SCRTD
METRO RAIL PROJECT

Additional Investigations of Energy Management Alternatives for the Starter Line of the SCRTD Metro Rail Project

March 1982

Prepared for
Southern California Rapid Transit District

BOOZ·ALLEN & HAMILTON INC.

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March 15, 1982

Mr. Richard Gallagher
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Southern California Rapid Transit District
425 South Main Street
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Subject: Additional Investigations of Energy Management Alternatives for the Metro Rail Project, WBS 13DAC.

Dear Mr. Gallagher:

Enclosed is our final report on the subject investigations and recommendations regarding the use of vertical profiles. Additional analyses and evaluations were conducted based on information from the following sources:

- Booz, Allen report entitled "A Study of Energy Management Alternatives for the Starter Line of the SCRTD Metro Rail Project", December, 1981.
- Simulation runs made by SCRTD staff using the computer programs developed by Booz, Allen and SRI International.
- JPL studies of gravity assisted rapid transit.

As requested by your staff, the report provides a narrative summary of pertinent information from these sources.

Our additional investigations include a financial analysis of energy cost savings and additional capital investments associated with vertical profiles. This analysis was necessary to substantiate any recommendation to use vertical profiles.

Recommendations are presented in three key energy management areas. These include:

- Vertical profiling
- Propulsion equipment
- Automatic train control subsystem.

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In addition, topics for further study are offered which will aid in refining the application of energy management techniques during the Metro Rail project.

We are pleased to have completed this important study for you. At your earliest convenience we suggest that we present a brief summary of our studies at which time we can also personally address your questions and those of other Metro Rail managers.

Contact Frank Condos or myself to establish a mutually satisfactory time for our meeting.

Very truly yours,

BOOZ·ALLEN & HAMILTON Inc.

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SUMMARY OF ENERGY MANAGEMENT RECOMMENDATIONS

The recommendations on design approaches for energy management are listed below.

1. On the basis of cost analysis, select a vertical alignment incorporating gravity-assist vertical profiles as the preferred alternative for the Metro Rail Project.

2. Select a 4-percent grade based on higher net present value of energy savings. To justify grades exceeding 4 percent, further analysis is required on:

   - Tunnel muck-out costs
   - Energy savings
   - Subsystems capability
   - Impact of failures on operations.

   Based on the information presently available, 4-percent grades are believed to be a reasonable compromise between maximum energy savings and adverse impact on operational effectiveness.

3. Specify propulsion equipment with regenerative braking. Increased energy savings will result whether vertical profiling is used or not.*

4. Specify a train control system with automatic speed regulation and with performance modification features that include coast. Increased energy savings will result whether vertical profiling is used or not.*

Recommendations for further simulation and study and recommendations for further analysis of additional costs associated with vertical profiles are presented in Section 6 of this report.

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* Booz, Allen & Hamilton Inc., A Study of Energy Management Alternatives for the Starter Line of the SCRTD Metro Rail Project, Final Report, December 1981.

1. INTRODUCTION

Contained in this report are additional analyses and further clarification to the information found in the December 1981 final report entitled "A Study of Energy Management Alternatives for the Starter Line of the SCRTD Metro Rail Project."

The estimates for energy costs are revised based on the data of previous simulation runs conducted by Booz, Allen and SCRTD staff. Incremental capital costs for the dipped guideway are identified and summarized for each station-to-station link and for the starter line configuration. The cost data are summarized, and comments on the most recent Jet Propulsion Laboratory (JPL) reports on vertical profiles are provided to assist in evaluating the specific application of the JPL recommendations to the Metro Rail Project. Finally, recommendations are made concerning energy management alternatives and further analysis that should be undertaken during Preliminary Engineering.

(1) Report Objectives

The objectives of this report are to:

- Refine the energy data acquired in the previous simulation runs by applying correction factors for:
  - Cut-and-cover sections
  - Crossover locations
  - Efficiencies of the traction power subsystems and equipment
  - Additional car weight
  - Blockage ratio of the tunnels.
- Refine the estimates for annual energy costs by:
  - Incorporating the latest operating plan
  - Establishing a new estimate for energy cost per kilowatt-hour.
- Review and comment on the JPL reports with regard to incremental capital costs, energy cost savings, and other technical aspects of vertical profiling.

- Assemble the data on incremental capital costs identified by the SCRTD staff and in the JPL reports.

- Provide a financial analysis of energy cost savings and additional capital costs.

Finally, the findings in this report should be the basis for decisions concerning the extent to which vertical profiling will be considered in the design of the system. Further, the analytical techniques developed provide a framework for necessary refinement during the design process.

(2) Scope

The scope of the analysis contained in this report is limited to achieving the objectives stated above without conducting further simulation runs. Recommendations are provided, however, on the requirements for conducting additional simulation. Following the review of this report, a decision should be made on the follow-up steps for simulation activities so that the data may be further refined and the related conclusions substantiated with a higher level of confidence.

(3) Organization

The remainder of this report is organized into the following sections:

- Revised Application of Energy Data From Previous Simulation Runs

- Review of Additional Capital Costs, Operating Costs, and Maintenance Costs for Vertical Profiles

- Summaries of Cost Data, Cost Comparisons, and Conclusions

- Review of JPL Reports

- Recommendations.

2. REVISED APPLICATION OF ENERGY DATA FROM PREVIOUS SIMULATION RUNS

A new interpretation of the computer simulation runs is presented in this section.

(1) Propulsion Energy Data and Design Parameters

As stated in the introduction, the data are from computer runs already conducted and the objective is to reinterpret the available data before proceeding with additional simulation activities to obtain new and refined data.

Subsequent to the final presentation of the initial energy management study, runs were made to provide additional data on the effect of depth variation for 4-percent grades. At the same time, the input data on civil speed limits were modified, and new computer runs were made for 6-percent grades. Table 1 summarizes the design parameters used in the computer model. Table 2 shows the computer simulation results, which provide the data for all subsequent analysis of energy costs in this report.

TABLE 1
Design Parameters

PARAMETERS	VALUE OR COMMENT
Length of station platform	450 feet
Grade in station	0%
Vertical curve start	At end of platform
Vertical curve rate of change	1% per 60 feet at crest (low speed) 1% per 100 feet in dip (high speed)
Length of tangent sections	200-foot minimum between curves
Vehicle weight (empty)	75,000 pounds
Maximum running speed	70 mph
Maximum civil speed limit	75 mph
Maximum acceleration rate	2.7 mph/s
Motor characteristic	High performance
Brake rate	2.2 mph/s

TABLE 2

Propulsion Energy and Savings for Station Pairs

TABLE 1

Propulsion Energy and Savings for Station Pairs

STATION	DIRECTION	SPEEDS (MPH)	TRAVEL TIME (SEC)	NO PROFILE (KWH)	4% GRADE PROFILE 20 FT (KWH)	4% GRADE PROFILE 30 FT (KWH)	4% GRADE PROFILE 40 FT (KWH)	6% GRADE PROFILE 30 FT (KWH)	6% GRADE PROFILE 40 FT (KWH)	6% GRADE PROFILE 50 FT (KWH)	6% GRADE PROFILE 60 FT (KWH)	MAX. ENERGY SAVED (KWH)
North Hollywood												
	In	51,70,57	157	29.0	27.0	27.2	28.3	26.7	26.9	27.8	29.2	2.3
	Out	57,70,51	158	57.8	55.4	55.6	56.6	54.7	54.8	56.0	57.3	3.1
Studio City												
	In	70	165	30.7	27.1	25.9	24.3	26.2	23.6	22.4	21.7	9.0
	Out	70	165	55.3	52.4	50.7	48.5	50.5	48.8	47.6	46.3	9.0
Hollywood Bowl												
	In	57	79	17.8	16.3	16.3	16.7	15.8	15.4	15.7	16.6	2.4
	Out	57	74	33.2	30.5	30.6	31.1	29.0	27.8	27.9	28.7	5.4
Cahuenga/Hollywood												
	In	57	99	18.7	16.3	16.3	17.3	15.8	15.6	16.3	17.5	3.1
	Out	57	99	35.0	32.4	32.6	33.1	31.2	30.7	31.6	32.7	4.3
Fountain/La Brea												
	In	70,51	98	30.9	27.9	27.3	27.5	26.7	26.6	26.0	27.0	4.9
	Out	51,70	99	37.7	35.1	34.4	34.1	34.2	33.7	33.4	33.3	4.3
Fairfax/Santa Monica												
	In	70	80	26.5	23.1	23.2	23.2	22.0	21.2	21.0	21.0	5.5
	Out	70	81	45.0	41.8	41.0	41.0	40.0	38.5	37.5	36.8	8.2
Fairfax/Beverly												
	In	51	118	17.9	16.6	17.0	18.7	16.2	17.6	18.3	20.0	1.7
	Out	51	118	24.1	22.5	22.8	24.2	22.1	23.4	23.9	25.4	2.0
Wilshire/Fairfax												
	In	70	80	36.0	32.1	30.4	29.0	30.2	29.2	26.8	26.0	10.0
	Out	70	80	30.7	27.2	25.7	24.2	25.5	24.3	22.2	21.6	9.1
Wilshire/La Brea												
	In	70	132	38.1	35.2	33.5	32.0	33.2	32.2	30.0	29.3	8.8
	Out	70	132	40.4	36.4	34.6	33.0	34.9	33.4	31.7	30.4	10.0
Wilshire/Western												
	In	57	55	24.0	21.0	21.0	21.0	21.0	21.0	21.0	21.0	3.0
	Out	57	55	18.6	16.3	16.3	16.3	16.3	16.3	16.3	16.3	2.5
Wilshire/Normandie												
	In	57	55	23.3	20.5	20.5	20.5	20.5	20.5	20.5	20.5	2.8
	Out	57	55	18.7	16.3	16.3	16.3	16.3	16.3	16.3	16.3	2.4
Wilshire/Vermont												
	In	70	82	34.3	30.2	28.5	27.0	29.3	27.3	25.6	24.3	10.0
	Out	70	82	32.5	29.7	27.9	26.0	27.6	25.6	23.9	23.2	9.3
Alvarado Street												
	In	70,51	88	36.3	33.3	31.5	30.1	31.5	30.5	27.9	26.6	9.7
	Out	51,70	92	31.6	29.5	29.0	28.9	28.6	28.6	28.4	27.9	3.7
7th & Flower												
	In	51	60	17.2	15.7	16.1	16.1	16.1	16.1	16.1	16.1	1.5
	Out	51	59	17.2	15.4	15.8	15.8	15.8	15.8	15.8	15.8	1.8
5th & Broadway												
	In	57	55	23.7	21.0	21.0	21.0	21.0	21.0	21.0	21.0	2.7
	Out	57	55	18.6	16.3	16.3	16.3	16.3	16.3	16.3	16.3	2.3
Civic Center												
	In	57	76	21.9	18.7	18.1	19.3	17.6	18.1	18.4	19.7	3.3
	Out	57	76	22.7	19.8	19.3	20.5	18.6	19.4	19.3	20.7	4.1
Union Station												
TOTALS			2959	945.4	859.0	842.7	837.9	831.4	816.5	802.9	806.5	162.0

(2) Energy Savings Considering Cut-and-Cover Sections and Crossover Locations

Cut-and-cover construction and crossover locations reduce the opportunity for vertical profiling and associated energy savings. This section discusses the estimated reductions in energy savings caused by cut-and-cover construction and/or crossovers. Table 3 summarizes the propulsion energy requirements for a single round trip of a six-car train. Also shown are the energy savings for selected combinations of restrictions on maximum grade and maximum additional tunnel depth added by the vertical profile.

The minimum energy case is based on selecting the individual profiles that give maximum savings for each station-to-station run as indicated in Table 2.

The Metro Project Alignment Profile, Revision B, dated January 13, 1982, was reviewed with SCRTD staff. It was established that cut-and-cover construction would be used for the following sections:

- From Union Station to Civic Center
- From Studio City to North Hollywood.

The "Cut & Cover" column of Table 3 shows the effect on energy savings when the vertical profile alternative is not applied to the cut-and-cover sections listed above.

In order to accommodate crossovers, an alternative was identified that has additional cut-and-cover construction in the following sections:

- From 5th/Broadway to 7th/Flower
- From Wilshire/Vermont to Wilshire/Normandie
- From Wilshire/Fairfax to Fairfax/Beverly
- From Cahuenga/Hollywood to Hollywood Bowl.

The last column of Table 3 shows the effect on energy savings from the six sections of cut-and-cover construction. In Table 3 it is assumed that vertical profiling is not included beyond the crossover region. To compute the additional savings of partial vertical profiling in the sections containing crossovers, it is necessary to identify specific locations for the crossovers and to rerun the computer simulation.

TABLE 3
Propulsion Energy and Savings per Train per Round Trip

	MAXIMUM GRADE (%)				MAXIMUM DEPTH (FT)				MINIMUM CASE [1]	CUT-&-COVER [2]	CUT-&-COVER & X-OVERS [3]
	No Profile	4%,20'	4%,30'	4%,40'	6%,30'	6%,40'	6%,50'	6%,60'			
TOTAL ENERGY (KWH)	945.4	859.0	842.7	837.9	831.4	816.5	802.9	806.5	783.4	796.2	816.3
SAVINGS (KWH)	----	86.4	102.7	107.5	114.0	128.9	142.5	138.9	162.0	149.2	129.1
% SAVINGS	----	9.1%	10.9%	11.4%	12.1%	13.6%	15.1%	14.7%	17.1%	15.8%	13.7%

ASSUMPTIONS:

TRAINS OPERATE AT MAXIMUM PERFORMANCE WITHOUT OPERATIONAL DISTURBANCES.
LOSSES FROM SUBSTATION INPUT TO VEHICLE TRACTION OUTPUT ARE NOT INCLUDED.

NOTES:

1. ASSUMES NO CUT-AND-COVER OR CROSSOVER TUNNEL SECTIONS.
2. ASSUMES CUT-AND-COVER TUNNEL SECTIONS AT UNION STATION/CIVIC CENTER AND STUDIO CITY/NORTH HOLLYWOOD.
3. ASSUMES CUT-AND-COVER AT UNION STATION/CIVIC CENTER AND STUDIO CITY/NORTH HOLLYWOOD AND CROSSOVERS AT 5th & BROADWAY/7th & FLOWER, WILSHIRE & VERMONT/WILSHIRE & NORMANDIE, WILSHIRE & FAIRFAX/FAIRFAX & BEVERLY AND CAHUENGA & HOLLYWOOD/HOLLYWOOD BOWL.

Additional crossover locations were identified near North Hollywood Station and Union Station, but these do not affect the energy savings.

In summary, the energy savings of 17.1 percent for the minimum energy case are reduced to 13.7 percent when the cut-and-cover sections are incorporated.

Table 4 shows similar analysis of energy savings with 6-percent grades limited to 4 percent.

TABLE 4
Propulsion Energy Savings per Train per Round Trip at 4-Percent Vertical Profile

	NO PROFILE	4% GRADE—MAXIMUM DEPTH				MIN. CASE[2]	CUT-&-COVER[3]	CUT-&-COVER & X-OVERS[4]
		20′	30′	40′	50′			
TOTAL ENERGY (KWH)	945.4	859.0	842.7	837.9	826.7	814.5	826.1	841.7
SAVINGS	———	86.4	102.7	107.5	118.7	130.9	119.3	103.7
% SAVINGS	———	9.1%	10.9%	11.4%	12.5%	13.8%	12.6%	11.0%

ASSUMPTIONS:
TRAINS OPERATE AT MAXIMUM PERFORMANCE WITHOUT OPERATIONAL DISTURBANCES.
LOSSES FROM SUBSTATION INPUT TO VEHICLE TRACTION OUTPUT ARE NOT INCLUDED.

NOTES:
1. DATA FOR 50′ RUNS ARE ESTIMATED. COMPUTER RUNS FOR THIS DEPTH ARE NOT AVAILABLE.
2. ASSUMES NO CUT-AND-COVER OR CROSSOVER TUNNEL SECTIONS.
3. ASSUMES CUT-AND-COVER TUNNEL SECTIONS AT UNION STATION/CIVIC CENTER AND STUDIO CITY/NORTH HOLLYWOOD.
4. ASSUMES CUT-AND-COVER AS IN NOTE 3 AND CROSSOVERS AT 5th & BROADWAY/7th &FLOWER, WILSHIRE & VERMONT/WILSHIRE & NORMANDIE, WILSHIRE & FAIRFAX/FAIRFAX & BEVERLY, AND CAHUENGA & HOLLYWOOD/HOLLYWOOD BOWL.

(3) Compensation Factors for Energy Calculations

In previous studies, the only compensation was for passenger load. This was achieved by applying a multiplication factor of 1.165 to the computed energy data. Revised compensation factors are discussed below. The intent is to reinterpret the energy data as far as practicable without rerunning the simulation.

1. Compensation for Heavier Car and Different Passenger Load

The car weight used in the simulation was 75,000 pounds; the car weight has been revised to 80,000 pounds. The average passenger load used in the previous studies was 12,375 pounds, corresponding to 75 people with an average weight of 165 pounds. This loading assumes that passenger-miles are equivalent to seat-miles if there are 75 seats per car. On an annual basis such loading is considered to be representative of a well-patronized system. The average loaded weight of 92,375 pounds results in a weight compensation factor of:

$$\frac{92,375}{75,000} = 1.232.$$

2. Compensation for Power Distribution Efficiency and Vehicle Propulsion Efficiency

The following average efficiencies are assumed:

- Traction power distribution at 90 percent
- Propulsion motor and motor controller at 85 percent
- Drive train and gear box at 95 percent.

These efficiencies give an overall efficiency of 72.7 percent.

3. Compensation for Train Resistance

An additional 5 percent is added to the overall energy requirement to compensate for operating in a tunnel as opposed to an open space.

(4) Calculation of Traction Energy Requirement

Table 2 indicated that a round trip of a six-car, unloaded train requires 945.4 kilowatt-hours (KWH) of energy. For a round-trip travel distance of 37.4 miles:

- The train energy requirement is 25.28 KWH per mile.
- The car energy requirement is 4.213 KWH per mile.

Application of the compensation factors gives:

Traction Energy Requirement =

$$4.213 \times \frac{1.232}{0.727} \times 1.05 = 7.496 \text{ KWH/car-mile.}$$

Assuming regeneration at 12.5 percent, then:

Traction Energy Requirement =

$$7.496 \times (1 - 0.125) = 6.559 \text{ KWH/car-mile.}$$

The overall compensation factor results in a traction energy requirement of 6.559 KWH/car-mile compared with the 4.213 KWH/car-mile which assumed a car weight of 75,000 pounds and 100-percent efficiency of traction power distribution and propulsion equipment.

Table 5 summarizes energy data acquired by SCRTD staff from other operating properties.

TABLE 5
Reported/Estimated Energy Consumptions
(Kilowatt-hours)

Property	Traction Only	Traction Plus Car Auxiliaries	Vehicle Plus Other Loads
BART	4.2*	4.5	-
PATCO	6.4	7.68	-
WMATA	-	10.25	-
MARTA	-	8.4	14.0
NYCTA	5.0**	7.4**	-
CTA	-	-	12.0

* With regeneration.
** 75-foot car.

Comparative analysis of the above data for individual traction energy consumption requires additional information on acceleration duty cycles, average passenger loads, top speeds, average speeds, and other factors. Therefore, the value of 6.559 KWH per car-mile will be used in the subsequent analysis of this report.

(5) Revision To Reflect Current Operating Plan

Table 6 summarizes the system statistics of the current Operating Plan.

TABLE 6
Summary of Operating Statistics

Day	Days/Year	#Trains	#Car Trips	Train-Hrs.	Car-Hrs.	Car-Miles
Weekdays	255	167	954	190.3	1,088	35,680
Saturdays	52	104	560	117.0	468	20,994
Sundays/Holidays	58	80	320	90.0	370	11,968
Annual	365	52,633	290,950	59,830	323,236	10,884,232
Annualization Factor (Annual/Weekday)		315	305	314	297	305

Car-miles per year are calculated to be 10,884,232. Therefore, the annual traction energy consumption is 10,884,232 miles at 6.559 KWH/car-mile, that is, 71.4 million kilowatt-hours.

(6) Energy Costs

The Los Angeles Department of Water and Power has predicted the following average price per KWH for industrial users:

Fiscal Year Ending June 30	Price* (cents)
1980	4.60 (actual)
1981	5.69 (actual)
1982	6.27
1983	7.50
1984	8.16
1985	8.84
1986	9.58
1987	9.91
1988	10.47
1989	11.29
1990	11.98
1991	12.92
1992	14.01

The price increases include escalation factors for a general inflation rate of 9 percent, a fuel oil cost inflation rate of 12 percent, and a coal cost inflation rate of 6 percent.

Cost savings are calculated using the actual 1981 energy cost of 5.69¢/KWH. Additional costs for power factor correction and peak loads are not included.

(7) Summary of Annual Traction Energy Costs and Annual Traction Energy Savings

For the no-profile case, estimated annual energy cost for traction is $4.062 million. The following savings are estimated if vertical profiling is used:

- For vertical profiles with grades up to 4 percent, estimated savings are 11.0 percent or an annual savings of $446,820 in 1981 dollars.

- For vertical profiles with grades up to 6 percent, estimated savings are 13.7 percent or an annual savings of $556,500 in 1981 dollars.

Note that these savings include regenerative propulsion equipment and are based on conservative design criteria.

*Sources: 1980, 1981: LADWP, computer printout, August 31, 1981.
1982-1992: SCRTD memo, February 18, 1982.

3. REVIEW OF ADDITIONAL CAPITAL COSTS, OPERATING COSTS, AND MAINTENANCE COSTS FOR VERTICAL PROFILES

Additional costs associated with vertical profiling have been identified for:

- Tunneling
- Ventilation equipment
- Sump pumps
- Operation and maintenance.

(1) Incremental Capital Cost for Tunneling Incorporating Vertical Profiles

The incremental capital cost of vertical profile tunneling for grades up to 4 percent has not been identified. Although this cost is not zero, it is assumed to be zero for purposes of this analysis. Vertical profiling at 6-percent grade adds a cost of $43.00 per linear foot of tunneling because of additional muck-out requirements (source: Sperry, Lehman report).

(2) Ventilation Equipment

The Metro Rail staff's estimated cost for increased emergency ventilation with vertical profiling is $120,000 per station pair.

(3) Sump Pumps

Additional sump pumps are required because of the vertical profile. The approximate locations of the additional sump pumps are shown in Figure 1.

Pumps are located where the construction of a vertical profile necessitates the addition of a sump pump. The installed cost of each pump is estimated at $150,000. Pumps are assumed to drain both tunnels and have built-in redundancy with annunciation of failure.

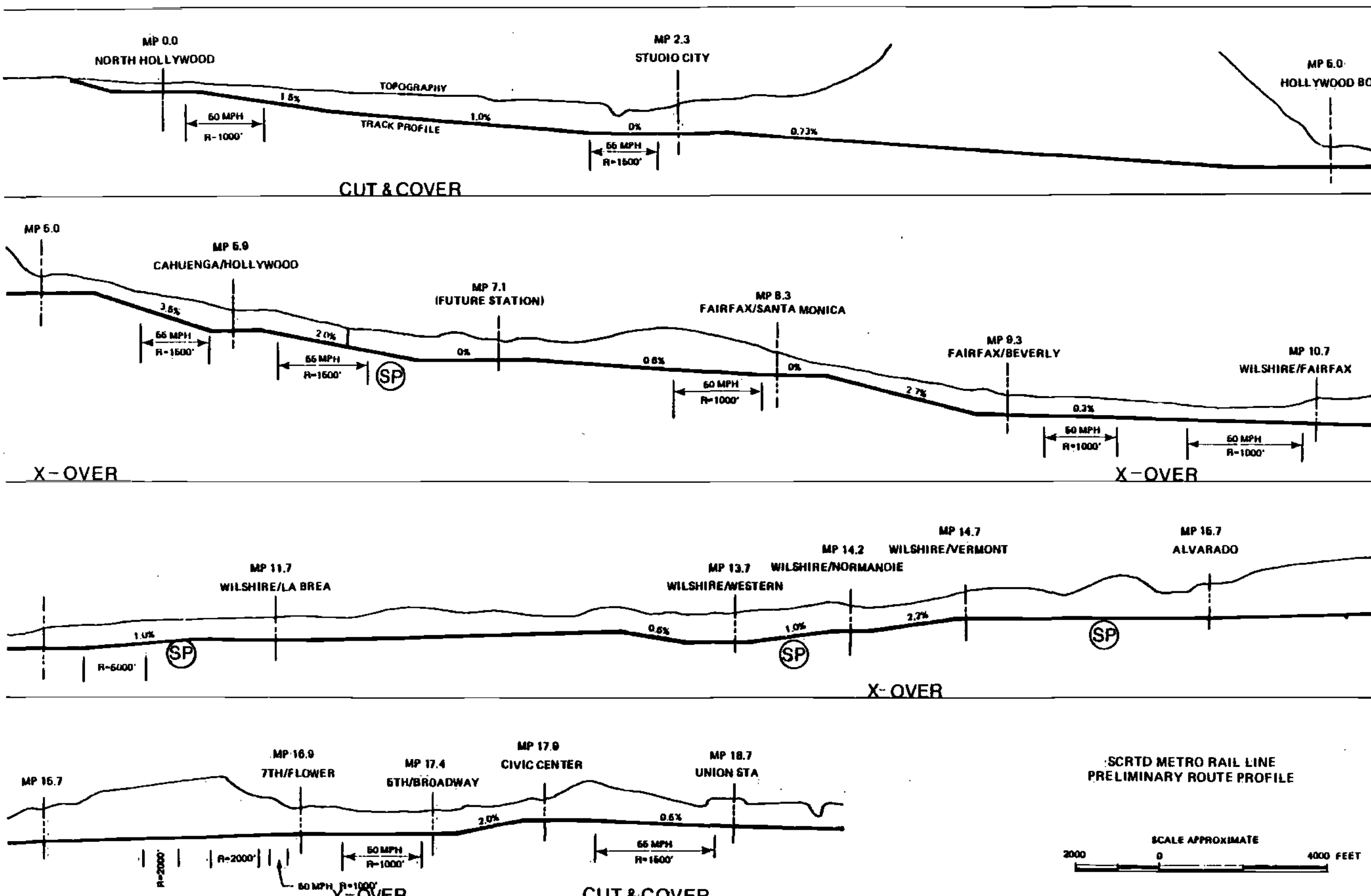
(4) Operation and Maintenance

Operation and maintenance costs and savings for vertical profiles have not been derived at this time, exclusive of traction power.

*   *   *   *   *

FIGURE 1

Preliminary Route Profile Showing Approximate Locations of Additional Sump Pumps



Source: SCRTD Sketch, Preliminary Grade Allocations.
Modified by Booz, Allen to include speed restrictions of horizontal curves.

Table 7 summarizes the additional capital cost of dipped guideways with grades up to 6 percent. The additional capital cost of dipped guideways with grades up to 4 percent is shown in Table 8. A column is included for "other costs" for future revisions to the tables.

Although additional capital costs were evaluated for a system design with mid-line ventilation shafts, further financial analysis was not conducted when this alternative was rejected by the SCRTD staff.

TABLE 7
Summary of Additional Capital Cost Factors
for 6-Percent Grades
(Thousands of Dollars)

STATION PAIR	DISTANCE BETWEEN STATION PLATFORMS	VERTICAL PROFILE		COST OF 6% GRADE AT $86/FOOT*	EMERGENCY VENTILATION EQUIPMENT	OTHER COSTS	SUMP PUMPS @ $150,000	TOTALS
		GRADE	DEPTH					
	(FEET)		(FEET)	($000)	($000)	($000)	($000)	($000)
NORTH HOLLYWOOD**								
STUDIO CITY	11,900	cut & cover	–	–	–		–	–
HOLLYWOOD BOWL	13,550	6%	50	1165.3	120		–	1285.3
CAHUENGA/HOLLYWOOD	4,170	crossover	–	–	–		–	–
FOUNTAIN/LA BREA	5,900	6%	40	507.4	120		150	777.4
FAIRFAX/SANTA MONICA	5,650	6%	50	485.9	120		–	605.9
FAIRFAX/BEVERLY	4,700	6%	60	404.2	120		–	524.2
WILSHIRE/FAIRFAX	6,800	crossover	–	–	–		–	–
WILSHIRE/LA BREA	4,900	6%	60	421.4	120		150	691.4
WILSHIRE/WESTERN	10,200	6%	60	877.2	120		–	997.2
WILSHIRE/NORMANDIE	2,190	4%	20	–	120		150	270
WILSHIRE/VERMONT	2,190	crossover	–	–	–		–	–
ALVARADO	5,010	6%	60	430.86	120		150	700.86
7th & FLOWER	5,820	6%	60	500.52	120		–	620.52
5th & BROADWAY	2,430	crossover	–	–	–		–	–
CIVIC CENTER	2,200	4%	20	–	120		–	120
UNION STATION**	3,950	cut & cover	–	–	–		–	–
TOTALS	–	–	–	4792.78	1200	–	600	6592.78

* $43/foot for each guideway.
** Portal Ventilation factors are not included.

TABLE 8
Summary of Additional Capital Cost Factors
for 4-Percent Grades
(Thousands of Dollars)

STATION PAIRS	DEPTH	EMERGENCY VENTILATION EQUIPMENT	OTHER COSTS	SUMP PUMPS @ 150,000	TOTALS
	(FEET)	($000)	($000)	($000)	($000)
NORTH HOLLYWOOD**					
	–	–		–	–
STUDIO CITY					
	40*	120		–	120
HOLLYWOOD BOWL					
	–	–		–	–
CAHUENGA/HOLLYWOOD					
	40	120		150	270
FOUNTAIN/LA BREA					
	40	120		–	120
FAIRFAX/SANTA MONICA					
	40	120		–	120
FAIRFAX/BEVERLY					
	–	–		–	–
WILSHIRE/FAIRFAX					
	40*	120		150	270
WILSHIRE/LA BREA					
	40*	120		–	120
WILSHIRE/WESTERN					
	20	120		150	270
WILSHIRE/NORMANDIE					
	–	–		–	–
WILSHIRE/VERMONT					
	40*	120		150	270
ALVARADO					
	40*	120		–	120
7th & FLOWER					
	–	–		–	–
5th & BROADWAY					
	40	120		–	120
CIVIC CENTER					
	–	–		–	–
UNION STATION**					
TOTALS	–	1200	–	600	1800

*Possibility of depth increase up to 48 feet for additional energy cost savings.
**Portal ventilation factors are not included.

4. SUMMARIES OF COST DATA, COST COMPARISONS, AND CONCLUSIONS

A summary of the energy costs is presented in this section. Factors limiting cost savings are discussed, and additional capital costs of vertical profiles are compared with energy cost savings.

(1) Energy Cost Savings From Vertical Profiling

The annual savings and the upper bounds on annual savings are discussed separately below.

1. Annual Savings

The baseline annual cost of propulsion energy for the non-dipped system is estimated to be $4.062 million. Savings resulting from vertical profiling are:

- For vertical profiles with grades up to 4 percent, minimum estimated cost savings are 11.0 percent of baseline or $446,820 per year.
- For vertical profiles with grades up to 6 percent, minimum estimated cost savings are 13.7 percent of baseline or $556,500.

With additional vertical profiling in sections containing crossovers, the savings for 4-percent grades will be more than 11.0 percent but not more than 12.6 percent. For 6-percent grades, the savings will be more than 13.7 percent but not more than 15.8 percent.

2. Upper Bounds on Annual Savings

Increased service levels due to ridership growth will realize additional energy savings resulting from vertical profiles. The cost data developed in Section 2 of this report are based on 1995 operating statistics. Detailed operating statistics for future ridership growth are not available, but assuming that annual car-miles would increase by 20 percent, then corresponding energy cost savings will increase by a factor of 1.20 if average car loading is assumed to remain constant.

An upper bound on annual energy savings for 4-percent grades is obtained by adjusting $446,820 for additional profiling in sections with crossovers and for ridership growth. This upper bound is $614,174. Similarly, for 6-percent grades the upper bound is $770,164. However, additional vertical profiling in crossover sections will increase capital costs for ventilation by $480,000.

In this report, credit is not taken for equalization of trip times. The energy savings of vertical profiles will increase if trip times are equalized with the no-profile case. Further analysis is required to estimate the exact extent of the savings, and it is recommended that penalties for operational perturbations also be included if this analysis is conducted. Equalization of trip times is discussed further in Section 5.

(2) <u>Present Value of Energy Cost Savings</u>

The major factors in determining the present value of the energy savings due to the dipped profile alignment are the:

- Inflation rate for electricity cost
- Discount rate (the cost of money).

The average annual inflation rate of electricity is 7.5 percent over the period 1989-1992, as forecast by the Los Angeles Department of Water and Power. The rate is assumed constant over the 30-year period analyzed.

For the purposes of this analysis, two discount rates are assumed, 13.3 percent and 10 percent. The present yield on 30-year U.S. Treasury bonds is 13.3 percent, which thus represents the cost for the U.S. Government to borrow money. Ten percent is the approximate yield on California tax-exempt bonds, and represents the cost for local authorities to borrow money. These discount rates provide a range of comparisons.

The capital investments of $1.8 million for 4-percent grades and $6.6 million for 6-percent grades were assumed to occur, on average, 3 years prior to the start of revenue service and accumulation of energy cost savings.

The energy cost savings were calculated over a period of 30 years. Using a longer time period, such as 40 years, does not significantly alter the present value of the savings. At 10-percent interest rates, a dollar of energy savings 40 years from now is only worth 2.2¢ today; at 13.3 percent it is worth less than 0.7¢.

Figure 2 shows the annual cost savings for vertical profiles with up to 4-percent grades. The graph shows the capital cost ($1.8 million) followed by a period of no revenue service, followed by the cumulative energy cost savings during revenue service. Table 9 lists the actual dollar values for the energy cost savings. It should be noted that savings begin at $555,083, not at $446,820 as calculated in Section 2. Since the energy savings do not begin for 3 years after the capital costs have been spent, 3 years of inflation have been added to the annual energy cost savings, as follows:

$$\$446,820\ (1 + .075)^3 = \$555,083$$

Table 10 summarizes the present value of the energy savings for 4-percent and 6-percent grades for the baseline savings and the upper bound savings. The last column, "Net Present Value," is the present value of the savings less the capital costs.

TABLE 10
Present Value of Annual Energy Savings for Vertical Profile
(Thousands of Dollars)

GRADE		ANNUAL SAVINGS (CONSTANT DOLLARS)	PRESENT VALUE OF SAVINGS		CAPITAL COSTS	NET PRESENT VALUE	
			@13.3%	@10%		@13.3%	@10%
4%	1995 DESIGN	$447	$5,914	$9,143	1,800	$4,114	$7,343
	UPPER BOUND	$614	8,129	12,567	1,800	6,329	10,767
6%	1995 DESIGN	$557	7,366	11,387	6,593	773	4,794
	UPPER BOUND	$770	10,194	15,760	6,593	3,601	9,167

FIGURE 2
Present Value of Cumulative Energy Savings
for 4-Percent Grade: 1995 Design

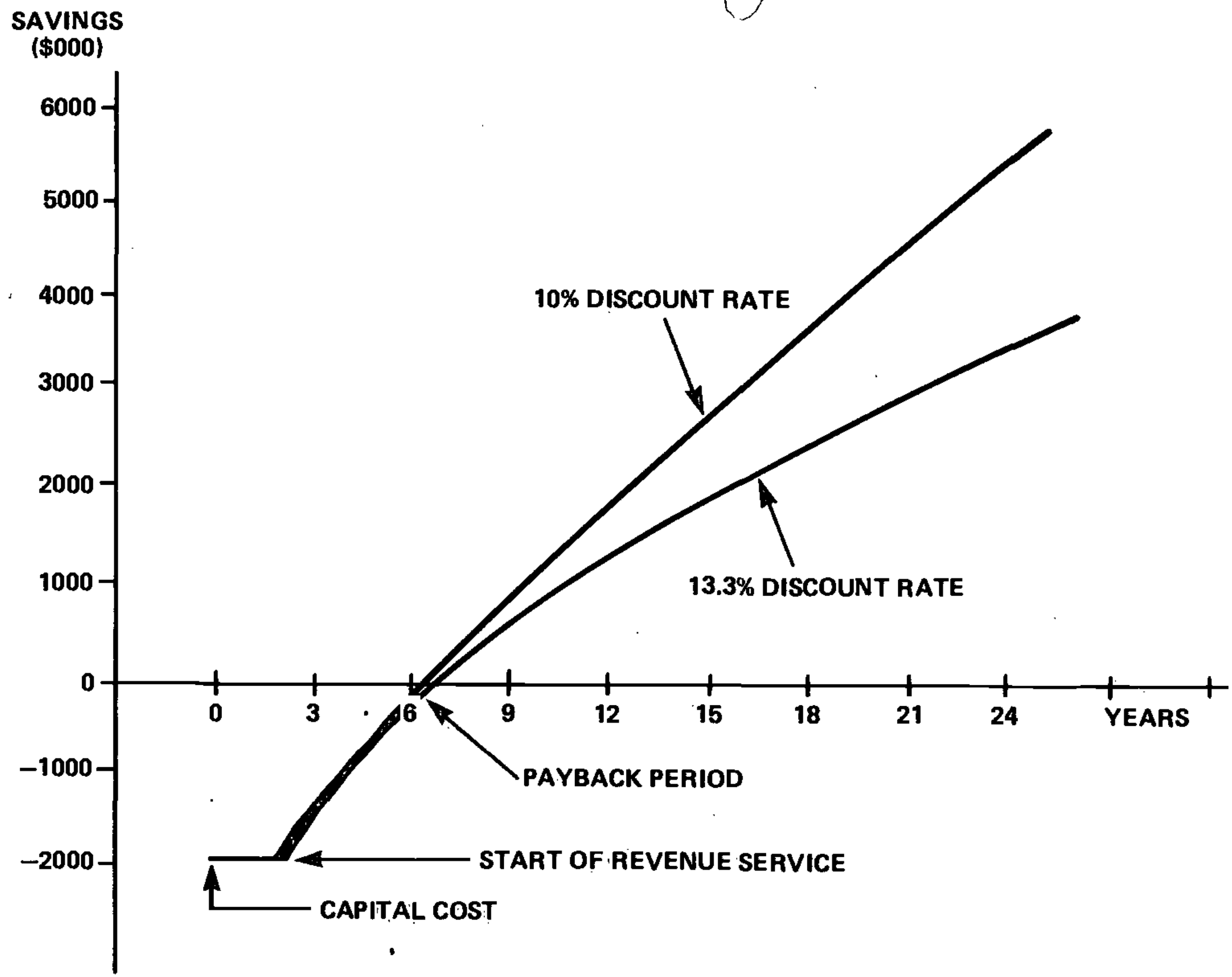


TABLE 9

Energy Cost Savings by Year for 4-Percent Grade: 1995 Design
(Thousands of Dollars)

Year	Cost Savings	Present Value of Cumulative Cost Savings @ 13.3%	Present Value of Cumulative Cost Savings @ 10%	Year	Cost Savings	Present Value of Cumulative Cost Savings @ 13.3%	Present Value of Cumulative Cost Savings @ 10%
0	$-1800	$-1800	$-1800	17	$1528	$2266	3552
1	0	-1800	-1800	18	1642	2439	3847
2	0	-1800	-1800	19	1766	2604	4136
3	555	-1418	-1383	20	1898	2760	4418
4	597	-1056	- 975	21	2040	2908	4694
5	641	- 713	- 577	22	2193	3049	4963
6	690	- 387	- 188	23	2358	3182	5227
7	741	- 77	193	24	2535	3309	5484
8	797	216	564	25	2725	3429	5736
9	857	495	928	26	2929	3543	5981
10	921	759	1283	27	3149	3651	6145
11	990	1009	1630	28	3385	3754	6456
12	1064	1247	1969	29	3639	3851	6685
13	1144	1473	2300	30	3912	3944	6909
14	1230	1687	2624	31	4205	4031	7129
15	1322	1890	2940	32	4521	4114	7343
16	1421	2083	3250				

(3) <u>Findings and Conclusions</u>

The findings and conclusions of the financial analysis are:

- For both 4-percent and 6-percent grades, the net present value of the dipped profile alignment is positive, meaning that the electricity savings more than justify the additional capital cost.

- The energy savings more than repay the principal and interest on money borrowed to build the dipped profile. This is true even at the higher discount rate.

- Specifically, in the 4-percent grade case, if the $1.8 million was borrowed at an interest rate of 13.3 percent for a period of 30 years, the annual payment (similar to a home mortgage) would be $245,000. Since that amount is less than the energy savings of $447,000, there is a net savings of $202,000 the first year.

- The net present value of the cases analyzed ranges from a low of $773,000 for the 6-percent grade, the 1995 patronage forecast, and a discount rate of 13.3 percent, to a high of $10,767,000 for a 4-percent grade, the upper bound of patronage, and a discount rate of 10 percent.

- Both 4-percent and 6-percent grades are cost-beneficial on net present value and absolute annual savings bases.

- If the primary objective is to maximize annual savings, then grades up to 6 percent should be considered.

- The net present value would be maximized with grades of approximately 4 percent.

5. REVIEW OF JPL REPORTS

The studies conducted by JPL and its subcontractors were reviewed for applicability to the starter line of the Metro Rail Project. The review focused on the design and cost aspects for vehicle traction, ventilation, tunneling, and propulsion energy. Tunneling aspects were included in Section 3. The key findings on ventilation cannot be directly related to the configuration of the SCRTD starter line. The other two areas are discussed below.

(1) Vehicle Traction

Two important conclusions were drawn from the L. T. Klauder and Associates report entitled "Assessment of the Impact of Dipped Guideways on Urban Rail Transit Systems - Traction and Push-out Studies" dated July 24, 1981. They are:

- "No serious obstacles exist in running MU (Multiple Unit) trains on grades up to 10 percent with push-out requirements."
- "Motor sizing is not a factor; standard motors for level system are acceptable."

These conclusions support Booz, Allen's previous analysis which concluded that no problems should be encountered in operating on grades of 6 percent maximum. The previous analysis* of operations with propulsion failure indicates that grades should be limited to 6 percent to avoid push-out problems with stalled trains that result in increased system blockages.

(2) Propulsion Energy

The Jet Propulsion Laboratory (JPL) prepared a report entitled "Gravity-Assisted Rapid Transit Supplemental Analysis," which provides a comparison of various operating strategies, station lengths, grades, and running lengths between stations. Figure 3 (taken from the JPL report) shows the results. The upper set of curves is for a control strategy which takes maximum advantage of the time savings for dipped guideway operation. The coasting and station stopping strategies required go beyond the present state of the art in train control technology and involve significant development cost and risk exposure. The lower set of curves, however, is representative of the approach taken by Booz, Allen.

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* Booz, Allen & Hamilton Inc., A Study of Energy Management Alternatives for the Starter Line of the SCRTD Metro Rail Project, Final Report, December 1981.

FIGURE 3
Dipped Guideway Energy Savings Over Level for Selected Variable Geometric Conditions

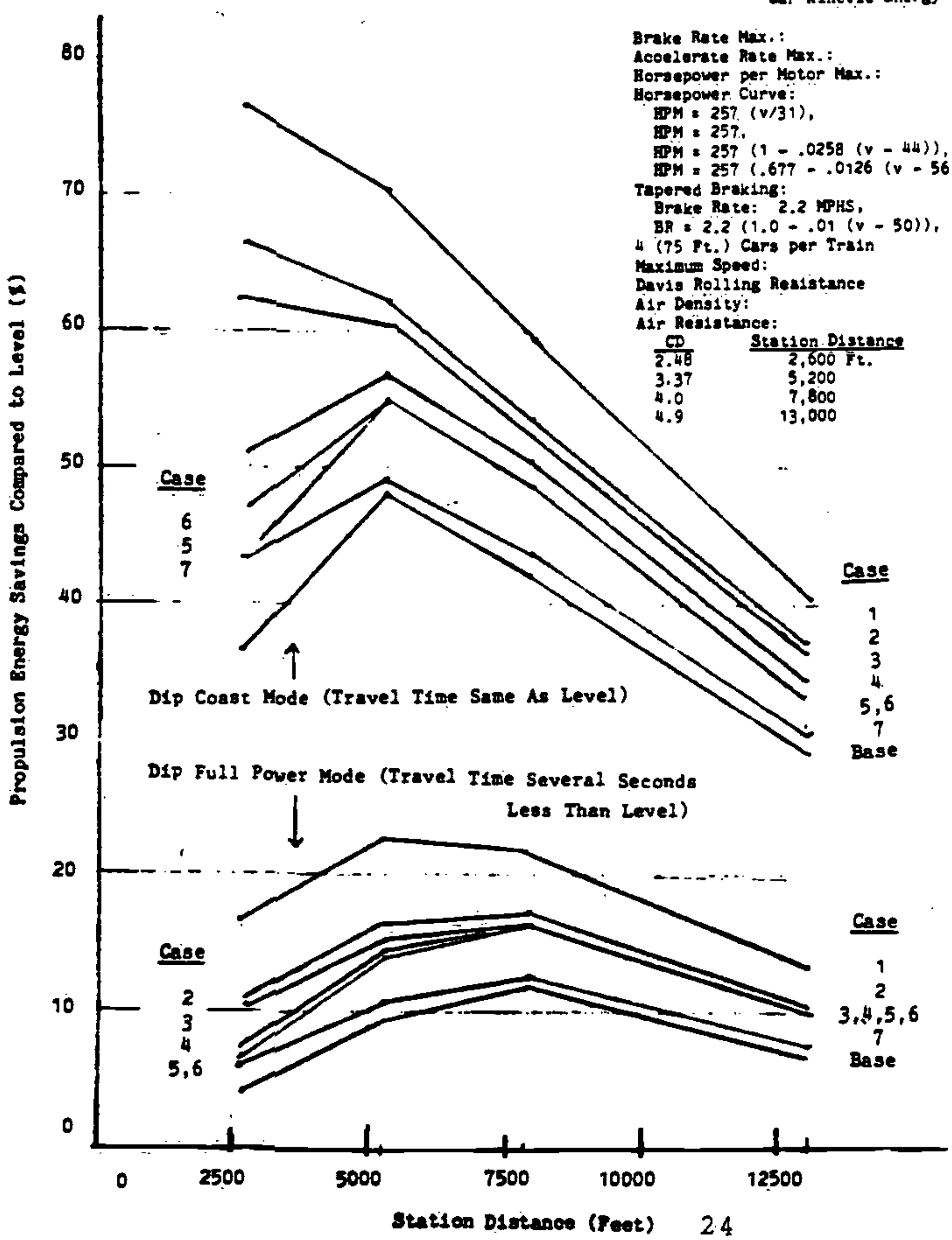
Variable Conditions

Case	Max. Grade	Max. Dip	Vertical Curve Rate Crest, Sag	Station Level Length	Dip 2600 Ft. Stations	Grade 2600 Ft. Stations	Dip Minimum Tangent Length
1	10%	100	30, 30 Ft./%	0 Ft.	85 Ft.	10%	300
2	8	80	50, 50	0	60	8	300
3	6	80	50, 50	0	51	6	300
4	6	80	60, 100	200	35	5	200
5	6	80	60, 100	300	32.5	5	200
6	6	80	60, 100	300	37.2	6	100
7	6	60	70, 70	300	32.5	5	300
Base	6	60	100, 100	300	21	3	300

Fixed Conditions

Train Frontal Area:	90 $Ft.^2$
Train Weight:	336,000 Lbs.
Beta = Car Kinetic Energy (Translation & Rotation) / Car Kinetic Energy (Translation) =	1.08
Brake Rate Max.:	2.2 MPHS
Accelerate Rate Max.:	3.0 MPHS
Horsepower per Motor Max.:	257
Horsepower Curve:	
HPM = 257 (v/31),	0 < velocity < 31 MPH
HPM = 257,	31 < v < 44
HPM = 257 (1 - .0258 (v - 44)),	44 < v < 56.5
HPM = 257 (.677 - .0126 (v - 56.5)),	56.5 < v < 75
Tapered Braking:	
Brake Rate: 2.2 MPHS,	0 < v < 50
BR = 2.2 (1.0 - .01 (v - 50)),	50 < v < 75
4 (75 Ft.) Cars per Train	
Maximum Speed:	75 MPH
Davis Rolling Resistance	
Air Density:	RHO = .00238 $Slug/Ft.^3$
Air Resistance:	$F(A) = 1/2\ (RHO)\ (A)\ (CD)\ v^2$ Lbs.

CD	Station Distance
2.48	2,600 Ft.
3.37	5,200
4.0	7,800
4.9	13,000



The JPL report states that comparison of similar inputs to its simulation program and Booz, Allen's yielded a difference of less than 1 percent in the output results. JPL states that a savings of 57 percent is possible using vertical profiling. This 57-percent savings is for an idealized case at a specific station spacing distance, with a 6-percent grade, 80-foot maximum dip, a relatively short station platform length, and an advanced train control strategy.

The 57-percent savings includes credit for matching run times. The savings are significantly reduced by the design constraints of the starter line configuration. These constraints include:

- Cut-and-cover construction
- Crossover and pocket track locations
- Differences in station elevation
- Vertical curve criteria
- Requirement for tangent platforms
- Restrictions imposed by speed limits in horizontal curves
- Capabilities of state-of-the-art train control equipment.

Although the constraints can be individually or collectively examined for effects on cost savings, such examination is beyond the scope of this report. If credit is taken for matching run times, then the percentage savings calculated in Section 2 will increase by a ratio estimated to be 1.1:1. Additional simulation is required to substantiate this estimate and to evaluate the savings of coasting for a level system against the savings of coasting for a dipped system.

6. RECOMMENDATIONS

Recommendations are presented regarding:

- Energy management alternatives
- Areas requiring further simulation and study
- Further evaluation of additional costs.

(1) Recommendations on Energy Management Alternatives

The recommendations on design approaches for energy management are listed below.

1. On the basis of cost analysis, select a vertical alignment incorporating gravity-assist vertical profiles as the preferred alternative for the Metro Rail Project.

2. Select a 4-percent grade based on higher net present value of energy savings. To justify grades exceeding 4 percent, further analysis is required on:

   - Tunnel muck-out costs
   - Energy savings
   - Subsystems capability
   - Impact of failures on operations.

   Based on the information presently available, 4-percent grades are believed to be a reasonable compromise between maximum energy savings and adverse impact on operational effectiveness.

3. Specify propulsion equipment with regenerative braking. Increased energy savings will result whether vertical profiling is used or not.*

4. Specify a train control system with automatic speed regulation and with performance modification features that include coast. Increased energy savings will result whether vertical profiling is used or not.*

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* Booz, Allen & Hamilton Inc., A Study of Energy Management Alternatives for the Starter Line of the SCRTD Metro Rail Project, Final Report, December 1981.

(2) Recommendations for Further Simulation and Study

Further simulation and study are recommended in some areas. These are described below.

1. Run the profile geometry (PROGEN) program to establish the 4-percent design profiles. Incorporate the current design data including the revisions to station elevations, revisions to distances between stations, exclusion of a future station at Fountain/ La Brea, tentative pocket track and crossover locations, and any changes to the horizontal alignment. The 4-percent design profiles thus established are intended to provide the Ways and Structures Division with a vertical alignment baseline for further civil engineering evaluation.

2. Perform additional analysis to establish optimal vehicle performance for the specific 4-percent design profiles established in 1 above. Major performance considerations are: the nominal acceleration at low speed, the velocity at which nominal acceleration cannot be sustained, and the rate of decline in available acceleration as velocity increases up to the nominal top speed of 70 mph. The specific analysis of the starter line configuration may be supplemented by parametric analysis if change in optimal performance due to system expansion is of concern.

   The performance criteria thus established should be evaluated against state-of-the-art traction motors, traction motor controllers, and speed regulation equipment as a prelude to finalizing performance specifications for the propulsion and speed regulation equipment of the vehicle and train control subsystems. In this context, performance modification features, including coasting, are considered functions of the speed regulation equipment.

3. Where possible, select by inspection the crossover and pocket track locations at the end of a station which yields the most energy savings.

4. Perform a tradeoff study to determine additional energy savings against average increases in trip times, if the top speed of the system were reduced.

(3) Recommendations for Further Evaluation of Additional Costs Associated With Vertical Profiles

Additional costs associated with vertical profiles should be further evaluated. These costs are discussed below.

1. Capital Costs

The present value analysis is particularly sensitive to the marginal capital cost estimates. Therefore, continued refinement of marginal capital costs should continue through Preliminary Engineering. Similarly, refinement of energy savings and present value analysis is also warranted.

2. Sources of Costs and Savings Not Presently Identified

New questions on the costs and savings of vertical profiles are likely to be continually asked during Preliminary Engineering and Final Design. It is recommended that each be evaluated and considered in a periodic reevaluation of the design criteria for vertical profiles.

3. Sources of Costs Identified But Not Estimated for This Report

All major sources of costs and savings identified to date have been addressed in this report. Several minor sources, however, have been identified but not included. It is recommended that all such costs and savings be evaluated. Examples are costs associated with:

- Increase in guideway length due to the vertical profiles
- Operation and maintenance of additional sump pumps
- Maintenance of the emergency ventilation equipment required to increase ventilation capacity for vertical profiles
- Additional train control equipment, including development costs, that is not otherwise justifiable.

Intangible costs have also been associated with vertical profiles. They result from:

- Reduction in ultimate system capacity caused by lower throughput of sections with downgrades where increased safe braking distance is required
- Increased difficulty of emergency evacuation and access by the emergency services
- Increased sensitivity to equipment failures, especially those resulting in abnormal passenger transfers between revenue cars.

It is recommended that such concerns be ultimately resolved in a design review setting.