as much as that required for the Antelope Valley alignment at the same grade

(2,218 working days versus 1,125 working days, respectively). The same relationship also resulted for the 2.5% maximum grade options, though with a slight increase in the mean construction time for the Antelope Valley alignment due to increased total length of tunneling.

Economics Analysis and Findings

Overview

An economic risk analysis of the two alignment alternatives and two maximum grade options was conducted, based on the results of the technical analysis reported in the preceding section. This analysis consisted of a review of the technical literature on high-speed rail cost estimating methods, analysis of key economic and financial risk factors, a separate computer simulation of various cost and schedule risk scenarios, and a combined economic benefit/cost assessment of the project.

Literature Review

The review of existing literature on high-speed rail cost methods found that estimates from other countries or corridors within the United States are only of limited usefulness in predicting costs for the California project. Published cost estimates for high-speed transit systems range from as little as $10 million per mile to more than $100 million per mile. Several factors affect high-speed project costs, including local conditions, the local economy, and differences in assumed technologies – e.g., conventional rail vs. Maglev technology. Thus, in the case of high-speed rail projects, it is unusually important to use local, project-specific data when estimating costs and predicting risks.

Risk Analysis

Four risk factors were considered in the economic analysis:

- Tunneling and geological risk (derived from the technical analysis);
- Cost escalation risk (increases resulting from unforeseen schedule slippage);
- Financial costs of delay (not considered in the technical analysis); and
- Methodological uncertainty.

Computer simulation results for construction cost are shown below for the Tehachapi Crossing segment (Table 1) and total high-speed rail project (Table 2).

The total project cost in Table 2 includes construction and contingency, plus vehicle acquisition, stations, support facilities, and program implementation.

Risk analysis simulation results for project completion time for the Tehachapi Crossing segment are shown in Table 3, below, in terms of total workdays and years to complete.

Economic Benefit/Cost Analysis

In addition to considerations of cost, it is noteworthy that the California High-Speed Rail Act of 1996 calls for completion of a high-speed rail network that will generate jobs and

Table 1

Construction Cost Risk Analysis – Tehachapi Crossing Segment

($2003 in Millions)

Alignment / Maximum Grade	Mean Expected Outcome	80% Confidence Interval	
		Lower Bound	Upper Bound
With 3.5% Maximum Grade			
I-5	$2,594	$2,315	$2,887
Antelope Valley	$2,342	$2,106	$2,597
Difference (I-5 less Antelope Valley)	***$252***	***$209***	***$289***
With 2.5% Maximum Grade			
I-5	$2,969	$2,621	$3,331
Antelope Valley	$3,001	$2,724	$3,287
Difference (I-5 less Antelope Valley)	***-$31***	***-$102***	***$44***

Table 2

Construction Cost Risk Analysis – Entire High-Speed Rail Project

($2003 in Millions)

Alignment / Maximum Grade	Mean Expected Outcome	80% Confidence Interval	
		Lower Bound	Upper Bound
With 3.5% Maximum Grade			
I-5	$27,808	$24,691	$31,210
Antelope Valley	$26,830	$24,116	$29,598
Difference (I-5 less Antelope Valley)	***$977***	***$575***	***$1,612***
With 2.5% Maximum Grade			
I-5	$27,966	$25,086	$31,153
Antelope Valley	$27,610	$24,945	$30,393
Difference (I-5 less Antelope Valley)	***$356***	***$141***	***$760***

Table 3

Completion Schedule Risk Analysis – Tehachapi Crossing Segment
(Workdays / Years to Complete)

Alignment / Maximum Grade	Mean Expected Outcome	80% Confidence Interval	
		Lower Bound	Upper Bound
With 3.5% Maximum Grades			
I-5	2,250 (7.5)	1,731 (5.8)	2,814 (9.4)
Antelope Valley	1,111 (3.7)	1,023 (3.4)	1,207 (4)
Difference (I-5 less Antelope Valley)	**1,138 (3.8)**	**708 (2.4)**	**1,606 (5.4)**
With 2.5% Maximum Grades			
I-5	2,157 (7.2)	1,694 (5.6)	2,662 (8.9)
Antelope Valley	1,460 (4.9)	1,175 (3.9)	1,789 (6)
Difference (I-5 less Antelope Valley)	**697 (2.3)**	**519 (1.7)**	**873 (2.9)**

economic growth. An economic benefit/cost analysis was conducted to determine which alignment would offer the best prospects for maximizing ridership and revenue, transportation and economic integration, and economic viability.

Ridership and Revenue. Assessing the trade-off between length and accessibility to users (number and location of stations) is key to selecting an alignment that will maximize ridership and fare revenue. The analysis indicates that the additional ridership generated by the greater access to residents and employers under the Antelope Valley option will more than offset the potential ridership advantage of a modestly shorter (6-9 minutes) end-to-end journey time using along the I-5 alignment. Total cumulative life-cycle ridership (33 years) under the Antelope Valley alternative would exceed that under the I-5 option by over 3 percent.

Economic Integration. This is the extent to which a new transportation investment will connect with, complement, and support other transportation modes and the businesses they serve, thereby maximizing the multiplicative economic benefits of these resources. Trackage through the Antelope Valley will provide two kinds of modal connectivity, namely an inter-modal connection for air travelers using the Palmdale Regional Airport, and a modal choice for long-distance auto users in the Antelope Valley growth corridor.

Due principally to the added accessibility afforded by the Antelope Valley over the I-5 option, the former is stronger in relation to intermodal connectivity and industrial agglomeration, which creates wealth and improved living standards at a regional scale. The estimated value of agglomeration economies associated with the Antelope Valley alignment is $540 to $818 million over the initial 33-year project life cycle.

Economic Viability (Benefit/Cost). The Antelope Valley option offers a greater promise of economic benefits that exceed the costs of achieving them. The benefits of the high-speed rail project would occur in the form of travel time savings and vehicle operating

cost savings for both rail passengers and other travelers; reduced accident-related costs; and diminished emissions of air pollutants and greenhouse gases. Over the first 33 years of operation, a high-speed rail system employing the Antelope Valley alignment would generate approximately $900 million in net benefits above that expected under the I-5 alternative.

Total Economic Impact. One of the factors supporting the Antelope Valley alignment is the potential for high-speed rail to generate significant long-term economic development impacts. The Antelope Valley is a natural location to accommodate future population and housing growth in California, and the high-speed rail system through the Antelope Valley would provide quick access to major cities both north and south of the valley.

The total economic impact associated with the Antelope Valley alignment over a period of thirty years could reach $3.1 billion, with an expected 38,000 additional jobs and over $2 billion in earnings. The investment would result in attracting about 17,000 new households to the Antelope Valley region, rather than to other locations in already crowded southern California areas.

Conclusions and Recommendations

To facilitate the comparison of the geological and construction risks involved in the two alternative alignments (I-5 and Antelope Valley) and overcome the problem of limited field data, a probabilistic model was adopted that incorporates the impact of different geological factors on the risks and productivity. The specific model employed was developed at the Massachusetts Institute of Technology and is called Decision Aids in Tunneling (DAT). The model allows for the comparison, in terms of construction time and cost, of various, feasible, design and construction solutions for a tunneling project, and for quantification of risks related to each solution. Through the use of this model, the analysis conducted during the study demonstrates the following:

- Although the total lengths of tunneling involved in the I-5 and the Antelope Valley alignments are similar, the ground conditions along the Antelope Valley are relatively more favorable and thus would involve less construction, financial, and contractual risk.
- For the 3.5% maximum grade option, the mean (average) construction time required for the I-5 alignment is almost twice that required for the Antelope Valley alignment. The same result applies for the 2.5% maximum grade option, with a slight increase in the mean construction time for the Antelope Valley alignment due to a somewhat greater total length of tunneling.
- Further, the Antelope Valley alignment is about 40% less expensive than the I-5 alignment under 3.5% maximum grade option, and 15% less expensive under the 2.5% maximum grade option, again due to increased total length of the tunneling. However, the increased tunnel length for the Antelope Valley alignment under 2.5% maximum grade would also reduce costs for corresponding external construction and environmental impact.

In general, the findings of this study confirm the concerns expressed by the City of Palmdale and other southern California stakeholders over the relative risks involved in

the two alternative alignments. These findings should permit the Authority to make a more informed decision regarding the choice of alignment, including the process to be followed in making that decision.

Further, it should be noted that the DAT model analysis did not simulate the financial consequences associated with increased construction duration. If the financial impact due to longer construction duration is taken into consideration, the final results significantly magnify the construction cost advantage of the Antelope Valley alignment.

On the basis of the analysis conducted, the following recommendations are offered:

1. Employ all Feasible Means to Reduce Uncertainties. Reducing uncertainties through site investigations, especially the preliminary investigation, for mechanized tunneling, is a key investment strategy for project sponsors. Site investigations designed to reduce geological uncertainties and thus confirm relative geological and construction risks should be conducted before a final choice of alignment is made.

2. Employ New, Innovative Technologies. Significant payoff can be realized through the use of technological innovation and risk management in complex underground projects with difficult and unexplored geology and employing relatively untested design concepts. For example, the technical feasibility and cost of constructing large seismic chambers in very wide fault zones is as yet unknown. Innovation means that the new concepts are competently developed, consistent with the limits of current knowledge and experience, and carefully matched to the specific conditions of the project.

3. Employ Best Contracting Practices. It is now almost universally accepted that project sponsors "own the ground" – that is, are responsible for the effects of the difficult geologic conditions which will be encountered. Sophisticated sponsors recognize this and seek ways to equitably share and allocate risk to the best entity that can foresee or control any particular risk. It is now accepted by many project developers that the contracting practice of accepting a fixed-cost low bid from a group of "qualified" contractors should not be adopted when the jobs are large, the geology uncertain, and potential for extremely high cost overruns escalate. Negotiated contracts with fair allocation of risks among the parties involved could be more cost effective and equitable.

4. Employ Risk Management Throughout Project Development and Implementation. Traditionally, potential risks associated with large tunneling projects have been managed indirectly through engineering decisions made during project development. However, many recent case histories have demonstrated this approach to be inadequate once construction has begun. Active risk management throughout the project can ensure that most potential problems are identified and addressed in a timely fashion so that appropriate and cost effective risk reduction measures can be implemented. The use of risk management in the early stages of a tunnel project is essential, particularly at the beginning of the planning process where major decisions, such as choice of alignment and selection of construction methods, can be influenced.

Technical 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 over1500 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 this 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 (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.

Economic Study Team

HLB Decision Economics, Inc. offers services in the areas of transportation economics and policy, and risk analysis consulting to government and industry throughout North America. Their staff of professional economists, transportation planners, engineers, and statisticians brings a practical approach to each assignment, supported by up-to-date analytical techniques.

HLB has conducted numerous feasibility and risk analysis studies, including multiple studies for the Federal Railroad Administration to assess rail project feasibility in over ten states nationwide, as well as major investment studies for large capital projects such as airport improvements and new toll highways.

This project was managed by Dr. Khalid Bekka, an applied economist with skills in transportation research, quantitative analysis, and regulation. Dr. Bekka holds Ph.D. and M.A. degrees in economics, an M.B.A. in operations management, and a B.S. in international business management. He has published and presented several articles in the transportation field in the U.S. and Europe.

Dr. Bekka was assisted by Dr. Stéphane Gros, a statistician and an applied economist with skills in research, computer programming, quantitative analysis, and survey design. Dr. Gros holds a Ph.D. degree in economics, an M.S. in economics, an M.S. degree in applied statistics, and a B.S. in econometrics.

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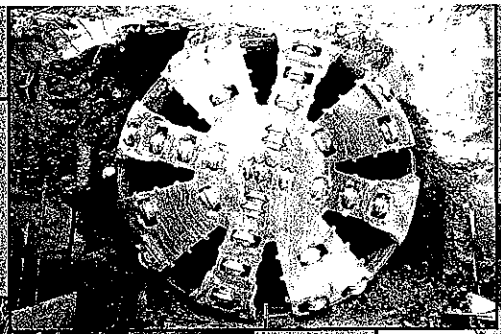
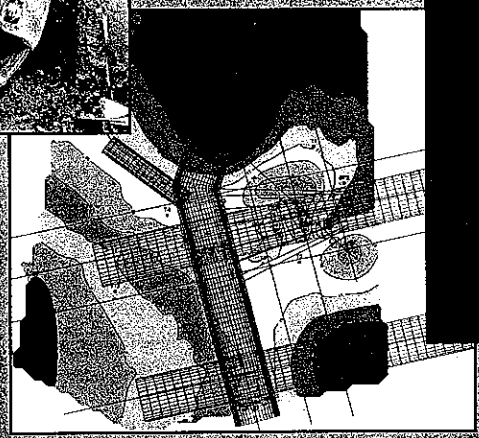




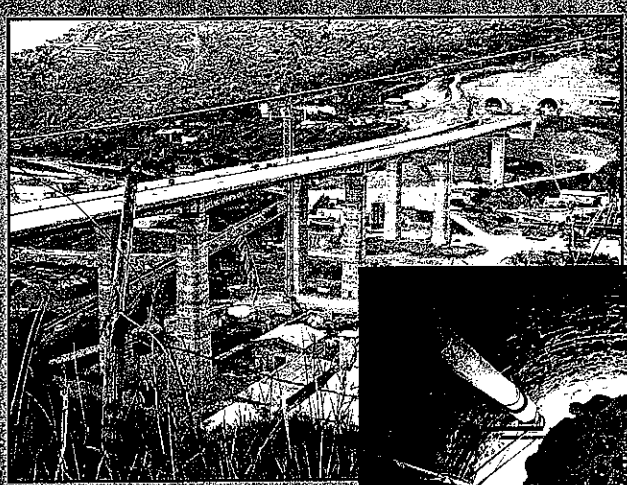
FINAL REPORT

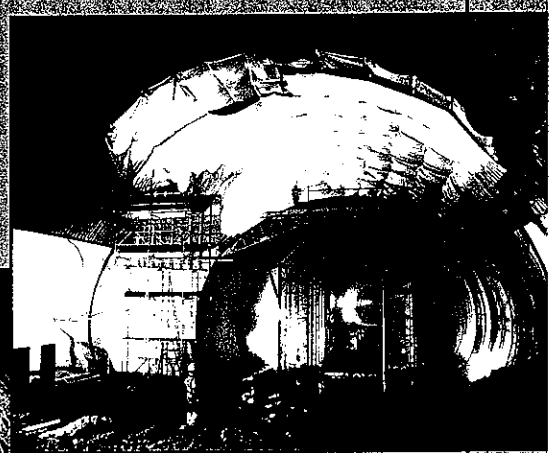
A comparative analysis of Tunnel Construction Times, Costs, and Risks Associated with the choice of High Speed Rail Tunneling Alignment between Los Angeles and Bakersfield

Submitted to the City of Palmdale — January 31, 2003

TRANSMETRICS
Engineering & Construction Management

GEODATA





TRANSMETRICS, INC. is a civil engineering firm providing engineering, transportation planning, and construction management services to public and private sector clients. In business since 1982, TRANSMETRICS primarily serves the transportation industry. However, in the past ten years, TRANSMETRICS has expanded its services to include major private and public projects such as educational, medical, and municipal facilities, and the design and relocation of interstate utilities.

TRANSMETRICS offers a wide range of construction management services. Our engineers have the experience to lead a project from the planning and design stage to construction in an efficient and cost effective manner.

Because of its diversified workload and clientele, TRANSMETRICS actively participates in a variety of industry organizations which include:

- American Railway Engineering and Maintenance Association (AREMA)
- American Public Transportation Association (APTA)
- American Society of Civil Engineers (ASCE)
- International Association of Public Transport (UITP)
- American Public Works Association (APWA)
- National Society of Professional Engineers (NSPE)

TRANSMETRICS
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Transforming ideas into projects and monitoring them until completion: this is our daily task. During more than 16 years activity in the field of geo-engineering we have intensified and diversified our competence, following a strategy of multi-disciplinary growth.

Geodata is an independent geo-engineering company which, since it was founded in 1984, has grown and developed in Italy and throughout the world. Geodata employs more than one hundred professionals who specialize in geo-engineering and subsurface projects. Their skills and extensive experience has made Geodata S.p.A. one of the most respected names in the tunneling industry worldwide.

Geodata works with construction companies and public or private authorities in planning subsurface works and in various sectors of ground engineering. Geo-engineering is our core business; it is our specialization and our strength. Geodata is in a position to supervise this work throughout the specific stages: from preliminary surveys and territorial planning to design and from the optimization of the conventional and mechanized construction techniques to monitoring of the construction progress.

Geodata management has been an active participant in the International Tunneling Association where they present various reports and lead workshop discussions. Its key advisor, *Sebastiano Pelizza* served as President of the International Tunneling Association from 1995-1998.

GEODATA

TRANSMETRICS
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January 31, 2003

Mr. Stephen H. Williams, Director
City of Palmdale, Department of Public Works
38250 Sierra Highway
Palmdale, CA 93550

Subject: Final Report: Comparative Analysis of the Tunnel Construction Times, Costs, and Risks associated with two alignments for the High Speed Rail crossing of the Tehachapi Mountain Range between Los Angeles to Bakersfield

Dear Mr. Williams:

Transmetrics/Geodata having completed the subject analysis, is pleased to submit its final report to the City of Palmdale.

This report outlines the geologic challenges involved in the two tunneling options under consideration by the California High Speed Rail Authority. It is intended to assist everyone involved in a decision making role, to consider all the risks and costs inherent in the selection of one alignment over the other.

Prior to the start of the analysis, the study team members made a site visit, obtained extensive mapping and documentation from the U.S. Geological Survey and the California Geologic Survey, and held a teleconference with the program manager retained by the California High Speed Rail Authority.

On behalf of the study team, I would like to thank you and your staff, all the individuals and agencies contacted, and the consultants and staff of the California High Speed Rail Authority for your cooperation and assistance during the conduct of our work.

We look forward to working with you and your staff in the weeks to come and will respond to any questions regarding the analysis.

Very truly yours,

TRANSMETRICS, INC.

Jack Ybarra
President