Report No: UMTA-CA-12-345-82-1

GRAVITY-ASSISTED RAIL TRANSIT (GART)

Volume I: Summary

Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

(JPL PUBLICATION 82-106)

April 1982

FINAL REPORT

This Document is available to the U.S. Public through the National Technical Information Service, Springfield, Virginia 22161

Prepared for

U.S. DEPARTMENT OF TRANSPORTATION

Urban Mass Transportation Administration
Office of Rail and Construction Technology
Washington, D.C. 20590

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The research described in this report was carried out by the Jet Propulsion Laboratory, California Institute of Technology, and was sponsored by the Department of Transportation through an agreement with the National Aeronautics and Space Administration.

FOREWORD

This summary report contains the unedited versions of the summaries and/or conclusions from the reports (References 1-4) by the four consultants involved in this study. For clarity, a comment page was added by JPL since some key information from other portions of the consultants' reports is not included in the excerpts. Their complete reports are contained in a separate Appendix volume (Reference 5) which can be obtained directly from JPL or NTIS.

JPL carried out a number of brief studies. Since they are quite short, they are included in their entirety in this summary report. These JPL studies extend the consultant efforts, provide for a uniform set of conditions for relating the consultants studies on a common basis, and address some issues that were not included in the consultants scope of effort.

The JPL summary (Findings section) of the study is felt to be a realistic assessment of the key issues of this study of the Gravity Assisted Rail Transit (GART) system for future subway rail transit systems.

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16. Abstract

his study investigated several system operational aspects of Gravity-Assisted Rail Transit (GART) or mined urban subways which were not studied in depth during previous feasibility studies: perational stability (minimum acceptable headways); traction aspects (especially push-out from the ottom of a dipped guideway); and ventilation (with emphasis on fire safety). In addition, a eevaluation of the cost differential of tunnel construction for a GART guideway compared to a onventional (essentially level) system was obtained. These studies were carried out by consultants elected from among those considered to be recognized experts in their respective fields. No major roblems (safety, technical, or cost) were found for a GART system relative to a conventional ystem. The operational stability of a GART system is generally superior to that of a conventional ystem. Present day operational technology ensures that traction and motor power are adequate for a ollowing train to push-out a "dead" train up a 10-percent grade for a 100-ft rise. Because of the ravity assist, considerable coasting is possible while still matching the minimum transit time of a onventional system. As a consequence, a GART system will cost significantly less to operate than a onventional system due to much less traction energy and peak power requirements, less ventilation, id air-conditioning requirements; and increased reliability in train subsystems because of lower ider-car temperatures and less motor and braking demands. Furthermore, a GART system will not cost ignificantly, if any, more to construct than a conventional system. The slight increase in inneling costs due to the increased grades and the additional fire-safety requirements will be ountered by lower ventilation and air-conditioning requirements and less impact of guideway onstruction upon utilities and nearby structures.

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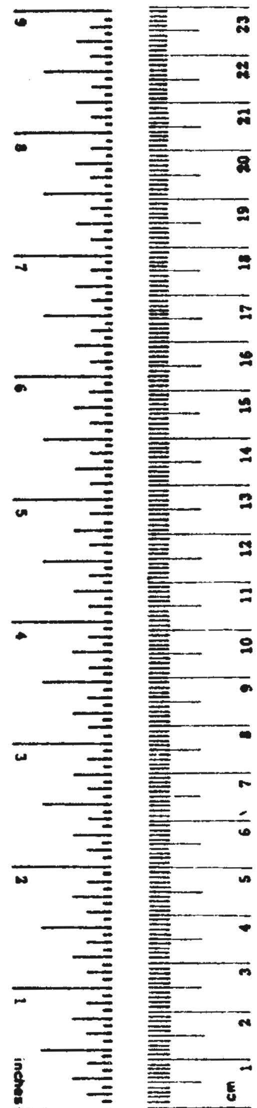
METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

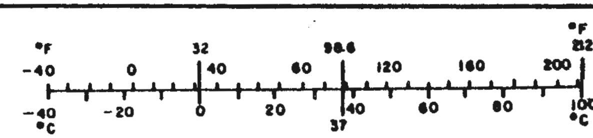
Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.



Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



ACKNOWLEDGMENTS

JPL is very appreciative of the four consulting organizations and their contributing staffs for their enthusiastic involvement in the study of a Gravity Assisted Rail Transit (GART) systems. As with all R&D studies, it required great effort to identify and focus on the key issues and evaluate them within the limited scope of the effort. It is gratifying to know that they were all successful in their respective areas of endeavor. The continual interchange of opinions and the resolution of the differences were essential to the meaningfulness of this summary report on GART compared to conventional ("level") subway systems.

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SECTION 1. INTRODUCTION

1.1 BACKGROUND

The Office of the Secretary of the U. S. Department of Transportation (DOT) had JPL carry out a study on innovative design features based upon proven technology for subway rapid rail transit systems. This resulted in a set of reports listed as Reference 6. One important finding of this previous study is the significant savings (greater than 50%) in traction energy that could result from the use of gravity to aid in the acceleration and deceleration phases of station-to-station operation. This was accomplished by the use of extensive coasting while still matching the minimum (or longer) transit times of a conventional subway system having level (or at least essentially constant grades) between stations. Subsequently, the Urban Mass Transportation Administration (UMTA) of DOT requested that JPL study the system cost and service aspects of tunnel diameter and short subway trains (four cars) compared to the usual long trains of 8-10 cars (with their 2-3 minute headways) along with another look at the tunneling costs of dipped vs. level guideways. This work is reported in Reference 7. In addition to verifying that the tunneling cost difference was indeed small, this study showed that GART results in significant capital cost savings (about 30%) for operation with shorter trains on less headway which improved service (less waiting between trains) and maintained high capacity (32,000 riders per hour in each direction).

It should be noted that gravity-assisted rail transit systems (dipped guideways) have been proposed and used since the first subways were built in the 1800s. The increasing tendency to use mined rather than cut-and-cover tunnel construction techniques, along with the continuing dramatic rise in energy costs, have greatly stimulated the present interest in GART. Although the recent studies (References 6 and 7) show great promise for dipped guideways, some perceived problems prevented the GART approach from being fully accepted as a viable approach.

For example, a common reaction is that GART may work well in theory, but on a busy rapid transit line subject to random delays, GART could result in overall greater energy consumption because trains would be required to apply power on the upgrade portion of a dip because they had to slow down or stop in the dipped portion of the GART guideway. Other inhibiting concerns are the handling of a disabled train at the bottom of a dip and the fire safety consequences of dipped guideways which have segments that can be far deeper than those of conventional systems. Finally, in spite of the two studies, there was still concern over the construction cost differences of mined tunnels for GART vs. conventional systems. Therefore, UMTA had JPL perform this current study to investigate these areas of concern.

1.2 OBJECTIVES

The primary objective of this study was to investigate operational details of the GART system which were not studied in depth during the previous feasibility studies. The specific operational areas selected were: normal train operations (traction energy requirements and schedule stability, i.e., minimum acceptable headways); traction aspects (especially push out from the bottom of a dipped guideway); and ventilation (with emphasis on fire safety). The secondary objective was to obtain a re-evaluation of the cost differential of tunnel construction for a GART guideway compared to a conventional system.

These technical objectives were to be obtained in such a manner that the transit industry (operators, suppliers, builders and designers) would accept the findings.

1.3 APPROACH

The study was divided into five tasks. Consultants carried out the study areas in four specific areas. The fifth task was to coordinate the effort and to provide an overview (which culminated in this summary report). To ensure general acceptance of the study's findings, consultants were selected from among those considered to be recognized experts in their respective fields.

The contributing consultants for Tasks I-IV and key personnel are:

Tasks	Consultants	Key Personnel
I Operations	Gibbs & Hill, Inc.	David Weiss
II Traction/Push-Out	Louis T. Klauder & Associates	William Frandsen
III Ventilation and Safety	Kaiser Engineers, Inc.	R. E. Murphy W. W. Houppermans
IV Tunneling Costs		P. E. Sperry R. L. Lehman*
V Coordination/Overview	JPL	Bain Dayman Louis Rubenstein

* Of J. F. Shea Co., Inc.

All consultants were fully familiar with the studies of References 5 and 6 and with the objectives of this study. To the degree practical (performance time-schedules were not conducive to optimum coordination), each consultant was informed of the significant conditions and assumptions of the others and each was instructed to study the problem in light of his own knowledge and general engineering approach. In no way did JPL attempt to have any consultant carry out his assigned task in a manner that differed from any other study they would carry out. JPL's main coordination effort was to ensure that each consultant had the same understanding of the characteristics of GART and conventional subway systems so that the respective findings would relate well with each other.

SECTION 2. FINDINGS

2.1 OVERALL HIGHLIGHTS

No major problems (safety, technical or cost) were found for a Gravity-Assisted Rail Transit (GART) system relative to a conventional "level" (essentially constant grade in between adjacent stations) system that would detract from including a GART approach as a consideration for a viable subway system design. The GART system* has many distinct advantages over a conventional system and only a few disadvantages.

The normal operation of a GART system is generally superior to a conventional (level) system. At headways greater than 90 s, the operational stability of a GART system (having a 6% maximum grade) is superior to that of a conventional system. This is due primarily to the shorter travel time possible with GART by fully powering it until braking is initiated.

Currently operational technology ensures that traction and motor power are adequate for a following train to push out a "dead" train up a 10% grade. To ensure push-out capability up a 6% grade requires only proper slip-slide control; no major hardware revisions are necessary.

The GART system requires less than half the traction energy while matching the minimum transit time of a conventional system for normal operation on 6% grades and 80-ft dips. (The savings would be somewhat increased for greater grades and depths and vice versa.) Furthermore, the braking energy of GART is a small fraction of that for a conventional system (around 25% or less). A GART system also has the option of decreasing its peak power requirements by a substantial amount while matching the minimum run times of a conventional system and still saving nearly 50% of the traction energy. The operational requirements for maximizing the energy savings are readily implementable (full power on downgrades, coasting, and then full braking on the upgrade).

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* System implies an operational policy which takes advantage of the dipped guideways.

As a consequence of the large energy savings, station air-conditioning and tunnel ventilation requirements for normal operating conditions of a GART system are significantly lower than for a conventional system. On the other hand, as a consequence of the increased grades of the GART system, fire safety ventilation requirements of a GART system are substantially more than for a conventional system. This is to ensure that fresh air can be forced downgrade past a burning train.

A GART system will cost significantly less to operate than a conventional system. The savings are a result of less traction energy and peak power requirements, decreased air conditioning requirements; and expected increased reliability in train subsystems due to lower under-car temperatures and decreased motor and braking demands. Furthermore, a GART system will not cost significantly, if any, more to construct than a conventional system. The slight increase in tunneling costs, due to the increased grades and the additional fire-safety ventilation requirements, may be offset by the lower ventilation and air conditioning requirements and less impact of the guideway upon utilities and nearby structures with stations close to the surface, a more convenient location for the riders and for joint development opportunities. In any event, the life-cycle costs of the GART system would be lower than of an equivalent conventional system.

2.2 INDIVIDUAL HIGHLIGHTS

Gibbs & Hill, Inc.: In the matter of schedule stability, the GART systems will perform better than conventional systems at headways of 120 s or more. At 90 s, conventional systems will perform somewhat better. These comparisons are based upon the use of standard signaling systems and approaches.

The use of GART will reduce traction energy requirements by about 14% while decreasing transit time between station pairs by several seconds. (The coasting option necessary for matching run times of the level system was not included in this energy study*.) This significant energy saving was based

* When coasting is used on the GART guideway to match the minimum run time of the conventional level system, the traction energy savings would be more than triple the 14% figure (see page 7).

upon a very conservative dipped guideway design: imperceptible vertical acceleration; 6% maximum grades (3% for station spacings of 2600 ft); and 60-ft maximum dips (21 ft for station spacings of 2600 ft).

Louis T. Klauder & Associates: No serious obstacles exist in running multiple unit (MU) trains on grades up to 10% even with the push-out requirement. The standard motor would be sufficient for push-out on a 6% grade and would need little, if any, redesign for the 10% case. In either case, current state-of-the-art operations slip-slide controls must be incorporated to ensure the required adhesion for push-out. Once incorporated, push-out on a 6% grade can be accomplished for virtually any foreseeable condition. However, because of weight transfer problems, there are some conditions under which push-out cannot be accomplished for 10% grades. One such condition is a fully loaded train pushed out by a lightly loaded train. If such a case occurs, two trains would be required to accomplish the push-out. In no case are any problems anticipated for starting up a grade or stopping on a grade (as long as stopping distance is not a critical factor on a downgrade).

Kaiser Engineers, Inc.: For comfort control, the GART guideway results in substantially less station air conditioning and guideway ventilation loads than the level system. For example, a GART system with no mid-line ventilation shafts requires about 10% less air conditioning at the stations than a level system with a mid-line ventilation shafts. It is interesting to note that, at the severest outdoor ambient conditions, a GART system runs cooler with no mid-line ventilation shafts than with them. However, in the case of a level system, if there are no mid-line ventilation shafts, then the station air conditioning must be increased above the 10% more than the GART system. These results are for the case when the GART system is on partial coast, and its inter-station travel time is still several seconds less than for the least time the level system is capable of attaining.

The air conditioning-ventilation requirements for a transit time matching GART system would be further decreased than shown in this study. However, this conservative comparison should adequately account for the occasional times a train will have to power up a grade instead of the planned coasting into the station. Considerably less braking effort is required for the GART system than for level systems, resulting in far lower temperatures in the resistor grids. This then results in lower temperatures for the many nearby subsystems located underneath the car or, at least, in fewer heat protection requirements for them.

Twin single-track tunnels result in lower ventilation and air conditioning requirements than double-track tunnel systems. This is due to the substantial amount of induced air flow in single-track tunnels. The air flow induced in a double-track tunnel is considerably lower because of the flow-reversing effect of trains running in opposite directions even if only one train is in the tunnel at a time. Twin tunnels also provide the practicality of a secure fire evacuation route, i.e., use the other tunnel.

In the case of fire safety, a mid-line ventilation shaft is not required for a level system for blowing an adequate amount of air past a burning train; the normally-sized fans in the ventilation shafts located at the ends of the stations are adequate. But because of the requirement of blowing hot air downhill past a burning train stalled on a grade, fans of substantially larger capacity are required for a GART system at the stations if there are no mid-line ventilation shafts with fans. This requirement could be greatly decreased or eliminated by inhibiting the air flow between the station-end ventilation shafts and the station itself. This could be done with a water curtain or a retractable membrane. Although this would also be helpful to the conventional level system, it will minimize the fire safety ventilation requirement differences between the two systems.

P. E. Sperry & R. L. Lehman: Tunneling costs for a GART guideway are only slightly more than for a typical "level" system: 2% more for a 6% maximum grade and 4% more for a 10% maximum grade. These differences compare favorably with the estimates of References 5 and 6. These cost differences are independent of the guideway depth for most of the Los Angeles basin extensive alluvial geology if there are no nearby surface structures.

The costs were not included for mid-line ventilation shafts, utility relocation, and work on nearby building foundations. It is reasonable to expect the deeper guideways will incur less additional expense due to the presence of utilities and structures, and that GART guideways would be deeper (on the average) than those of level systems. As a mid-line ventilation shaft is desirable for a level system, its cost will increase as the guideway depth is increased to avoid problems with surface structures.

JPL

Traction Energy: The dipped guideway of the GART system allows for options in the transit time and traction energy savings between stations. One option was illustrated by the Gibbs & Hill study where the minimum transit time option of GART was selected, resulting in a decrease of several seconds in transit time between stations, while still saving about 14% in traction energy. Had coasting been incorporated so that the transit time on the GART system depicted by Gibbs & Hill matched the minimum time for the level system, the energy saving would be about 44%, triple the 14% they had indicated. This 44% energy savings would increase to 57% by a slight increase in the vertical curvature rate, still with a 6% maximum grade.

The Gibbs & Hill analysis did not consider the effects of coasting on traction energy on either GART or level systems, as this would have required modification of their existing computer simulation models. Such a modification would have required resources in excess of those available for the overall study. JPL had previously developed a computer program (Reference 6) that could calculate the traction and braking energies for dipped guideways where the train accelerates (at partial or full power) into the dip, coasts, and then brakes to a stop at the next station.

The Kaiser Engineers (KE) study selected an operational mode that combined the transit and energy saving features of the GART guideway: they incorporated partial coast, hence achieving about half the maximum time savings while still achieving most of the energy savings. By extending the coasting period to increase the transit time 4 s to match the minimum of the level guideway, the traction energy savings would then be nearly 70% (a significant increase from the 50% of their studies). This matching of transit time would further decrease the required station air conditioning and under car temperatures for the GART system. It was also beyond the available resources for KE to match the GART transit time to the minimum transit time of the level system. The effect of transit time on energy savings is described in detail in Section J of Reference 6.

Another viable option of the GART system is the capability of effecting substantial decreases in the peak power requirements and still matching the transit times of the level system while retaining nearly all of the energy saving aspects. This can result in a 40% decrease in the peak power requirements. If the energy costs are based upon peak demand as well as amount used, this option could result in significant savings in energy costs.

Vertical Curvature: The rate of transition from level to maximum grade affects the performance of a GART system. The 100 ft length per percent grade change selected by Gibbs & Hill for their studies results in an imperceptible vertical acceleration to the riders. This is believed to be an unnecessarily conservative requirement, especially since it does have considerable impact upon the traction energy savings. The effect is small for longer station spacings when the amount of maximum grade or the depth of the dip is not affected, but is large for station spacings below 3000 ft where the dip depth is limited. By using a vertical curvature rate of 50 ft/% grade change, the maximum grade can reach 6% for station spacings down to 2600 ft. The vertical acceleration will then be felt by the riders, but will be considerably less than either the longitudinal accelerations due to speed accelerations and braking and lateral accelerations due to horizontal turns. Furthermore, at levels of about 0.1 g, the vertical accelerations are more tolerable than the other two; it can barely be felt and it does not cause riders to lose their balance.

Car Reliability: For the case of the Kaiser Engineers study, the maximum brake grid resistor temperatures are about 500°F less for a GART system than for a typical level system. Had the GART inter-station transit time been increased 4 s by extending the coasting time to match the minimum time of the level system, the maximum grid resistor temperatures for the GART system would be decreased even more. For the 500°F difference, it is estimated that nearby-located components will have a 20 to 60% decrease in failure rate for the GART system over the level system. Otherwise, additional active and/or passive (insulation) cooling or a higher standard of components must be incorporated into the level system cars to match the reliability of the GART cars.

<u>Operations</u>: For 6% maximum grades, the Gibbs & Hill GART system has the option of saving 2 to 6 s of transit time between stations (2 s for the 2000-ft spacing). The time savings would be larger for a less restrictive vertical profile than their 100 ft/% grade change. For the 10% maximum grade GART system assumed for the 5000-ft station spacing of the Kaiser Engineer studies, the time savings option is 8 s.

This time saving can be very beneficial in recovering schedule if a problem arises. This was shown in the Gibbs & Hill study where the capacity is larger for the GART system than the level system for headways greater than 90 s. It is believed by JPL that a more interactive control system would further improve the GART headway/capacity capabilities over the level system. With current operational technology, tighter limits on train speeds in the station region along with shorter (or moving) blocks will virtually eliminate the one operational disadvantage of the GART system over the level system: the need to provide for braking on the downslope just past the station.

SECTION 3. REFERENCES

1. Operations Analysis of Gravity-Assisted Rapid Transit, Final Report by Gibbs & Hill on JPL No. Contract 955934, October 1981.

2. Assessment of the Impact of Dipped Guideways on Urban Rail Transit Systems: Traction and Push-Out Studies, Final Report by Louis T. Klauder & Associates on JPL Contract No. 955987, July 1981.

3. Assessment of the Impact of Dipped Guideways on Urban Rail Transit Systems: Ventilation and Safety Requirements, by Kaiser Engineers, Inc., on JPL Contract No. 956018, Report No. 82-008-R, January 1982.

4. Additional Construction Costs of Dipped Guideways for Urban Subway Rail Systems, Final Report by P. E. Sperry and R. L. Lehman on JPL P.O. No. MP-730117, March 1981.

5. Gravity-Assisted Rail Transit (GART) - Volume II: Consultant's Reports*, Report No. UMTA-CA-12-345-82-II by JPL, April 1982.

6. Alternative Concepts for Underground Rapid Transit Systems (ACURTS), Report No. DOT-TST-77-31 by JPL, March 1977.

7. Effects of Tunnel and Station Size on the Costs and Service of Subway Transit Systems, Report No. UMTA-CA-06-0116-79-2 by JPL, November 1979.

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* Contains the above References 1-4 in their entirety.

SECTION 4.

CONSULTANT STUDY SUMMARIES/CONCLUSIONS

4.1 OPERATIONS

An unedited reprint of the abstract, summary and conclusions of the Gibbs and Hill report (Ref. 1) is presented. Notes by JPL appear below:

The conclusions stated by Gibbs & Hill are based upon the following conditions:

1. Full power on GART guideway until braking initiated (hence transit time between stations significantly less than for level system).

2. Maximum conditions of GART guideway
   a. 6% grade (3% for 2600 ft station spacing)
   b. 60 ft dip (21 ft for 2600 ft station spacing)

3. Imperceptible vertical acceleration (less than 0.104 g)

4. Conventional signalling system (Each station-to-station track segment is divided into 6-11 blocks, depending upon station spacing, but is the the same whether the guideway is level or dipped).

5. Maximum train speed
   a. 70 mph for energy calculations
   b. 55 mph for headway studies

6. Maximum braking rates:
   a. 2.20 mphps for energy calculations
   b. 1.65 mphps headway studies

OPERATIONS ANALYSIS OF GRAVITY ASSISTED RAPID TRANSIT

Prepared for:

Jet Propulsion Laboratory
California Institute of Technology
4800 Oak Grove Drive
Pasadena California 91103

JPL Contract 955934

This work was performed for the Jet Propulsion Laboratory, California Institute of Technology, sponsored by the U.S. Department of Transportation, Urban Mass Transportation Administration, through an agreement with the National Aeronautics and Space Administration.

FINAL REPORT
October 1981

GIBBS & HILL, INC.
ENGINEERS DESIGNERS CONSTRUCTORS

ABSTRACT

This study compares in detail gravity assisted rapid transit (GART) with 6 percent grades before and after each station and conventional systems in terms of energy consumption, run time, line capacity and schedule stability under abnormal circumstances. The study draws on procedures and computer programs that have been applied to engineering designs and studies of actual transit systems.

Parametric analyses of run times and energy consumption include the impact of alternate accelerating and braking levels. The capacity analysis uses a network simulation program to determine the location and severity of all signal delays. Based on results of initial simulations, the block design was revised to eliminate bottlenecks in normal operations. The systems are then compared at headways of 80 to 180 seconds.

One month of incidence reports of a modern operating transit system are reviewed to determine the failures to be simulated. The impact of failures resulting in station delays (30 to 360 seconds), speed limit reduction (20 mph and 30 mph to one or more trains), vehicle performance (75 percent acceleration) are compared at scheduled headway of 90 to 180 seconds.

Results show that GART reduces energy consumption by 8-15 percent and that accelerating and coasting policies can provide similar savings to either system. GART operations perform as well or better than level systems at headways of 120 seconds and more. At 90 second headways the level system performs better due to an inherent advantage at maximum capacity.

II SUMMARY AND CONCLUSIONS

In this section the principal results and conclusions of the analyses discussed in Sections IV, V, VI and VII, and dealing with run time and energy consumption, crossover location, line capacity and failure impact, respectively, are covered. The results are based on comparison of two hypothetical guideway configurations, each similar in plan to the proposed Southern California Rapid Transit District system. However, the study is parametric in nature to preserve generality. Results are obtained for interstation distances ranging from 2600 feet to 13000 feet, for headways between 80 and 180 seconds, and for delay conditions of varying severity. Figures III-1 and III-2 show the guideway profiles.

a. Run Time and Energy Consumption

This analysis has been conducted using Gibbs & Hill's TRAPER single train performance calculator (TPC) computer program. The program has been widely used to perform similar computations for a number of operating rapid transit systems.

Comparisons between the dipped and level systems cover the effects of: interstation distance, acceleration and braking rate. The braking rate variation provides some indirect measure of the benefit of coasting since a lower braking rate causes trains to end acceleration and begin the station stop farther upstream. A more precise estimate of these benefits requires the explicit modeling of coasting policies. Results also cover criteria for the civil design of vertical curves. This is because the common design allowance of 100 feet of vertical curve for each one percent of grade change precludes the use of 6 percent grade in the shortest interstation distance, 2600 feet. A 6 percent grade is used for all the longer interstation distances.

Taking the last item first, two alternate vertical curve standards are considered: 60 feet and 80 feet of vertical curve for each one percent grade change. These criteria reduce the length of the vertical curve and permit the grades to be located closer to the stations. This has a small effect on run times.

The main effect of the baseline criterion is that it restricts the grades to 3 percent when stations are only 2600 feet apart. A 6 percent grade using the 100 foot criterion would need 600 foot vertical curves. Four vertical curves, each 600 feet long, separation of at least one train length between each, plus a 300 foot station add to 3600 feet. The 80 foot criterion enables a grade of 3.75 percent and the 60 foot criterion enables a grade of 5.0 percent.

The impact of the various vertical curve standards is greatest at the 2600 foot interstation pairs. The 80 foot criterion reduces run time by 0.4 percent and energy consumption by 1.4 percent compared with the 100 foot criterion. The 60 foot criterion would reduce run time by 1.1 percent and energy consumption by 5.5 percent. At the 5200 foot interstation distances the benefit is much less. The 60 foot criterion would reduce run time by 0.4 percent and energy consumption by 1.6 percent. The benefit diminishes at greater interstation distances since the proportion of energy expended maintaining speed increases. In view of the small incremental benefit in this study and the uncertain stature of these alternate criteria, the 100 foot vertical curve criterion was retained for the dipped guideway scheme.

The analysis shows that dipped guideways can significantly reduce energy consumption. Running time is also improved, but to a lesser extent. Table II-1 summarizes the results presented in Tables IV-3 and IV-6. It shows the range of percent increase or decrease that can be achieved by dipped or level guideways, at full or half acceleration, using full or 75 percent braking rate. The range is taken over the four different interstation distances tested for each case. As shown, all three measures reduce energy consumption but only the dipped guideways cut run time.

These results tend to confirm the energy savings reported in the JPL Study (op.cit.). The JPL study used 10 percent grades and different vehicle performance characteristics than are used in this study. Consequently, the total energy consumption on both dipped and level guideways in the JPL study is considerably higher than in this study. However, the percentage savings of the dip, at full acceleration and full braking, is about 15 percent in each study for the interstation distances of 5200 feet and more where the maximum dip is realized. At the shortest interstation distance a saving of about 8 percent is forecast in each study.

b. <u>Crossover Location</u>

Two locations for crossovers on the dipped system are considered. One is near the station before the dip begins. The other is in the middle of the dip. Operating requirements, such as the need to make smooth, programmed station stops even when the crossover signal is red or to turn back before descending the dip, preclude crossovers at the two shortest interstation distances studied, 2600 and 5200 feet. If crossovers are needed there, then a level guideway might be used.

TABLE II-1

Summary of Run Time and Energy Consumption Changes

Scheme	Acceleration & Braking	Run Time Changes	Energy Consumption Changes
Level	Full	----------------Baseline----------------	
Dipped	Accel, Brake	- 1.6% to - 3.6%	- 7.0% to -16.5%
Level	Half Accel,	+ 8.1% to +17.5%	-10.8% to -29.9%
Dipped	Full Brake	+ 3.5% to +12.8%	-26.4% to -36.9%
Level	Full Accel,	+ 3.4% to + 8.6%	- 1.2% to -5.1%
Dipped	3/4 Brake	+ 1.2% to + 5.7%	-12.1% to -19.3%
Level	Half Accel,	+11.6% to +23.9%	-12.2% to -34.4%
Dipped	3/4 Brake	+ 7.2% to +19.5%	-28.8% to -42.0%

Notes: Range is over four interstation distances

Car characteristics given in Appendix are those of the Washington Metro car. Maximum depth of dips is 60 feet.

If the crossover is located near the station, the beginning of the dip is farther from the station to avoid locating the crossover on a vertical curve and to allow space between the crossover and the dip for trains to reverse direction. (See Figure V-1a.) This displacement of the dip slightly reduces its benefits for normal operations. Locating the crossover between the dips, as shown in Figure V-1b, does not affect normal operations but is disadvantageous when rerouting is required. Trains must decelerate for the crossover and then accelerate again. The crossover speed limit in each case is 22 mph.

The alternate crossover locations are compared under two operating scenarios: when operations are normal and the crossover is not used and when the crossover is needed to switch tracks. In the first case, putting the crossover near the station saves both energy (6.8 percent to 8.7 percent) and run time (1.8 percent to 2.7 percent).

However, when the crossover is needed for switching, locating the crossover in the dip, between the grades, saves energy (41.7 percent to 48.1 percent) and run time (6.3 percent to 7.2 percent) depending on interstation distance. The reason for the larger differences in energy and run time is that trains must accelerate twice--once leaving the station and again when clearing the crossover. The run time advantage of putting the crossover near the station also results in improved headways because of the opposing moves involved.

c. Line Capacity

The capacity analysis is based on the use of Gibbs & Hill's TRANSPORT network simulation computer program. Other Gibbs & Hill programs were used to design the signalling systems for the dipped and level guideways.[1] All of these programs have been used in the past to perform similar tasks for operating rapid transit systems.

Several results stem from this part of the study.

1. The dipped system operates most efficiently at a moderately high speed, 55 mph or more. This is because trains accelerate to 55 mph at the bottom of the dip and are at this same speed on their stopping profile at the bottom of the upgrade leading to the next station. If the speed is lowered to increase capacity then trains will power up the lower portion of the upgrade.

[1] For a description of these programs and techniques, see D.M. Weiss and D.R. Fialkoff, "Analytical Approach To Railway Signal Block Design," ASCE Transportation Engineering Journal, February 1974.

2. If designed to operate only at top speed, the dipped system would have a lower minimum headway than the level system. Although each system operates well at two-minute headways at top speed, neither does well at 90-second headways.

3. To operate 90-second headways, it is necessary to reduce speeds in the station approaches. At these reduced speeds, the level system has an inherently greater capacity.

4. The final signal block designs, revised after analysis with TRANSPORT, permit minimum headways of 87-seconds on the dipped system and 81-seconds on the level system. This makes operation at 90 second headways more stable on the level system than on the dipped system. These values of minimum headway are near the theoretical limits, although further revision of the block designs might permit a small reduction.

The minimum headway is the lowest headway at which trains traveling at given speeds can operate if always separated by at least safe braking distance. This usually occurs when one train is leaving a station and the following train is approaching the station. At top speeds the critical point on the dipped system occurs when the following train is at the bottom of the upgrade. In this case the safe braking distance on the dipped system is less than that of the level system because of the influence of the grade on braking.

However, as speed is reduced to lower the minimum headway, the safe braking distance on both the dipped and level systems decreases and the critical point moves closer to the station entrance. At the station entrance however the safe braking distance for the dipped system is greater than that of the level system because of the influence of the downgrade leaving the station.

To transmit a given speed command in a block, a length of track equal to the safe braking distance must be clear downstream. A 40 mph command in the block preceding the station requires a clear track for 1240 feet on the level system. Since this length includes track downstream of the station, the downgrade on the dipped system raises the safe braking distance to 1970 feet.

Note that the safe braking distances are required by the signal system even where a train is scheduled to stop in a station. This is because station stopping is not enforced by the signal system. The assumptions for safe braking distance are more conservative than those of the nominal station stopping brake rate. See Section III.c.

d. Failure Impact

An analysis of the incident reports and summary operating statistics for the Washington Metro was used to identify typical failures and to determine the range of durations of each. Since the purpose of this analysis is to distinguish the impact of failures on the dipped and level system, major failures that result in system paralysis or call for the intervention of a dispatcher were not studied.

Four types of failures are simulated: minor station delays (30 and 60 seconds), major station delays (180 and 360 seconds), acceleration limit for one train (75 percent), acceleration limit for all trains (three stations and systemwide, 50 percent) and top speed limit for all trains (one station, 20 mph and 30 mph). All failures are simulated on both the dipped and level guideways at each of three operating headways: 90 seconds, 120 seconds and 180 seconds. A total of 54 experiments are performed.

In each experiment, a fleet of trains at each headway is dispatched at one terminal, the failure occurs and the run time of each train in the fleet is measured to each station. These times are compared to a control run time in which no failure occurred. The difference in run time for each train in the fleet is tabulated to determine the impact of the failure. The results of the failure experiments are discussed in detail in Section VII.

In general, the dipped system performs as well or better than the level system at headways of 120 seconds or more. At 90 second headways the level system is usually superior due to its inherent capacity advantage.

Station Delays

In these experiments one train is held at the fourth station for between 30 and 360 additional seconds extra. The results are that when delays are major (180 seconds or 360 seconds) or when headways are at their peak (90 seconds) the impact of the failure is more severe on the dipped system. This is because the minimum headway of the level system is less than that of the dipped system (81 seconds versus 87 seconds).

The impact on the level system is greater in the minor delays. The reason for this turnabout is that when the system is less saturated and trains run at top speed the dipped system has more capacity. This is because at higher speeds the safe braking distance is greater and causes the critical headway point to occur farther from the station. On the dipped system it occurs at the bottom of the dip instead of the entrance to the station as at minimum headway. At the bottom of the dip, the safe braking distance is less than that of the level system.

Acceleration Limits

In general, acceleration failures cause smaller delays on the dipped system because motive power provides only a portion of the total power. This is shown in the following table.

Failure	Run Time Increase (seconds)	
	Dipped System	Level System
Half Acceleration, 3 Stations	26	34
Half Acceleration, Systemwide	145	203
75% Acceleration, One Train	50	69

The minimum headway acceleration failures increase the time for trains to clear away from stations. When this occurs on the dipped system, the minimum headway becomes greater than the 90 second operating headway. Thus although delays are less than the level system at 180 and 120 seconds, the dipped system cannot operate at 90 second headways while the level can.

Top Speed Limits

The top speed limit is imposed between the first and second stations. The 20 mph limit adds 60 seconds of run time to the dipped system and 64 seconds to the level system. The 30 mph limit increases run times 31 and 32 seconds respectively. The 30 mph limit does not create any additonal delays for either system at any headway. The 20 mph limit permits scheduled headways of 180 or 120 seconds but both systems break down during 90 second operations.

Figure III - 2 Guideway Profiles

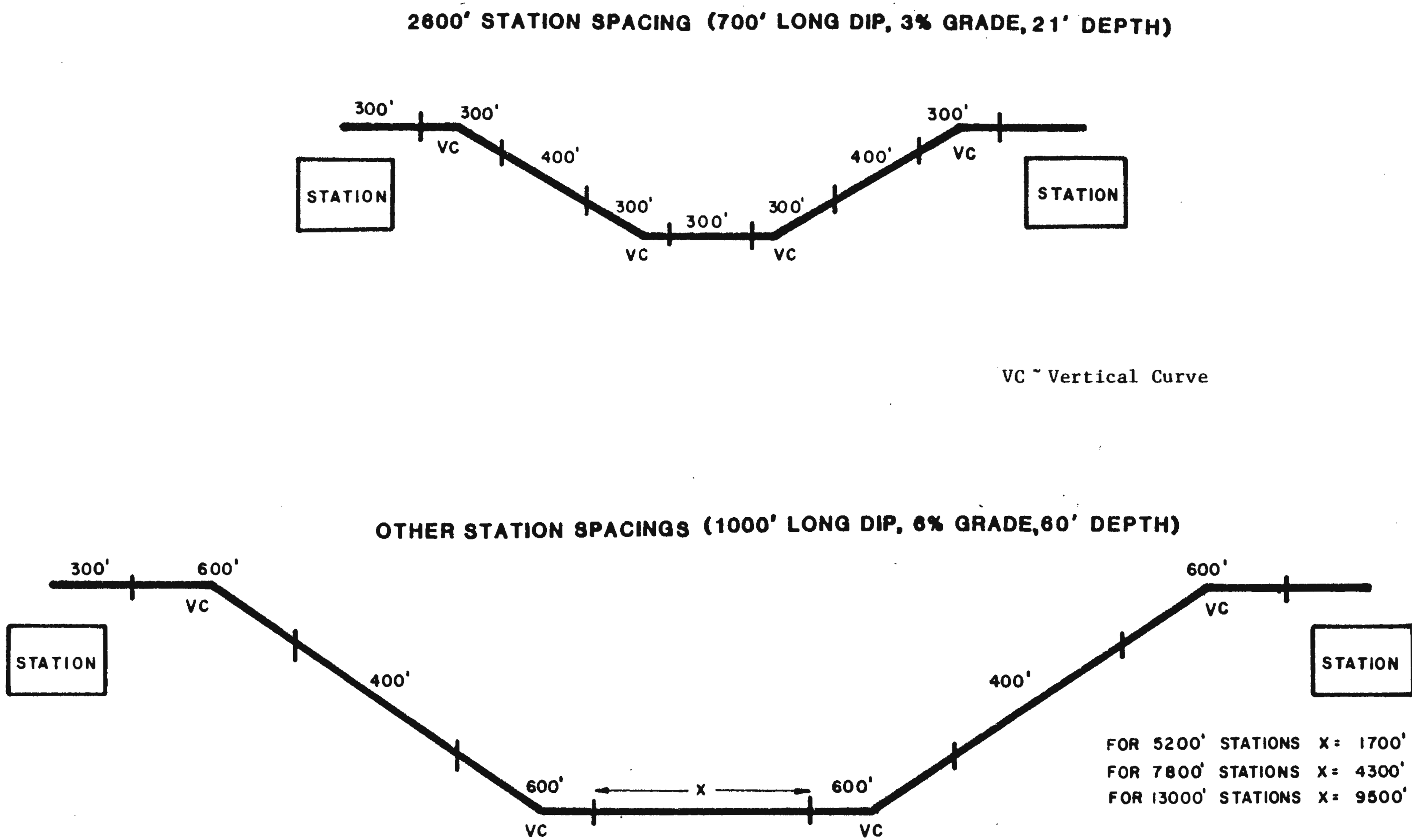
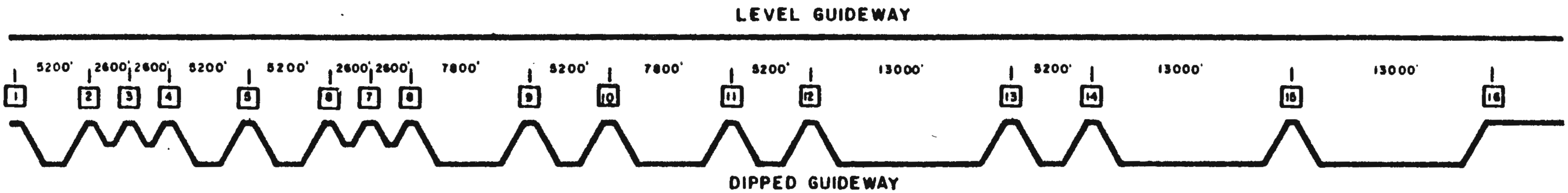


Figure III-1 Guideway Schemes



KEY

1 - STATION (300' LONG)

DIPPED GUIDEWAY DESIGN CRITERIA

VERTICAL CURVES: 100' FOR EACH 1% CHANGED

DIPS: 3% 700' LONG ON 2600' STATIONS (21')

6% 1000' " " OTHER " (60')

MINIMUM DISTANCE BETWEEN VERTICAL CURVES:

ONE TRAIN LENGTH (300')

4.2 TRACTION

An unedited reprint of the conclusions of the Louis T. Klauder and Associates report (Ref. 2) is presented. Notes by JPL appear below:

The information stated here by Louis T. Klauder and Associates is based upon the following conditions:

1. Advanced slip-slide control systems that are currently in revenue operation.

2. Maximum GART guideway grades of 10% of 1000-ft length.

3. The WMATA modified car with an advanced slip-slide control was used for the study vehicle.

FINAL REPORT

ASSESSMENT OF THE IMPACT OF DIPPED GUIDEWAYS ON URBAN RAIL TRANSIT SYSTEMS

TRACTION & PUSH-OUT STUDIES

July 24, 1981

Prepared By

Louis T. Klauder and Associates
Consulting Engineers

CONCLUSION

I have attempted to cover a great deal of material in this document, and it is not a simple matter to bring it all to a head in just a few words. In the beginning days of the assignment, there was admittedly some skepticism as to the viability of the proposed scheme. Although ostensibly I was unable to focus on any explicit arguments against operation on ten percent grades, I did harbor implicit objections predicated largely, I presume, on the notion that no one had ever operated a modern, large scale transit system with grades of this magnitude.

I envisioned all sorts of difficulties, especially with the pushout scenario---the principle task in the investigation. I foresaw problems with both the adhesion and tractive effort demands. The subsequent investigation did not prove my suspicions to be unfounded: there are difficulties with the adhesion and the tractive effort demands, but it did show that these difficulties are manageable. I think the Europeans survey trip, more than anything else, convinced me of this.

At the outset of the investigation, I had suspected that the biggest problem would be motor sizing. In addition, I felt that the effects of weight transfer would be small, if not negligible. As it turns out, I had my priorities reversed. The motor sizing problem, which derives from a large tractive effort demand during the pushout event, is not as severe as anticipated. The results of the 1,000' computer run indicate that the WMATA car motor current will run approximately double that for full rate, just over the normal trip point, for a period of only 69 seconds. This is reasonable, and should not seriously affect the motor design.

Weight transfer effects, on the other hand, turned out to be somewhat larger than anticipated. Of course, these effects are the function of several variables; e.g. grade, inertial loading, passenger loading and distribution, and drawbar pull. But in the "worst case", which is always possible, the combined effect puts some very high limits on the adhesion required. In order to preclude delay and shutdown due to operational inability to move disabled equipment, compensatory measures will have to be taken when it comes time to determine the vehicle configuration. There are many options, such as building in the capability to distribute tractive efforts, in both propulsion and braking, on a per truck, or if at all feasible, a per axle basis. Another option would be to select the vehicle and truck geometries in a manner such that the tendancy toward weight transfer under the specific conditions set forth in this report would be diluted to the extent that the magnitude of the phenomenon would be minimal. There are even operational options, which, should they be available in a given situation, would mitigate weight transfer effects. One option would be to relocate the passenger load to the "uphill" truck area. We looked at this analytically (cf. Appendix, KJP-20; dated June 10, 1981) and determined that the adhesion requirement (i.e., the ratio of tractive effort to the axle normal force) dropped significantly. Another operational solution would be to increase the ratio of live cars to cars in dead haul. This would mitigate not only the adhesion required, but the tractive effort requirement as well.

Regardless, solutions do exist. The bulk of the work would be selecting the most efficient one for the projected vehicle and following its inception on the fleet.

All in all, from the work we have done, it would be fair to say that no serious obstacles exist in the running of cars on ten percent grades, even with the pushout requirement. Careful consideration will have to be given to several important areas, such as the ones noted above, when the vehicle specification is drafted. But given this, it can be concluded that vehicle design will not impact the concept of operation on dipped guideways.

4.3 VENTILATION

An unedited reprint of the abstract and conclusions of the Kaiser Engineers report (Ref. 3) is presented. Notes by JPL appear below:

The information stated here by Kaiser Engineers is based on the following conditions:

1. Ventilation characteristics
   a. Conventional practice

2. Guideway characteristics
   a. 5000 ft station spacing
   b. 10% maximum grade for GART
   c. 100 ft dip depth for GART

3. Train characteristics
   a. 4 MU cars each of 75-ft length
   b. 48.5 tons per car

4. Operating characteristics
   a. 70-mph maximum speed for study
   b. 3-mphps deceleration and initial acceleration rate
   c. 120-s headways
   d. 25-s station dwell time

5. Transit time
   a. Maximum for level (full acceleration until braking)
   b. 4 s less than level between adjoining stations. (If at full acceleration until braking, it would take 8 s less.)

ASSESSMENT OF THE IMPACT OF DIPPED GUIDEWAYS

ON URBAN RAIL TRANSIT SYSTEMS

VENTILATION AND SAFETY REQUIREMENTS

REPORT NO. 82-008-R

FINAL REPORT

JANUARY 1982

JPL CONTRACT NO. 956018

Prepared by

KAISER ENGINEERS, INC.
P. O. BOX 23210
OAKLAND, CALIFORNIA 94623

This work was performed for the Jet Propulsion Laboratory, California Institute of Technology sponsored by the National Aeronautics and Space Administration under Contract NAS7-100.

ABSTRACT

This report documents a study performed by Kaiser Engineers to evaluate the ventilation and fire safety requirements for subway tunnels with dipped profiles between stations as compared to subway tunnels with level profiles. This evaluation is based upon computer simulations of four tunnel configurations with normal train operations and an additional computer simulation of a train fire emergency condition. Each of the tunnel configurations evaluated was developed from characteristics that are representative of modern transit systems. No attempt was made to optimize the ventilation and train operational aspects for each tunnel configuration. Rather, only the parameters describing tunnel size and profile between stations were varied. The results of the study indicate that: 1. The level tunnel system required about 10% more station cooling than dipped tunnel systems in order to meet design requirements. 2. The emergency ventilation requirements are greater with dipped tunnel systems than with level tunnel systems. Although mid-tunnel fan shafts are not essential for emergency ventilation, their elimination should come only after full consideration of: the additional station fan capacity needed to provide the same airflow capability, the loss of a potential evacuation route, and the increased sensitivity of the emergency ventilation procedure to fan failure. 3. Further study should be made of train performance on a dipped guideway system, and the possible penalities for deviations from the preferred acceleration and braking zones.

Note: See Figures A and B for definition of ventilation systems assumed for operations and required for fire safety.

IV. CONCLUSIONS

From the abundance of data that was produced for this study the following conclusions are thought to be the most significant.

1. Less ventilation equipment is required to maintain design conditions with a dipped tunnel system than with a level tunnel system. One way the difference in ventilation equipment can be quantified is as a difference in mechanical cooling capacity. For this study the dipped tunnel system requires about 10% less mechanical cooling than the level tunnel system.

2. A single track, level tunnel system can require less ventilation equipment to maintain design conditions than a double track dipped tunnel system. This difference appears to be sensitive to the specific train operation and specific system design. The double track tunnel system receives fewer air changes due to train operation than the single track tunnel system. Therefore the double track tunnel system is at a disadvantage when an "open system" ventilation design concept (which relies heavily on air changes with outside air for cooling) is being considered.

3. Station entrance air velocities are more independent of train operation in a single track tunnel system than in a double track tunnel system. The peak entrance air velocities are about the same in either case.

4. Train operation on the dipped tunnel system must be carefully tailored to the profile in order to obtain the most benefit. There can be significant penalties to pay in terms of energy consumption or heat loads if the trains are not allowed to accelerate on the downgrade or brake on the upgrade.

5. The greater the heat loads in a system, the more efficient the ventilation equipment will be if it provides air changes rather than mechanically cooled air. For example, under platform exhaust equipment working with a 90°F design temperature will remove 33% more heat if the air it removes is 110°F rather than 105°F.

6. For train fires in stations, an all exhaust mode of fan operation can be used to provide adequate ventilation for evacuating patrons. This is true whether the system is a level system or a dipped system. In either case, mid-tunnel fan shafts are not necessary as long as there are fans at the ends of each station that continue to operate during the emergency.

7. For a train fire emergency in a tunnel, a dipped tunnel system is more difficult to adequately ventilate than a level tunnel system. This is due to the buoyancy effect of hot air on the grade in the dipped system which makes it more difficult to move air downhill. Although it may be possible to provide adequate ventilation during a tunnel train fire emergency on a dipped system without mid-tunnel fan shafts, the airflow capacity of the station fans required to achieve this objective is substantial. The effects of mid-tunnel fan shafts are more pronounced with a single track tunnel system than with

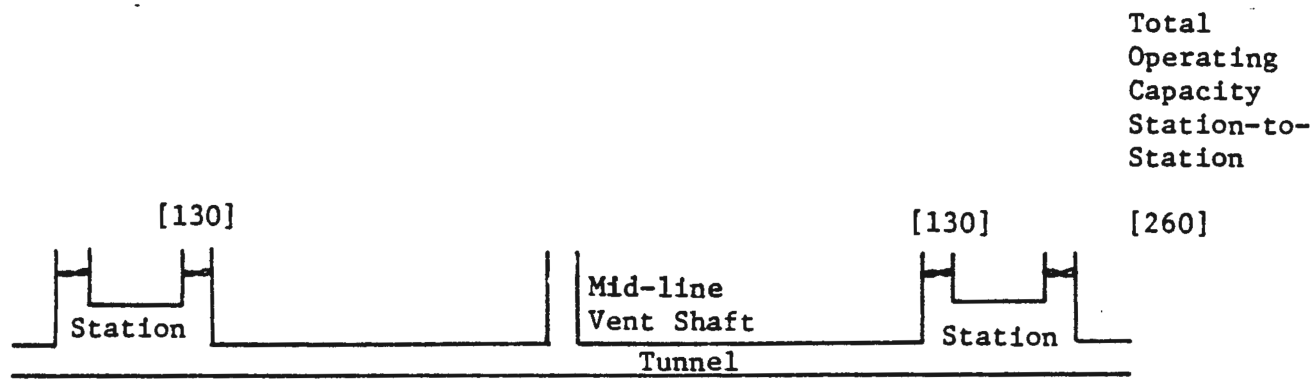
the double track tunnel system. In the single track tunnel system the use of station fans only can allow air to bypass the tunnel with the train and flow through the adjacent tunnel.

8. The use of mid-tunnel ventilation shafts is valuable in several respects. In all but the single track dipped system the mid-tunnel vents provide a means of reducing heat in the tunnels. During a train fire emergency, the use of the mid-tunnel ventilation fans makes the overall ventilation scheme less sensitive to the loss of a fan, and the ventilation shaft can provide an evacuation route for patrons.

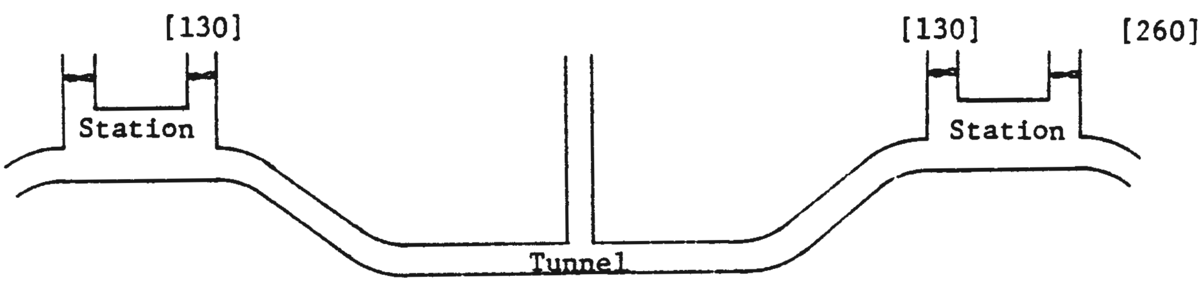
9. There are other measures that can be taken to enhance fire safety during a train fire emergency in addition to emergency ventilation. These include the reduction of the fire load on the vehicles, the addition of cross passages from one single track tunnel to another and the provision for fire barriers such as closable doors that can reconfigure the tunnel aerodynamic network in order to make the ventilation equipment most effective.

10. There is no significant difference between the single track over-under and side-by-side tunnel configurations in terms of ventilation. The cummulative effects of train induced airflows in stairways will be the most notable difference. For either type of tunnel configuration, the stairway air velocities must be evaluated based upon the expected train operations and ventilation design.

Fig. A. Schematic of Ventilation System Assumed for Computer Simulations of Normal Operations



Level Guideway with Mid-line Vent Shaft



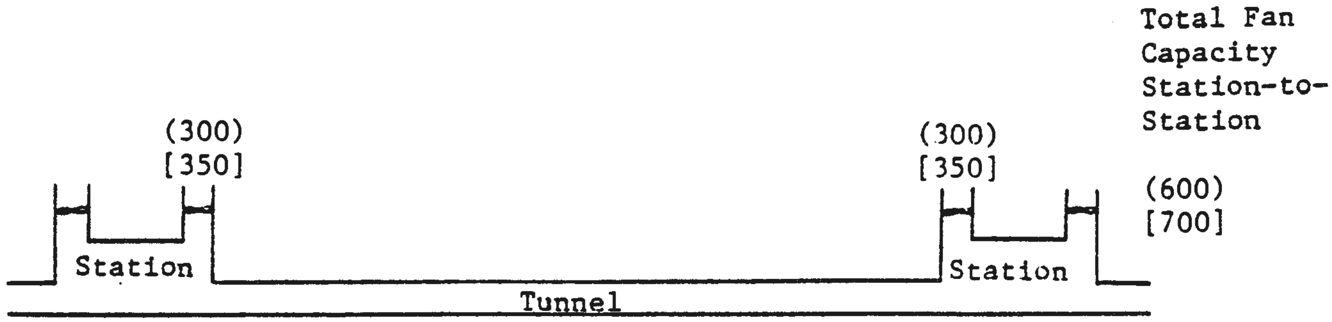
Dipped Guideway with Mid-line Vent Shaft*

Note:

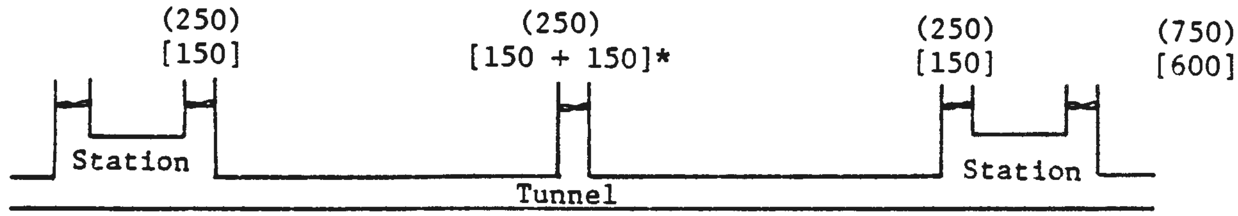
Total operating fan capacity same for double-tracked tunnel as for twin single-tracked tunnels.
[ ] Fan capacity in 1000 cfm at station.

*For conditions studied, the dipped guideway with twin single-track tunnels will run cooler without the mid-line vent shaft than with it.

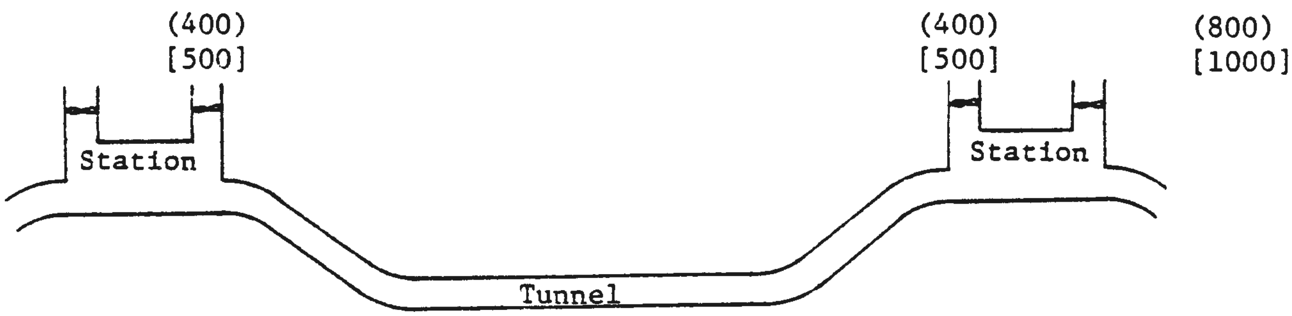
Fig. B. Schematic of Ventilation System Requirements for Fire Safety



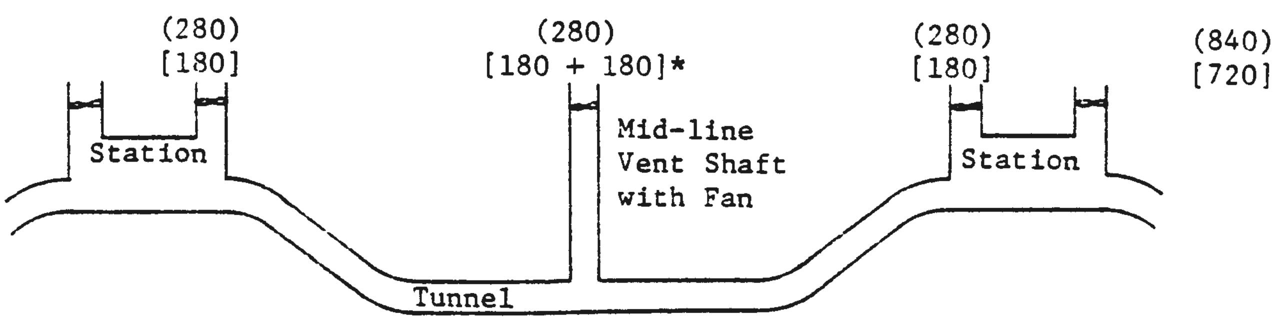
Level Guideway with No Mid-line Vent Shaft



Level Guideway with Mid-line Vent Shaft



Dipped Guideway with No Mid-line Vent Shaft



Dipped Guideway with Mid-line Vent Shaft

Fan Shaft Capacity in 1000 cfm

( ) ~ Double-track tunnel
[ ] ~ Twin single-track tunnels

*Each single-track tunnel has its own mid-line shaft. At the station regions a common shaft serves both tunnels.

4.4 TUNNELING COSTS

An unedited reprint of the summary of the Sperry-Lehman report (Ref. 4) is presented. Notes by JPL appear below:

The information stated here by Sperry & Lehman is based on the following conditions:

1. Los Angeles basin type geology
   (primarily along Wilshire Blvd.)

2. No cost considerations given for
   a. Utility relocation
   b. Impact on nearby structures
   c. Stations

3. Current proven practices
   a. Tunnel boring
   b. Muck hauling

ADDITIONAL CONSTRUCTION COSTS OF DIPPED GUIDEWAYS FOR URBAN SUBWAY RAIL SYSTEMS

Prepared by:

P. E. Sperry, Tunnel Consultant
R. L. Lehman, Chief Engineer, J. F. Shea Co., Inc.

March 1981

II. SUMMARY

This study concludes that it is feasible to construct a dipped profile subway system using conventional rail haulage, supplemented with brakeman cars to safely bring runaway trains to a stop. This conclusion is contrary to the results of two previous studies which held that rail haul (without cable assist) was impossible on grades over 5%. This study is based on twin, single track, 16'-8" finished diameter tunnels lined with precast segments for initial and final support. These tunnels drop (vertically) 100 feet between stations on either 6% or 10% grades.

The results of this study are:

Grade	Haulage System	Additional Cost $/Ft.
6%	50 T Locomotive	43
10%	90 T Locomotive	77
10%	Cable-Assist Rail	152
10%	Conveyor	149

See Table I for a comparison based upon Los Angeles basin geology with the results of the previous studies.

The possibility of using very large locomotives on steep grades is not attributed to any singular advance in the state-of-the-art, but depends on several unrelated advances and assumptions:

1. The use of large locomotives in the Chicago TARP tunnels.

2. The use of a 45 T locomotive on WMATA A-11a to pull loaded 80 CY (loose) muck trains up a 5% grade.

3. The routine use of brakeman cars in the mining industry and the favorable consideration, by CAL-OSHA, of their use on the assumed subway grades.

4. The fact that tunnels in the assumed geology will be excessively ventilated to dilute methane, thus not requiring any additional ventilation for very large locomotives.

5. The assumption that rail can be kept clean and dry and that sanders will work, producing a higher than usual coefficient of friction.

TABLE I

Comparison of Study Results

Study	Haulage System	Grade	Escalation To 4/81 (1)	Base Case $/LF (2)	Dipped Profile $/LF (3)	Increase $/LF	% Increase
Dec. 1976 (Ref 2)	Cable Assist Rail	10%	56%	2710	2808	98	3.6
Nov. 1977 (Ref 3)	Conveyor	10%	47%	1955	2076	121	6.2
Apr. 1981 (5)	90 T Locomotive	10%	N/A	1955 (4)	2032	77	3.9
Apr. 1981 (5)	Cable-Assist Rail	10%	N/A	1955 (4)	2107	152	7.8
Apr. 1981 (5)	Conveyor	10%	N/A	1955 (4)	2104	149	7.6
Apr. 1981 (5)	50 T Locomotive	6%	N/A	1955 (4)	1998	43	2.2

(1) Based on Bureau of Reclamation construction costs for concrete lined tunnels.

(2) $ per LF of tunnel. Double for LF of subway.

(3) Based on 10% x 100' dip with concrete segments.

(4) Equal to November 1977 study escalated base case. Used because it is very close to $1900 of upper side of authors' tunnel cost range plot.

(5) This report.

SECTION 5. JPL ANALYSIS

January 1982

Jet Propulsion Laboratory

California Institute of Technology

Pasadena, CA

5.1 INTRODUCTION

These analyses are supplemental to the ones conducted by Gibbs & Hill as part of this project. The results of the G&H analyses were consistent with earlier efforts by JPL in estimating the energy savings of dipped over level guideways, under the full power mode, at an average for various station distances of 13%. The G&H analyses did not investigate the impact of using the time savings of dipped guideways to gain additional energy savings. By use of a coast mode where the maximum power is applied in the dipped system, then turned off, large additional energy savings can be achieved, while matching the original transit times for the level system. The coast mode can increase the energy savings of the dipped system by a factor of 3. Additional energy savings can be achieved for the dipped system by varying several system design parameters. These will also be investigated in this supplemental analysis.

5.2 SUMMARY

Table 1 summarizes the traction energy savings of GART.

Table 1
Traction Energy Saving of GART Over Level (Base Case)

Interstation Distance (ft)	Simulation	Power Profile	Traction Energy Savings (%)	Transit Time Savings (%)
2600	G&H	Full	7.0	1.7
	JPL	Full	4.2	3.0
	JPL	Coast*	36.3	Match
5200	G&H	Full	12.7	1.6
	JPL	Full	15.2	5.9
	JPL	Coast*	51.7	Match
7800	G&H	Full	16.5	3.6
	JPL	Full	19.3	4.8
	JPL	Coast*	45.7	Match
13000	G&H	Full	14.2	2.5
	JPL	Full	16.0	3.3
	JPL	Coast*	37.2	Match

*Just enough coasting on GART to cause transit time to match the level case. Maximum dip height = 60 ft, grade = 6%, vertical curve rate = 100 ft/°/o, level station length = 300 ft.

Weighting the energy savings of Table 1 by the frequency of interstation distances and energy consumption results in the following systemwide saving, (Table 2), for the transit network described in the G&H report.

Table 2
GART Systemwide Energy Savings

No. of Inter-Station Distances	Relative Level Case Energy Use	Interstation Distance	Power Profile	Percent Traction Energy Savings Per Station	Weighting Factor	Total Relative Savings
4	1	2600 ft	Full	4.2	4.0	16.8
6	1.6	5200		15.2	9.6	146
2	2.1	7800		19.3	4.2	81
3	3.1	13000		16.0	9.3	146
15					27.1	390
4	1	2600 ft	Coast	36.3	4.0	145
6	1.6	5200		51.7	9.6	496
2	2.1	7800		45.7	4.2	192
3	3.1	13000		37.2	9.3	346
15					27.1	1179

Full Power Mode Energy Savings (390/27.1) = 14%
Coast Mode Energy Savings (1179/27.1) = 44%

These energy savings can be further increased by appropriate design changes. Reference to Figure 1, "Dipped Guideway Energy Savings Over Level for Selected Variable Geometric Conditions," indicates the magnitude of additional savings. This chart indicates the energy savings of combinations of design parameters that lead to several high energy saving conditions. The systemwide savings for the Case 3 condition (Maximum Grade = 6%, Maximum Dip Height = 80 ft, Vertical Curve Rate = 50 ft/%, and Station Level Length = 0) are 57% over the level in the coast mode.

A second energy advantage of the dipped system is that peak power requirements can be reduced an additional 40%, without affecting the total energy savings or travel times compared to the level case. Depending on the train schedule and premium peak hour electrical energy charges, this can have a significant effect on operating cost. This additional saving is achieved by limiting the maximum horsepower drawn by the traction motors while still maintaining a high acceleration rate below a cutoff speed.

The dipped guideway saves braking energy in addition to traction energy. The upgrade of the dip provides a braking effect without use of the traditional method of converting the energy from the cars' dynamic braking into heat dissipated by the brake grid resistors. As part of this project, Kaiser Engineers investigated the impact of the reduced traction and braking energy requirements on the tunnel ventilation design. A secondary effect of the reduced heat energy generation is lower under car temperatures. This can improve the reliability of car electrical components by at least 20-60%.

The energy related advantages of the dipped guideway (GART) system over the level system are summarized below:

Energy Advantages of GART Over Level	
Full Power Mode Savings	
Base Case - Energy	14%
Run Time	2-6%
Coast Mode Savings	
Base Case - Energy	44%
Run Time	0
Case 3 - Energy	57%
Run Time	0
Peak Power Requirement	
Maximum HP Reduction Single Train	40%
Component Reliability	
Braking Grid Resistor Max Temp Reduction	$450^{\circ}F$
Impact on Under Car Electrical Component Reliability Increase	20-60%

5.3 ENERGY SAVINGS

Approach: The parameters used in the G&H level case energy computations were entered into the JPL level case computer program (Track). These parameters are listed in Figure 1 under Fixed Conditions, except for the aero resistance coefficient, C_D. G&H used a constant coefficient of 1.338 instead of the more realistic ones (different and higher) used by JPL for different interstation distances.

Runs were completed for the level case on the JPL program and compared to the results of the G&H (TRAPER) case. These are summarized in Table 3.

For the level (G&H coefficient) case there is good agreement on the transit times (0-3% difference), but a less satisfactory agreement for the energy consumption (7-28% difference). A manual check was conducted on the energy consumption on one of the TRACK cases. The horsepower curve was multiplied at 100 ft increments by the velocity from the computer printout. The traction energy used in 100 ft increments was computed and summed for the total interstation distance and found to agree within 1% of the computer printout. Since the transit times for the TRACK and TRAPER cases virtually matched, no error was introduced by using the computer generated velocity profile.

An additional test of the TRACK program was conducted. The Southern California Rapid Transit District (SCRTD) had conducted energy calculations of alternate track profiles using an independent third program. The same input parameters, when used in the TRACK program, produced results that agreed with the SCRTD analysis within 1%.

No explanation could be found to account for the differences in calculated energy consumption of the TRACK and TRAPER programs. One possibility is the use of an .02 sec time increment in the TRACK program and a 1.5 sec increment in the TRAPER program.

The TRACK program was rerun with the revised aerodynamic coefficients as indicated in Table 3. These are more representative of the drag characteristic of long single track tunnels. They are based on earlier analytical and experimental work conducted at JPL and described in "Alternative Concepts for Underground Rapid Transit," JPL, 1977, Vol. II-A, pg. B-2.

The result of the higher aero resistance coefficients is to slightly increase the traction energy requirements for the short station spacings (2600 ft) and to almost double for the long station spacings (13,000 ft).

Since the higher coefficients are more realistic, their associated travel time and energy consumption were selected as the comparison standard for savings developed by the dipped guideway. The values are indicated in Table 3.

A similar comparison was made for the dipped case using the G&H TRAPER results and the JPL dipped program results. The same aero coefficient (C_D = 1.338) was used in each case. The results are similar to the level case, 1-2% difference on transit times and 17-21% difference on calculated energy consumption. The results are indicated in Table 4.

Table 3

Comparison of JPL and G&H Level Case

Station Distance	Constant Aero Coefficient* — Time: G&H (sec)	Time: JPL (sec)	Time: Ratio JPL/G&H	Traction Energy: G&H (kwhr)	Traction Energy: JPL (kwhr)	Traction Energy: Ratio JPL/G&H	Variable Aero Coefficient: C_D	Time: JPL (sec)	Energy: JPL (kwhr)
2600 ft	54.4	54.44	1.00	15.7	16.79	1.07	2.48	54.5	16.96
5200	79.2	81.33	1.03	21.3	26.27	1.23	3.37	81.85	27.32
7800	104.7	105.17	1.01	24.9	31.07	1.24	4.00	106.48	36.29
13000	150.8	152.45	1.01	28.8	36.79	1.28	4.90	154.4	52.67

* Fixed conditions same for each program as noted in Figure 1, except for aero resistance coefficient. In this comparison, JPL programs were modified to use $C_D = 1.338$, consistent with G&H case.

Table 4

Full Power Dipped Case Comparisons

Station Spacing (ft)	Time G&H (sec)	Time JPL (sec)	Time Ratio JPL/G&H	Energy G&H) (kwhr)	Energy JPL (kwhr)	Energy Ratio JPL/G&H
2600	53.5	52.9	0.989	14.6	16.1	1.101
5200	77.9	76.5	0.982	18.6	22.3	1.119
7800	100.9	100.1	0.992	20.8	25.1	1.206
13000	147.0	147.4	1.003	24.7	30.9	1.252

Conditions: Max Dip = 60 ft, Grade = 6%, Station Level Length = 300 ft, Vertical Curve Rate = 100 ft/%.

Although the TRAPER and TRACK and DIPPED programs result in different absolute values for run time and energy calculations, their results are consistent for the percentage improvement of the full power mode GART case over the level case.

In addition to the fixed conditions which do not vary between the level and dipped systems, there are four additional parameters required in defining a dipped system. These parameters, along with several potential values, are listed in Table 5. The purpose of the table is to illustrate the large number of case combinations that can be considered in comparing level and GART systems.

The required number of runs was reduced by starting with an initial case in the mid range of potential design parameters and examining excursions in various directions. Several extreme maximum conditions were also considered to define an upper limit of the benefits available from these combinations of parameters.

Although not considered in these examples, significant additional benefit could be achieved by using a braking rate of 3 mphs instead of 2.2 mphps which is established as a signal system minimum design condition. Car performance for the purpose of energy calculations can repeatedly exceed the minimum braking rates.

Additional analyses are also conducted on reducing systemwide peak power requirements and the effect on car component reliability of reduced under car temperatures.

Table 5

Number of GART Design Options

Parameter	Values to Investigate	Number of Cases
Maximum Dip Height	60, 80, 100, 120 ft	4
Vertical Curve Rate	30, 50, 70, 100 ft/%	4
Station Level Length	0, 300, 600	3
Maximum Grade	4, 6, 8, 10%	4
	No. Case Combinations	192
	Power Modes per Case	2
	Station Distances per Case	4
	Potential No. Simulation Experiments	1536

Results: The results of the computer simulations are presented in a series of six figures. Figure 1 lists the fixed conditions which are common to the subsequent figures and also to the level case. Each figure lists the specific variable conditions. Figure 1 indicates energy savings for combinations of conditions which are expected to yield large savings. Note the large improvement over the base case, particularly for the 2600 ft stations (36% to 64%), even with a 6% grade. A systemwide average of 13% increase occurs between the base case and Case 3, coast modes. Figure 2 displays the effect of maximum dip height on energy savings compared to the level. Two sets of curves are indicated, one for the coast mode and a second set for the full power mode. No values are indicated for the 2600 ft station distance, since for the grades and curve rates shown its maximum dip height is less than 60 ft.

The charts indicate that beyond a 100 ft dip, there is a loss in energy savings. This occurs since the train now brakes on the dip.

Figure 3 indicates the effect of various grades. Other than for the 5200 ft station distance, there is only a small benefit in grades above 6%. The 10% grade is not shown since it is not geometrically compatible with the indicated parameters.

Figure 4 indicates the effect of the rate of vertical curve. It has a pronounced effect on increasing the energy savings for the 2600 ft station in the coast mode (from 36% to 56%). This large increase is due to the maximum allowable grade and dip height also increasing as the curve rate is increased.

Figure 5 indicates the effect of level station length. A level length of 300 ft would correspond to a level platform equal to the train length. A 600 ft length corresponds to a level length beyond the station, perhaps to accommodate a switch track. Zero level length corresponds to the entire station platform being on a vertical curve. For the case shown, the average grade from the middle to either end of the platform is 2.15 percent. The strong impact on the 2600 ft case is due to multiple effects of increased grade and dip height permitted with the shorter level length.

These analyses indicate a smaller variation in energy savings when single parameters are varied (Figs. 2-5) than when similar parameters are varied for the combination of conditions leading to large energy savings (Fig. 1). This may be due in part to the effect of one parameter modifying that of another. For example, if maximum dip heights are limited to 60 feet, the effect on energy savings of different grades is less than if maximum dip height is 80 feet.

Figure 6 indicates the potential for reducing peak power requirements. It is implemented by lowering the maximum horsepower levels, while maintaining a high acceleration. Note that for the 20 and 40% peak power levels, the energy savings over the level case is substantial, but the travel time increases. For peak power levels of 60 and 80%, the full power mode travel time is less than the level case travel time. Additional energy savings are developed by use of coasting in which the dipped travel times match the level. Figure 6 indicates that peak power reductions over 40% are feasible while still maintaining the minimum travel time at the level system.

Figure 7 is a profile of the train motive horsepower for the level case and case where the maximum horsepower for the dipped system is limited to 60% of the level system. The total motive energy consumed is the area under the curves. The effect of reducing the dip maximum horsepower is to slightly prolong the time period of the powered phase (increase coast start distance), keeping the motive energy approximately constant. Reference to the computer test run printout indicates that the motive power profile for the dipped case with no special restrictions on maximum horsepower is very close to that of the level case for the first 15 seconds, then slightly below the level case, until the start of coasting.

This chart shows the power requirements of a single train. The power requirements of the entire transit system are determined by the manner in which these profiles overlap during the same time period. A test schedule and electric rate tariff, when used in conjunction with these profiles, can determine the relative peak power requirements and associated fees of the level system, and dipped system with reduced single train peak power.

Cause of Energy Savings: An increased understanding of the operating principles of the dipped system can be developed by reference to Figure 8, "Traction and Time Profiles Vs. Distance for Dip and Level Systems." The dashed time line is for the level case; the solid lines are for the dipped full power and the dipped coasting modes. The examples shown are for an interstation distance of 5200 ft, case 5.

The dotted line in the lower left corner is the accelerating force due to gravity, calculated as the train weight multiplied by the grade. A similar, but decelerating, force would exist on the upgrade, but is not shown in this chart. The solid and dashed lines in the lower left-hand corner are the motor traction forces for the level, dipped full power, and dipped coast mode. The dashed line in the lower right-hand corner is the braking force for the level case.

Note that the motive traction force is initially high, but within several hundred feet the train builds velocity, and the tractive force decreases. Within 1000 feet of the initial station, the magnitude of the traction force approximates the gravity force. This extra accelerating force enables the dipped system to develop a time advantage over the level system. At the stopping station, the travel time for the full power dip is nearly six seconds less than for the level case. The dip coast run utilizes this time advantage to cut the motive power at 900 ft, thereby increasing the travel time over the remaining distance to match the level case for the total distance, but providing significant additional energy savings. The areas under the force-distance curves are the traction energy.

This result is less surprising when one considers the actual work done when a train moves between two stations on a level track. If there were no rolling resistance or air resistance, a minute force and amount of energy could move the train between the two stations, although it might require several days. As the magnitude of the traction force is increased, the travel time is decreased. The applied traction force accomplishes little useful work in a physical sense, but it does save travel time. The traction force increases the kinetic energy of the train, which must be removed by the braking system for the train to stop at the next station.

The dips provide much of the required accelerating and braking forces, in lieu of the traction motors. As a maximum, the dips could supply all but the energy required to overcome aero and rolling resistance. Reference to the computer runs indicates that for the level case in Figure 8, approximately 14% of the motive power is used to overcome these two resistances. The remaining 86% of the motive energy is the maximum that the dipped profile might save.

Another advantage of the dipped profile is the reduction in braking force effort. The instantaneous braking force for the level case is shown in the lower right-hand corner. The forces for the dipped cases are the same magnitude as in the level case, but are initiated at a later time and distance. The area under the brake face curve is the braking energy. For the case shown, the dip coast mode reduces the amount of braking effort energy by 74%.

Note also for the case shown that in the dipped full power mode run between 3000 and 3600 feet the motor power is used to overcome aero and rolling resistance only. Between 3600 and 4000 feet, some energy is expended in powering up the dip. The dip coast mode run does not expend any energy in powering up the dip.

<u>Decreased Braking Rate</u>: A brief computer simulation using the JPL DIPPED/SUBWAY program was made to determine the effect of braking rate which is independent of grade upon the energy savings of a GART guideway. The case investigated was for the correct $C_D = 3.37$ (termed "variable") for 5200 ft station spacing. The dipped profile was: 60 ft deep, 6% maximum grade, 70 ft/% vertical grade change at top and at bottom.

Previous calculations by JPL assumed that the grade added to the braking rate. The conservative assumption of not using grade to assist in the braking rate decreases the energy savings somewhat from 50.6% to 46.4%. These results are shown in the following table where the coasting period was adjusted to match (or vary) the transit time.

Effect of Braking Rate Independent of Grade
on
Traction Energy Savings

Guideway	Power Profile	Transit Time (sec)	T (sec)	Traction Energy (kWh)	TE Savings (%)	Braking (mphps)
Level	Full	81.85	-	27.32	-	2.2
GART	Full	76.56	-4.29	24.57	10.1	2.2+Grade
GART	Coast	81.85	0	13.49	50.0	2.2+Grade
GART	Coast	81.53	-0.32	13.82	49.4	2.2+Grade
GART	Full	78.71	-3.14	23.05	15.6	2.2 Total
GART	Coast	81.85	0	14.65	46.4	2.2 Total

This brief study was made because the feature of adding the maximum level braking rate to the GART upgrade gravity braking rate is not presently incorporated into existing systems, merely because there has been no need for it. The hardware to accommodate this mode of operation is in the car, only software changes to the control logic would be required.

Modern propulsion control systems contain a feedback loop which uses information from an axle angular-speed meter to regulate the applied braking effort. Older propulsion systems do not have this feedback loop, and the question of the addition of dynamic and grade braking effects does not arise. However, due to the advantage of applying the proper acceleration and coasting profiles in GART, only the modern automated train and propulsion control systems would achieve the optimum energy savings.

Inquiries* were made with several propulsion/braking manufacturers to determine if there is a problem in modern transit equipment being modified so that the effect of braking due to gravity adds to the dynamic braking, rather than the dynamic braking being redced as the grade braking increases over a set level. There replies supported the opinions already given by both Klauder Assoc. and Gibbs & Hill. The desired feature is within the state-of-the-art: there is no problem to incorporate this feature in present-day equipment.

* Manufacturers personnel contacted include:

Ken Fraelich, Westinghouse Electric
Jack Caldwell, Garrett AiResearch
Bob Dobbin, General Electric

5.4 CAR RELIABILITY

Dipped guideways result in lower car under-floor temperatures, which will cause a significant improvement in car component reliability. The magnitude of this reliability improvement can be gauged in the following brief analysis.

As part of the ventilation analyses in this project (conducted by Kaiser Engineers), the following differences between a dipped and level system under car temperatures was calculated. Note since the ventilation model reports temperatures for fixed distance increments in the train profile, it is feasible that the absolute maximum or minimum will not be listed. This explains the otherwise unexpected report that the level case minimum temperatures are lower than the dip case.

Brake Grid Resistor Temperatures (^{o}F)

	Level	Dipped	Difference
Minimum	305	332	27
Maximum	1089	612	477

The higher brake resistor grid temperatures for the level case will result in higher temperatures for the surrounding under car equipment. A thermal model could develop the impact of dipped versus level operation on the temperature history of each of the under car subsystems and components. Such a model was beyond the scope of this project, but it is reasonable to estimate that a 450^{o}F difference in braking grid resistors will lead to a difference of 100^{o}F in other under car components. The reduced traction power and dynamic braking requirements of the dipped system also help to lower motor and under car temperatures.

It could be argued that a prudent car design contains measures to counteract many of the effects of the heat dissipated from the braking resistors. These include heat shields, higher grade insulation, blowers, and under car forced ventilation at stations. These countermeasures do have a price which will be reflected in terms of the car construction cost, station construction cost, and in availability of under car space. The availability of these countermeasures does not negate the statement that the energy savings of dipped guideways result in reliability improvements that are worthy of more detailed investigation.

Standard reliability handbooks can be used to estimate the effect on component life of a 100^{o}F drop in the operating environment temperature. The reliability model for many electronic components contains an electrical base failure rate related to operating temperature that is multiplied by various factors dependent on design quality or operating stress, other than temperature. An improvement in the electrical base failure rate, due to lowering the operating temperature, will lead to a proportional improvement in the overall component electrical failure rate. The failure rate model for rotating components such as motors or blowers is the sum of the electrical failure rate plus a mechanical wear out rate.

The tables of Military Standardization Handbook, MIL-HDBK-217B, "Reliability Prediction of Electronic Equipment," can be used to estimate that change in the electrical base failure rate. Failure rates for several typical components at temperatures of 50^{o}C and 90^{o}C will be compared. The results are summarized in the following table.

A reduction in failure rates of 20-60% is indicated for the components examined. The failure rate for the total car is a function of the system and subsystem design in addition to the component failure rates. Proper design or the selection of higher quality components may compensate for the reduced reliability due to higher temperatures, but at an increase in cost.

It is clear that the increase in reliability due to lower under car temperatures can be significant and is worthy of detailed analysis. It is another significant advantage of GART over a level system.

Comparison of Electrical Base Failure Rate

Component	Reference In MIL-HDBK-217B	Temp.	Failure Rate (per 10^6 hr)	Reduction In Failure Rate
Resistor, Power	Table 2.5.3-12	50°C 90°C	.0187 .036	40%
Capacitor, Fixed Paper	Table 2.6.1-6	50°C 90°C	.0002 .0003	33%
High Speed Motor	Table 2.8.1-3	50°C 90°C	.0020 .0025	20%
Blowers	Table 2.8.2-2		.0020 .0025	20%
Relays	Table 2.9-2	50°C 90°C	.0066 .0110	40%
Connectors	Table 2.11-5	50°C 90°C	.015 .037	60%

5.5 RIDE COMFORT

In the course of the study it became apparent that the GART energy savings were sensitive to several geometric design criteria. Conventional transit systems may have utilized criteria that were more restrictive than necessary, primarily because no benefit was foreseen in more in-depth investigations. Several of these criteria are related to practices in railroad and highway engineering and were carried over to transit with little change. A closer look at several of the issues affecting criteria for vertical curve rate, vertical acceleration, and minimum tangent length follows.

Vertical curves are transition curves between sections of tangent track at different grades. The form of the curve are parabolas in the vertical plane.

A vertical curve is usually specified in terms of the horizontal distance per each unit change in grade; e.g., a vertical curve rate of 100 ft/% would require 600 ft for transition from the horizontal to a grade of 6%.

If a parabola were drawn on an x-y coordinate system, its slope or grade at any point is:

$$\text{grade} = \frac{dy}{dx}$$

Let K be the vertical curve rate:

$$\frac{1}{K} = \frac{d\ (\text{grade})}{dx} = \frac{d^2y}{dx^2}$$

The equation of the parabola is:

$$y = \frac{x^2}{2K} + C_1\, x + C_2$$

If the maximum point of the parabola passes through the origin, the shape can be described as:

$$y = \frac{x^2}{2K}$$

The average grade for a vertical curve of length L is:

$$\overline{\text{grade}} = \frac{1}{L}\int_0^L \frac{xdx}{K} = \frac{L}{2K}$$

The relation of vertical curve rate to the radius of an approximating circular arc can be found by considering the equation of a circle of radius R:

$$x^2 + y^2 = R^2$$

Differentiating and solving for the vertical rate of change at $x = 0$, $y = R$:

$$\frac{d^2y}{dx^2} = -\frac{1}{R}$$

or

$$\text{Vertical Curve Rate:} \quad \frac{1}{K_{parabola}} \quad \frac{grade}{Ft} = \frac{-1}{R_{circle}} \quad \frac{1}{Ft}$$

$$K\ (Ft/\%) = R\ (Ft)$$

A table of several equivalent values follows:

Vertical Curve Rate	Radius of Curvature of Approximating Circular Arch
100 Ft/%	10,000 Ft
70	7,000
60	6,000
50	5,000
30	3,000

A train traveling on a vertical curve experiences a vertical acceleration which can be calculated as follows. The equation of the vertical curve passing through the origin is:

$$y = \frac{x^2}{2K}$$

Vertical acceleration:

$$a_y = \frac{d^2y}{dt^2} = \frac{d}{dt^2}\ \frac{x^2}{2K} = \frac{1}{K}\ \frac{d}{dt}\ x\ \frac{dx}{dt} = \frac{1}{K}\ x\ \frac{d^2x}{dt^2} + \frac{dx}{dt}^{2}$$

$$a_y = \frac{1}{K}\ (x\ \ddot{x} + (\dot{x})^2)$$

If the train is traveling at constant velocity

$$a_y = \frac{1}{K} (\dot{x})^2$$

Using a circular arc to approximate the vertical curve results in the same acceleration value

$$a = \frac{v^2}{R} = \frac{v^2}{K}$$

Representative values follow:

__Vertical Acceleration__

Constant Velocity	Vertical Curve Rate	Vertical Acceleration
20 mph	100 ft/%	.003 g
↓	60	.005 g
	30	.009 g
75 mph	100	.038 g
↓	60	.063 g
	30	.125 g

The jerk rate due to the vertical curve is

$$j = \dot{a}_y = \quad = \frac{d^3y}{dt^3} = \frac{d}{dt} (x \ddot{x} + (\dot{x})^2) \quad \frac{1}{K}$$

$$j = \frac{2}{K} (x \dddot{x} + 3 \dot{x} \ddot{x})$$

In regions where the braking force or accelerating force is constant, the vertical jerk becomes

$$j = \frac{6}{K} (\dot{x} \dddot{x})$$

e.g., if $x = 50$ mph
$x = 2.2$ mph
$K = 60$ ft/%

$j = .007$ g/sec

Typical accelerations and descriptions of their significance are found in the following tables. It should be noted that in a transit situation horizontal accelerations are more critical than vertical ones, in that these can cause a standing passenger to lose his balance.

Tests for passenger comfort on curved railroad tracks[8] resulted in the following ride comfort descriptors related to horizontal acceleration.

Ride Comfort and Acceleration

Horizontal Acceleration	Passenger Response
0 - .04 g	Not Perceptible
.04 - .12 g	Perceptible
.12 - .20 g	Strongly Noticeable
.20 -	Uncomfortable

Ride comfort parameters specified[9] on several recent automatic guideway transit systems are:

AGT Ride Comfort Parameters

Maximum Lateral Acceleration	.06 - .13 g
Maximum Vertical Acceleration	$\pm$ .10 g
Maximum Longitudinal Acceleration Near Crest	.06 - .13 g
Maximum Lateral Jerk	.06 - .20 g/sec

A summary of acceleration levels for selected transportation systems follows:

Summary of Selected Longitudinal Acceleration & Jerk Level[10]

System	Service Braking g's	Acceleration g's	Jerk g/sec
Frankfurt Subway	.175	.145	
Montreal Metro	.113	.113	
London Underground	.16	.09	.045
Penn Centro Commuter	.103	.103	
NYCTA Subway Co.	.07 - .137	.114	
BART Car	.124	.137	.068
Typical Rail Transit	.12 - .14	.137	
PCC Street Car	.143 - .165	.165 - .196	
Trolley Coach	.171 - .205	.137 - .217	
Motor Bus	.046 - .158	.022 - .252	
Elevators (Vertical)	.1 - .3		
Aircraft (Takeoff)		.5	
Automobile	.25 - .3		

It is clear that the vertical accelerations and jerks imposed by the vertical transition curve are significantly less than the values found in many transportation systems.

Before examining vertical curve criteria in transit systems, it is interesting to note practices in highway engineering since they appear to be related.

There are three prime design controls in highway vertical curves: stopping sight distances, passenger comfort, and aesthetics of the roadway.(11)

On crest vertical curves, the stopping sight distance requirement can be met by adhering to the following equation.

$$L_{min} = 3\ v$$

The minimum length of the vertical curve is 3 multiplied by the motor vehicle velocity (mph).

With regard to comfort on vertical curves, the ASHTO guide uses 1 fpss (.03 g) as the desirable maximum vertical acceleration, and presents general expression for this criteria:

$$L = \frac{A\ v^2}{46.5}$$

where A is the algebraic difference in grades, v is in mph, and L is the length of the vertical curve in feet.

The minimum length for aesthetic reasons is:

$$L_{min} = 100\ A$$

The acceleration criteria expressed in the foregoing equations are more restrictive than those noted in the previous tables. This may be partially explained by a desire to minimize the distractions and difficulties that might cause a motor vehicle driver to remove his attention from the road and/or handling of the vehicle.

A transit signal system and track eliminate many of the potential hazards present in a highway vehicle, except for the need for stopping sight distance at a station. In spite of this, many of these design criteria have been carried over to transit system design. As noted in the Gibbs & Hill report, vertical curve criteria of 100 ft/% are representative of current practice. The criteria utilized on the MARTA system are typical. These are described in several design documents.(12)

These documents note that rates of change of grade chosen in the MARTA system result in a maximum acceleration of 0.02 g in a crest curve and 0.04 g in a sag curve. Their support of these values is based on reference to the previously described highway engineering criteria.

The MARTA guidelines retain four criteria that are strongly related to the ASHTO highway guidelines and a fifth that is related to the vehicle specifications. These are:

$$L = \frac{v^2 A}{30} \quad \text{(Crest Curve)}$$

$$L = \frac{v^2 A}{60} \quad \text{(Sag Curve)}$$

$$L = 3\ v$$

$$L = 100 \text{ ft min (applies to vertical tangent track, too)}$$

Vehicle couplers specified to accommodate a maximum vertical rate of curve of 100 ft/1.5%.

After review of the rationale for the design of vertical curves, it does not appear that there is any significant obstacle to utilizing vertical curve rates significantly different from 100 ft/% even less than the G&H investigated alternate of 60 ft/%.

5.6 LIFE CYCLE COSTS

It was not the intention of this study to make a comparison of the system cost of a GART and a comparable conventional subway system. Nevertheless, a rough comparison was made to illustrate the magnitude of likely life-cycle cost benefits of the GART approach. Using cost information developed in References 6 and 7, and this current study, preliminary estimates were made. The costs are given in 1976 dollars, assuming 5¢/KWH. The following table lists the major costs for which estimates were made in the mentioned documents:

Life-Cycle Costs
($\$10^6$ per route-mile)

Item	Level	GART
Tunneling	13.3	13.6 (2-1/2% more)
Mid-line vent shafts	1.3#	0
Additional fans for fire safety	0	0.5 (estimate)
Present value of electrical power@	5.4	4.0 (25%* less)
Subtotal	20.0	18.1 (10% less)

@ A factor of ten on the 1976 yearly cost.
* A conversative net savings from the idealized 50% savings.
\# Can be replaced by additional ventilation fans and cooling capacity at station.

A number of items were left out because the cost information was not developed. In most cases, the inclusion of these costs would tend to widen the cost advantage of GART. Several favorable cost examples are:

(1) GART stations are likely to be at less depth than conventional ones in order to utilize the benefits of a dipped guideway, hence resulting in less excavation volume of the assumed cut-and-cover construction method.

(2) The deeper guideways of the GART system would have less influence on utilities and nearby structures.

(3) The GART system requires less station air conditioning capability.

(4) Less maintenance on the propulsion and braking subsystems due to lighter duty cycle.

(5) Lower power demand option for GART while matching transit time of level system.

Several examples of omitted items which would tend to increase the system costs for GART over level guideways are: increased sump pump capability, more adits between the parallel tunnels for improved fire safety, maintenance equipment to operator on greater than normal grades, and additional redundancy on the vehicles to minimize need for push-out. It is not expected that these and other negating factors will outweigh the uncosted favorable factors, of which five are listed just before.

As a result, it is clear that a GART system costs less than a conventional one. Many cost items common to the two types of systems were omitted for convenience. Hence the percentage saving would be less, but the absolute difference would probably exceed the $2 million per route mile shown.

5.7 REFERENCES

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4. Additional Construction Costs of Dipped Guideways for Urban Subway Rail Systems, Final Report by P. E. Sperry and R. L. Lehman on JPL Contract 9559XY, March 1981.

5. Alternative Concepts for Underground Rapid Transit Systems (ACURTS), Report No. DOT-TST-77-31 by JPL, March 1977.

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12. "Basis of Geometric Criteria," for Metropolitan Atlanta Rapid Transit Authority," Parsons Brinckerhoff Tudor Bechtel, 1974, Pgs. 3, 17, 18. "Contract for Procurement of MARTA Transit Vehicles, CQ 310," 1975, Pgs. 2-4, MARTA.

Figure 1. Dipped guideway energy savings over level

Variable Conditions

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

Fixed Conditions

Train Frontal Area:	90 ft^2
Train Weight:	336,000 lb

$$\text{Beta} = \frac{\text{Car Kinetic Energy (Translation \& Rotation)}}{\text{Car Kinetic Energy (Translation)}} = 1.08$$

Brake Rate Max.:	2.2 mphps
Accelerate Rate Max.:	3.0 mphps
Horsepower per Motor Max.:	257
Horsepower Curve:	
HPM = 25 x (v/31)	0 < velocity < 31 mph
HPM = 257	31 < v < 44
HPM = 257 x (1 - 0.0258 (v - 44))	44 < v < 56.5
HPM = 257 x (0.677 - 0.0126 (v - 56.5))	56.5 < v < 75
Tapered Braking:	
Brake Rate: 2.2 mphps	0 < v < 50 mph
BR = 2.2 (1.0 - 0.01 (v - 50))	50 < v < 75
4 (75 ft long) Cars per Train	
Maximum Speed:	75 MPH
Davis Rolling Resistance	
Air Density:	RHO = 0.00238 slug/ft^3
Air Resistance (v in fps):	F(A) = 1/2 (RHO) (A) (CD) v^2 lb

CD	Station Spacing
2.48	2,600 ft
3.37	5,200
4.0	7,800
4.9	13,000

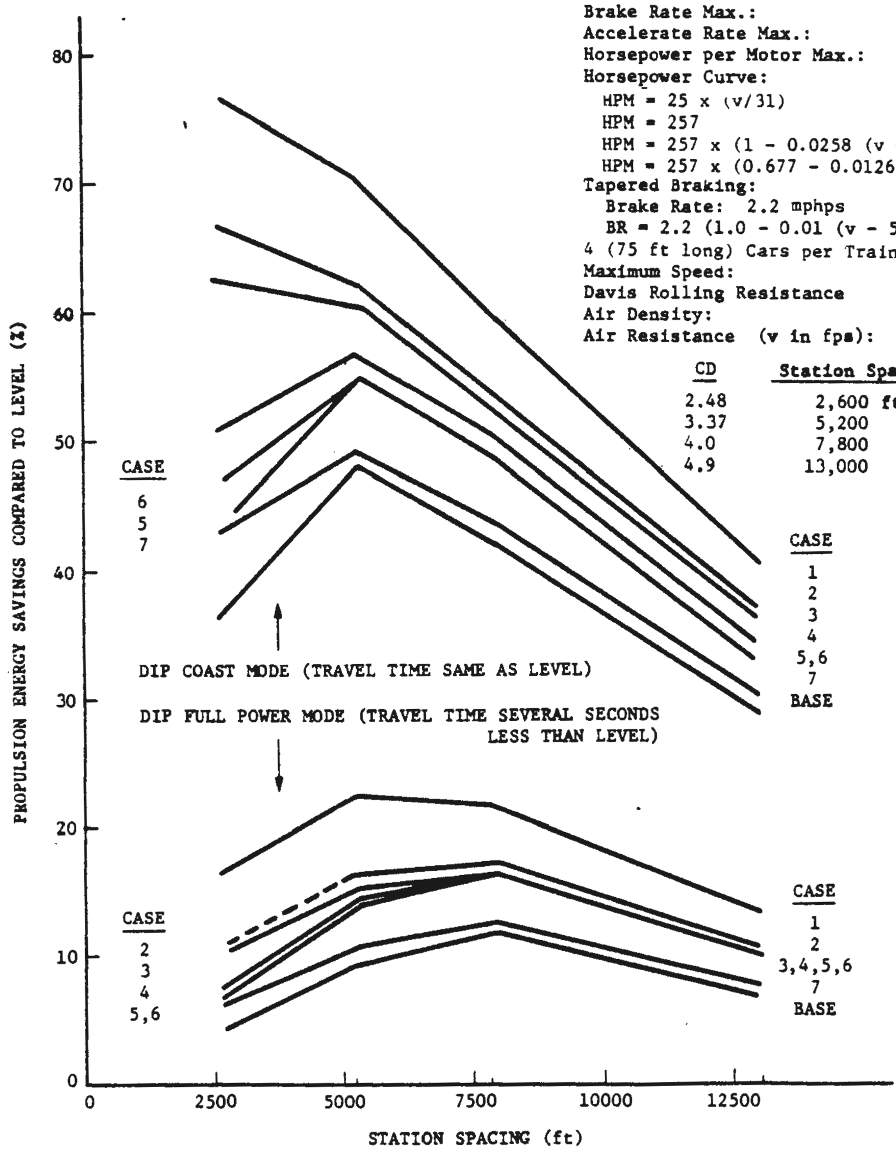

Figure 2. Effect of dip height

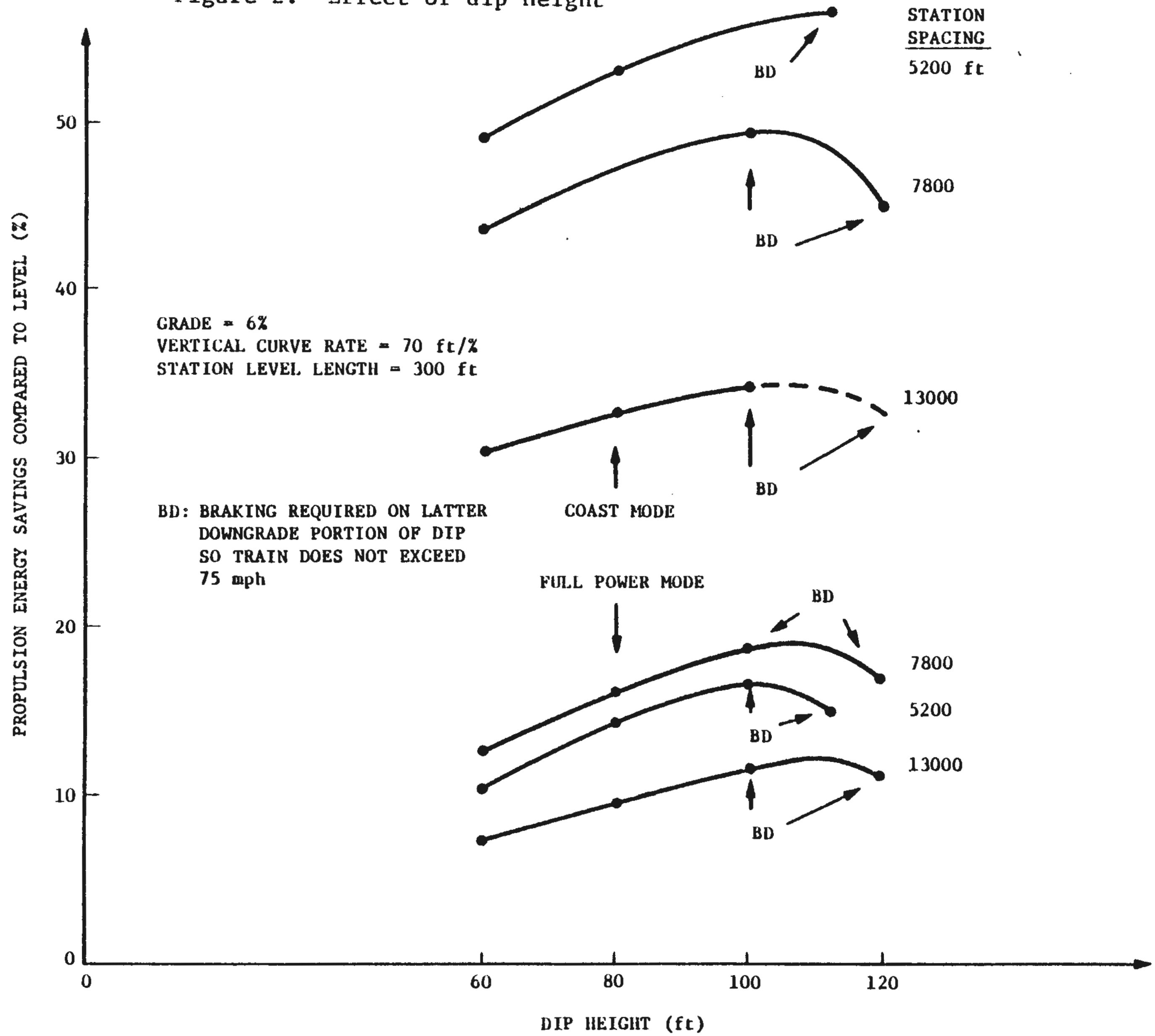

Figure 3. Effect of grade

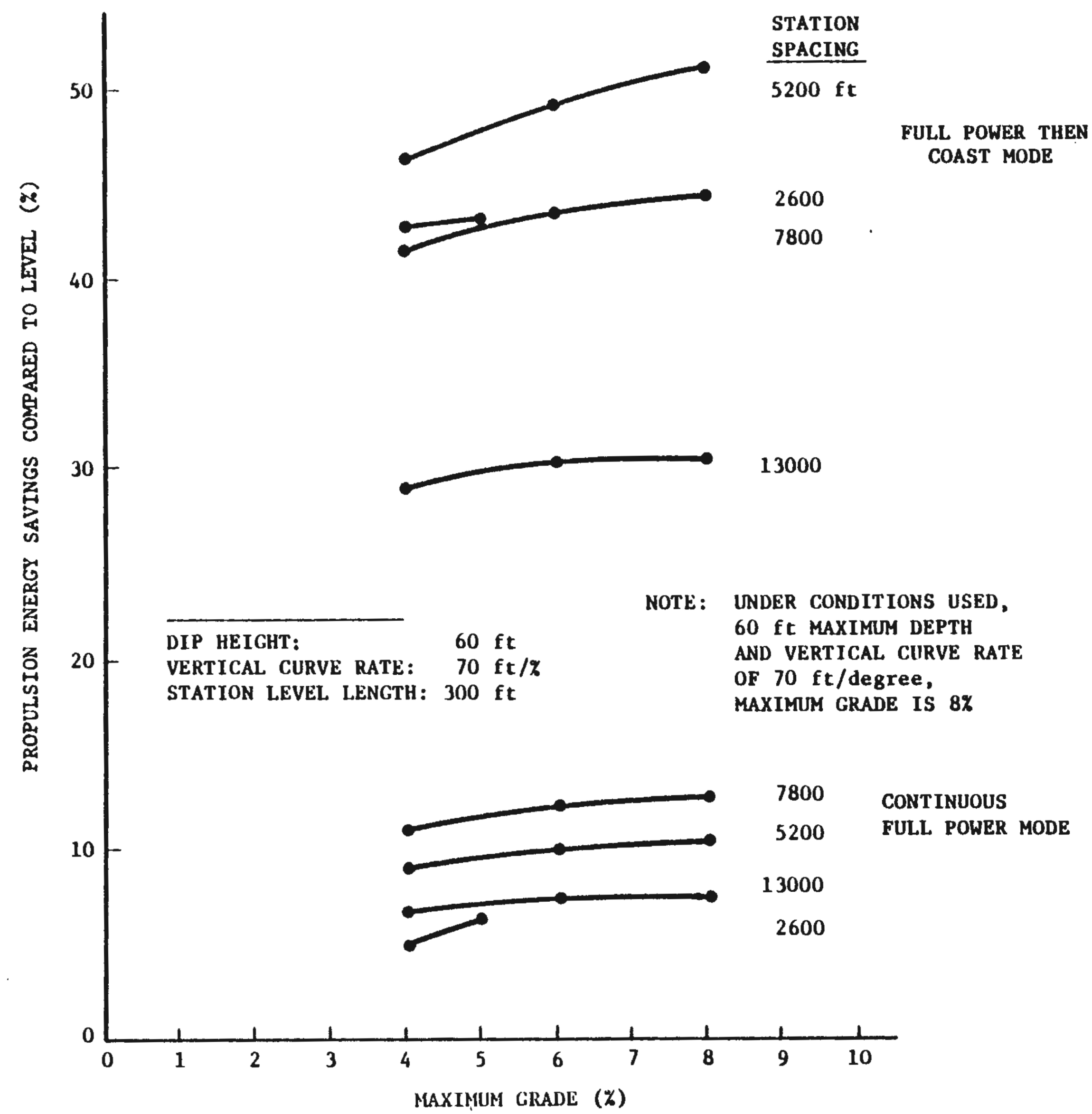

Figure 4. Effect of change rate of vertical curve

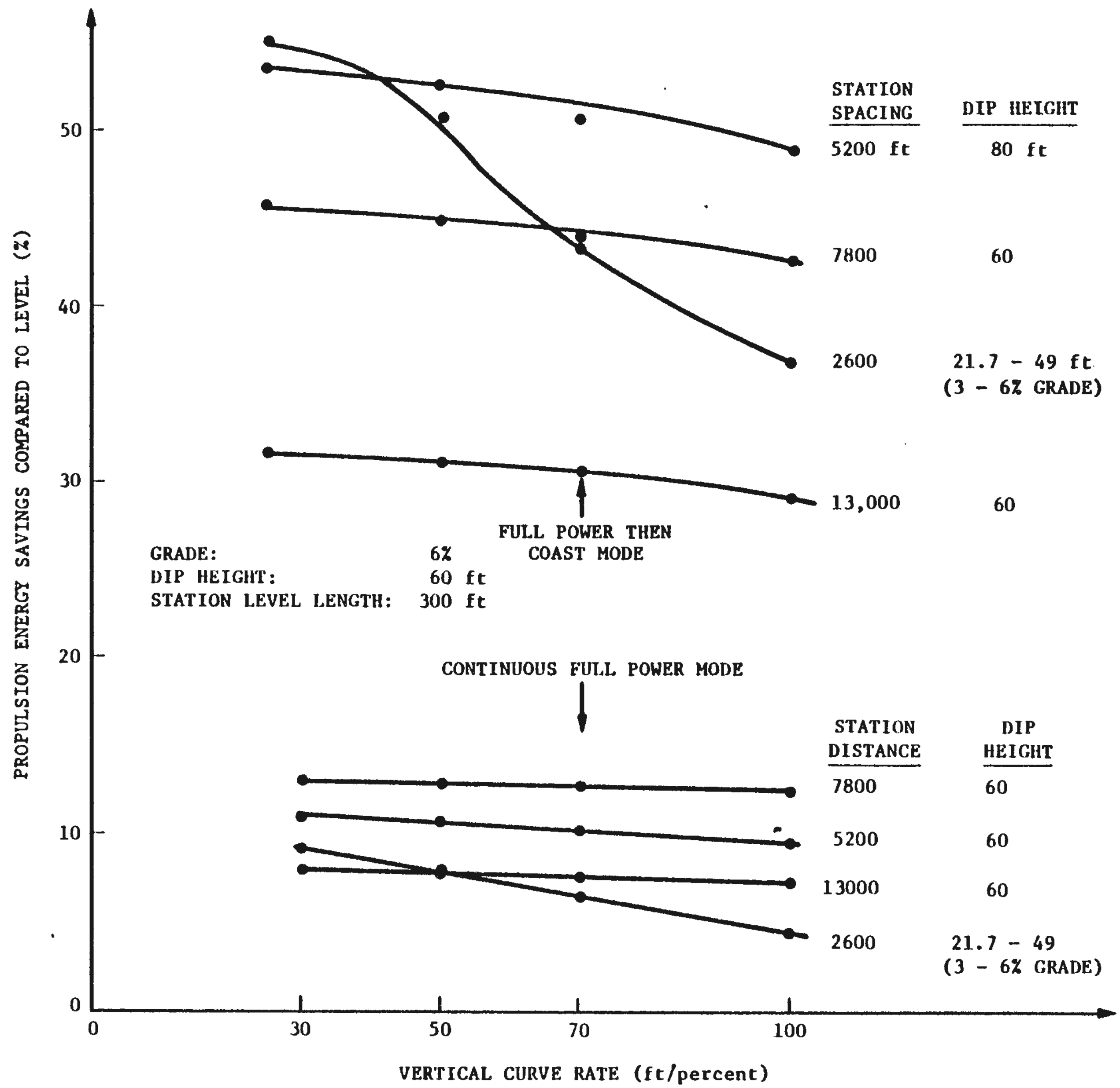

Figure 5. Effect of level length of station

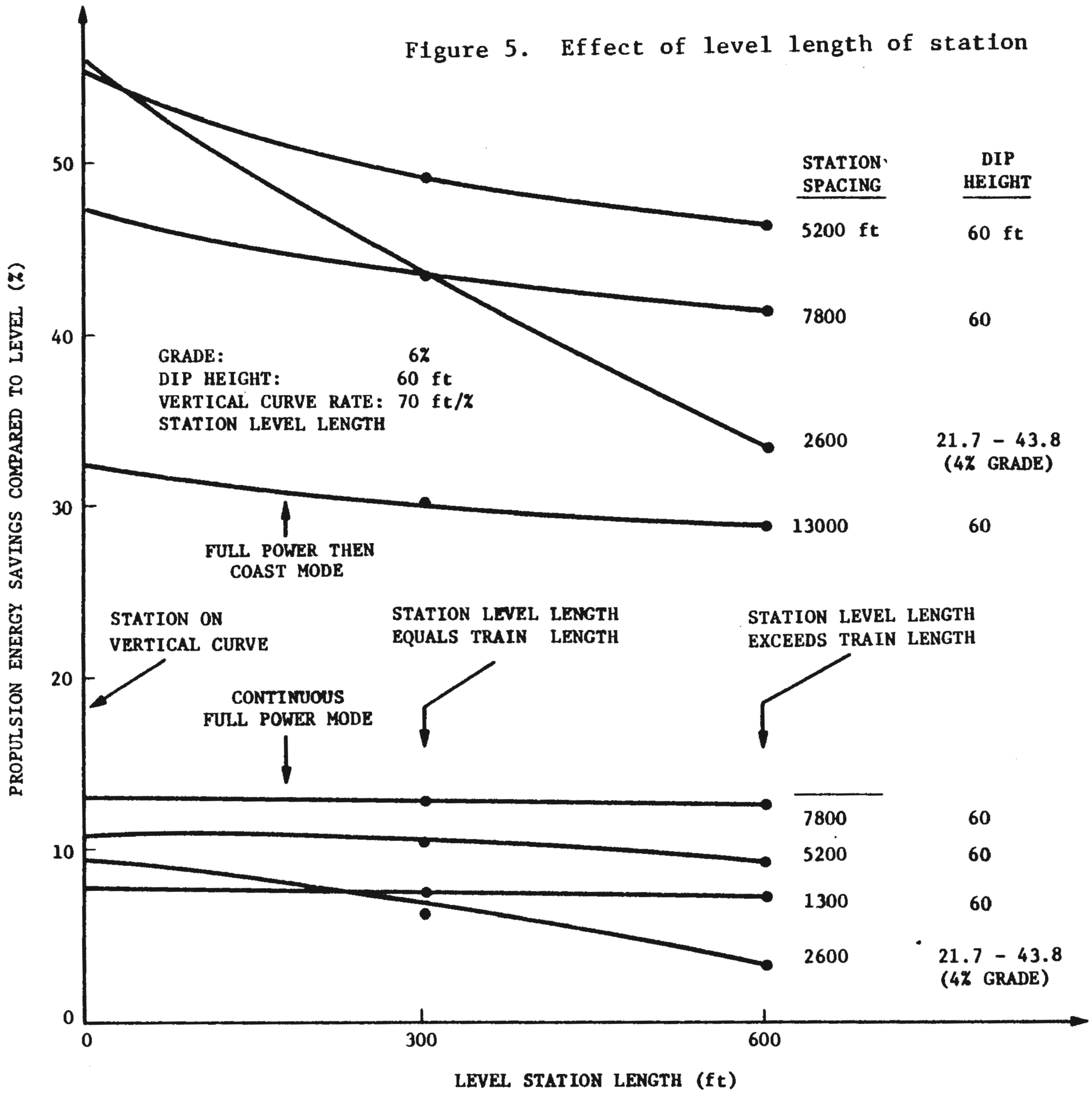

Figure 6. Effect on energy and run time of reducing peak horsepower

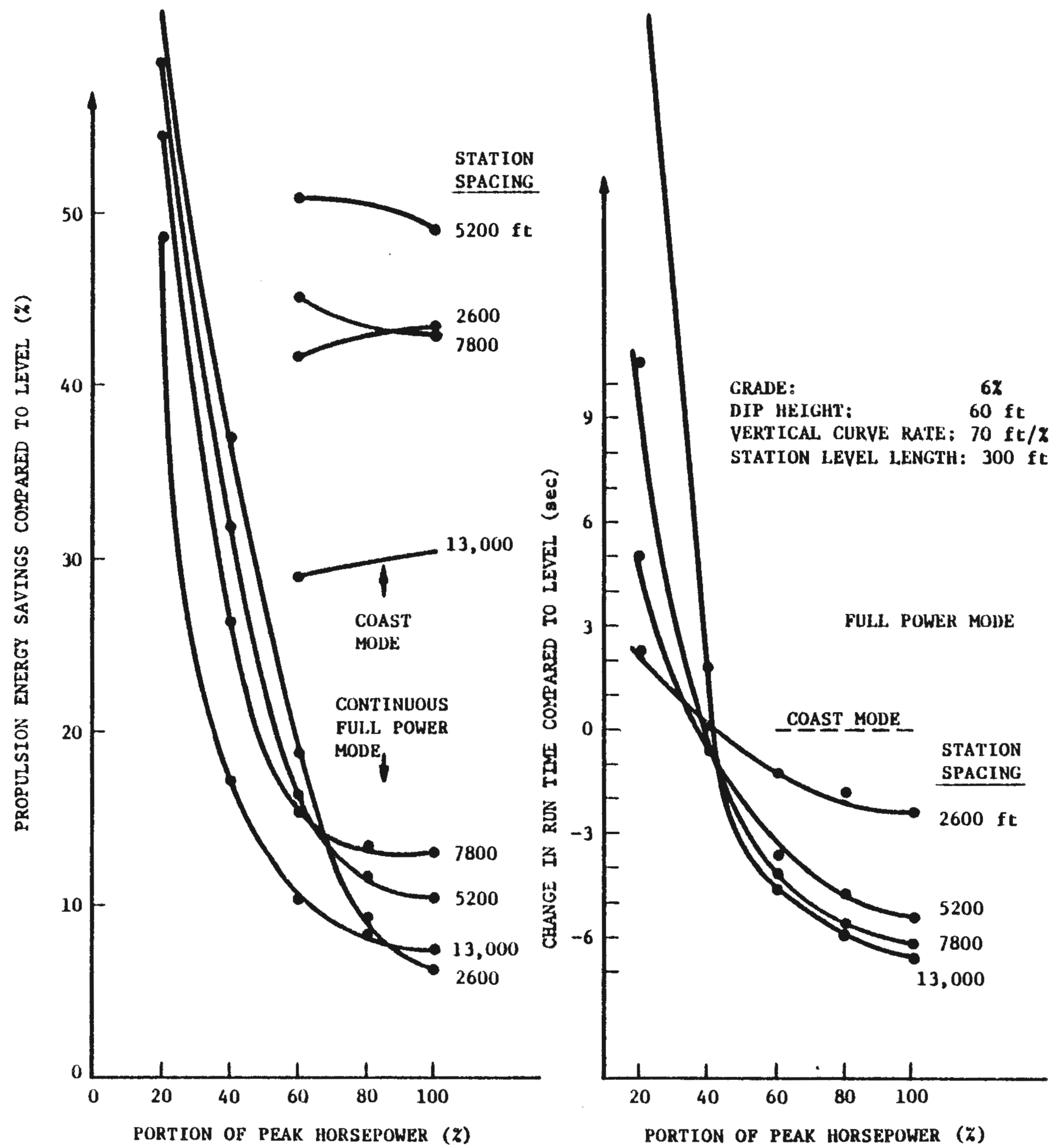

Figure 7. Traction and time profiles vs distance for dip and level system (station spacing 5200 ft)

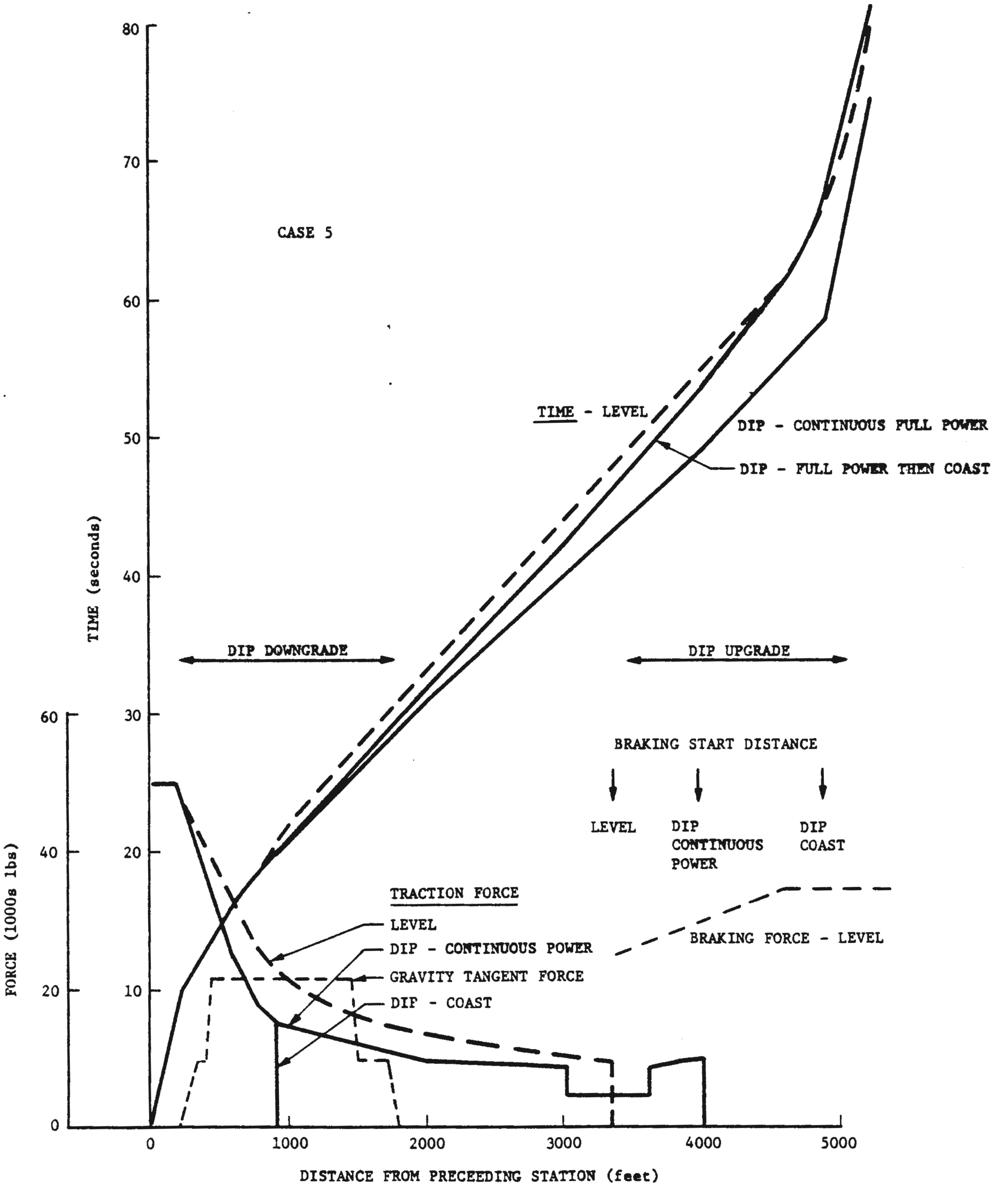

Figure 8. Motive power profile - comparison of level and dipped with reduced peak horsepower