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EFFECTS OF TUNNEL AND STATION SIZE ON THE COSTS AND SERVICE OF SUBWAY TRANSIT SYSTEMS

Jet Propulsion Laboratory
California Institute of Technology
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NOTICE

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16. Abstract This brief study was initiated by the Office of Rail Technology and Construction of UMTA in DOT to determine the feasibility of less spacious, hence less costly underground rail mass transit system designs that would adequately meet a wide range of requirements. The two elements considered are tunnels and stations, both located in favorable geology.

The major cost saving expected from alternative tunnel designs (up to six million dollars per route mile) results from using pre-cast concrete segment liners in place of steel. The saving expected for a two-foot decrease in the diameter of twin, single-track tunnels is about two million dollars per route mile from 13 million dollars for pre-cast concrete segment liners (a saving of about 16%). The cost per route-mile of a double-track tunnel appears to be 15-25% higher than for the twin, single-track tunnels.

The effective cost saving expected from stations with four-car train capability instead of the usual eight-car trains is substantial; nearly one-fourth or seven million dollars per station (or per route-mile since the average spacing is about a mile). The saving in station costs can be obtained while improving service to the user (lower transit time and less waiting for trains) up to a capacity of 36,000 riders per hour in each direction.

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PREFACE

Caution should be exercised in using the absolute values of the cost comparisons in this report. The exact levels for an actual transit system are subject to the many realistic conditions that exist at that time and place. However, the cost estimates upon which the analysis of this study is based are consistent with each other. Therefore, use of the percentage differences of the various cost comparisons would be the preferable approach when applying these results to the design of a new system.

UNIT CONVERSIONS

in (")	=	2.54 cm
ft (')	=	0.3048 m
ft^2	=	0.0929 m^2
yd^3 (cy)	=	0.7646 m^3
mile	=	1609.3 m
mph	=	1.6093 km/hr

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SECTION I

INTRODUCTION

Recent designs of U.S. rail mass transit systems are similar in approach for meeting the primary service requirements of capacity, headway, and average travel speed. They use long trains with high-performance capabilities, operating in large-diameter, single-track tunnels on headways of no less than three minutes with long station dwell times. This philosophy results in a high cost system. The high capital costs incurred by these recent systems have caused problems in obtaining funds for additional systems and expanding current ones. This raises the following questions: How much savings can be obtained by designing systems having smaller tunnels and stations? What are the effects on service of such less pretentious systems designs?

This study was initiated to provide some insight to the above questions. Tunnel cost data were generated specifically for this study to examine the effects of tunnel diameter on costs in a favorable geology, like the Los Angeles (L.A.) basin. Other pertinent cost estimates and actual bid costs were used to develop a realistic cost model which included the cost of electrical energy as a function of tunnel diameter. Existing cost estimates for underground stations with platforms of various configurations were combined with the capital costs and operations of trains to develop a cost model for stations. Then, the cost and service aspects of a number of less pretentious systems were compared to those of recent design with high cost. In addition, since energy conservation is of great current and future concern, several approaches capable of decreasing electrical energy are included with brief comments.

SECTION II

BACKGROUND

All recently designed U.S. subway systems, some already in at least partial operation, have long station platforms that can accommodate trains of eight to ten cars and tunnels about $16\frac{1}{2}$ ft. in diameter. The theoretical maximum capacity of such large stations is in excess of 70,000 riders per hour in each direction. However, the actual use is substantially less. Even if the use would eventually approach the full capability, it is not clear that it would be in the best interests of a system to have such high corridor and station concentrations of riders. It may be preferable to spread out the system in the manner of the London Underground or the Paris Metro which have less capacity but more routes. A comparison of the stations of the recently-designed U.S. systems with New York and London is made in Table 1. It is clear that the maximum attainable capacities of the new U.S. systems are substantially greater than the actual maximum requirements of the current, long-established systems located in the densely populated cities of New York and London.

The characteristics of the tunnel guideways of the newer U.S. subway systems are shown in Table 2 with similar information on smaller size foreign systems. The tunnel diameters of the U.S. systems are substantially larger than those in the United Kingdom. With the U.S. cars about $10\frac{1}{2}$ ft. in width and $10\frac{1}{2}$ to $11\frac{1}{2}$ ft. in height, it is not apparent that the car size is the controlling reason for the 16'8" tunnel diameters.

Even if it were, perhaps a satisfactory car design can be made with somewhat decreased dimensions so that smaller tunnel diameters are practical. Cross-sections of the tunnels occupied by a car from these systems are shown to scale in Figure 1. It should be noted that the U.S. places heavy reliance on steel or poured concrete to line tunnels rather than the less costly, pre-cast concrete segments.

The guideways and stations are major cost elements of a subway, rapid rail transit system, about a half and a third, respectively, of the overall cost (Reference 1). Since the construction costs of these two elements are related to the excavated volume, it is worthwhile to look at the relationship between size (volume) and construction cost. Also, the operational consequences of the volume of these elements should be examined to put the cost comparisons in the proper perspective. This study investigates these issues.

Table 1. Characteristics of Underground Stations

Location	Platform Length (ft)	Capacity (Riders/Hr/Direction)	
		Maximum[1]	Actual[3]
San Francisco - Oakland (BART)	700	90,000	22,500
Washington, D.C. (WMATA)	600	72,000	36,000
Atlanta (MARTA)	600	72,000	-
Baltimore (MTA)	600	72,000	-
New York (NYCTA)	525-625		62,000
London[2]	435	45,600	45,600

[1] Assuming 75 ft long cars carrying 225 riders each at crush conditions with trains operating on 90 sec headways.

[2] Assuming 55 ft long cars carrying 150 riders each at crush conditions with trains operating on 95 sec headways.

[3] BART minimum headways are 6 min.; WMATA are 3 min.

Table 2. Characteristics of Tunnel Guideways

Location	Tunnel Diameter (ft)	Tunnel Liner	
		Material	Texture
BART	16'8"	Steel (or Poured-In-Place Concrete)	Ribbed (Smooth)
WMATA	16'8"		
MARTA	16'8"	Steel (or Poured-In-Place Concrete)	Ribbed (Smooth)
Baltimore	16'8"	Steel	—
London	12'7"	Pre-Cast Concrete Segments	Smooth
Glasgow	11'	Steel	Ribbed

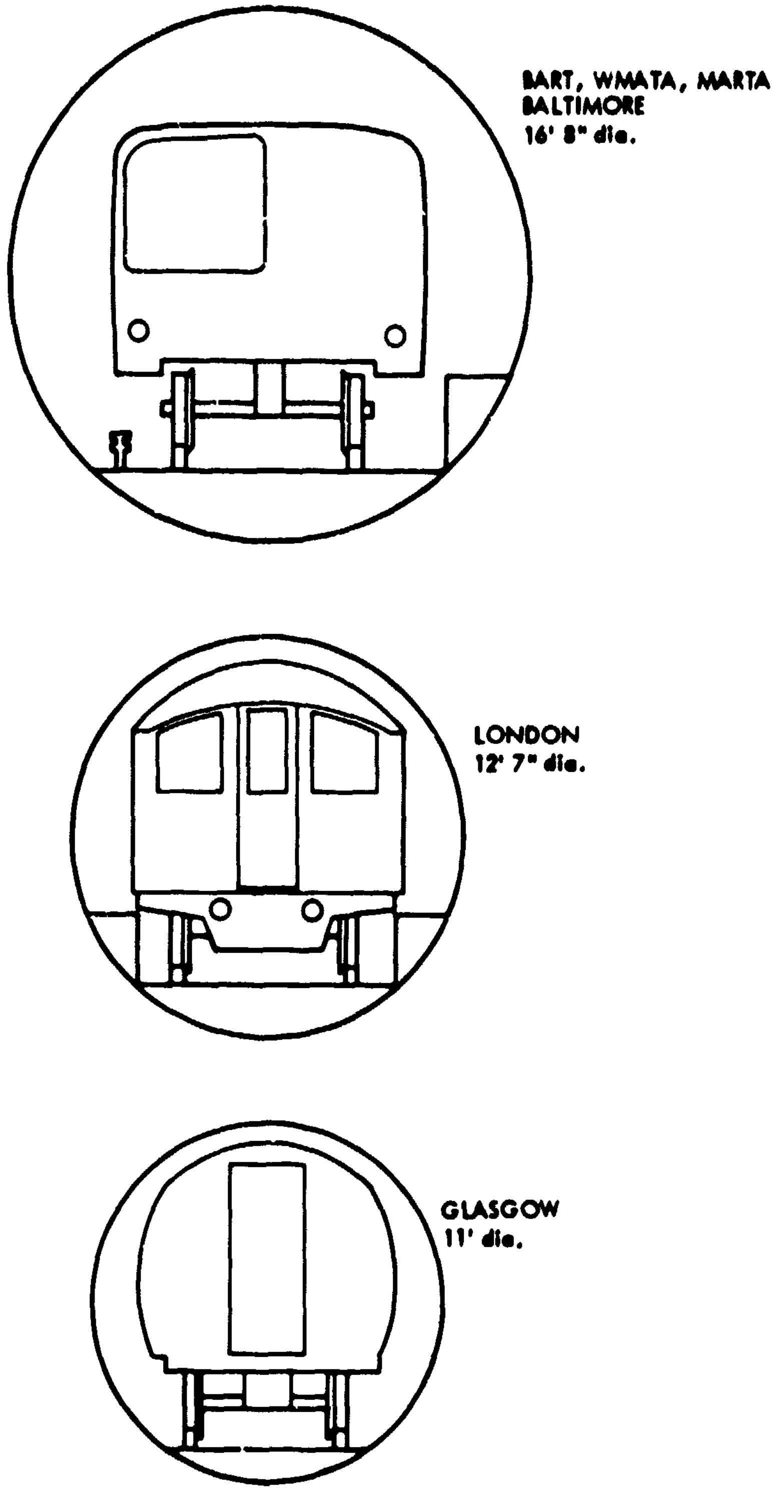

Figure 1. Comparison of Subway Tunnel Diameters

SECTION III

TUNNELS

The major effort of this study was to look at the cost of bored tunnels related to their design and diameter. Cost estimates were made especially for this study by an experienced consulting engineering firm (Reference 2) which should be comparable to similar estimates made previously (Reference 1). To establish absolute level credibility, actual tunnel bid prices experienced by the Los Angeles Area Metropolitan Water District (Reference 3) and Flood Control District (Reference 4) are included. The estimates obtained from the consulting engineering firms are based upon a favorable hypothetical geology* like the actual L.A. basin situation.

A. BASIC COST INFORMATION

1. Engineering Estimates

The cost estimates of Reference 2 were based on four tunnel designs: (a) side-by-side twin single-track tunnels; (b) over/under twin single-track tunnels; (c) single-bore over/under tunnels; (d) and a double-track tunnel with and without a dividing wall. In addition, effects of small changes in the tunnel diameter on the cost were estimated for (a), (b) and (d). The cost estimates of Reference 1 were for only (a) and (b) but included a steel liner and the pre-cast concrete segments-type liner considered in Reference 2. However, the concrete segment liner designs of Reference 2 differ from those in Reference 1. Excerpts from the tunnel cost estimates of Reference 1 and 2 are included as an appendix to this report.

Sketches indicating types of tunnels considered and liner design features are shown in Figure 2. Note the significant differences in design of pre-cast concrete segment liners for the twin tunnels between References 1 and 2. The design of Reference 2 incorporates the basic invert and walkways as part of the actual liner. The design of Reference 1 requires an additional pass to pour the basic invert and walkway. It was not the intention of either cost estimate to come up with an optimum design; the main purpose was to obtain a base cost from which differences could be figured for various changes such as diameter, type of liner and tunnel design, and inclusion of a 10 percent grade for dipped guideway. With that as a caveat, the cost estimates are shown in Table 3. The costs of the single track tunnels were doubled to be comparable with the costs of the double-track tunnels.

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*48% of boring distance is in sedimentary rock.
44% of boring distance is in alluvium above water table.
8% of boring distance is in alluvium below water table.

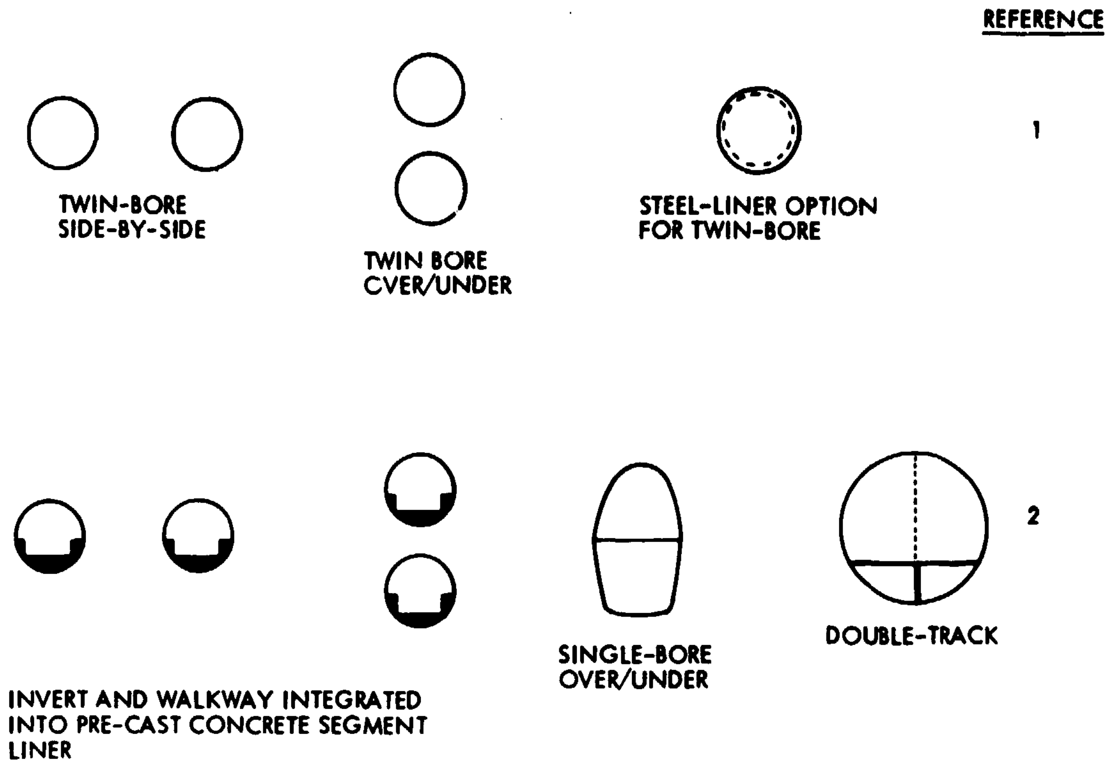


Figure 2. Basic Designs of Guideways for Which Cost Estimates Were Made

The cost estimates of References 1 and 2 differ for the same basic types of tunnels in the same specified geology. Two causes readily stand out: 1) the two-pass* liner design of Reference 2 vs the three-pass of Reference 1; 2) in Reference 2, the prime construction contractor planned to build the liners; in Reference 1, the liners were to be procured on a separate contract, hence additional expense.

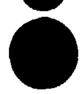
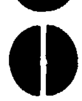
These two account for about two-thirds of the difference. The magnitude of the remaining difference is quite normal for separate estimates on the same project.

2. Bid Prices

A considerable number of tunnels of sizes suitable to transit tunnels have been built in the Los Angeles basin by both the Metropolitan Water District of Southern California (MWD) and the Los Angeles County Flood Control District (FCD). The MWD tunnels are the most closely related to transit tunnels because of the range of diameters

*A pass is defined as the number of times a crew must work their way through the tunnel during the construction process.

Table 3. Cost Estimates of Various Tunnel Designs and Diameters

Guideway Configuration	Type of Tunnel (Bored)	Type of Liner	Size	Cost/ Lin. Ft. (2-Dir.)	Dollars of Year	Ref.
	Horiz. Twin Single Track	PCCS	14'8" D	2420	1977	1
	Horiz. Twin Single Track	PCCS	16'8" D	2660	1977	
	Horiz. Twin Single Track w. (100' - 10%) Dip	PCCS	16'8" D	2824	1977	
	*Vertical Twin Single Track	PCCS	16'8" D	2660	1977	
	*Single-Bore Over/Under	PCCS	29'6" H x 19'7" W	2940	1977	
	Double Track	PCCS	30' D	2314	1977	
	Double Track	PCCS	33' D	2466	1977	
	Double Track with Dividing Wall	PCCS	33' D	2491	1977	
	Horiz. Twin Single Track	PCCS	14'8"	3234	1976	2
	Horiz. Twin Single Track	PCCS	16'8"	3474	1976	
	Horiz. Twin Single Track w. (100' - 10%) Dip	PCCS	16'8"	3600	1976	
	*Vertical Twin Single Track	PCCS	16'8"	3600	1976	
	Horiz. Twin Single Track	Ribbed Steel	16'8"	4674	1976	

*Matches over/under stations. If side-by-side stations are used, costs would be higher.

PCCS - Pre-Cast Concrete Segments.

(12½ - 20½ ft.) and lengths (4000 - 30,000 ft.). However, the MWD water tunnels have concrete linings that are thicker than required for transit use in order to withstand the pumping pressures. Corrections have been made for this in arriving at cost and internal diameter figures that are appropriate for transit tunnels. The pertinent MWD data (Reference 3) are shown in Table 4, with the corrections discussed above as well as those to mid-1977 dollars.

A representative sample of FCD data (from Reference 4) appears in Table 5. It has been adjusted to mid-1977 dollars to be comparable to the estimates (Reference 1) made specifically for this study. The

Table 4. Bid Costs of Tunnels for the Metropolitan Water District of Southern California

Tunnel	Newhall	Castaic #1 & #2	Balboa Outlet	San Fernando	Source
Bid year	1966	1967	1968	1969	Ref. 3
Length (ft)	26,000	18,500	3,800	29,100	
Bore Diam. (ft)	26	26	16	22	
Finished Diam. (ft)	20½	20½	12½	18	
Cost per ft ($) (Bid Year)	1011	870	398	670	
CCI Correction Factor to Mid-1977	2.73	2.56	2.18	2.28	Engineering News-Record
Cost per ft ($) (Mid-1977)	2758	2279	869	1529	
Finished Diam. (ft) corrected to transit tunnel	24	24	14½	20	This study
Cost per ft ($) corrected to transit tunnel*	2460	2058	816	1346	
*Includes:					
Correction for 48' D construction shaft	-77	-	-	-69	
Correction for less concrete	-221	-221	-53	-114	

Table 5. Bid Costs of Tunnels for the Los Angeles County Flood Control District

Project	I.D. (in)	Length (ft)	Cost Per ft ($) (Bid Date)	Bid Date	CCI Correction Factor To Mid-1977	Cost per ft ($) (Mid-1977)
146	144	646	247	9-53	4.75	1,173
62	141	198	432	4-55	4.46	1,926
59-1	123	2,688	200	10-56	3.42	684
65-1	144	362	550	10-56	4.07	2,237
84	213	114	1,042	12-56	4.08	4,252
Sycamore Scholls	192	1,951	772	6-58	3.67	2,832
67-2	138	155	473	9-59	3.40	1,677
59-1	144	906	250	10-59	3.41	853
480-3	138	837	512	1-62	3.17	1,624
1701-1	144	144	571	8-67	2.49	1,422
Santa Anita	108	700	652	4-68	2.50	1,630
6502	123	1,010	400	4-70	2.29	916
1105-2	123	6,002	401	4-70	2.29	918
5241	120	1,529	410	5-70	2.29	940
Chino Creek	192	570	959	6-71	1.87	1,792
1109-2	172	2,245	630	12-71	1.75	1,103
1102	185	2,992	1,032	7-75	1.18	1,214

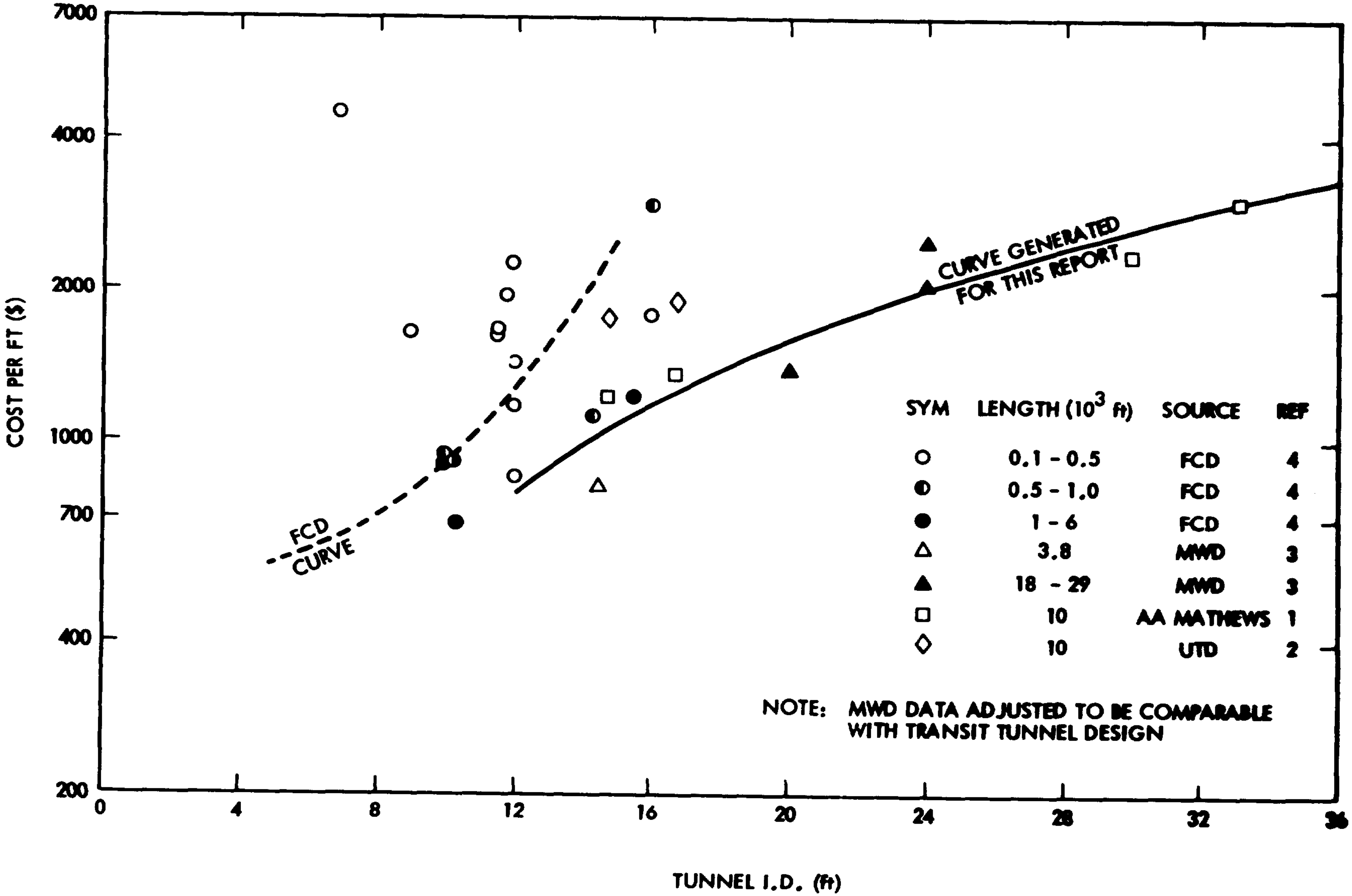


Figure 3. Cost Estimates for Various Tunnels (Converted to Mid-1977 Dollars)

corrected MWD and FCD bid cost data are shown in Figure 3 along with cost estimates of References 1 and 2. Also shown is a curve that FCD feels is representative of their data. The bid cost data, for the most part, are the final costs, and consequently are indicative of the actual situation in Los Angeles basin type geology.

3. Cost of Transit Tunnels

In establishing a tunnel cost curve for this study, heavy preference was given to the MWD data and that of Reference 1. The FCD costs are relatively high because of the short lengths of tunnels. The reason that data of Reference 2 is believed to be higher than that of Reference 1 has already been discussed. With this for guidance, a cost curve which is thought realistic, was generated on the semi-log plot of Figure 3 and transferred to the conventional linear plot in Figure 4. The cost curve of Figure 4 was used as a basis for comparing the effect of finished diameter on the cost of bored transit tunnels in L.A. basin favorable geology. Construction Cost Index (CCI) figures were used to convert costs from one period to another period in time.

A structurally-sound dividing wall is an appreciable part of the cost of a tunnel (5 percent), about \$125/ft. for the 33 ft. ID tunnel. Therefore the inclusion of it requires considerable study. Factors which must be considered include safety and ventilation. In a dipped system

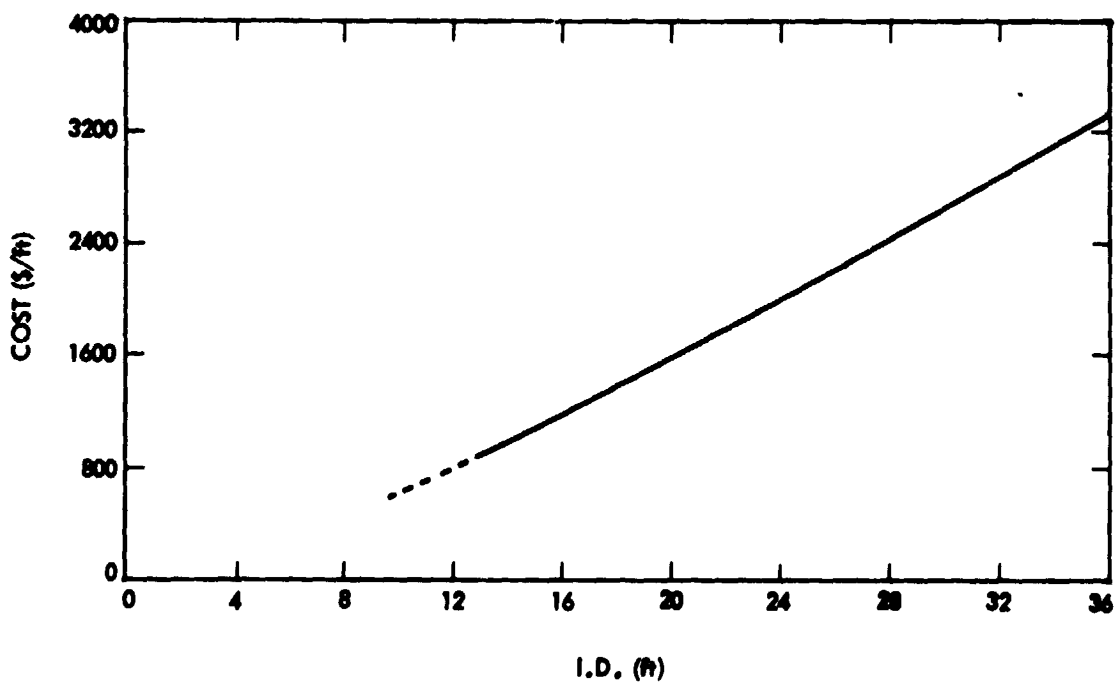


Figure 4. Cost Estimate for Transit Tunnels In Favorable Geology (Mid-1977 Dollars)

(described in Reference 1) in which mid-line vent shafts for temperature control are not needed, it is necessary to provide a nearby safe area in case of fire in a tunnel. This exists for twin single-track tunnels. But, in the case of a double-track tunnel, a dividing wall is necessary to provide for this need; it also improves the temperature control aspects of the system.

B. SIZE CONSIDERATIONS

Although the cost of a bored tunnel is related to its size (diameter), there are a number of construction and operation-related implications that must be considered before making a rational decision on tunnel size. A list of the more apparent ones are in Table 6.

This list is not all inclusive. Further study may turn up some other significant considerations of tunnel size that must be included in the process for selecting the tunnel size. It is not the purpose of this study to perform an evaluation of these considerations, but rather to identify them. The effort of this study was limited to the effect of the tunnel diameter on the capital costs of the guideway and of the electrical energy. These are discussed in the following section.

C. TRADE-OFF ANALYSIS

Based upon the assumed favorable geology, a preliminary trade-off analysis was made of the equivalent lifetime cost of tunnel size. Only two considerations from the list in Table 6 are included in this study: tunnel cost and electrical energy for propulsion.

To proceed with the analysis, the first step is to quantify the significant dimensional characteristics of the tunnels. They are shown in Table 7. It is interesting to note that the blockage ratio (ratio of train frontal area to net tunnel cross-section area) for the small double-track tunnel (30 ft. D) with a center dividing wall is appreciably less than that for the large (16'8") single-track tunnel. The environmental aspects of this are discussed in Section III-C2.

1. Energy Costs

To estimate the electrical energy cost, information from Reference 5 is used. It is based upon six-car trains attaining a top speed of 60 mph between stations 5000 ft. apart. The electrical energy consumption is 1441 kwh per hour per direction for trains with 50 percent blockage running in 16'8" D tunnels on two-minute headways. The conversion factor to 4 car trains is 0.667 while that to 80 mph attained speed is 1.425 giving a combined correction factor of 0.95 to convert data to conditions assumed for this study. In addition, correction factors from 1.066 for 12½ ft. D tunnels to 0.958 for 36 ft. D tunnels for the same frontal area cars must be applied. For the base case of

Table 6. Considerations of Tunnel Size

1. Construction

   a. Cost
   b. Interference with subterranean structures and utilities
   c. Surface settlement
   d. Surface traffic to haul muck and construction supplies

2. Design

   a. Vehicle size

      (1) Revenue
      (2) Maintenance

   b. Turn radius of guideway
   c. Guideway power voltage level and pick-up mode
   d. Post-construction addition of equipment in tunnel

3. Operation

   a. Power required to overcome aerodynamic resistance
   b. Piston-effect on air velocity in station.
   c. Pressure pulses

      (1) System users (especially aboard trains)
      (2) Wayside structures and maintenance personnel

   d. Noise

      (1) Riders aboard trains and in stations
      (2) Transmission to outside of tunnel

   e. Walkways

      (1) Maintenance during operation
      (2) Evacuation of users
      (3) Access by emergency crews

   f. Psychological effect on users

Table 7. Tunnel Dimensional Characteristics

Diameter	Area (ft^2)		Dividing Wall	Blockage Ratio # (%)
	Gross[@]	Net		
14'8"	168	155	NA	65
16'8"	218	200	NA	50
30'	706	520	No	19
30'	706	250*	Yes	40
33'	854	660	No	15
33'	854	315*	Yes	32

NA - Not Applicable
* - Net in each direction
\# - Assuming trains are not decreased in frontal area for smaller tunnels
@ - Based on tunnel internal diameter

this study, 2944 kwh per hour are required per route-mile for operation of trains on two-minute headways in two directions, including station air conditioning. The variation with tunnel diameter is shown in Figure 5. Note that the variation of electrical energy is at most only [illegible] percent from the base case of 16'8" D twin-bore tunnels. That variation would be even less if the train frontal area was affected by the tunnel diameter, a very likely situation. The base cost of electrical energy per year per route mile is about \$0.54M assuming five cents per kwh and 300 trains per direction per day.

2. Effective Cost of Guideway

The data of Figure 4 (tunnel costs) and Figure 5 (energy requirements) were used to estimate the effective or life-cycle cost of a guideway as a function of tunnel diameter. In order to do so, the cost of electrical energy per year was determined and then given a present worth value (equivalent capital cost). The yearly cost of energy at five cents per kwh was on the order of \$0.54M. The differences in the

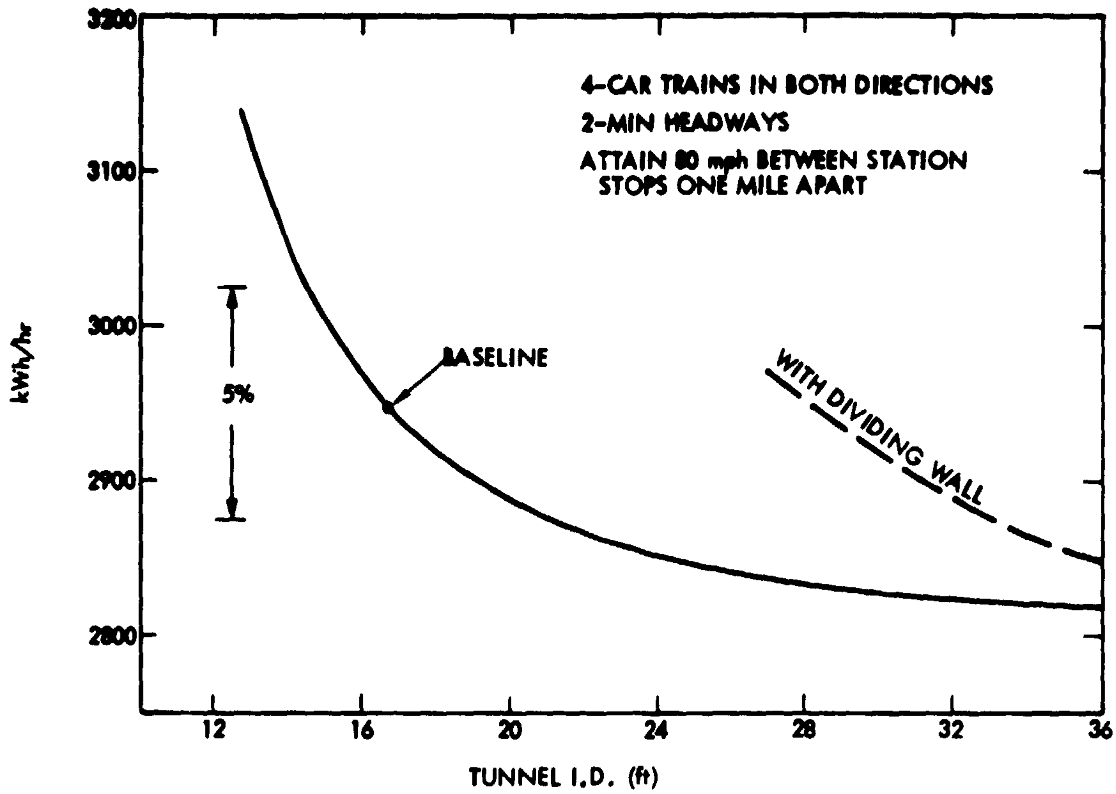


Figure 5. Effect of Tunnel Diameter on Energy Requirements (Per Hour Per Route Mile)

equivalent capital costs (ten times the yearly cost*) were added to the construction costs of the tunnel guideways. Table 8 shows the calculation procedure and the effective costs. Effective cost curves are shown in Figure 6 for three guideway configurations: twin single-track tunnels; and single double-track tunnel with and without an impervious vertical dividing wall between the two directions of travel. The variation in capital cost as a function of tunnel diameter is virtually

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*Since a variation in the capital cost of an element of a subway system affects the yearly operational cost, it is necessary to determine the life-cycle cost to make realistic comparisons. The life-cycle cost is made up of the capital cost and the present worth of the anticipated annual costs. Assuming constant annual costs in current dollars, the "present worth factor" to be applied to the annual cost is the inverse of the assumed discount rate for an infinite lifetime.

Using the customary 10% discount rate, the "present value factor" is $9\frac{1}{2}$ for a 30-year lifetime period. For simplicity, a factor of 10 is used throughout this study for determining life-cycle costs.

Table 3. Effective Cost of Transit Tunnels

Bore Diam. (ft)	Type of Track	Dividing Wall	Construction Cost Per Mile ($m)	kWh/hr*	Cost of[3] Electrical Power Per Year ($ M)	Effective Cost of Tunnel Per Mile ($ M)	Effective Cost Saving (%)
12'8"	Single	None	8.98	3138	0.573	9.34	29.8
14'8"	Single	None	11.09	3017	0.551	11.23	15.6
16'8"	Single	None	13.31	2944	0.537	13.31	0
20	Single	None	16.90	2885	0.527	16.80	-26.2
27	Double	None	12.20	2844	0.519	12.02	9.7
30	Double	None	13.83	2826	0.516	13.62	-2.3
33	Double	None	15.84	2820	0.515	15.62	-17.4
36	Double	None	17.69	2820	0.515	17.57	-32.0
27	Double	Yes	12.79	2971	0.542	12.84	3.5
30	Double	Yes	14.46	2918	0.533	14.42	-8.3
33	Double	Yes	16.50	2879	0.525	16.38	-23.1
36	Double	Yes	18.38	2850	0.520	18.21	-36.8

*30 4-car trains per hour in each direction reaching 80 mph.
@ 10-hours per day at 5 cents per kWh.

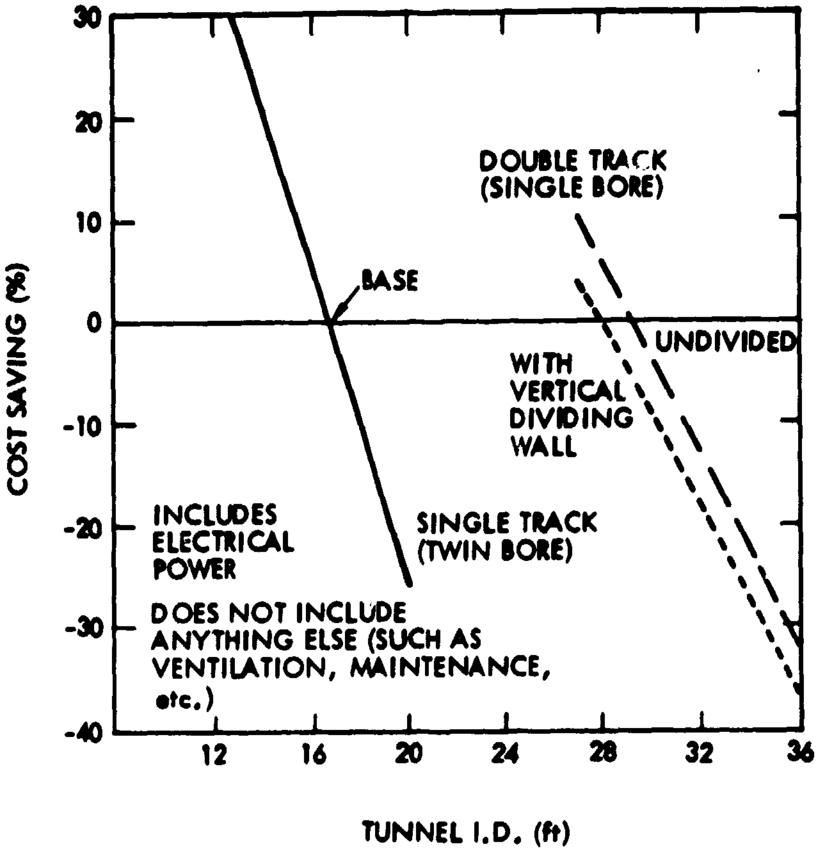

Figure 6. Savings in Guideway Costs as a Function of Tunnel Diameter

all due to the construction cost. The energy cost has little effect on the effective tunnel cost. The life cycle energy cost varies by less than $1\frac{1}{2}$ percent of the construction cost (except that it is 4 percent for the 12'8" D tunnel, but would be lower if the car were sized as the tunnel diameter varied.

In the favorable geology assumed for this study, the cost of a double-track tunnel (33 ft. ID.) is noticeably higher (about 17 percent) than the equivalent width twin, single-track tunnel guideway (16'8"). The cost is even greater (another 6 percent) if a dividing wall is incorporated in the double-track tunnel. However, one must exercise caution in using the cost-saving information of Figure 6 which is based upon the cost curve assumed in Figure 3. Since no tunnels larger than 27 ft. I.D. have been constructed in the L.A. basin, it was not possible to evaluate the relative cost estimates of Reference 1 for tunnels having finished diameters of 30-36 ft.

The cost saving of smaller diameter single-track tunnels is substantial. A decrease in diameter from 16'8" to 14'8" results in a cost saving of nearly 16 percent (over \$2M per route mile out of \$13.3M which includes the effective life cycle cost of the electrical energy).

Although this is a significant savings, it must be weighed against the other factors related to tunnel size listed in Table 6.

shown in Figure 5, the effect of tunnel diameter upon the electric energy is small, less than 15 percent in going from twin single-track 12'0" D tunnels to 36 ft. D double-track tunnels. If saving electrical energy is a primary concern, several other approaches can be considered. One is to decrease the system speed. A decrease from 80 mph to 50 mph would cut the energy requirement in half, but with the penalty of increasing the average travel time by about a fourth (Reference 1). This increase could be unacceptable if the subway system must compete with private vehicles using a freeway system.

Another approach which also can decrease the energy requirement by half is to incorporate gravity assist between stations by dipping the guideway some 100 ft. using 10 percent grades (6 percent grades would save about 40 percent of the energy). Further details on this approach can be found in Reference 1. It is worth noting that an alternative use of such gravity assist is to decrease transit time between stations by over 10 percent with about 16 percent less electrical energy than for the level (or constant grade) guideway. Braking energy of such a dipped system is only 15 percent of that for a level system.

The effect of tunnel diameter on the costs of items other than energy are not included in this analysis. Excluded were the effects on car design (size), guideway maintenance, and ventilation. It is likely that maintenance costs decrease with increasing tunnel cross-section area as there is more room to work in. In fact, if the cross-section area is quite large, then it is [illegible]asible to carry out some maintenance concurrent with operation. As the tunnel cross-section decreases, the piston [illegible] will increase. This helps the control of air temperature, but can create excessive drafts in the stations. Ventilation shafts may be required to bring the drafts into tolerance for small cross-sectional areas or to assist in temperature control for large cross-sectional areas of tunnel guideways. A fairly detailed study is required to determine the effect of tunnel diameter on the number of ventilation shafts. [illegible] a matter of interest, the costs of vent shafts determined in Reference 1 are shown in Table 9. Since these costs can be an appreciable [illegible] of the guideway cost, they must be included to have a [illegible]ingful [illegible]ign trade-off study.

Table 9. Cost Estimates of Ventilation Shafts

	Depth (ft)	Cost $M
At Station	80	0.25
Between [illegible]	80	1.3
	180	1.85

SECTION IV

STATIONS

The stations of the newer subway systems in the U.S. (BART, WMATA, MARTA, and Baltimore) are quite large. Since stations are a significant portion of the capital costs, considerable savings in future systems can be obtained by having smaller stations. This study looked at smaller stations: their cost savings compared to the normal large stations; implications upon the system capacity (riders per hour in each direction) and what could be done to increase the capacity of such smaller stations. It is reasonable to consider smaller stations since the actual required capacity of the system may be substantially below the theoretical maximum capacity (see Table 1).

A. BASIC COST INFORMATION

Cost information, developed in References 1 and 6, was normalized in Figure 7 where the unity cost ratio represent $18.2M. Two features are apparent. The information on the cost variation due to platform length agrees within 5 percent for the two sources (well within the accuracy band as each estimate was of the 15-20 percent type used for preliminary design work). The other feature is that the effect of platform width on the station cost is about half again more than that of platform length for the same platform area of the station.

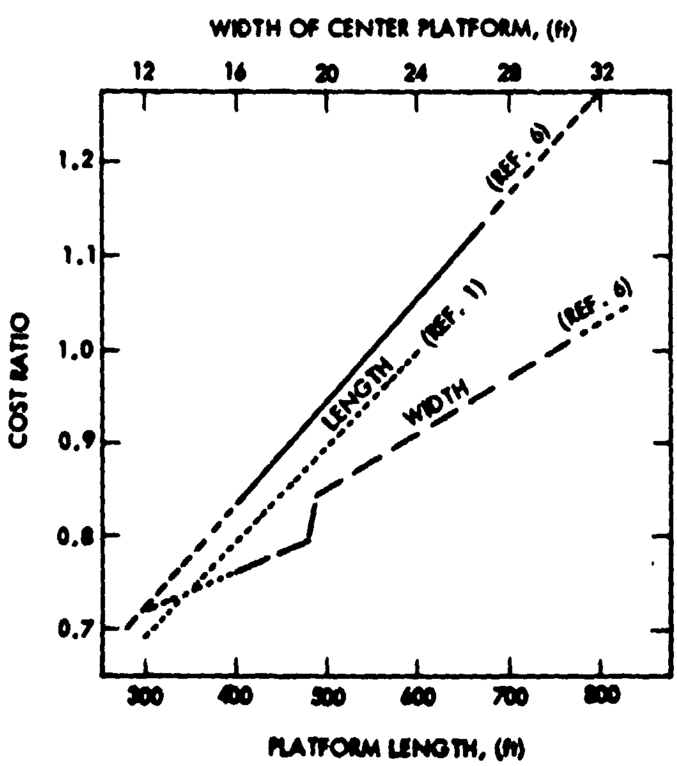

Figure 7. Relative Costs of Underground Stations as a Function of Size

The effect of platform width on the station cost can be taken directly from Figure 7. However, the effect on station cost of a change in the platform length must be adjusted for a corresponding change in the guideway length.

This would not be the average cost of a mile long guideway due to all the start up and fixed costs which are included in the guideway cost. For the purposes of this study, \$1500/route ft. was used (about one-half of the average of the two estimates for the base 16'8" D twin-bore tunnels contained in Table 3).

B. SERVICE ASPECTS

The service aspects of a rail transit system are defined as the capacity, headway, and system effective speed. They are dependent primarily on the station design, train performance, and Automatic Train Operation (ATO) system. The effect of a change in the station platform design and length on the service aspects is the factor considered. However, in order to develop a better understanding of the consequences of station design, it is first necessary to describe the attributes of the system speed.

1. System Speed

Station spacing, dwell time, and top cruise speed of a subway train on tangent level track (no curves and no grade) are the major factors in the system effective speed (average speed from one end of the system to the other). Cruise speed and station spacing affect both the transit time between stations and the minimum headway. The information in Reference 1 was used to illustrate the effect of system speed (cruise speed) upon system effective speed. The average speed between stations of varied spacing is shown in Figure 8 for both the 50 mph and 80 mph systems. The resulting system effective speed (block speed) as a function of station dwell time is shown in Figure 9. The system used is the hypothetical 23½ route mile system described in Reference 1 in which the average spacing of the 23 stations is about one mile. For 30-sec dwell times, the system effective speed is 34½ mph for the 80 mph system and 28 mph for the 50 mph one. It is interesting to note that a difference in dwell time of 30 sec is roughly equivalent to the 30 mph difference in the two system speeds.

System speed also affects the minimum safe headway at which trains can operate. The primary factor in this is the time or (distance) required to come to a stop. The 80 mph system of Reference 1 can operate on 90-sec headways with 30-sec dwell time and yet have in excess of a 30-sec safety margin. This margin permits reasonable requirements for an ATO system and still allows adequate time to take care of the problems of normal operation, except for excessively long dwell time at the stations. A way to minimize dwell times is discussed later. The margin for the 50 mph system is just a little more since the difference in stopping time is less than 2 sec. at the normal stopping rate of 2 mphps; but the safety margin can be increased to 40 sec. if consideration is

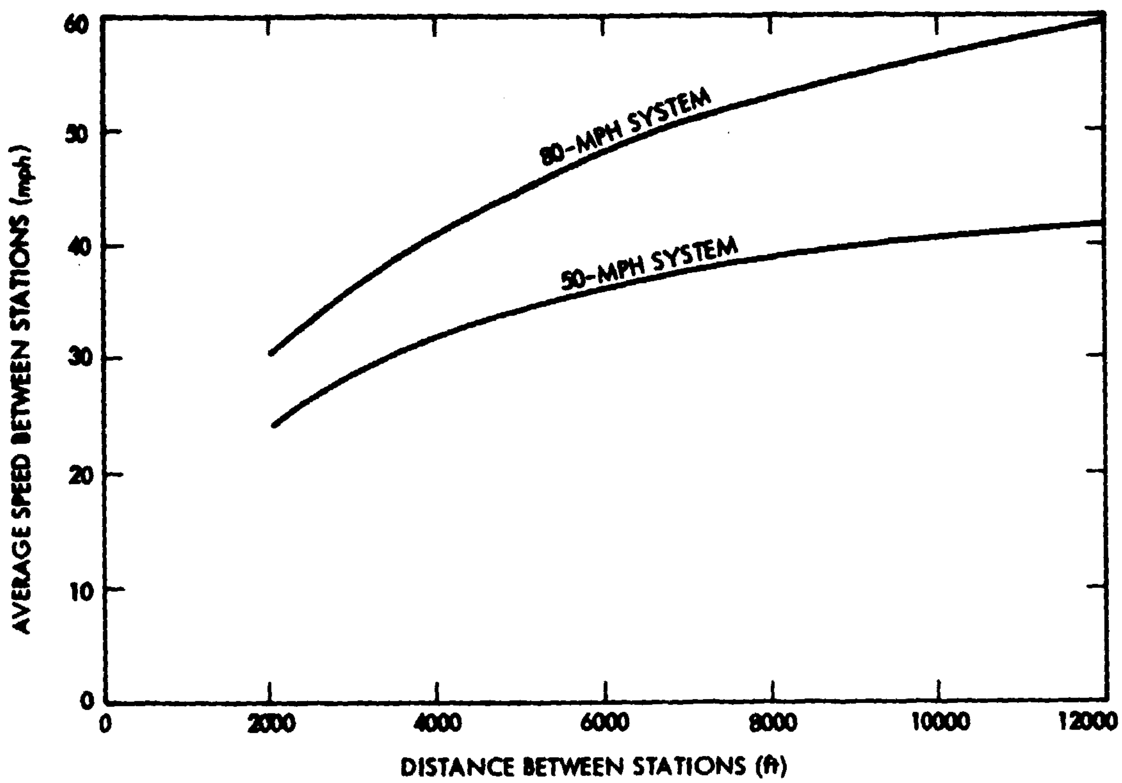

Figure 8. Effect of System Top Speed on Average Speed Between Adjacent Stations

given for a 3 mphps emergency stopping rate (which is the same as the normal stopping rate for the 80 mph system).

2. Headway and Station Dwell Time

Station dwell times of 30-sec. are practical to attain in a normal system only during off-peak hours. A normal system is one in which the riders leave and enter the train on the same side, using the same doors. At peak hours, this time can be as much as 90 sec. Therefore, normal systems allow for this by having minimum headways on the order of 3 min. and, to supply the necessary capacity, use long trains (up to 10 cars for BART on 6 min. headways) which results in long, expensive stations.

It is practical to minimize station dwell time at peak hours simply by having active platforms on both sides of a train. This allows riders to leave the train through doors on one side while riders get on from the other side. This is the procedure used in the system at the Tampa Bay airport. By delaying opening the doors on the entrance side by about 3 sec., it has been demonstrated that 20-30 sec. is adequate to empty a full load of 125 people and then load up to 125 people (Reference 7).

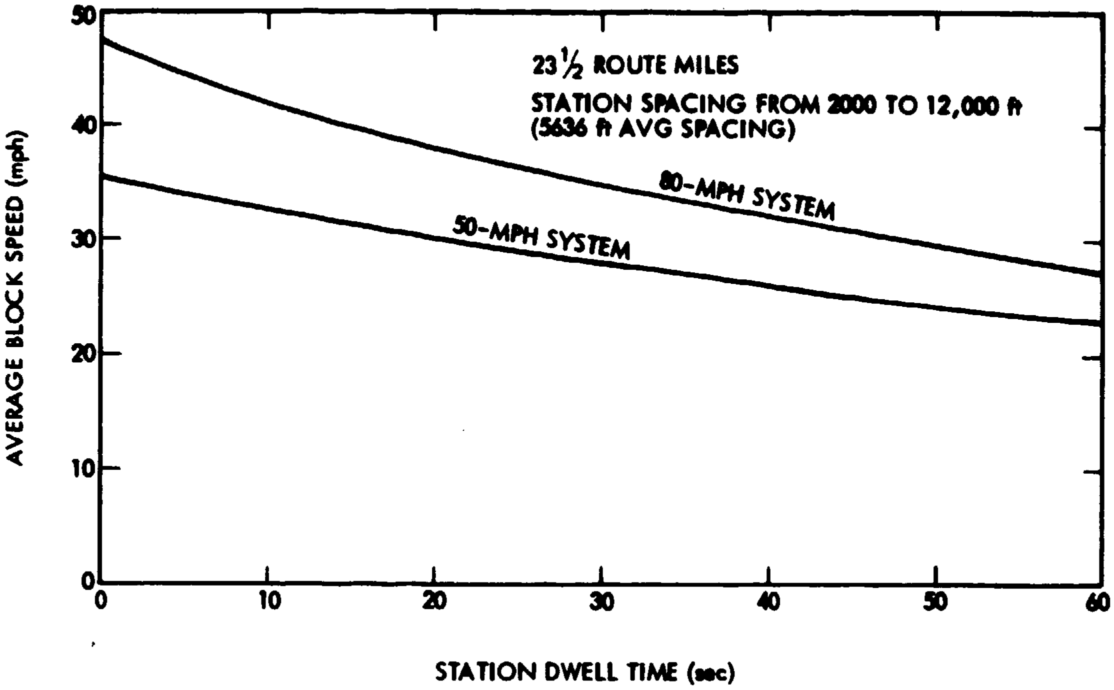

Figure 9. Average Block Speed

Although there is a difference between unloading all riders in a full car (for an airport system) or just a portion of them (for a mass transit system), the "through-loading" principle will greatly decrease the station dwell time in a mass transit system. This has already been demonstrated in the Sao Paulo system where platforms on both sides of the trains are in use at a number of high capacity stations. Dwell times less than 30 secs. have been consistently achieved, giving headways as little as 80 secs. on an operational basis (Reference 8).

It may not be practical to accomplish through-loading for a station with tracks on a single level because of street-width limitations. But, if there were no such limitations, the substantial 20 percent increase in the station cost would be a deterrent to through-loading. However, through loading can be conveniently provided for in a station with two levels (the over/under station described in Reference 1 and shown in Figure 10). This two-level station, with platforms on each side of the train at each track level is considerably narrower and is somewhat less expensive then the normal 55 ft. wide single-level station (having a 30 ft. wide center platform). For through loading, the single-level station would have to be 69 ft. wide to accommodate a 20 ft. wide platform in the center with a 12 ft. wide platform on each side. The two-level station is 45 ft. wide with a 15 ft. wide platform on each side of the tracks.

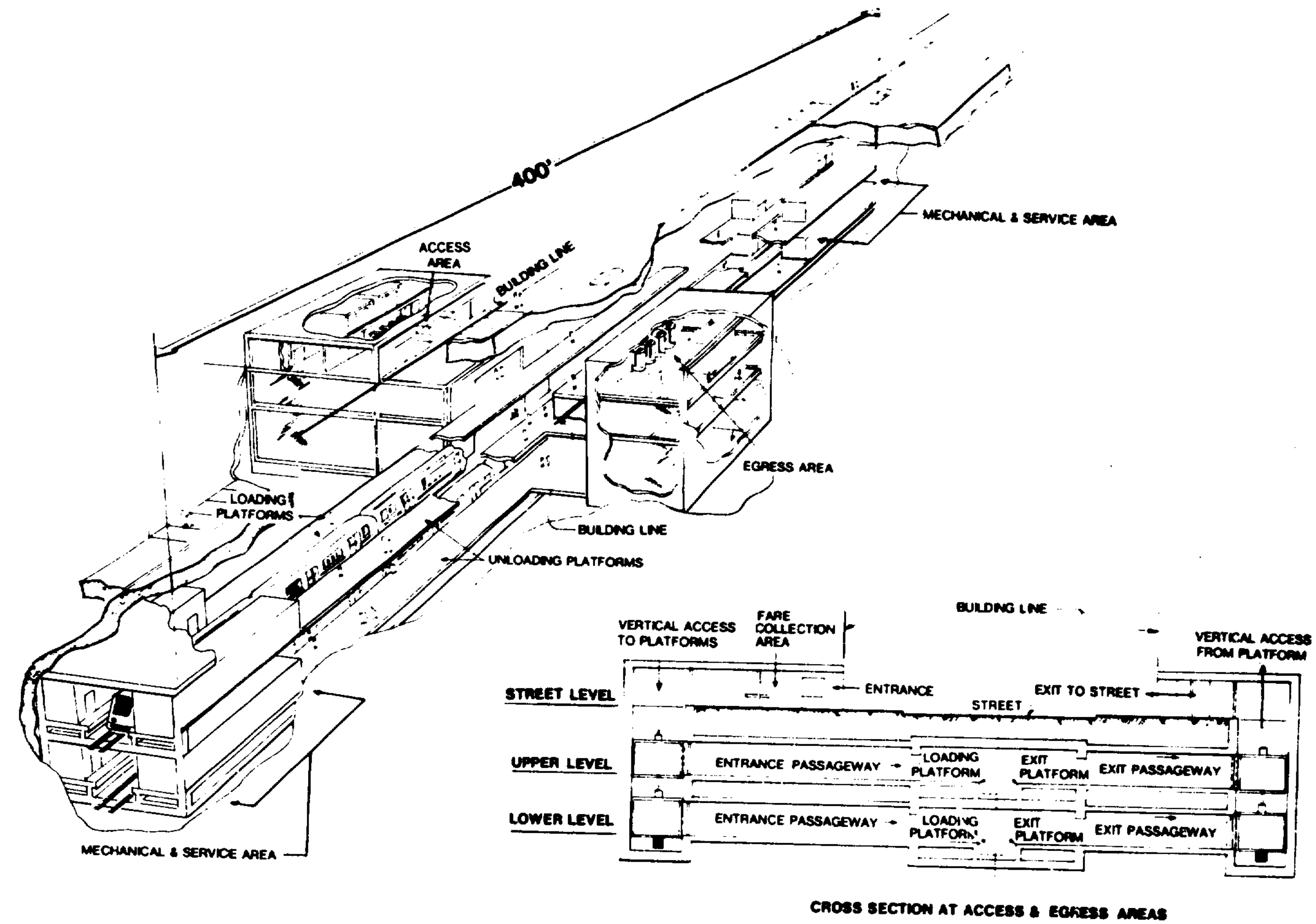

Figure 10. Over/Under Station Design (400-ft Overall Length - 300-ft-Long Platform)

3. Capacity

As shown in Table 1, the required capacity of the recent systems is substantially below that of the theoretical maximum capacity, hence, it can be handled by shorter stations. Capacities up to 36,000 riders per hour in each direction can be accommodated by 4-car trains operating on 90-sec. headways with 225 riders per car. The 90-sec. headways have been shown to be achievable in a practical manner in the preceding section and the 225 riders per car is a normal condition even for the newer U.S. systems at peak conditions.

It should be pointed out that capacities much greater than 30,000 riders per hour per direction may not be desirable. The London Underground (Reference 1) feels that capacities in the order of 60,000 concentrates too many people along a corridor. Their solution is to spread out the people by having more lines, and limiting the capacity to 45,000.

C. TRADE-OFF ANALYSIS

The effective capital costs of a system as a function of train length, capacity, headway, and system speed are estimated. Several cost assumptions are required to come up with a cost estimate: the cost of train drivers and the differential cost of cars for 50 mph and 80 mph systems. (The effective capital cost of each driver is taken to be $500K, ten times the yearly cost of $50K which includes all burdens as well as salary.) Each car for the 50 mph system is assumed to cost 0.9* of one for an 80 mph system, or about $485K (based on the $539K per car per Reference 1).

1. Cost Elements

The total number of trains required for the hypothetical 23½ route-mile system is shown in Table 10. The total number includes the trains actually operating on the route, five trains in reserve at the ends of the route, and ten percent operating spares (the additional 10 percent of unoperative spares are not included in the following table as no drivers are required).

The cost of the train drivers is shown in Table 11. The number of drivers on duty per week is assumed to be 2½ times the number of operable trains shown in Table 10. This factor takes into account the two-shift operation each day, spare drivers, peak hours operations, and the lower operation during weekends and holidays. The 50K yearly cost of each driver covers vacations, sick leave, fringe benefits as well as the salary and typical burden costs.

*If a factor as low as 0.75 is used, the conclusions are not altered. The values 0.75 - 0.90 bound the probable cost factors with the high end being the more likely.

Table 10. Total Number of Operable Trains
(36,000 Riders per Hour per Direction)

Dwell Time (sec)	Headway (sec)				
	60	90	120	180	240
20	87	59½	46	33	26
30	95*	65	50	35	28
		(80)		(42½)	
40		70½	54½	38	29½
60		81½	61	43½	34

( ) Indicates 50-mph system. Otherwise 80 mph system.
* Allows for no safety factor

Table 11. Effective Yearly Cost of Drivers ($\$10^6$)
(36,000 Riders per Hour per Direction)

Dwell Time (sec)	Headway (sec)				
	60	90	120	180	240
20	10.88	7.44	5.74	4.13	3.25
30	11.88	8.11	6.24	4.38	3.49
		(9.99)		(5.30)	
40		8.62	6.81	4.74	3.69
60		10.17	7.62	5.43	4.25

( ) Indicates 50-mph system. Otherwise 80 mph system.

The cost of the total number of cars, based upon the same maximum capacity of 4-car trains on 90-sec. headways is shown in Table 12. For example, 8-car trains would run on 180-sec. headways. The numbers of cars per train for headways of 60, 120 and 240 secs. come out to be fractional ($2\frac{2}{3}$, $5\frac{1}{3}$, and $10\frac{2}{3}$). This does not invalidate the rationale of the analysis as corresponding changes in headways would result in integral numbers of cars per train. The total number of cars is 10 percent above the number of operable ones shown in Table 10.

Several things are noteworthy in Tables 10 and 11. Although the route maximum capacity in riders per hour is the same for each point in both tables (namely 36,000 riders per hour in each direction), the yearly cost of drivers and the capital cost of trains are sensitive to both headway and dwell time. Therefore, increased costs incurred in decreasing dwell time are at least partly offset by the decreased costs of drivers and train cars. Also, the cost of drivers increases with decreasing headway while the cost of train cars decreases (although there are less cars, there are more trains but of shorter length). The additional effective cost of drivers (multiply their yearly cost by ten) exceeds the cost savings of train cars. Note that the total costs of all the cars and the yearly cost of the drivers for a 50-mph system exceed those for the 80-mph system (this excludes the cost effects on other parts of the system).

Table 12. Cost of Total Number of Cars ($\$10^6$)
(36,000 Riders per Hour per Direction)

Dwell Time (sec)	Headway (sec)				
	60	90	120	180	240
20	137.6	141.1	145.5	156.5	164.4
30	150.2	154.2	158.1	166.0	177.1
		(170.8)		(181.4)	
40		167.2	172.3	180.2	186.6
60		193.3	192.9	206.3	215.0

( ) Indicates 50-mph system. Otherwise data are for 80-mph system.

The station costs are based upon the estimates in Reference 1. Table 13 shows the cost of various stations adjusted for the additional lengths of lined tunnel for the shorter stations.

An estimate of the guideway electrical energy costs, based on \$600K per year per route mile (described in Section III C-2) is \$14.1M per year. This is for the 80-mph system running on the 23½ route-mile hypothetical system operating part of the time at a maximum capacity of 36,000 riders per hour per direction. The energy cost for the 50-mph system would be somewhat less than half of that (see Reference 1) or about \$6M per year.

2. Effective Cost of Stations

The estimates of the preceding cost elements related to length of trains, headways and dwell times at a single capacity were combined to determine the effective cost of various station sizes (platform lengths). Since the current high performance systems utilize long trains on "relaxed" headways, the base condition was (1) single-level stations with 600 ft. long platforms, (2) 8-car trains running on 180 sec. headways, (3) speeds to 80 mph, (4) dwell times to 60 sec. at peak hours (giving a maximum capacity of 36,000 riders per direction per hour). For convenience, the cost of the one transfer and 22 line stations was based on the underlined costs of Table 13 applied linearly to other platform lengths. However, it should be noted that for stations having platform lengths of 300 ft., the construction cost of the 23 over/under-type stations averages nearly \$6M (about one-third) less per station than the \$435M cost of the conventional single-level stations having 600 ft long platforms.

Table 13. Construction Cost Estimates of Underground Stations (\$$10^6$) #

Type	Number of Track Levels	Platform Length (Station Overall Length) ft		
		600 (800)	300 (500)	300 (400)*
Line	One	<u>18.2</u>	<u>13.0</u>	12.2
	Two	-	12.4	11.8
Transfer	Two	<u>34.6</u>	<u>24.9</u>	23.2
	Four	-	30.9	29.2

Includes cost of extra tunnel length with decreasing station length

*These stations have utility areas on each end which are only 50 ft long instead of the normal 100 ft ones. This is feasible only if dipped guideways are used because the requirements for electrical power and ventilation are considerably decreased.

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Enough information has now been developed that life cycle costs can be determined for systems having varying station platform lengths, but the same line capacity of 36,000 riders per hour per direction. The effective cost levels would be altered when all considerations are included. But it is believed that the dominant cost drivers have been included, hence the differences are realistic. The effective system costs are shown in Table 14. Each is a sum of the capital costs of stations and cars, and the effective capital cost of drivers (assumed to be 10 times the yearly cost of drivers). The maintenance costs of the extra cars have been omitted, but they should be proportional to the cost difference of the cars. The maintenance costs per car for the 50-mph system is expected to be somewhat lower than for the 80-mph system. Naturally, trains will not be made up of fractional cars. The data can be easily adjusted to integral numbers of cars by corresponding changes in the headways and platform lengths.

The costs of the ATO system as a function of headway were not included. This is because the difference in costs is small since current ATO systems are made to handle headways down to below 90 sec. A relaxation of the headway ATO requirement to 180 sec. will not result in an appreciable saving (Reference 8).

At peak capacity, the 8-car system will not be able to operate with dwell times under 60 sec. Therefore, the base case for Table 14 has a cost estimate of about $696K (8-car trains on 180 sec. headways with 60 sec. dwell times). The estimated cost of the same system factors

Table 14. Life-Cycle Cost Comparisons of Systems Having Different Lengths of Station Platforms (80-mph Systems Having 36,000 Riders Per Hour Per Direction Maximum Capacity)($M)

Headway (sec)	60	90	120	180	240
Cars per train	$2\frac{2}{3}$	4	$5\frac{1}{3}$	8	$10\frac{2}{3}$
Length of station platform (ft)	200	300	400	600	800
Dwell Time (sec)					
20	515.9	526.4	555.2	632.8	714.6
30	538.5	546.2 (500.6)	572.8	644.8 (588.4)	729.7
40		564.3	592.7	662.6	741.2
60		605.9	621.4	695.6	775.2

( ) indicates 50-mph system. Otherwise 80-mph system.

for the equivalent-capacity 4-car system (4-car trains on 90 sec. headways with 30 sec. dwell times) is \$540M, some \$156M or 22½ percent less. Since Table 14 is for the normal center platform stations, a \$6M decrease in the \$546M was incorporated to account for the lower cost of the over/under stations having platforms on both sides of each train. This permits through-loading which is essential for keeping station dwell times down to 30 sec. at peak capacity operation. The corresponding effective savings in cost for a 6-car system (running on 135 sec. headways) would be about 11 percent over that of the 8-car system.

As can be seen in Table 14, the cost for a 50-mph system is about 9 percent less than that of an 80-mph system for the factors included. If the effective capital cost difference of \$81M for the electrical energy was excluded, then the cost of the 50-mph system would be larger than the 80-mph systems. Hence, the cost of electrical energy and the way it is accounted for in the life cycle of a rapid rail mass transit system must be given careful consideration. If the electrical costs are important, then serious consideration should be given to the dipped system, especially if transit time is also of great importance. This makes the high-speed system the attractive one from a service standpoint.

Additional calculations were carried out for systems having capacities from 12,000 to 48,000 riders per hour per direction as a function of platform length. The cost comparisons are comparable to those shown in Table 14.

3. Reserve Capacity

Even if capacities in excess of what a 2, 4, or 6-car system can accommodate (18,000, 36,000 or 54,000 rider per hour per direction, respectively) are eventually anticipated, it may not be to the best interests of the commuting public and areas adjacent to the stations to initially build in the provisions for extending train length at a later time. First of all, such increased capacity requirements may never be realized. If they are not, then considerable initial costs in constructing stations with long platforms are incurred that will be of no value. Furthermore, even if their increased capacities are realized, that will be so for only a fraction of the system. Since the platform length of all stations is normally set by the train length required to handle the maximum capacity along only a small segment of the system, the cost of these lower capacity stations is higher than needed for their specific requirements.

Perhaps it would be better to build the system to handle the capacity expected after 10-15 years of operation. At that time, if it becomes clear that extra corridor capacity is required, then additional route segments would be constructed that parallel the original route. The cost effectiveness of this approach is not clear, but it has a number of desirable features. First of all, there will be no waste of money constructing a system for a capacity that it will never attain. Secondly, should the parallel-route means of extending the capacity be required, it will be paid for by those who will benefit from it. And, finally, a careful look can be taken at the implications of a heavy concentration of capacity along a single line. Is it really sensible to carry as many as 72,000 riders per hour per direction along a single route using 8-car trains, with up to half that many people using a single station? Is it really sensible to have that high a concentration of feeder buses serving such a high-capacity line? Might not it be preferable from a surface traffic point of view to spread out the feeder buses, etc?

The direct cost of the subway rail transit system is not the only cost that should be considered. Just as the sociological and economical costs to the community should be considered during the construction phase (which can be exemplified by cut-and-cover construction vs. mining), the same sociological and economical factors should be considered when the entire mass transit system is in full operation. It is a tremendous responsibility upon the designers of a rail transit system since that system will play an important role in how a community develops. Therefore, considerable thought and planning must be given to the design of the final system.

SECTION V

CONCLUSIONS

A number of significant conclusions resulted directly from this study. Several other cost savings were identified in the text but are not included in this Section because they resulted from previous studies. However, they and others should be seriously considered in the design of a subway rail transit system.

A. TUNNEL DIAMETER

1. Decreasing the diameter of twin-bore tunnels from 16'8" to 14'8" would result in a cost saving of $2M out of $13M (16%). Although this is less than the $6M saving per route mile reported in Reference 1 in using precast concrete segment liners instead of steel, it is nevertheless significant.

2. The cost of an equivalent size double-track tunnel (33' D vs. 16'8" D) is about 17 percent greater than that for the twin single-track tunnels.

3. The inclusion of a full-height, center dividing wall for safety and/or ventilation purposes will further increase the cost of a double-track tunnel over twin single-track tunnels by about 6 percent.

4. Tunnel diameter has a small effect on the system energy requirements. The use of single, undivided double-track tunnel of 36 ft. D over twin 12'8" D tunnels will save less than 15 percent of the propulsion and ventilation energy. This is not enough to compensate for the additional capital cost of the double-track tunnel.

B. STATIONS

Systems designed to accommodate the expected peak loads (riders per hour per direction) by operating on headways greater than 90 sec. are unnecessarily expensive. Considerable savings can be accomplished by operating on 90 sec. headways with shorter trains, allowing stations to have correspondingly shorter platforms. This is practical as long as the shorter trains can handle the peak capacity. The maximum capacity of 4-car trains running on 90 sec. headways is 36,000 riders per hour in each direction when there are 225 riders in each car.

1. The saving in effective capital cost of stations designed for 4-car trains rather than 8-car trains is nearly $7M per station (over one-third of the station construction cost). This saving includes consideration for changes in the required numbers of train drivers and cars.

2. Shorter station dwell time also decreases the system cost, but to a lesser degree than shorter headways. A decrease in dwell time from 60 to 30 sec. decreases the effective system capital cost by over $2M per station because less trains and drivers are required.

3. The realistically achievable capacity of stations with platforms which can accommodate 8-car trains is substantially below 72,000 riders per hour per direction. This is because 90-sec. headways cannot be achieved during peak hours since dwell times can be as long as 90 sec. for the normal, center-platform configurated station.

4. It is practical to achieve dwell times of less than 30 sec. at peak hours by utilizing through-loading. The cost of a station for through-loading is somewhat less than the normal center-platform station if two-levels-of-track design is used.

C. SERVICE ASPECTS

When designing a transportation system, the perceived service aspects must be included as a primary design criterion.

1. Shorter dwell times and headways improve the service aspects and can do so at lower costs.

    a. Shorter dwell times decrease the travel time across the system.

    b. Shorter headways decrease the waiting time for the riders. They also decrease the congestion throughout the station (platforms, escalators, elevators, stairs and the areas immediately surrounding the station).

2. The cost-saving of a system designed for lower speed results from the saving of electrical energy and not from the somewhat less-expensive cars. However, this is accomplished with the penalty of longer travel times across the system, other factors being equal. A proportional saving in traction effort is accompanied by an increase of half that proportion in travel time. For the example shown in this study, an energy saving of 55 percent is realized by decreasing the system speed from 80-mph to 50-mph, but the average travel time across the system is increased by about 25 percent. Such an increase is a deterrent to public acceptance of the system.

SECTION VI

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APPENDIX A

TUNNEL COSTS ESTIMATES,
UNDERGROUND TECHNOLOGY DEVELOPMENT CORPORATION

(Excerpts from Reference 1)

Because Reference 1 is widely available, only the final cost estimates of the tunnels for the 23½ route mile system are included in this appendix.

TABLE A1

SUMMARY OF CONSTRUCTION COSTS, SIDE-BY-SIDE TUNNEL GUIDEWAYS

PARAMETERS \ STUDY CASE	I	II	III	IV
TUNNEL GRADING	Level (Constant)	Level (Constant)	Level (Constant)	Level (Constant)
STRUCTURE CONFIGURATION	Side-By-Side Steel liner	Side-By-Side Seg. Conc. liner	Side-By-Side Steel liner	Side-By-Side Seg. Conc. liner
TUNNEL PRODUCTION RATES	61 [illegible].ft/day	61 [illegible].ft/day	100 [illegible].ft/day	100 [illegible].ft/day
COST OF TUNNEL CONSTRUCTION (for 23½ route miles)	$518.4M	$411.5M	$490.1M	$380.9M

NOTE:

For 2 ft. reduction in tunnel I.D. from 16 ft. 8 in to 14 ft. 8 in.
$30,210,000 decrease in cost of tunnels for 23½ route miles.

TABLE A2

CONSTRUCTION COSTS OF ALTERNATE TUNNEL GUIDEWAY DESIGNS

PARAMETERS \ STUDY CASE	I	II	III	IV	V	VI
TUNNEL GRADING	Profile Graded 10%	Level (Constant)	Profile Graded 10%	Profile Graded 10%	Level (Constant)	Profile Graded 10%
CONFIGURATION	Side-by-side seg. conc. liner	Over/under Seg. Conc. liner	Over/under Seg. Conc. liner	Side-by-side Seg. Conc. liner	Over/Under Seg. Conc. liner	Over/under Seg. Conc. liner
TUNNEL PRODUCTION RATE	About 60 ℓ.ft/day	About 60 ℓ.ft/day	About 60 ℓ.ft/day	100 ℓ.ft/day	100 ℓ.ft/day	100 ℓ.ft/day
COST OF TUNNEL CONSTRUCTION (for 23½ route miles)	$446.2M	$446.2M	$464.7M	$414.1M	$414.1M	$432.6M

APPENDIX B

TUNNEL COSTS ESTIMATES, A.A. MATHEWS, INC.

(Excerpts from Reference 2)

Since Reference 2 is not readily available, some of the text and sketches showing the cross-section of the different types of tunnels studied are included along with the summary tabulation of the cost estimates. Considerable details of the estimated costs are contained in Reference 2.

ALTERNATE CONCEPTS FOR TUNNEL TRANSIT SYSTEMS

ACTTS

Prepared by A. A. Mathews, Inc.
Arcadia, California

1. Introduction

The Alternative Concepts for Underground Rapid Transit Systems (Phase I) preliminary cost estimâtes were based on conventional side-by-side, single track tunnels at approximately level grade, on dipped profile and one tunnel above the other. In each estimate the temporary and permanent support of the tunnels consisted of precast concrete segment liners. Following the excavation, the tunnel invert track base concrete was poured in place in one operation, then the walkway concrete was poured in place.

The objective of this study is to develop preliminary tunnel designs and construction techniques that were not considered in Phase I, and to provide a direct comparison with the Phase I twin side-by-side and dipped profile tunnels. The comparison study will take full advantage of the different construction techniques to determine if there is a cost saving.

The scope of this study did not permit a design optimization; therefore, A. A. Mathews, Inc. selected a specific design for each set of tunnels that was felt to be structurally sound and practical to build. There were no stress analyses made on the conservative lining approach taken, and it is possible that with in depth study, further cost savings could be effected in this area.

2. Description of Work

A. Purpose:

Generate construction cost estimates within a ±20% accuracy of a detailed cost estimate normally supplied when relatively unrestricted by time or funds.

Description of Work (Continued)

B. The following tunnel configurations were considered in this study:

1. Twin bore, side-by-side tunnels, 16' - 8" finished diameter, level to 3% maximum grade.

2. Twin bore, side-by-side tunnels, 16' - 8" finished diameter, dipped profile with 10% grade out of and into stations at maximum of 100 ft below stations.

3. Single bore, oval design for over and under trackways in one level grade tunnel approximately 30' high x 19" wide finished dimension.

4. Single bore, twin trackway level grade tunnel approximately 33 ft finished diameter.

C. Lining:

In this study it was considered feasible to manufacture the precast concrete segments for tunnel support that would not only serve as primary support, but would also be the permanent support and tunnel lining and would be cast with the walkway, curbs, etc. as an integral portion of the ring segments.

A saving is made in producing the concrete segments through the use of a special machine that uses only one form in which very low slump concrete is vibrated to the extent that the form can be removed as soon as the vibration is stopped and the segment is self-supporting at that time.

The estimates include costs of backfill grouting behind the segments and include one pass through the tunnel after excavation is completed to place a screeded invert leveling course.

Description of Work (Continued)

D. A typical 5,000 LF section of twin tunnel or a single 5,000 LF section of twin track tunnel was selected as being an optimum length of tunnel for this study. If there were sections of tunnel that were of greater length, the cost per foot of tunnel should decrease with respect to equipment rental charges.

E. The construction methods used to produce the estimates are enumerated with the descriptive material attached to each estimate and are in general those in common usage together with various innovations required to handle the geologic parameters.

F. Geologic Parameters:

1. Level tunnels

   a. Sedimentary rock 48%

   b. Alluvium above watertable 44%

   c. Alluvium below watertable 8%

2. Dipped Profile Tunnels

   a. Sedimentary rock 52%

   b. Two 100 foot wide faults per mile in rock section.

   c. Alluvium above watertable 36%

   d. Alluvium below watertable 12%

G. Remarks

The estimates have been produced in accordance with current construction practice and have used only those rates of tunnel advance that were felt to be acceptable under the geologic conditions set forth.

Description of Work (Continued)

G. Remarks (Continued)

In three of the various tunnel configurations, it was deemed necessary to use tunnel shields with hydraulic arm and hoe digging arrangements that can be converted to a rotary cutting head for use in the rock sections. In the over and under tunnel section, normal drill and blast methods were used in the rock sections. In all cases, the precast support segments were assumed to be erected within the tail section of the shield.

In the three level tunnel sections, diesel locomotives and cars were assumed as a means of hauling the excavated spoil to a shaft or station where a crane was used to hoist the material to the surface. In the dipped tunnel profile an extended conveyor was used for spoil removal and a specially built trailer with a load-haul-dump vehicle attached to each end of the trailer was used to handle pre-cast segments, pipe, men, and other materials. The small amount of concrete placed in the tunnel inverts was placed with concrete pumps fed by agitator cars. It was assumed that concrete was purchased at $35.00 per cubic yard.

The estimates include only the tunnel excavation, spoil disposal, support, pumping, backfill grouting, placing concrete invert, and mobilization, plant set up, and demobilization.

Mobilization and demobilization are estimated as a function of the amount, weight, size and type of equipment and varied from 60 working days on the twin tunnels to 95 days on the 33 foot finish single bore tunnel.

Description of Work (Continued)

G. Remarks (Continued)

Escalation for construction schedules of up to one year was allowed at 7% on all labor, permanent material and expendable supplies. In those estimates covering up to one and one half year 11% escalation was allowed on the same items.

With proper ventilation, strict monitoring and explosion proof equipment, explosive gases should present no serious problem in excavating the tunnels. The cost of explosion proof equipment is somewhat higher than non-explosion proof equipment, but represents a small part of the total plant and equipment required and was not considered in this study.

The attached tabulation of costs indicate that the full circle double track 33 foot finish tunnel provides the lowest cost per foot of track.

In all of the four configurations, the daily rate of advance used was considerably lower than that used in ACURTS I and was felt to be reasonable for the assumed geology.

The 33 foot circular finish tunnel with side-by-side tracks had the lowest cost per lineal foot of finished tunnel for the following major reasons:

Required 29% less time than the dipped profile and over and under tunnels, and 19% less time than the parallel level grade twin tunnels.

The labor cost is 24% less than the over and under tunnel and 10% less than the parallel level grade twin tunnels.

Description of Work (Continued)

G. Remarks (Continued)

The permanent material is little different than the over and under tunnel, but is 36% less than either of the parallel twin tube tunnels.

The amount of excavated material in the section used for the 33 foot circular side-by-side track tunnel is 20% greater than the over and under tunnel and 38% greater than the parallel twin tube tunnels, however, this is more than offset by the saving in labor and permanent materials.

All four schemes have relatively the same costs for expendable supplies, equipment operation and equipment rental.

It should be pointed out that the 33 foot circular finish tunnel section can be revised to an oval shape so that there is less excavation and concrete which would produce a further reduction in cost.

If the invert of the 33 foot circular finish tunnel section was filled to track grade with stone ballast rather than a poured concrete grade as used in this estimate, a further savings can be realized.

As previously indicated, the single bore over and under tunnel used a slightly different approach for alluvial excavation than the other tunnels and used a drill and blast system in the rock portion.

For direct comparison purposes, assume that this tunnel is excavated in the same manner as the 33 foot finish single bore tunnel. With the heavier segments and the need to place the cross brace from side to side, the estimated progress would be at 32 feet per day in the dry alluvium and assume that progress in the

Description of Work (Continued)

G. Remarks (Continued)

rock would be the same as in the 33 foot finish tunnel. The total time of excavation would then be 188 days or 25% less than the original scheme, and produce a cost of $1,269 per track foot of tunnel or $36.00 above the 33 foot finish tunnel.

It should be noted that the over and under tunnel is assumed to match up with over and under stations. If the stations were required to be all on one level, the cost of the over and under tunnels would increase due to the extra horizontal and vertical curves required to match the stations.

As alternatives, estimates were made for 14'-18" finish side-by-side, level grade tunnels and for a single 30 foot finish twin track level grade tunnel. These two estimates were obtained by using the same crews as in the previous estimates and used a slightly higher production rate. An examination of the results indicates that the cost was reduced, and that the major savings occurred in permanent material (concrete) and in the lesser amount of spoil to haul away. The labor costs did not change appreciably and in many instances it was felt that there would be no change in the labor, particularly in the indirect costs.

PROJECT ACTT

OWNER ______ BID OPENING DATE ______

TABULATION OF COSTS

ESTIMATE NO 2012

SHEET NO 1

ITEM NO	WORK SCHEDULE DESCRIPTION	QUANTITY	UNIT	LABOR UNIT	LABOR AMOUNT	PERM MATERIALS UNIT	PERM MATERIALS AMOUNT	SUPPLIES UNIT	SUPPLIES AMOUNT	SUB CONTRACTS UNIT	SUB CONTRACTS AMOUNT	EQUIP OPERATION UNIT	EQUIP OPERATION AMOUNT	EQUIP RENTALS UNIT	EQUIP RENTALS AMOUNT	TOTAL UNIT	COSTS AMOUNT	MARKUP AMOUNT	BID UNIT	BID AMOUNT
1	Two single track circular tunnels 16'-0" finish level grade, each 5,000 ft long, side by side	10,000	LF	413.63	4,136,315	341.91	3,419,098	[illegible]7.97	1,379,772	39.90	399,110	24.48	244,842	140.22	1,402,230	1,126	11,262,067	2,060,130	1,330	13,[illegible]
1A	Two single track circular tunnels 16'-0" finish dipped profile, each 5,000 ft long	10,000	LF	437.71	4,377,098	330.03	3,300,275	[illegible]1.38	1,613,771	39.90	399,110	20.00	200,063	156.03	1,560,333	1,103	12,027,363	2,200,345	1,412	14,115,[illegible]
2	One-two track over-under oval tunnel 19'-0" x 29'-6" finish level grade 5,000 ft long	10,000	LF	517.06	5,170,598	233.00	2,330,779	[illegible]3.46	1,734,611	76.03	760,150	23.00	229,902	105.60	1,056,044	1,213	12,115,044	2,300,109	1,470	14,[illegible]
3	One-two track side by side circular tunnel 33' finish level grade 5,000 ft long	10,000	LF	393.10	3,930,013	219.23	2,192,306	[illegible]	1,[illegible]	96.20	962,100	26.55	265,497	171.03	1,710,297	1,036	10,359,930	1,965,309	1,230	12,[illegible]
4	Two single track circular tunnels 16'-0" finish level grade, 5,000 ft long side by side	10,000	LF	397.23	3,972,309	200.05	2,000,509	[illegible]	1,[illegible]	49.16	491,270	23.95	239,547	161.05	1,610,407	1,016	10,110,376	1,986,135	1,210	12,[illegible]
5	One-two track 30 ft finish diameter tunnel, level grade, 5,000 ft long	10,000	LF	300.76	3,007,587	107.10	1,071,000	[illegible]7.06	1,170,[illegible]	81.71	817,155	23.17	237,679	166.48	1,664,140	964.98	9,648,979	1,909,706	1,157	11,[illegible]

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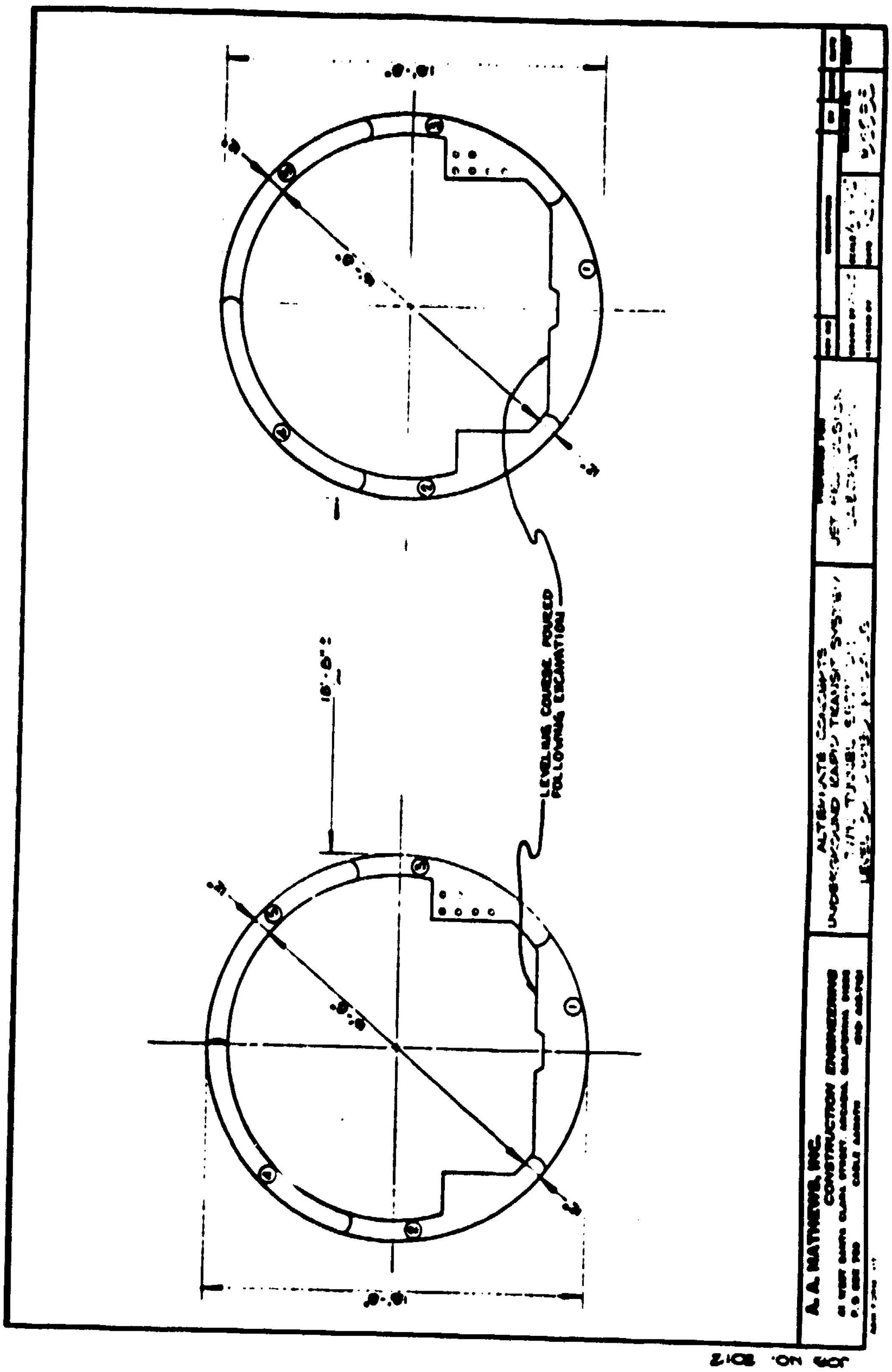
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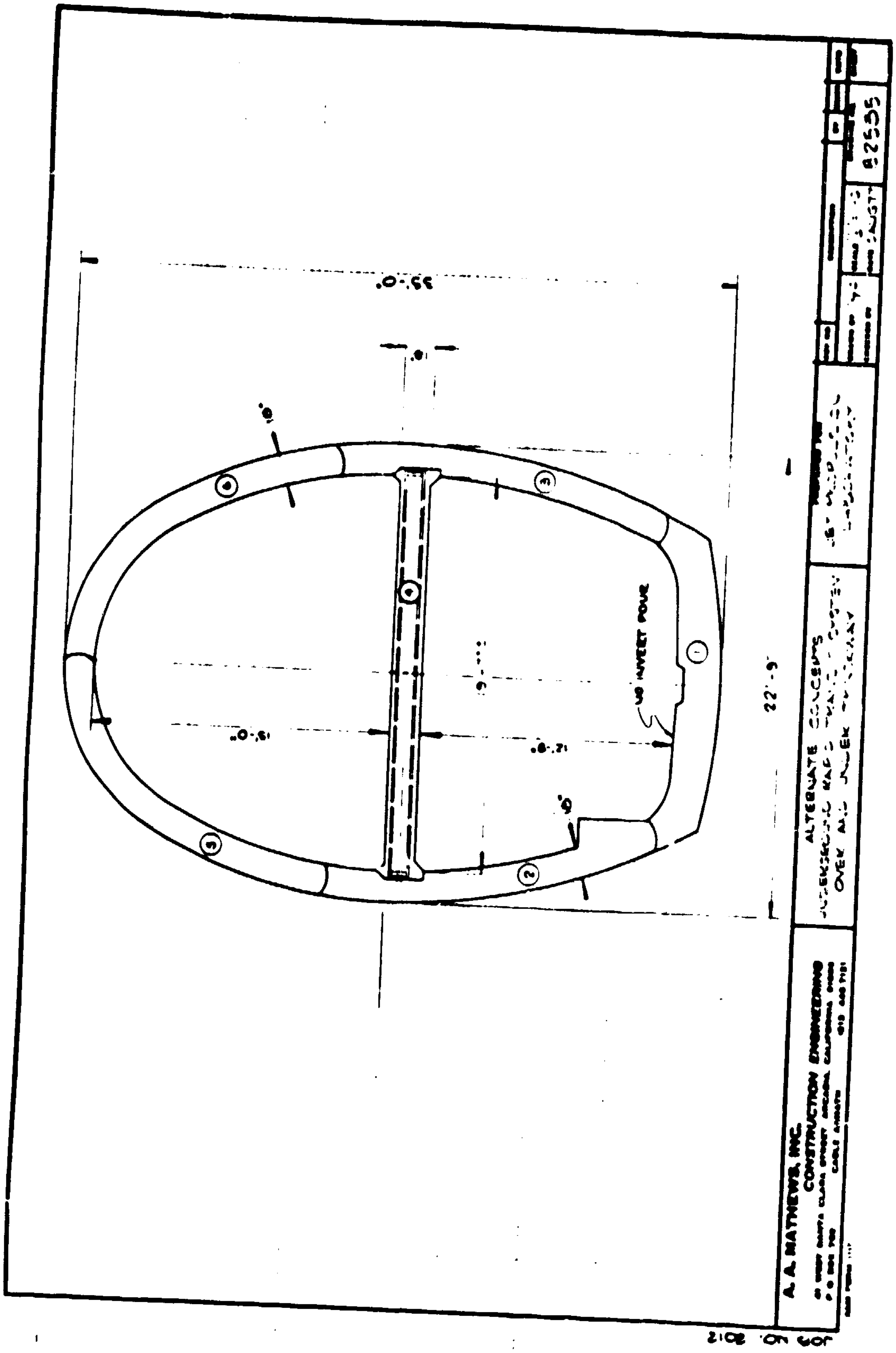
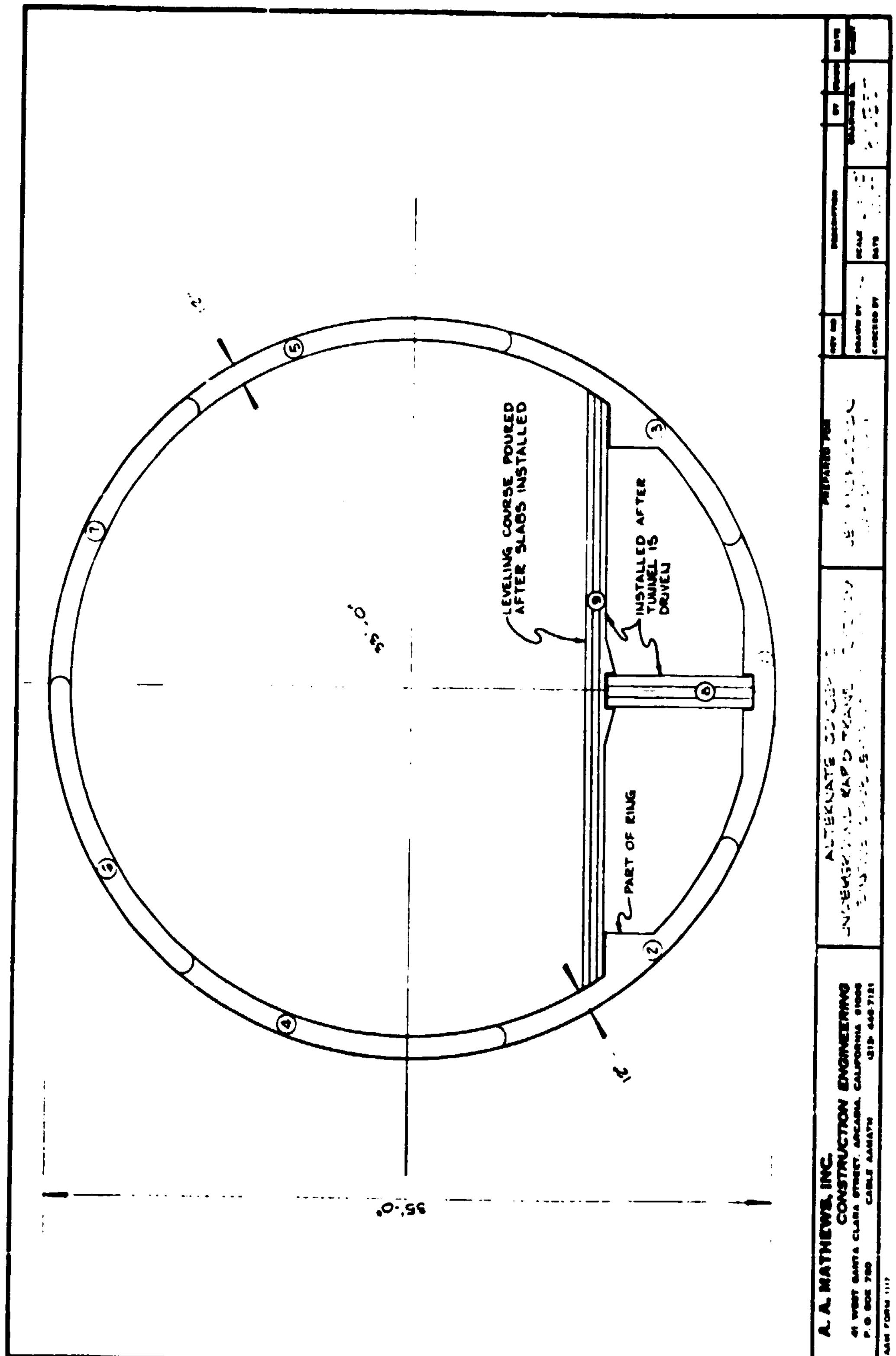
16'-0"
ALTERNATE CONCEPTS
UNDERGROUND RAPID TRANSIT SYSTEM
A. A. MATHEWS, INC.
CONSTRUCTION ENGINEERING
JOB NO. 2012



A. A. MATHEWS, INC.
CONSTRUCTION ENGINEERING
ALTERNATE CONCEPTS
OVER AND UNDER
35'-0"
22'-9"
15'-0"
12'-8"
16'
JOB NO. 2012



LEVELING COURSE POURED AFTER SLABS INSTALLED
INSTALLED AFTER TUNNEL IS DRIVEN
PART OF RING
33'-0"
35'-0"
A. A. MATHEWS, INC.
CONSTRUCTION ENGINEERING
CABLE AAMATH

PROJECT: ACTTS

OWNER: ______ BID OPENING DATE: ______

TABULATION OF COSTS

ESTIMATE NO. 2012

SHEET NO. 1

Item No.	Work Schedule Description	Quantity	Unit	Labor Unit	Labor Amount	Perm Materials Unit	Perm Materials Amount	Supplies Unit	Supplies Amount	Sub Contracts Unit	Sub Contracts Amount	Eqpt Operation Unit	Eqpt Operation Amount	Eqpt Rentals Unit	Eqpt Rentals Amount	Total Unit	Costs Amount	Profit Amount	Adjusted Bid Unit/LF	Adjusted Bid Amount
	TRACKWAY																			
1	Two single track circular tunnels 16'-8" finish level grade, each 5,000 ft long, side by side	10,000	LF	413.63	4,136,315	341.91	3,419,070	[illegible]7.98	1,379,772	59.90	599,010	24.48	244,842	148.22	1,482,230	1,126	11,262,047	2,068,158	1,330	13,330,205
1A	Two single track circular tunnels 16'-8" finish dipped profile, each 5,000 ft long	10,000	LF	457.71	4,577,091	350.83	3,508,275	[illegible]1.38	1,413,971	59.90	599,010	28.00	280,063	156.83	1,568,333	1,183	11,827,343	2,288,545	1,412	14,115,888
2	One-two track over-under oval tunnel 19'-9" x 29'-6" finish level grade 5,000 ft long	10,000	LF	517.64	5,176,370	233.08	2,330,779	[illegible]5.44	1,754,411	76.83	768,350	23.00	229,982	185.60	1,856,044	1,213	12,115,844	2,588,189	1,470	14,704,033
3	One-two track side by side circular tunnel 33' finish level grade 5,000 ft long	10,000	LF	393.10	3,931,013	219.23	2,192,306	[illegible]	1,010,017	96.20	962,000	24.55	245,497	171.83	1,718,297	1,036	10,359,930	1,965,507	1,233	12,325,437
4	Two single track circular tunnels 14'-8" finish level grade, 5,000 ft long side by side	10,000	LF	397.23	3,972,209	260.65	2,606,509	[illegible]0.74	1,307,430	49.16	491,570	23.95	239,547	141.86	1,418,409	1,014	10,118,374	1,986,135	1,210	12,104,509
5	One-two track 30 ft finish diameter tunnel, level grade, 5,000 ft long	10,000	LF	300.76	3,007,587	187.18	1,871,849	[illegible]7.07	1,270,641	81.71	817,155	23.77	237,679	166.41	1,664,148	966.90	9,668,979	1,903,794	1,157	11,572,773

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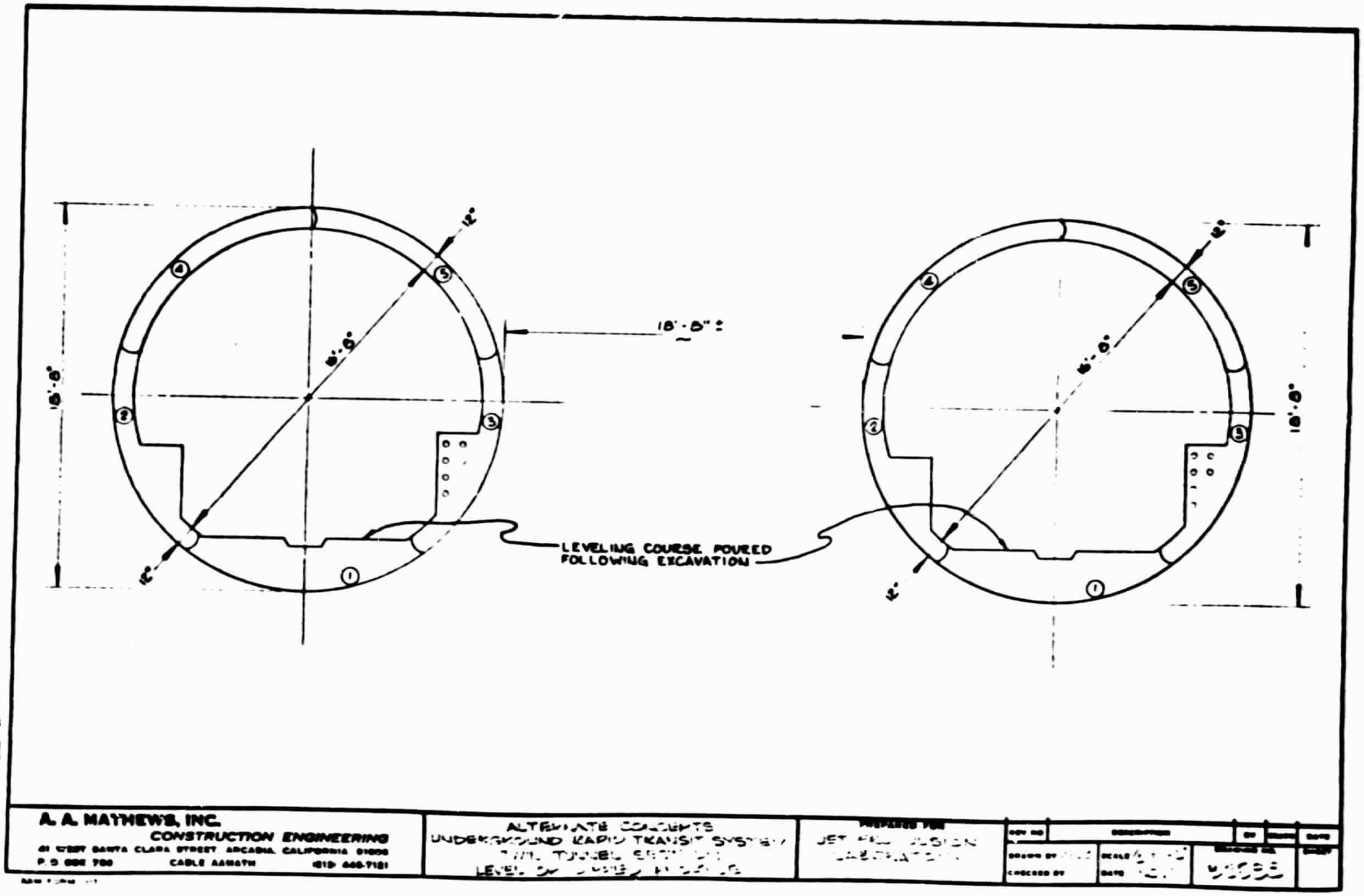
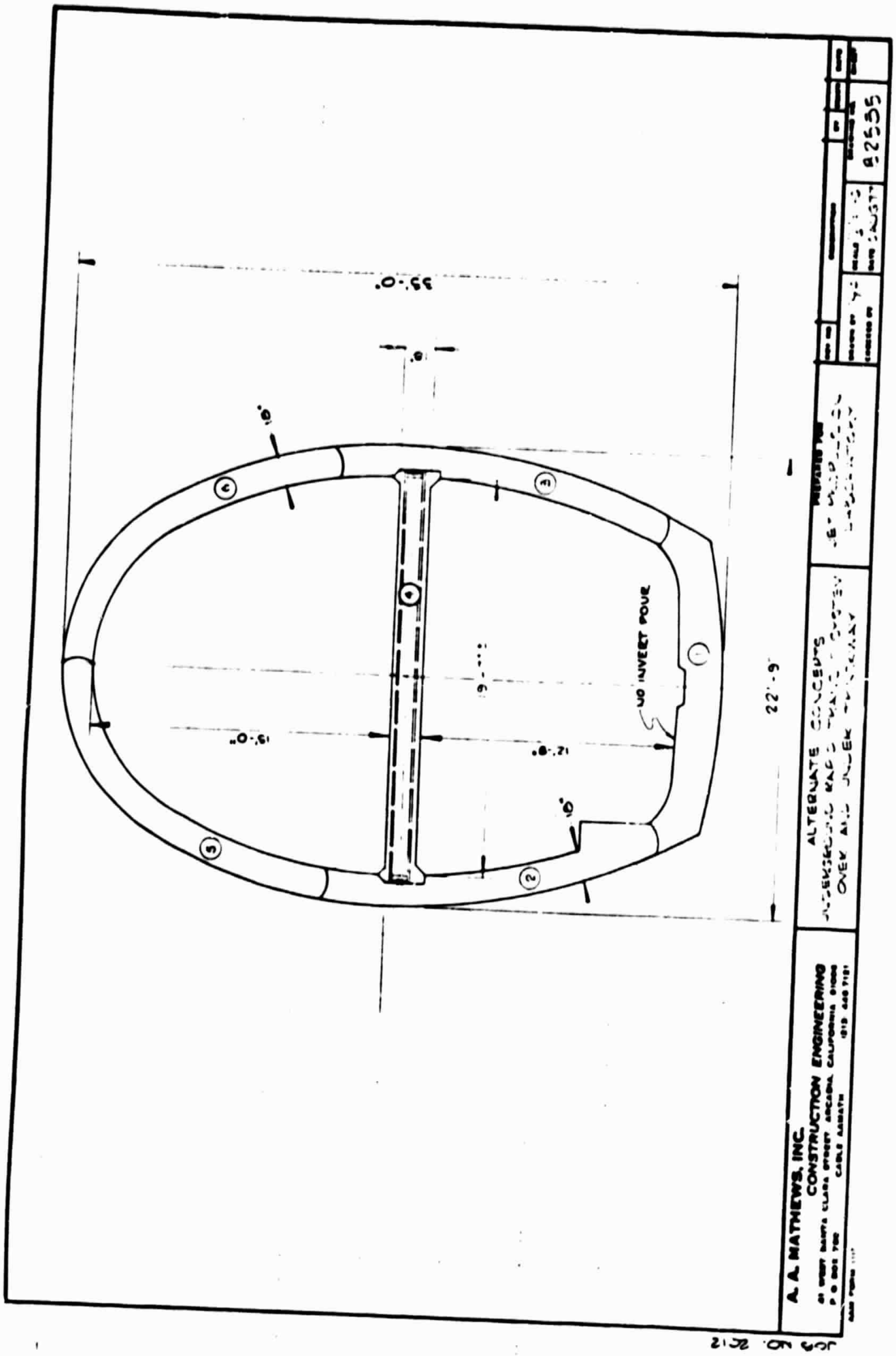
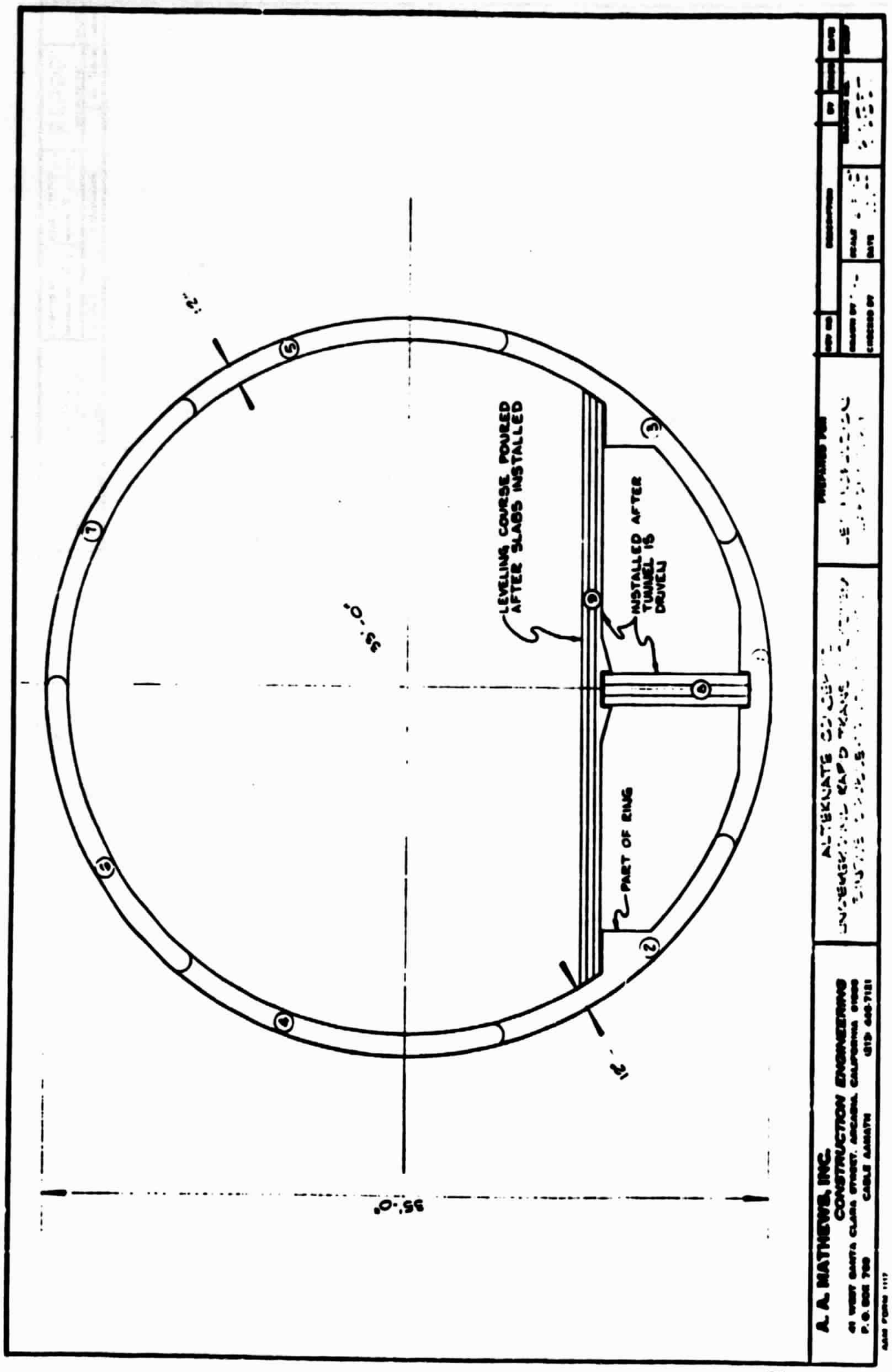

18'-8"
16'-0"
12"
18'-8" ±
LEVELING COURSE POURED FOLLOWING EXCAVATION
A. A. MATHEWS, INC.
CONSTRUCTION ENGINEERING
ALTERNATE CONCEPTS
UNDERGROUND RAPID TRANSIT SYSTEM
PREPARED FOR
JOB NO. 2012


A. A. MATHEWS, INC.
CONSTRUCTION ENGINEERING
ALTERNATE CONCEPTS
NO INVERT POUR
22'-9"
35'-0"
13'-0"
12'-8"
JOB NO. 2212


LEVELING COURSE POURED AFTER SLABS INSTALLED
INSTALLED AFTER TUNNEL IS DRIVEN
PART OF RING
33'-0"
35'-0"
12"
A. A. MATHEWS, INC.
CONSTRUCTION ENGINEERING