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ALTERNATIVE CONCEPTS FOR UNDERGROUND RAPID TRANSIT SYSTEMS

EXECUTIVE SUMMARY

Prepared by
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California Institute of Technology
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FINAL REPORT

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16. Abstract

A study was performed for the Office of the Secretary of the U.S. Department of Transportation to determine if construction costs and operating energy requirements of future high-performance underground rail mass-rapid-transit systems can be decreased while maintaining or improving service. The alternative design approaches studied were limited to well-established design concepts which differ from those used in the BART (San Francisco), WMATA (Washington, D.C.) and MARTA (Atlanta) systems. They include: gravity assist; over/under tunnels; over/under and short stations; various subway train propulsion configurations; and optimized operational control policies. Comparisons were made of several system designs for a specific route and patronage structure. These comparisons indicate that it is practical to significantly reduce construction costs and operational energy requirements of modern underground systems while improving service by incorporating alternative concepts. Without any attempt at optimization, savings in capital costs in excess of 24% and savings in energy as high as 70% in traction effort and 88% in braking are shown to be achievable.

The Executive Summary briefly describes the purpose, approach, and results of this study. It does not contain any supporting information. An extensive description of the study appears in Volume I. Volume II (divided into three separately bound parts) contains all the information that was generated and integrated in Volume I. Further details on the contents of these two volumes appear in the Appendix of this Executive Summary.

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ABSTRACT

A study was performed for the Office of the Secretary of the U.S. Department of Transportation to determine if construction costs and operating energy requirements of future high-performance underground rail mass-rapid-transit systems can be decreased while maintaining or improving service. The alternative design approaches studied were limited to well-established design concepts which differ from those used in the BART (San Francisco), WMATA (Washington, D.C.) and MARTA (Atlanta) systems. They include: gravity assist; over/under tunnels; over/under and short stations; various subway train propulsion configurations; and optimized operational control policies. Comparisons were made of several system designs for a specific route and patronage structure. These comparisons indicate that it is practical to significantly reduce construction costs and operational energy requirements of modern underground transit systems while improving service by incorporating alternative concepts. Without any attempt at optimization, savings in capital costs in excess of 24% and savings in energy as high as 70% in traction effort and 88% in braking are achievable.

FOREWORD

This Executive Summary briefly describes the purpose, approach, and results of this study. It does not contain any supporting information. An extensive description of the study appears in Volume I. Volume II (divided into three separately bound parts) contains all the information that Volume I is based upon. They can be obtained from the National Technical Information Service (NTIS), Springfield, Virginia, 22161, U.S.A. Further details on the contents of these two volumes appear in the Appendix of this Executive Summary.

The information for this study was contributed by a number of organizations and consultants. In directing this study, the Jet Propulsion Laboratory (Pasadena, CA) had the guidance of the Southern California Rapid Transit District (Los Angeles) which served as the technical advisor. The Underground Technology Development Corporation (Alexandria, VA) contributed the cost estimates and designs of the underground structures. Garrett-AiResearch Manufacturing Company (Torrance, CA) supplied information on the subway cars and the various propulsion configurations. London Underground (London) commented on the various operational aspects. Dr. A. Hammitt (Palos Verdes Peninsula, CA) and Professor A. Vardy (Cambridge, England) worked on the pressure pulse phenomena. Mr. R. Proctor of the Metropolitan Water District of Southern California (Los Angeles) provided direct information on tunneling in the Los Angeles Basin.

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I. INTRODUCTION

The design of urban subways has evolved over a long period of time. Current systems follow well-defined design principles which are well understood by the planners, designers, builders, operators, and the users. There is a strong reluctance to deviate from the normal procedures because of the unknown risks in capital and operational costs and the necessity for reliable service.

The conservative approach of today is not at all indicative of the early days of subways. Innovation was necessary because of the absence of sufficient, well-proven concepts. Following the first underground railroad system in London in 1863 (built by the cut-and-cover method), the development process was not slow and orderly because there was no history of well established practices. For example, the Tower Subway Company built the world's first tube railway under the Thames which began operation in 1870. Naturally, almost anything that was done was innovative. A circular shield was used to drive the tunnel and the lining was made up of cast-iron segments. The tunnel dipped down about fifteen feet in the middle in order to incorporate gravity as a propulsive force. Another propulsion mode utilized in this early period was pneumatic; air pressure acted against the train and pushed it along the guideway. In another system started in 1884 from London Bridge to the Elephant & Castle, under Arthur Street the line had the two single-track tunnels bored one above the other. The 19th century London systems overall speed, including station stops, was around 11-12 mph (today's systems range between 20-35 mph).

In 1900, serious consideration was given by London's Metropolitan line to use of an overhead three-phase 2000 V AC system in order to reduce the expensive requirement of substations. But, in the end the normally used approach of low voltage DC (600 V) won out. One could go on and on with the many innovations that were incorporated or at least seriously considered. Hopefully, these few early ideas serve to illustrate a number of things. Innovation is a normal "way of life", and many "new" approaches are, in fact, old. In the U. S. today, we have a situation which forces us to seriously consider innovative approaches. The costs of today's subway systems are high and escalating; in many cases, they prohibit building and operating a system even where it appears to be a practical means for supplying urban transportation needs. Furthermore, there is an energy shortage that is projected to become more severe.

Concepts looked at as long as 100 years ago should be re-examined since today's conditions are different; it is possible that approaches that have been discarded may now be appropriate. Also, there are new approaches which are possible because of today's highly advanced technology. They, too, should be included in a trade-off study for the design of a new system. Consequently, the U. S. Department of Transportation, as part of its overall effort to overcome the problem of high costs, initiated this study on the Alternative Concepts of Underground Rapid Transit Systems (ACURTS).

II. OBJECTIVE

The objective of this study is to determine if construction costs and operating energy requirements of future high-performance underground rail mass-rapid-transit systems can be decreased while maintaining or improving service. The alternatives are limited to well-established design concepts which differ from those used in BART (San Francisco), WMATA (Washington, D.C.) and MARTA (Atlanta). It is expected that some of the results of this study will also be applicable to extensions of existing transit systems.

To save capital costs and operational expenses, effort should be concentrated on the high-cost items. For capital costs that means tunnels and stations. The rolling stock acquisition costs are a small portion of the total system costs, and change would be important primarily, as it might reflect on the cost of tunnels and stations. For operational costs, labor and energy are the major items. This study considers only the capital and energy costs.

III. APPROACH

Many contacts were made during this study with designers, builders and operators of subway transit systems. One attitude common to many was the reliance upon the proven or familiar design concepts, accepting any problems that may be inherent. In order that this concern over change be minimized, the example alternative design concepts chosen for this study are those which are believed to have reached maturity in their development process. They are based upon firmly established technologies and should not require much, if any, additional development.

Cost estimates were made for various system designs based upon a hypothetical route structure. First of all, a baseline system was defined and costed. It is a composite of the BART, MARTA, and WMATA systems. Then, a similar costing was performed for three alternative systems which included a number of design concepts that differ significantly from the standard approaches of the baseline system.

The actual level of the construction cost estimates obtained for this study should not be used for predicting the costs of any particular system. They were generated with just enough substance so as to be able to be used to demonstrate changes in costs from the baseline system of the various alternative systems investigated. Therefore, it would be more realistic to use the percentage comparisons and cost differences rather than the dollar totals.

The alternative design concepts that were investigated are:

1. Gravity Assist (profile grading): Use gravity to help accelerate and decelerate trains in order to conserve electrical power and/or to decrease transit time.

2. Over/Under Tunnels: Simplify construction and guideway alignment. Permits convenient interventing where desirable.

3. Vertically-Oriented Stations: Match stations to over/under tunnels. Provide for through-loading of passengers. Shorten platform lengths.

4. Train Propulsion: Evaluate the system electrical and operational efficiencies for various propulsion approaches.

5. Operational Control Procedures: Assess the importance of minor changes in speed-distance profile.

The fifth category was not included at first. But, during the course of the study, many significant items surfaced that fell into it. The emphasis of this study was on the first three concepts.

IV. CONCLUSIONS

This study concludes that it is practical to significantly decrease the costs in the construction and operation of modern underground rail mass transit systems by incorporating alternative concepts into their designs and operation. It is believed that savings can be accomplished while improving the service without materially increasing the risks. This conclusion is based upon the investigations of a number of alternative concepts (which differ from those conventionally used in modern, high-performance systems such as BART, WMATA, and MARTA). This is very important because the costs of subway systems are escalating rapidly; this inflationary condition is hampering the expansion and updating of current systems and approval and construction of new systems.

Highlights of the findings are:

1. Depending on station spacing, up to 70% savings in traction effort energy and 88% savings in braking energy can be achieved by dipping the guideways (about a 100 ft drop with a maximum grade of 10%) between stations (Figure 6). The 10% grade should not create any operational problems that cannot be resolved in a reasonable manner. Up to 28% savings in requirements for the station environmental control will result. Three-fourths of all these savings are still possible if the maximum grade were limited to 5%.

2. The use of over/under stations (Figure 8) will allow platforms to be on both sides of the track and still keep the station within the width of the street. These double platforms allow for through-loading which, in turn, will decrease station dwell time. This will permit higher average speeds or reduced energy use with the same travel time than a train unloading at center platform stations. Also, the cost of the stations are slightly reduced.

3. A 22% saving in capital costs can be achieved for a side-by-side level system by:
    a. Using precast concrete segment liners for the tunnels rather than steel liners.
    b. Shortening all station platforms from 600 feet to 300 feet. Operation of 4-car trains on 90-sec headways can handle up

to 30,000 passengers per hour in one direction.

c. Integrating station design and construction with cross-overs and lay-ups.

The savings can be increased to 24% by dipping the guideway (Table 2).

4. From an energy saving point of view, the all-multiple unit (MU) train consist concept is the most attractive approach for the dipped guideway. However, if the use of other train consists, such as motor-trailer or locomotive-trailer cars can permit smaller diameter tunnels (which are less expensive) due to lower train height, the all-MU consist might not be optimum from an overall system cost point of view.

5. Significant savings in traction effort energy for a level system will result from optimizing the operational control policy. Introduction of a slight amount of coasting can save up to 20% of the traction effort energy at the small penalty of increasing transit time by only 1%.

These estimated savings result from non-optimized alternative systems and, furthermore, do not include all the savings noted. The inclusion of all possible savings, along with the optimization of each alternative system, will increase the savings indicated here by significant amounts.

During the course of this study many differing specifications of relatively standard systems were noted where there did not appear to be sufficient reasons for these differences. Several notable examples are: guideway power voltage level; minimum coefficient of adhesion for steel on steel; steel vs. concrete liners in tunnels. Also, in some instances it was not possible to obtain detailed design information on some critical aspects of such systems. Therefore, it is questionable if there presently exists sufficient information and if adequate procedures have been developed for carrying out an effective trade-off study of the design of even a conventional transit system. The problem for an alternative system is even greater. There is a very strong need to insure that adequate information and procedures exist for carrying out optimization studies on future subway mass-rapid-transit systems. Where they do not exist, they must be developed so that the potential effectiveness of these systems can be properly assessed. In light of the high costs of present systems, optimization of system design is essential.

V. RESULTS

To assist in quantifying the possible savings of a modern underground high-performance rail rapid-transit system, a hypothetical 23½ mile long system with 23 stations of varied spacing was derived (Figure 1). The costs estimated are not all inclusive; nor do they necessarily reflect the optimum practices and approaches, but they are uniformly applied to the various alternative systems considered. Many essential parts of a real operating system have been omitted because they were more or less common to the baseline and alternative systems being considered. Omitted elements include rail yards, maintenance sheds, operation and management offices, tracks, power substations and guideway electrification, ticketing, and station air conditioning equipment.

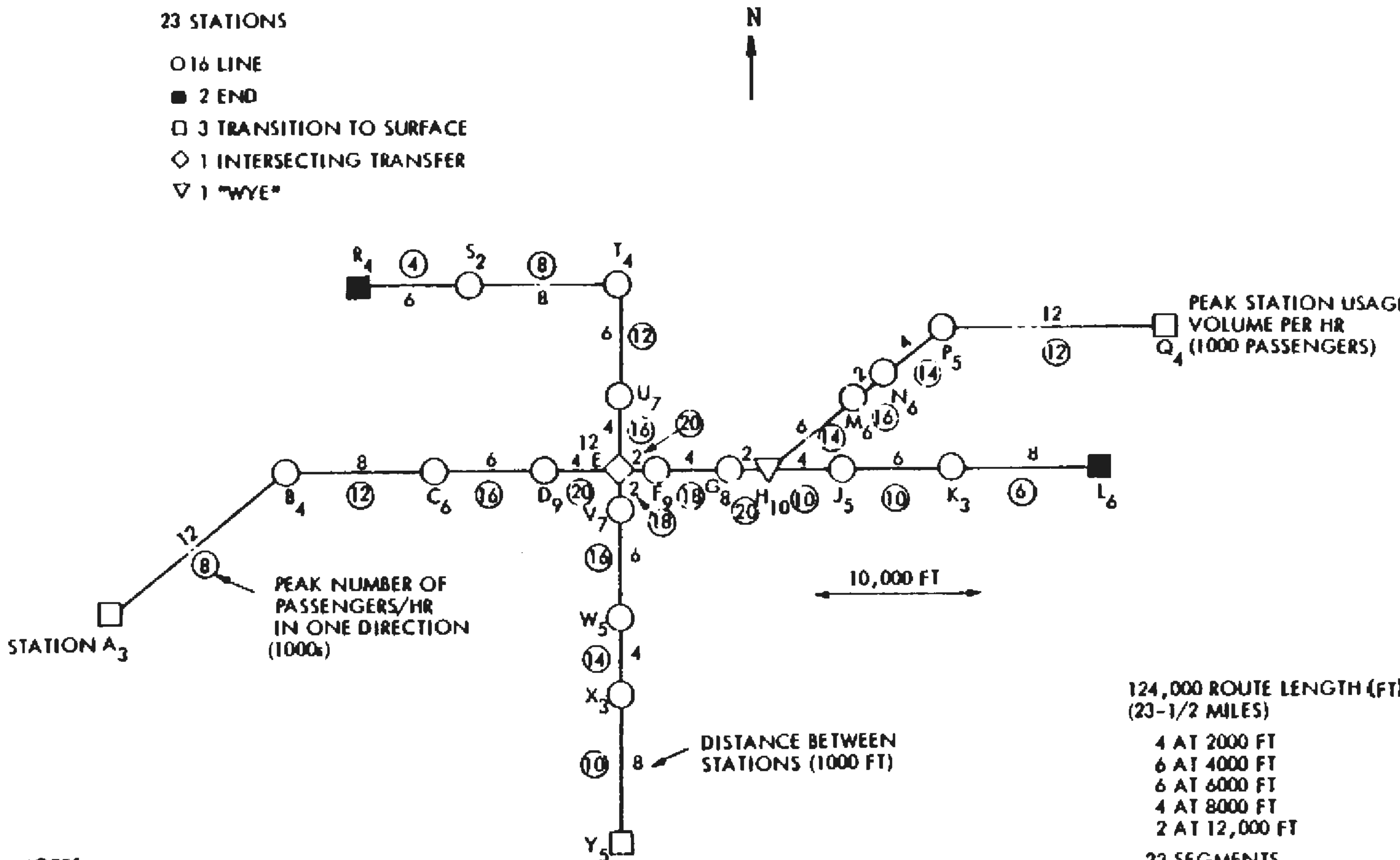
A. Subway Cars and Electrification

Three alternative concepts of propulsion configurations were very briefly considered:

- All-MU cars
- A mixture of motored and trailer cars
- Trailer cars with a locomotive at each end of the consist

For a level system, only the all-MU approach could meet tne transit time requirement of an 80 mph system. In a dipped system, the electrical energy requirements of the all-MU train were substantially less than for the other two propulsion configurations. Furthermore, the more powerful the propulsion system is for the MU, the less traction effort energy is used for the same transit time, although the peak power requirements are greater. However, other types of consists may result in trains of lower height. If so, tunneling costs could be less because the diameters can be smaller. As these other consists can give the same performance in a dipped guideway as the all-MU consist on the level, the all-MU approach may not be optimum for the dipped alternative systems.

A number of guideway electrification methods were considered. The use of higher voltage DC (say 1500-2000 V) in conjunction with an AC squirrel-cage asynchronous motor may prove advantageous over the baseline 750 V DC guideway with 375 V DC motors (211 hp). This type of motor is smaller,



NOTES:

1) PROVISION MUST BE MADE FOR TURNOUTS AND TURNBACKS.

2) INTERSECTING LINES STATION (◇) CAN BE EITHER CROSS-OVER (X) OR TANGENT. IN EITHER CASE, PROVISION MUST BE MADE TO TRANSFER TRAINS BETWEEN LINES.

Figure 1 - Baseline Subway System Route Structure

less costly and is inherently well suited for controlling slip because of its rapid torque drop when the shaft rotational speed does not match the input frequency. As a result, the coefficient of adhesion is substantially higher than normally accepted values. Furthermore, the maintenance is expected to be significantly less than for the DC motors.

Because of the lack of detailed information that was readily available, it was not possible to make adequate assessments of even the most promising of the various propulsion and guideway electrification options. Therefore, the baseline cars and guideway electrification design were left unchanged for the alternative systems. The car acquisition cost (250 cars at $0.54 M each) was included in the cost estimates since it represents a significant amount of the baseline system capital costs (about 11%). But, the cost of the guideway electrification subsystem was omitted since it was considerably less.

B. Baseline System

The baseline system is composed of pairs of single-track tunnels (Figure 2) which are made by a tunnel boring machine (TBM) in fairly ideal geology similar to that of the Los Angeles basin. These twin tunnels are on the same level about 80 feet below the surface and are spaced two to three tunnel diameters between centers. The 16 ft., 8 in. inside diameter results in a blockage ratio of 50% for the trains (the train frontal area of 100 ft^2 is half of the clear cross-section area of the tunnel). The tunnel lining is of steel segments.

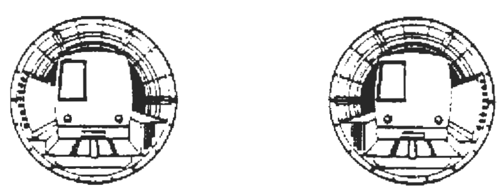


Figure 2 - Opposing Pair of Single-Track Tunnels for Baseline System

There are ventilation shafts to the surface about every 3,000 feet. All of the stations (800 ft. total length) have loading platforms (600 ft. long) that can accommodate 8-car trains. The platform of each station, located between the two oposing tracks, is reached from the surface by escalators (see Figure 3). Stairways are included for emergencies with small-capacity elevators for the handicapped. The stations are constructed by the cut-and-cover method, but are built independently of the cross-overs and lay-ups. The use of cut-and-cover construction for all stations of an actual system would severely constrain the route alignment.

The baseline car weighs 72,000 lbs. (empty), is 75 feet long, has 75 seats, and has every axle powered. Power is obtained from a 750 V DC third rail. It is capable of accelerating to 80 mph from a stop within 4,000 feet on level track in the open.

The capital costs are divided into three categories: Stations (includes blast shafts and vent-fans at station); Guideways (tunnels, mid-line vent shafts, auxiliary track segments such as cross-overs and lay-ups); and Train Cars. The capital costs for the baseline system are estimated to be:

TABLE 1

Train Cars (250)	\$ 135M*	(11%)
Stations (23)	435M	(36%)
Guideway (23½ route miles)	636M	(53%)
Total	\$1206M	(100%)

* \$135 million.

Information generated during this study is sufficient to synthesize many alternative systems. Only three were synthesized and none may represent the optimum. Detailed trade-off studies would be required to determine an optimum system, and its choice would be very sensitive to the specific geology, operational requirements, and financing which are among the many necessary considerations. The alternative systems considered are:

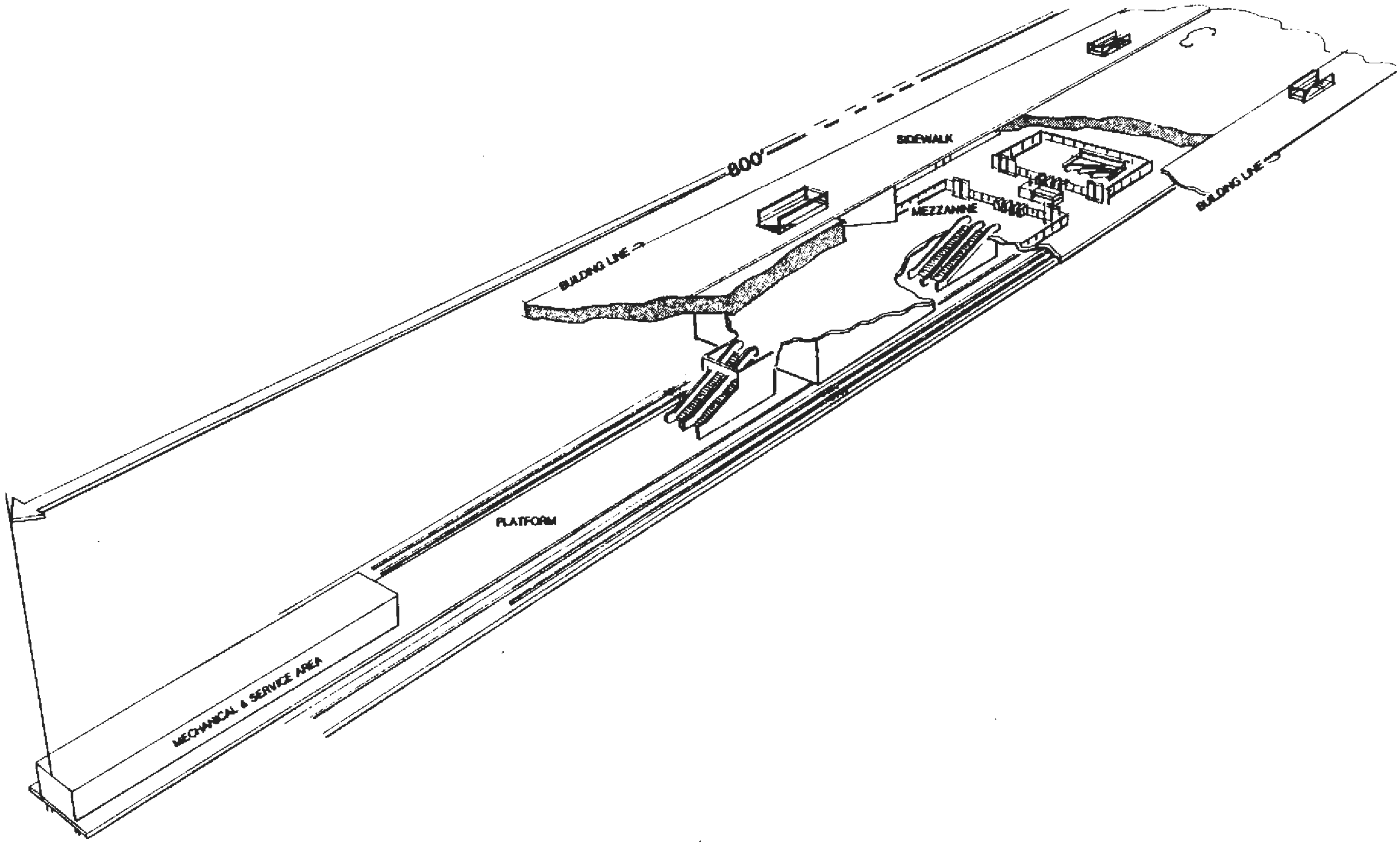


Figure 3 - Baseline Station (600 ft. long platform)

1. Level - Same as baseline except for shorter stations, 4-car trains and use of concrete rather than steel liners in the tunnels.

2. Dipped Guideways - Essentially the same as alternative system No. 1, but with dipped guideways and no mid-line vent shafts.

3. Dipped Guideways with Over/Under Tunnels and Stations- The same as alternative system No. 2, but with over/under tunnels and stations.

C. Alternative Systems

1. No. 1 - Level

There are a number of features of the baseline system that are amenable to cost savings without changing any realistic requirements of the basic system. For example, all the stations in the baseline system can accommodate 8-car trains, giving it the capability of handling over 60,000 riders per hour in one direction (200 riders per car with 90 sec headways). Therefore, it seems reasonable that shorter trains are acceptable. Limiting the system to 4-car trains at all stations gives a maximum capability of around 30,000 riders per hour (20,000 at a reasonably convenient loading of 125 passengers per car). This potential capacity would be acceptable for many systems and/or lines of systems. This change alone, which decreases the length of the loading platforms from 600 ft. to 300 ft., will save over 30% ($134M) of the station costs (see Figure 4).

There are a number of advantages of the shorter stations. They include:

- Lower capital cost.

- Shorter headways (for the same capacity).
  The consequent doubling of the number of train operators is not necessarily a disadvantage. It is possible that an 8-car train may require a person in addition to the operator because it may not be practical for a single operator to provide the necessary services over a 600 ft. distance (8-car) train. Certainly, the

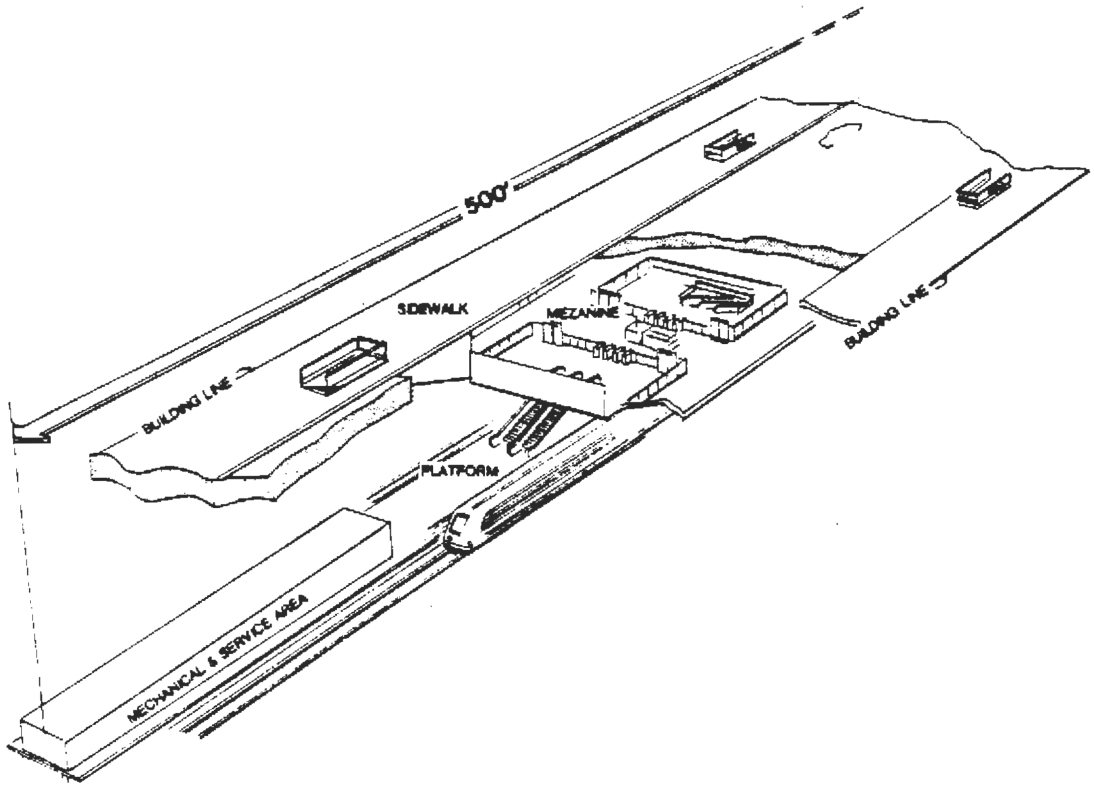


Figure 4 - Station for Alternative System No. 1 - Level Guideways
(500 ft. overall length - 300 ft. long platforms)

4-car trains with the shorter headway 2 min will provide improved service over the 8-car trains with 4 min headways. Shorter headways are a factor for encouraging increased use of a transit system. It should be pointed out that with automatic train operation, headways down to 90 sec appear to be safe even for the dipped guideway.

- Less walking inside stations.
  This will simplify security and minimize maintenance.
- Less surface disruption during construction.
  Even less for the over/under concept (later alternatives).

- Increased energy savings of dipped guideway (later alternatives). The sooner the train center-of-gravity reaches maximum grade, the less traction energy is required to achieve a given station-to-station transit time.

Major capital cost savings can also be accomplished in the guideway. The baseline tunnel liners are made of steel. The use of pre-cast segmented concrete liners will reduce the cost by about $600 per lineal ft of tunnel resulting in a saving of about $107M for the tunnels. Another saving that can be achieved in the guideway cost is to integrate the construction of the cross-overs and lay-ups with the stations. Although the savings for this change are really applicable to both the station and the guideway, they are all being allocated to the guideway. This saving is about $21M. Hence, the total capital cost savings for the stations and guideways of this Level alternative is around $262M or about 22% of the hypothetical baseline system.

2. No. 2 - Dipped Guideways

The utilization of gravity to assist in accelerating and decelerating the trains can decrease the energy requirements by as much as 70% for traction effort and 88% for braking (see Figure 5) for the same station-to-station transit time as for the level case.

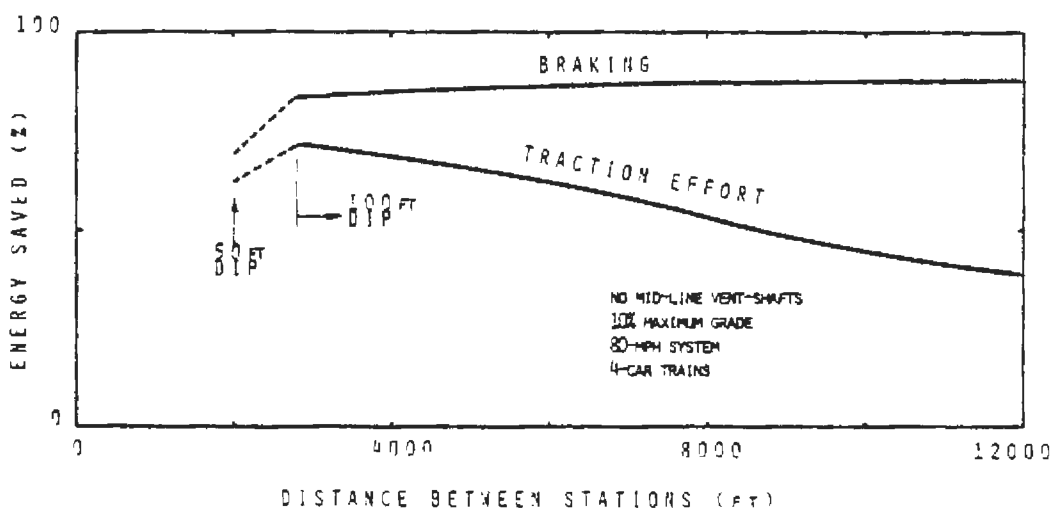


Figure 5 - Effect of Station Spacing on Energy Saved of Dipped Tunnel Over Level Guideway

Use of dipped guideways of greater depth and/or grade than that shown in Figure 6 will result in even more energy savings.

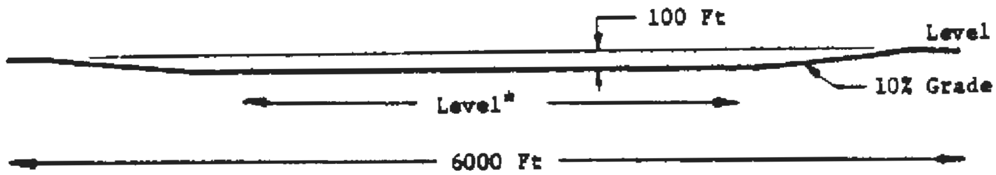


Figure 6 - Example of Dipped Guideway Profile (To Scale)

The overall saving in traction effort energy possible for a dipped system is expected to be about 50%. This is less than the maximum potential saving because of the various station spacings and the occasional deviations from nominal operating schedules. The large decreases in traction effort and braking energy significantly decrease the cost of providing acceptable environment in the stations and eliminate the need for mid-line vent shafts.

In order to utilize gravity assist, it is necessary to dip the guideway between adjacent stations. For the purposes of this study, the guideway dips 100 ft between stations separated by 4000 ft or more (50 ft dip for the 2000 ft segments) with a maximum grade of 10%. The 100 ft dip and 10% maximum grade are moderate in appearance, as can be seen in Figure 6 which is to scale. In order to keep the vertical accelerations below 0.1 g, the vertical radius at the top of the dip is 1500 ft; at the bottom it is 3000 ft.

The 10% grade is not expected to present any unacceptable operational problems. With moderate maintenance the coefficient of adhesion (μ) should be adequate to permit "push-out" from the bottom of the dip of a "dead" train by a following train. The values of μ for the current technology of slip control are even greater than those shown in Figure 7.

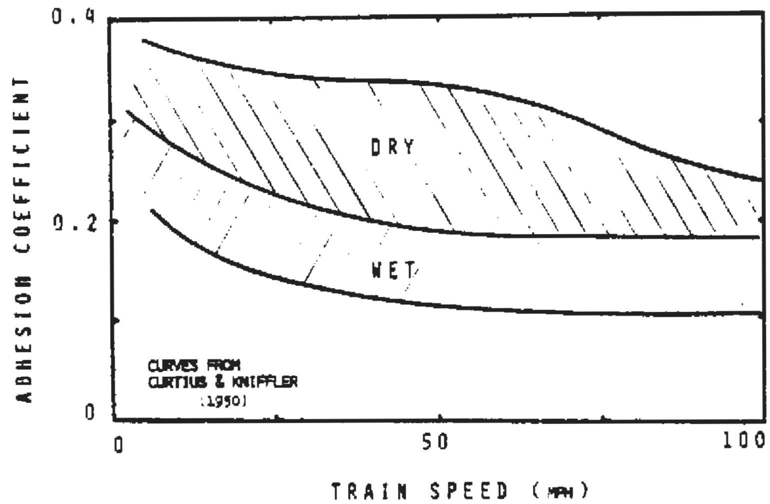


Figure 7 - Adhesion Curves for Steel Wheel on Steel Rail

An additional savings of approximately \$1M per station can be realized by decreasing the lengths of the utility areas in the stations from 100 ft on each end to 50 ft. Less space is needed due to the decreased requirements for tractive effort energy and air-conditioning because of the energy savings aspects of a dipped guideway. Also, the blast shaft requirements can be decreased since interventing between the adjacent tunnels is planned for 100-200 ft of the station ends. Assuming traditional construction methods, the cost of the dipped over the level guideway is about \$35M more due to outhauling muck up the 10% grade. However, due to the greatly decreased traction and braking energy requirements, no mid-line vent shafts are needed, hence saving about \$34M. In addition, costs for controlling the station environment are decreased. The overall capital savings of this system would be at least \$23M less than the level Alternative System No. 1. In addition to savings in capital costs, the use of dipped guideways will result in a saving in operating costs for the hypothetical 23½ mile long system. The electrical energy expected to be saved for traction effort and for controlling station environment is estimated to be about 115×10^6 KWH per year. At 5¢ per KWH, this is a \$5.7M saving per year. Assuming a

10% discount rate and no relative escalation in the cost of electrical power, this comes out to be a life cycle cost savings of some $57M (which can be considered equivalent to a saving in capital cost). If a relative escalation in the cost of electricity were included, the effective saving in capital cost would be greater.

In spite of the apprehensions expressed by both designers and operators, it is believed that 10% grades are not excessive. If adequate cleanliness of the rail were maintained, a coefficient of adhesion between the steel wheel and rail of 0.25 or more could be assured even on wet track. This would be adequate to permit a following-train to push a free-wheeling power-off train up the grade to the next station in the unlikely event it becomes necessary. This would require good slip control and the ability to overload the motors of the pushing train for the short period of time required to travel some 1000 ft up the 10% grade.

A listing of some of the major benefits of a 100 ft dip with 10% maximum grade are:

- Decrease traction effort energy by as much as 70%.
- Decrease braking heat energy by as much as 88%.
- Decrease station air temperature control requirements by 28%.
- Eliminate mid-line vent shafts for ventilation.
- Decrease transit time (which can be used to increase operational flexibility).
- Permit alternative designs of subway train propulsion configurations since less power per consist is required to maintain transit time than on level guideway.
- Allow stations to be above, on or just below surface (they do not have to be deep to match deep tunnels).
- Results in smoother (less) perceived acceleration and braking.

Because of the many benefits of the dipped guideways, it is worth further investigation into the matter of maximum acceptable grade in the dips. It should be pointed out that limiting the maximum grade in the dipped guideway to 5% would result in an energy savings of about 75% of the savings indicated for the 10% maximum grade that was studied.

3. No. 3 - Dipped Guideways with Over/Under Tunnels and Stations

Normally, twin single-track tunnels are located side-by-side (Baseline and Alternatives 1 and 2). This results in having stations with the pair of opposing tracks at the same level, hence, requiring a wide cut-and-cover excavation planform. For stations with the tracks one above the other (over/under), the cut-and-cover volume is reduced by 25%. The planform area is reduced by 50% from the Baseline station, which, in turn, reduces interference with utilities and disruption on street surface activities, hence the construction costs, can be significantly reduced. Furthermore, this configuration (see Figure 8) makes it practical to have loading platforms on both sides of the track and still fall well within the width of a street at stations with heavy patronage, thereby allowing for through-loading (passengers exit from one side of the cars and enter from the other). This should materially reduce dwell time in such stations, and hence, improve the train's average speed along the route. This may be a much more effective way of reducing route block time than by further increasing the train's speed capabilities. Even with platforms on both sides of the track at every station, the total station costs are $3M less than for Alternative System No. 2. Limiting the number of stations with paltforms on both sides would substantially increase this saving. The principal of tailoring stations to the expected use should be considered, as it can be very effective in decreasing costs.

The cost of constructing the tunnels would be increased by $17M over Alternative System No. 2 because of possible added precision requirements of close-proximity, vertically-oriented, separately-bored tunnels. It was not possible to pursue the single-bore approach for the over/under tunnel configuration. Once various construction problems are solved, this may be lower in cost than two side-by-side 16 ft, 8 in. D tunnels. Surprisingly enough, the costs of the cross-overs and lay-ups are somewhat less for the over/under system than for the equivalent side-by-side system. By restricting the versatility of the cross-overs and lay-ups to that deemed just essential, additional saving in construction costs of $31M would result. This saving was not included in the costs in Table 2.

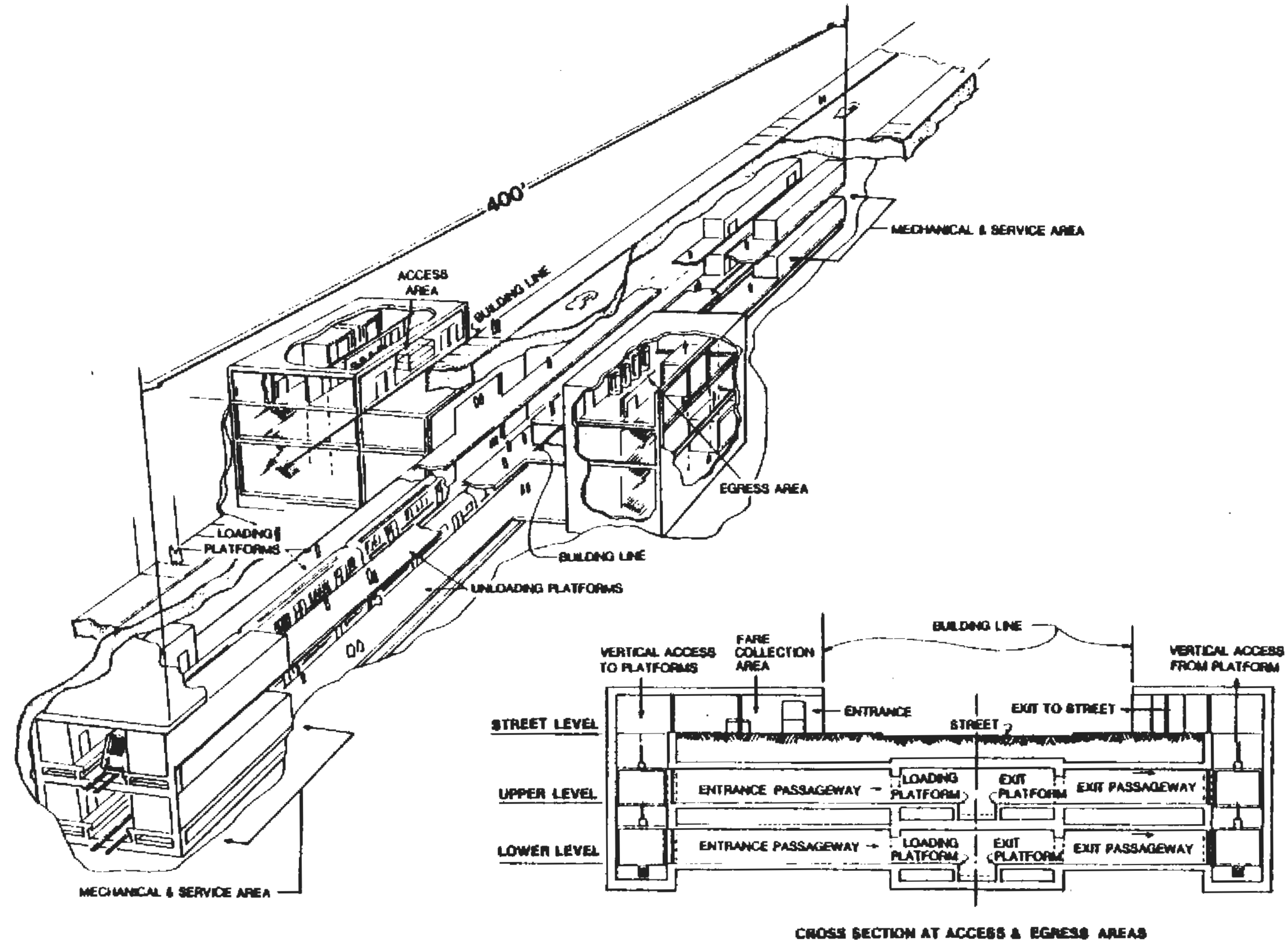


Figure 8 - Over/Under Station (400 ft Overall Length - 300 ft Long Platform)

The capital cost of this system is at most only \$14M more than for the Alternative No. 1 (Level) system. This \$14M could be made up in operating electrical power costs if it is decided to run the trains at lower performance levels, and yet maintain the same effective system speed because through-loading results in shorter station dwell times.

Perhaps for safety reasons one might consider having a single mid-line vent in every segment of the route that is 4000 ft or longer, the longest being 12,000 ft. If so, this would add \$32M to the capital costs. It should be pointed out the companion tunnel offers convenient safety to riders or maintenance personnel who must be evacuated from a particular tunnel due to fire or smoke. It may be more acceptable because of the relative ease of egress: a cross-passage would never be more than 300 ft away while the mid-line shaft can be 1000 ft away; the mid-line shaft would have a long stairway (from 80 ft for a level system to several hundred feet for a dipped system). The acceptability of the companion tunnel in lieu of mid-line shafts for safety considerations has already been established (i.e., in the Transbay tube and the Berkeley Hills tunnel of the BART system).

A summary of the estimated costs of the various systems discussed above is shown in Table 2.

The tunneling costs for all the systems presented are based upon a tunnel boring machine (TBM) advance rate of 61 ft per day. With the continuous improvement in TBM's and muck handling, it is reasonable to expect that an advance rate of at least 100 ft per day will be achievable in the geology assumed for this study. This would decrease the tunnel construction costs by about \$31M. This source of potential savings is certainly significant enough to encourage further development in tunneling technology.

Should car designs with lower heights be made available, then tunnels with smaller diameters may be practical. Tunnels that are 2 feet less in diameter than the baseline tunnels were estimated to result in a \$29M saving.

TABLE 2

Estimated Cost Comparisons of Alternative Systems
($\$10^6$)

	Baseline	Alternatives (1) Level	(2) Dipped	(3) Dipped-O/U
Cars (250)	135	135	135	135
Guideway	636	508(80)	509(80)	526(83) #
Stations	435	301(69)	277(64)	274(63)
Total	1206	944(78)	921(76)	935(78) #
Electrical Power* per year				
Amount 10^6KWH	235	240	120	120
Cost $\$10^6$(5¢/KWH)	11.7	12(102)	6(51)	6(51)

(Quantities in parenthesis are percent of respective Baseline values.)

*For traction effort and station air-conditioning only.

#Can be decreased by $31M by minimizing versatility of cross-overs and lay-ups.

The cost of mining stations of the same design as already described was estimated to be about double that of cut-and-cover construction. Perhaps the design of the stations can be changed in such a way as to make the cost of mining attractive. This should be looked into because of the relatively negligible societal disruption aspects of mined over cut-and-cover construction techniques.

D. Cost Analysis of Dipped Tunnels

In order to optimize the design of a transit system, it is necessary to develop a quantitative understanding of the total cost impact due to changes in every element of a complete system. A step that would improve the process in obtaining that understanding is shown by the following simplified analysis that was performed on the trade-off of tunneling construction costs of a dipped guideway against the expected energy costs over the life of the system. Normal life cycle, present-value costing process was used in which an inflation rate of 8% per year was assumed for the electrical energy costs and 10% per year discount rate was applied to these projected energy savings. These rates were arbitrarily chosen and are not considered to be necessarily the realistic ones for the next decade. For convenience, the tunneling costs were taken to occur at a single point in time expressed in average 1976 dollars (same as for all other cost estimates in this report).

For the purposes of carrying out a cost trade-off analysis, it is useful to plot the energy savings of a dipped guideway in the contour method shown in Figure 9. The information for this figure was obtained from computer studies of the energy requirements of a subway train in a dipped tunnel (Vol. IIA). It is interesting to note that the energy requirements can increase, rather than decrease, once the depth or the maximum grade has increased beyond a certain point. For the 80 mph system being considered, this point occurs at rather large depths and grades so this reversal in energy savings probably has no impact on a practical dipped system.

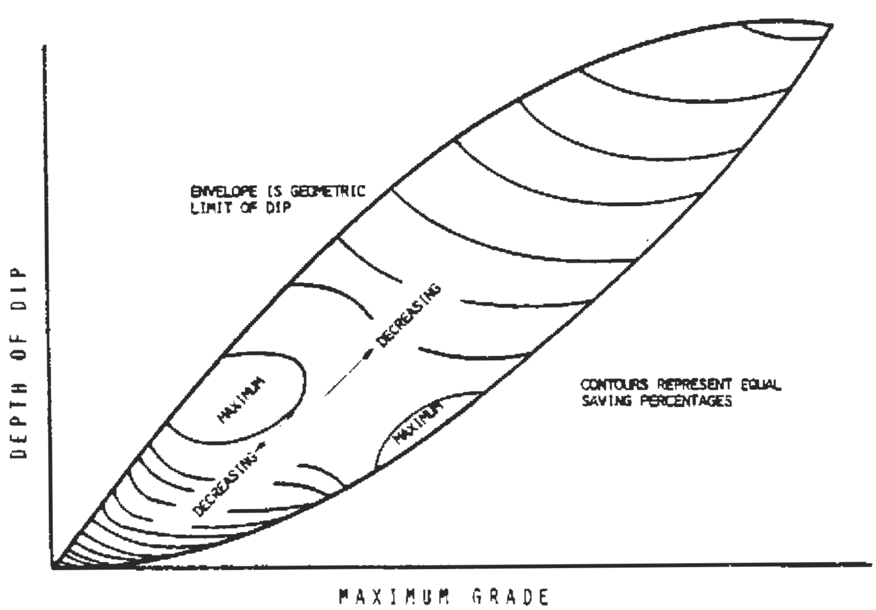


Figure 9 - Traction Effort Energy Savings of Dipped Guideway Over Level Tunnel

Tunneling costs are dependent upon the maximum grade, and there may be a discontinuity in these costs with grade if a change is required in the construction method due to the increased grade. The requirement of mid-line vent shafts for ventilation purposes decreases as the energy saved increases . . . and beyond a certain energy savings there is no longer a need for such shafts. However, up to this point, the construction costs of the shafts increase as the depth of the dipped guideway increases. When these construction costs are combined with the energy savings, it is possible to perform a present value analysis of tunnel construction costs and traction effort energy expressed in terms of equivalent proportional change in initial construction dollars. This was done for the example shown in Figure 10.

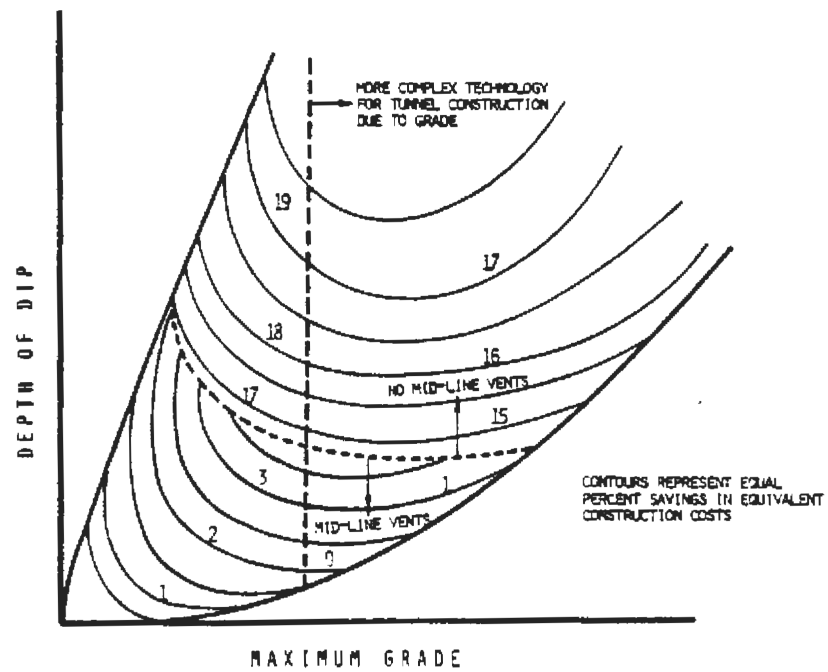


Figure 10 - Effective Savings in Tunnel Construction Costs Due to Dipped Guideway

The discontinuities in the effective cost savings contour are due to:

- Elimination of mid-line vent shafts once sufficient energy savings exist.
- Change of muck hauling approach beyond a certain grade.

Such discontinuities have a dominating effect on the resulting cost effectiveness of a dipped guideway. Therefore, in an actual design process, precise knowledge of where the discontinuities occur and their exact magnitude is essential. It should not be construed that the above indicated discontinuities are the only ones that exist. There could very well be others, such as for system maintenance and some means to augment the adhesion of the train should the grade be greater than 10%. For this investigation, two discontinuities were somewhat arbitrarily established in order to demonstrate their importance in the process. Furthermore, there are elements not having discontinuities that have also been omitted. In a realistic cost analysis for determining an optimum system, all elements must be properly included. This simple example serves to demonstrate the process that should be followed during system design.

E. Energy Conservation

1. Storage

The dipped guideway is one form of energy conservation by storage that can be used in a subway transit system. Another familiar method for storing kinetic energy is by the use of flywheels, either onboard or wayside. From the limited analysis of this study, it is not clear which flywheel location is optimum. The initial costs are higher for the onboard location, but the energy savings aspects may also be greater because of the limitation of the guideway distribution system for accepting much of a voltage variation for returning the energy to wayside flywheels. The increased cost of tunnel construction ($35M) due to the 10% grade of the dipped system is double the increased cost of having onboard flywheels ($17.5M for 250 cars at $70K/car). The onboard flywheel will increase the weight of each car by about 8000 pounds (the baseline propulsion system weight is 10,000 lbs). However, the anticipated savings in traction effort energy of the dipped guideway is double that of the onboard flywheel (50% vs. 25%). If the maximum grade of the dipped system were no more than 5%, the energy savings would be 37% and 25%, respectively, but the tunneling cost increase would then be about half of the increase in vehicle cost. It is assumed for the preceding comparisons that no mid-line vent shafts are required for either approach. Until a thorough design study and cost analysis are conducted, it is not possible to make a final choice. It should be pointed out that a realistic transit system may include level segments. This will influence the comparison.

2. Redistribution

The electrical energy generated during braking can be redistributed, rather than stored in the dipped guideway or in flywheels, or released into the tunnel environment by way of the resistor grids. For the baseline system, less than 5% savings can be obtained by energy regeneration to nearby trains. Energy regeneration back into the electrical utility grid would result in 8% savings.

3. Operational Control Policy

Another form of energy conservation deserving special attention is the rigid control of the power profile of a train's propulsion system. For a level system, up to 20% savings in electrical energy can be achieved by operating the train at 1% longer transit times than the minimum possible between stations. This slight extension in transit time is achieved by terminating the usual maximum acceleration to cruise speed sometime before reaching cruise speed (cruise speed being defined as the allowable civil speed, or if that was not yet reached, the speed at which braking is initiated) and then coast with power off until time to initiate braking to stop at the next station.

It is practical to do this for a system having automatic train operation. To accomplish it in a manually-run system may be difficult. Nevertheless, with the ever increasing shortage of energy and the continuous rise in electrical power costs, it may be worthwhile to incorporate this form of savings, especially since the effect on system effective speed is so slight. In principle, the slight increase in transit time can be made up by decreasing the station dwell time accordingly. To what degree this is practical is dependent upon the specific situation.

VI. RECOMMENDATIONS

It was necessary to limit the number of alternatives to be investigated in order to remain within the resource constraints of this study. Some of the approaches that were to be examined in enough depth to establish feasibility had to be eliminated because it was not possible to develop enough information in the time allocated to this study. These candidate approaches are listed in the two following paragraphs. It should be pointed out that even the alternative approaches that were found to be feasible in this study should be evaluated in a more thorough manner. This could be accomplished during a preliminary design trade-off study for a new or extended system.

Other alternative concepts that were only identified but merit study are listed with brief statements of possible advantages:

1. Stations on surface with dipped guideways: decrease cost of stations and yet have the guideways underground.
2. Elevated stations with guideways on surface, depressed or underground: use gravity assist to save power and improve speed.
3. Water (or air) curtains at tunnel portals to stations: minimize air blast and pressure pulses over loading platform.
4. Double-track tunnels: increase operational flexibility.
5. Advanced automatic train control system: obtain minimum safe headways for high-speed, high-capacity operation.

The depth of study of a number of alternatives was necessarily limited by the resource and time constraints of this study. It is believed that the following ones merit further study:

1. Single vertically-oriented oval bore for over/under tunnels.
2. Stations constructed by mining.
3. Train screens (solid wall with automatic doors for isolating the station platform from the guideway).

4. Various aspects of dipped guideways.
    a. Minimum practical headways.
    b. Maintenance.
    c. Operationally practical maximum grade for steel-on-steel system in a subway environment (include adhesion augmentation).
5. Higher voltage guideway electrification (AC and DC) with onboard AC motors.
6. Lower-height subway cars and locomotives (also consider higher blockage ratio).
7. Passenger handling between surface and platform.

Considerable information was generated during this study. However, its use was limited to the demonstration that less costly systems are feasible. With the acquisition of relatively small amounts of additional information, a meaningful parametric system trade-off study can be carried out. It would illustrate the cost impact of varying individual elements of the system and show what an optimum system design should be.

APPENDIX

Content of Vols. I and II

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*This Executive Summary is essentially comprised of these parts plus the Abstract.

VOL. IIA - SUPPORTING STUDIES: OPERATIONAL ASPECTS (152 Pages)

I JPL STUDIES ON

A. Performance and Energy Requirements

B. Effects of Dipped Guideways

C. Effects of Intervention

D. Operational Control Policies

II LONDON TRANSPORT (UNDERGROUND) STUDIES ON OPERATIONAL CONSIDERATIONS OF

A. Dipped Guideways

B. Headway and Dwell Time

C. Passenger Handling

D. Train Screens

VOL. IIB - SUPPORTING STUDIES: PRESSURE PULSE ANALYSIS (195 Pages)

I PRELIMINARY CONSIDERATIONS OF THE AERODYNAMICS OF DOUBLE TRACK TUNNELS by Dr. A. Hammitt

II COMPUTER STUDIES ON TUNNEL INTERVENTING by Prof. A. Vardy (Contains plots and tabulations for many geometries)

VOL. IIC - SUPPORTING STUDIES: CAPITAL EQUIPMENT (319 Pages)

I DESIGN AND COST ESTIMATES FOR UNDERGROUND STRUCTURES by Underground Technology Development Corporation

A. Introduction

B. Baseline System

C. Profile Graded System (Dipped Guideways)

D. The Over/Under System

E. Special Topics (Train Screens, Station Air Conditioning, Operational Safety)

F. Station Layouts

G. Selection of a "Best" Concept

H. Appendices (Geology and Cost Analysis Details)

II PERFORMANCE AND COSTS OF PROPULSION FOR A HIGH-SPEED MASS TRANSIT SYSTEM by Garrett-AiResearch Manufacturing Company

A. Introduction

B. Baseline Car - Characteristics and Performance

C. Effects of Energy Conservation on Baseline (Includes direct operating cost analysis)

D. Dipped Profile Performance and Costs

E. AC Wayside System and Traction Equipment