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ASSESSMENT OF THE TUNNEL TRAIN SYSTEM AT THE HOUSTON INTERCONTINENTAL AIRPORT

SRI INTERNATIONAL
MENLO PARK, CALIFORNIA 94025

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16. Abstract

This final report describes and assesses the Tunnel Train System at Houston Intercontinental Airport. The information and data presented in the report were collected by the authors through surveys of technical literature; formal site visits; interviews with operators, management, and engineering personnel; and a visit to the system manufacturer.

A draft form of this report, which is one of six site reports, has been reviewed by site personnel and the system manufacturer, according to the policy of the study's sponsor, the Urban Mass Transportation Administration (UMTA).

The purpose of the site reports is to provide a uniformly documented presentation of automated guideway transit installations for UMTA's Automated Guideway Transit Socio-Economic Research Program and for use by other research groups and interested parties.

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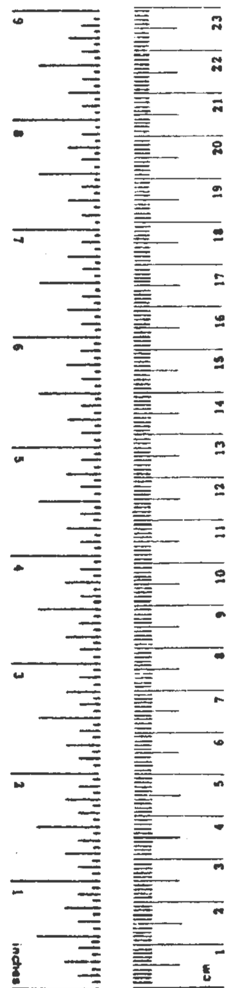
METRIC CONVERSION FACTORS

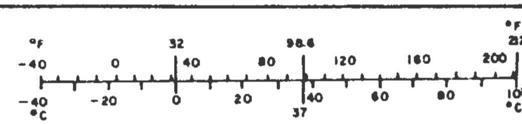
Approximate Conversions to Metric Measures

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



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



PREFACE

This project was conducted by the staff of SRI International's Transportation and Industrial Systems Center under the directorship of Dr. R. S. Ratner. Specifically, the work was completed in the Public Transportation Department directed by Mr. Joel Norman. Dr. Waheed Siddiqee, manager of the Transportation Systems Evaluation Program and supervisor of the project, coordinated the overall planning and policy level activities associated with the project.

Dr. A. M. Yen was the project leader and leader of Task 1, engineering-related data. Dr. M. Sakasita was the leader of Task 2, system economics and operational performance data. Mr. Marc Roddin and Ms. Nancy David shared the effort of Task 3, public perception. Mr. Clark Henderson was the leader of Task 4, the development process study. He also planned and monitored the special task effort for analysis of detailed cost data with the assistance of Dr. Sakasita.

Dr. R. Cronin, Mr. A. Hungerbuhler, and Mr. Steve Procter contributed to the project in an overall manner. Consultants to the project included Messrs. J. Barraza of DeLeuw, Cather (cost engineer); W. Flueckiger of GRC (cost analyst); J. W. Hall (guideway analyst); and F. T. MacInerney (mechanical engineer). The authors would also like to acknowledge Marjorie Cutler for her editing effort and various professionals and secretaries for their contributions to the project and the manuscript.

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1. EXECUTIVE SUMMARY

1.1 Summary Description

This report contains the interim findings of an assessment of the Rohr P-series Monotrain, an automated guideway transit (AGT) system used for passenger transport in the Houston Intercontinental Airport.

SRI International is conducting this assessment as part of an assessment program sponsored by the Urban Mass Transportation Administration (UMTA). The purpose of the program is to gain an in-depth understanding of the performance, capabilities, and limitations of existing domestic and foreign AGT systems. SRI is under contract to assess the systems at Houston Intercontinental Airport, Seattle-Tacoma International Airport (Sea-Tac), Fairlane Town Center, Tampa International Airport, WALT DISNEY WORLD, and King's Dominion Amusement Park.

In assessing systems at these sites, the overall objectives were to:

- Obtain factual engineering and operational data
- Obtain descriptive economic, system performance, and user perception data
- Review the design, development, and implementation process.

The findings are intended to establish the state of the art of AGT systems for ultimate use in planning, evaluating, producing, and deploying future AGT systems.

The AGT system at Houston is called the Tunnel Train. It is located underground below the airport terminal complex, which consists of two terminals (A and B) and a hotel. The train serves all three buildings as well as a parking area between the two terminals.

The system is a continuous 6,080 ft loop over which up to six three-car trains can operate in an unscheduled mode. The running surface of the guideway is the tunnel floor with sidewall and guidebeam-power rail assembly running down the middle. There is a pedestrian path in the area adjacent to the guideway. The four stations, each with two platforms, are on-line. The maintenance area is located off-line at one end of the loop.

The line-haul speed is 8 mph, with reduced velocity around curves and approaches to stations, giving a round-trip time of 18 min. Each car holds 12 passengers (6 standing and 6 seated); the crush load is 10 standees or 16 passengers/car. The line capacity under current operations (four trains) is 480 passengers/hr for normal capacity loading and 640 passengers/hr for crush loading.

1.2 General Findings

The unit terminal concept employed at the Houston Intercontinental Airport requires provision for interterminal transport. The existing terminals are 1/4 of a mile apart. As the airport expands and the two planned terminals are built, the maximum distance between terminals will be approximately 3/4 of a mile. A tunnel to contain the interterminal transport system was constructed, but the small dimensions of the tunnel and the design of the station areas restrict both the size of the vehicles and their speed.

The control system installed at Houston is very simple and has proved to be reliable. However, the required train spacing is large, and delays occur when more than four trains are operated. The result is that the AGT system at Houston is characterized as a low-speed, low-capacity system with relatively long headways.

Unlike the AGT installations at Sea-Tac and Tampa International Airport, use of the AGT system is not mandatory. It is a convenience for passengers who must carry heavy luggage in traveling from the parking lot to the terminal, between terminals, or between one of the terminals and the hotel. A pedestrian walkway is provided parallel to the guideway, and many airport users choose to walk.

Because the tunnel train operation is not viewed as an absolute necessity, a very high availability is not required. Consequently, there is no comprehensive preventive maintenance program, the availability is not as high as in other AGT systems, and the mean time to restore is fairly long. The following system reliability and availability figures for 1976 were derived from estimates made by the maintenance staff (no records are kept to allow accurate calculation): mean time between failures (system shutdown), 63 hr; mean time to restore, 2 hr; and availability, 0.97.

While reviewing the findings of the report one must keep in mind the restrictions of the site and the fact that the original performance specifications did not require a high performance system. The AGT system comes close to the original specifications despite the site restrictions.

The tunnel train can be characterized as a reasonably successful application of a low-speed system. The system itself is probably near its design limits; there is little probability of increased performance without major design changes. As such, the system should not be considered representative of the manufacturer's entire product line but rather in the light of the restrictions and needs of the application and how those needs are met by the design.

1.3 Outline of the Report

The report contains seven major sections and a comprehensive information checklist attached as Appendix A.

The background of the project, including a brief description of the UMTA program that provided the funding for this study, is given in Section 2, as is the method of approach used in the assessment.

The engineering system description and assessment is given in Section 3, which contains all major engineering subsystems including site-specific subjects. Tables summarizing the engineering description are provided whenever appropriate.

Section 4 addresses the subjects of operation, maintenance and reliability, and passenger-oriented system performance. The description of operations is standard, using such terms as capacity and headways. The study of maintenance and reliability centers around the maintenance policy practiced by the site operator whose professional goal is to maintain the system so as to accomplish high system availability. For uniform reference, however, calculations in this report have been made for mean time between failure (MTBF) and mean time to restore (MTTR).

Systems economics, including capital, operations and maintenance costs, are the subject of Section 5, which includes an examination of the data, escalation, and equivalent annual cost.

The development history of the system is thoroughly examined in Section 6 which includes all major events that led to the present AGT system. These features have numerous impacts on all subsequent designs.

A comprehensive checklist with standard AGT assessment measurements and units appears in Appendix A, and provides a convenient means of access to all system information for the reader.

2 INTRODUCTION

2.1 Background of the AGT Socio-Economic Research Program

In 1975 several Federal research programs in new transit systems were integrated to form a consolidated technology program--the Automated Guideway Transit (AGT) Program.

There are several programs within the general AGT Program: the Advanced GRT Program; the Automated Guideway Transit Technology (AGTT) Program for advancing all key aspects of AGT technologies; the AGT Applications Program for actual deployment projects, such as the Downtown People Mover (DPM); and the AGT Socio-Economic Research Program, which sponsors the assessment activities. The total AGT program is structured so that its elements complement and support each other for maximum achievement of program goals.

The AGT Socio-Economic Research Program had a modest beginning in 1973, when a macrolevel analysis of urban transportation with AGT emphasis was carried out. Beginning in 1974 the first of a series of AGT system assessments was initiated, namely the assessment of AIRTRANS system at Dallas/Fort Worth Regional Airport. Qualification guidelines for capital assistance funding of AGT systems were formulated.[1] An assessment of the Jetrail system at Love Field in Dallas, Texas was also conducted. The assessments of AIRTRANS, Jetrail and Cabintaxi/Cabinlift systems in W. Germany have been completed and published.[2,4,5] An assessment of the Morgantown system is underway.

In 1975 the program was significantly enlarged. Major research efforts were initiated in AGT system needs and market analyses, R&D delivery improvements, and socio-economic analyses of AGT systems including public perception, financial and institutional impediments to urban AGT system emplacements, and an expansion of the AGT assessment programs to include domestic airports, commercial sites and foreign sites.

An independent report on AGT systems was prepared by the Office of Technology Assessment (OTA) in June 1975 at the request of Congress.[3] This report, which was commissioned to provide the Senate Appropriations Committee with some background and status of AGT systems, has in part underscored the need for an ACT Socio-Economic Research Program.

During the 1976 Senate Appropriations Hearings, a new program area entitled "Social and Economic Research in AGT" and an appropriate level of funding were recommended. The Senate referenced the OTA report stating that the

> "finding of the OTA report is that social and economic research is needed on AGT systems. The Committee recommends providing $2 million for such research to be used to study the comparative advantages of AGT systems over other forms of mass transportation, evaluation of performance and cost experience of existing AGT systems, assessment of the market potential for urban application of AGT, and simulation and experimentation with existing AGT systems to determine what can be learned about the human response to them."

The goals of the AGT Socio-Economic Research Program are to:

- Determine the particular types of urban applications for which AGT systems are most appropriate.
- Identify and examine the institutional, social, economic, environmental, land use, and performance considerations associated with urban implementation of AGT and evaluate the acceptability of these characteristics by the various impact groups affected.
- Ascertain the capability of AGT systems to meet the mobility needs and the socio-economic requirements of the urban environment by a comparison of the performance and socio-economic characteristics of AGT and other transportation systems.
- Ascertain the nature and magnitude of the potential national market for the classes of automated guideway transit systems (SLT, GRT, and PRT) on a preliminary scale.
- Identify and assess policy options and financing mechanisms necessary to achieve significant implementation of AGT systems if warranted.
- Determine further research, development, and demonstration requirements for AGT system technology.
- Establish a central repository of current information on AGT socio-economic and performance characteristics and regularly disseminate this information to interested audiences in formats most useful to each.

Information obtained through this program will be valuable to local governments in undertaking their local alternatives analysis process, a recent UMTA requirement in seeking capital assistance funds. Furthermore, this Program will develop information to determine the domain of AGT in the hierarchy of urban public transportation and assess its merits and demerits associated with implementation in U.S. urban areas.

The AGT Socio-Economic Research Program is structured around several basic research activities, as follows:

- Generic Alternatives Analyses--This activity is to examine the relative merits and demerits of AGT systems in comparison to other forms of urban transportation.
- Assessments--The studies under this activity are concerned with the operating experience of existing AGT systems.
- Costs--Under this activity, detailed costs and economic studies are conducted for AGT systems.
- Markets--Under this activity, studies are conducted to estimate the market potential of AGT systems.
- Communications--This activity is concerned with disseminating information about AGT systems to all interested parties and receiving local expressions of views about AGT.

The work presented in this report was performed under the AGT Assessments activity.

2.2 Discussion of the AGT Assessments Activity

The UMTA AGT Socio-Economic Research Program defines the goal of the AGT Assessments as follows:

> These Assessments collect, aggregate, and uniformly present the performance and associated socio-economic characteristics from experience to date with AGT installations operating in public service, as well as document the implementation history and learning experiences of each major AGT deployment. The operational, economic, environmental, and passenger response data on all existing domestic and foreign AGT systems will be organized into a central inventory of AGT information for use in conducting the Generic Alternatives Analysis activity, the Markets activity, other activities of this research Program, and by other research groups and interested parties external to this program requiring such data.

To accomplish the above noted goal, several AGT assessment projects were initiated in 1975 for assessing existing domestic and foreign AGT systems and the Morgantown Personal Rapid Transit Demonstration Project.

This site report is one of several for the domestic AGT system assessment. The emphasis of the effort in conducting the assessment was in four major areas:

- Technology-related data--The performance of vehicle subsystems, steering, switching, propulsion, suspension, command and control, guideway, and power distributions are assessed, and the engineering system as a whole is reviewed. Many innovative designs are used in the engineering of the AGT systems. Assessments are based on the functions that an automated system must perform, its effectiveness, and its ability to be deployed in other environments.
- System economics and performance--The effectiveness of the AGT system is assessed by its throughput and layout parameters. System economics, capital, and operations and maintenance cost data are obtained and reviewed. Maintainability, from maintenance strategies and procedures to crew training, is thoroughly examined. Reliability, as a consequence of both maintenance and design, is assessed. Mean time between failure (MTBF) and mean time to restore (MTTR) are calculated wherever appropriate.
- Public response and acceptance--This subject is assessed both subjectively and objectively. Assessments by both owners and operators are obtained, and user perceptions are observed and recorded. An attempt is made to distinguish between the specified and actual comfort for passengers.
- System development process--The systems assessed represent the first generation of deployed AGT systems. The conception, design, development, procurement, testing, and acceptance of these systems vary greatly. In this task we review the entire development process and the relationship of the participants at each site to develop findings that will be applicable to planning and producing future AGT systems.

The rest of this report presents detailed discussions in these four areas.

3. TECHNICAL DESCRIPTION

3.1 System Description

The Houston Intercontinental Airport contains an AGT system called the Tunnel Train as an integral part of the airport circulation system. The system is a loop with 6,080 feet of guideway in an underground tunnel, which also contains a pedestrian walkway. The system connects the three main buildings of the airport (two terminals and a hotel) and a parking area. It operates in unscheduled automatic circulation mode only.

No fare is charged for the service. The presence of an alternate walking path makes the service nonessential in some respects, but the fact that the centers of the buildings are located some 1/4 mile apart would make it difficult for a passenger with luggage to walk the entire length of the airport. The unit terminal concept embodied at Houston (Figure 3-1) will increase distances as additional terminals are built, which will further increase the difficulty of walking.

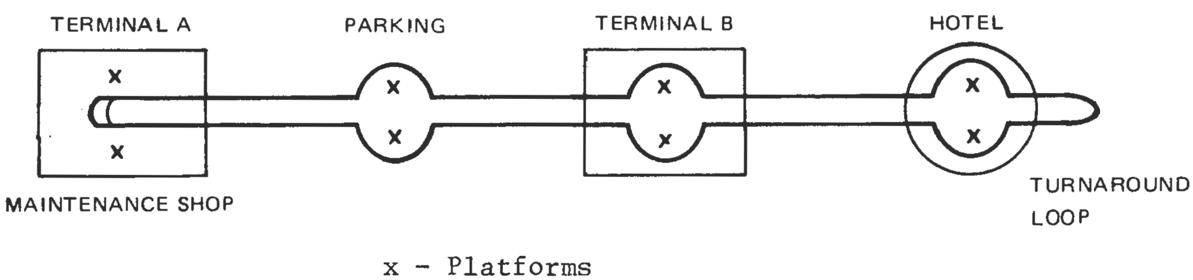

FIGURE 3-1 HOUSTON TUNNEL TRAIN SYSTEM

Figure 3-1 is a schematic of the existing guideway alignment. Stations are marked with x's. When additional terminals are built, they will be located along the same axis on the opposite side of the hotel from the present pair of terminals. The maintenance shop for the existing system is located under terminal A as shown.

Four of the six three-car trains normally operate counter-clockwise around the loop.* Each car has two three-passenger bench seats, one at each end of the vehicle. The floor space between the seats will accommodate up to six standees for the short trips within the airport. There is no dedicated luggage space, so the amount of luggage carried competes directly for floor space with standees. Figure 3-2 depicts a train just outside a station.

Line-haul speed is only 8 mph, twice that of a fast walker. However, when deceleration, reduced velocity around curves, and dwell time are taken into account, the mean speed is reduced to 3.7 mph, slightly faster than that of an average walker. If the wait time is more than a minute or two, a traveler without luggage or an airport employee will be tempted to walk rather than take the tunnel train, especially when the train trip would be only one or two stops.

A summary of the operating characteristics of the Tunnel Train is provided in Table 3-1. Additional details are provided in Appendix A.

3.2 Vehicle Subsystem

3.2.1 Description of Vehicle and Performance Parameters

The Rohr P-series Monotrain at Houston is fairly representative of the ultimate performance that the system is capable of providing within the given environment. The overall subsystem parameters are shown in Table 3-2.

As shown in Figure 3-3 each train consists of one "A" car, one "B" car, and one "C" car supported on four bogies. The two center bogies are shared. The lead bogie in the "A" car is not powered, but the other bogies are. The maximum train length is presently limited by the station size and power supply at Houston. For other installations it would appear practical to increase the train size by adding "B" cars.

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*One non operating train is kept ready to be inserted in the system quickly in case of any problems in any of the four operating trains. The other non-operating train is usually a train undergoing some maintenance work.

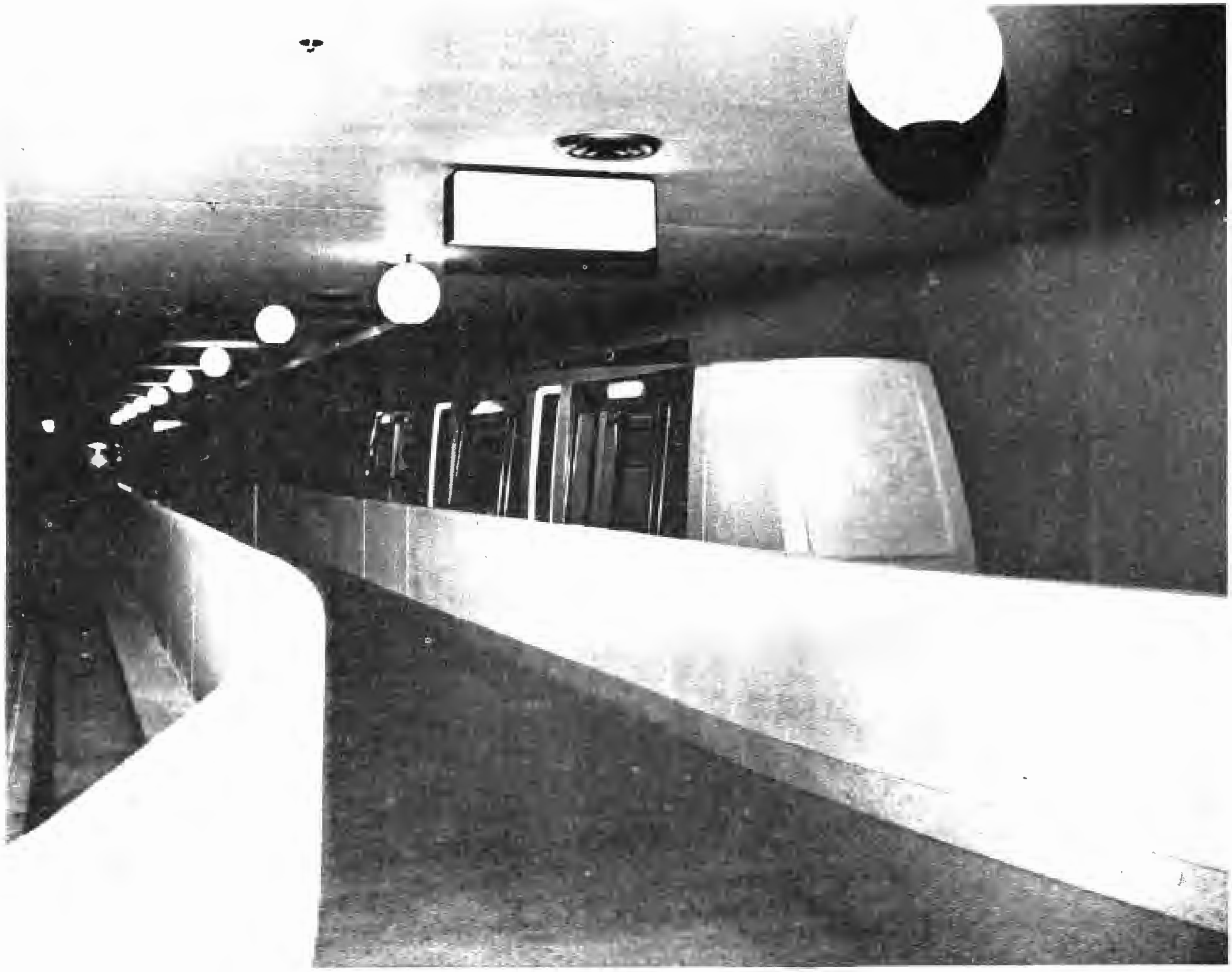

FIGURE 3-2 HOUSTON TUNNEL TRAIN

Table 3-1

OPERATING CHARACTERISTICS OF HOUSTON TUNNEL TRAIN

Manufactured by Rohr Industries	
Opened September 1972	
Vehicle	
Capacity	12 (6 seated) passengers; 3 cars per train
Maximum speed	8 mph
Headway	4.5 min
Number	4 trains (normal operations), 6 total
Type of operation	Train only
Command and control	
Type	Sector-block separation, control rail speed system, central monitoring and display
Management policies	Train remains in station until lead train departs next station
Modes	Automatic unscheduled loop
Guideway	
Length	6,080 ft
Type	Tunnel
Material	Concrete
Routing	Loop
Stations	
Number	4
Platforms	8
Berths	1
Operational	
Weather	Controlled environment
Trip speed (maximum)	8 mph
Capacity	
Maximum	640 passengers/hr @4.5 min headway
Nominal	480 passengers/hr @4.5 min headway

Table 3-2

ROHR VEHICLE SUBSYSTEM PARAMETERS
(3 car train)

	Houston Installation
Size (length × width × height; in ft)	40 × 5 × 7.5
Empty weight (lb)	7,200
Capacity (lb)	5,400
Floor area (ft^2)	105
Interior volume (ft^3)	750
Speed (maximum) mph	8
Acceleration (mph/sec)	3.0
Deceleration	
Service (mph/sec)	3
Emergency (mph/sec)	3.2
Jerk limits	
Acceleration (mph/sec^2)	1.5
Deceleration (mph/sec^2)	1.5
Maximum train length (number of vehicles)	3

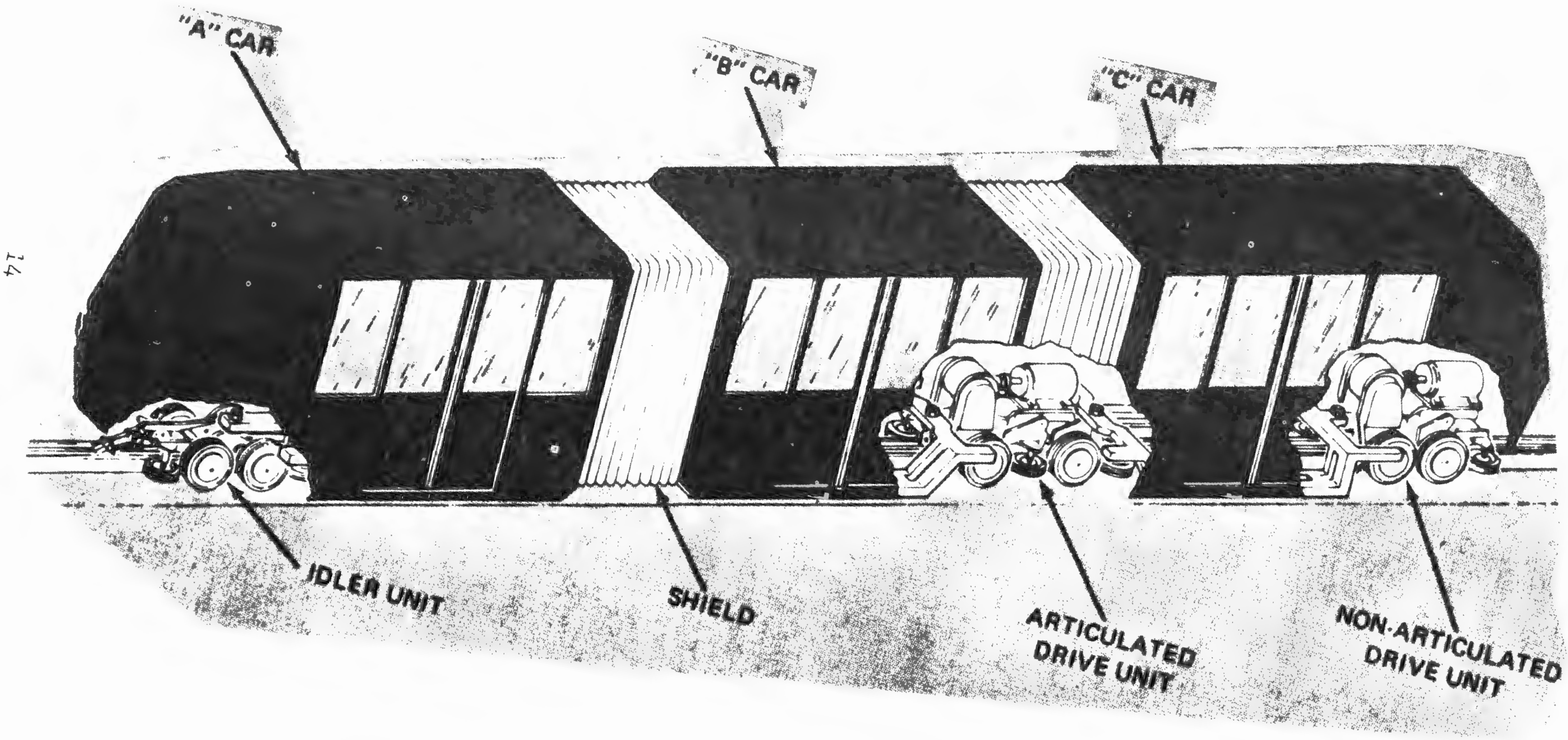

FIGURE 3-3 HOUSTON TUNNEL TRAIN VEHICLE AND BOGIES

The bogies have relatively narrow tracks. Although this allows a narrow guideway (possibly an important consideration in elevated applications), it has the disadvantage that irregularities in the guideway surface result in more sidesway and an uncomfortable ride.

3.2.2 Brakes

Each train has three types of brakes. Dynamic braking is used for normal service braking. As the train slows, the dynamic braking fades, and electromagnetically actuated drum friction brakes are applied to bring the train to a stop at the station. The drum brakes are mounted on the undriven wheels of the powered bogies (six wheels in all) and are made by Kelsey-Hayes. These brakes were originally designed for automotive trailer use and operate on low-voltage dc. In the event of a power failure, the brakes are applied by electricity from an onboard battery. A Stearns brake is mounted on the shaft of one of the motors. This brake is spring applied with electrical hold-off. It is applied in the event of complete electrical failure, and it is also used to hold the train at each station. Thus, the brake's operation is tested at every station. A degree of redundancy has been incorporated into both service and emergency braking systems.

3.2.3 Vehicle Structure

The vehicle is a steel frame structure with molded fiberglass components for almost all surfaces, both exterior and interior, including seats. The end units have fiberglass hinged nose sections that swing up for access to the control components. The inboard ends of the "A" and "C" cars and each end of the "B" car rest on the intermediate articulated bogies which couple the sections into a three-unit articulated train.

3.2.4 Minor Subsystems

3.2.4.1 Doors

The Houston vehicles have doors on one side of the vehicle only. They are biparting sliding doors, 40 in. wide,and electrically operated. The major shortcoming of the doors is that the safety edges do not cause the doors to retract, but only to stop their motion. There are no emergency exits from the vehicle other than the doors, which cannot be forced open once closed. In an emergency, an attendant must go to the vehicle and actuate the doors from the outside. In general, the operator feels that the overall experience with the doors has been acceptable.

3.2.4.2 Heating, Ventilating, Air-Conditioning

The Houston vehicles have only a ventilating fan in each passenger compartment, because they operate in an air-conditioned tunnel with a constant temperature of about 72°F.

3.2.4.3 Passenger Environment

The seating arrangement is one three-passenger bench seat at each end of the passenger compartments. There are horizontal grab rails on the side walls, but no grab rails or vertical stanchions for passengers in the middle of the standing area.

Windows are provided on one side of the vehicle, in the side panels and in the doors. They contribute significantly to relieving the confined feeling of a relatively small vehicle.

A stop button has been provided for passengers to stop the vehicle and to summon an attendant in case of an emergency.

3.3 Command, Control, and Communications

The command, control, and communications system (CC&CS) of the Rohr P-series Monotrain at Houston performs the following eight functions:

(1) Speed regulation

(2) Train separation

(3) Stopping

(4) Door operation (both vehicles and stations)

(5) Acceleration

(6) Deceleration

(7) Safety interlock

(8) Monitoring of train system.

The first six functions are part of the vehicle operations control; function seven is for vehicle protection; and function eight is for central control. These control functions are accomplished by hardwired circuits using standard cables, transistors, and gravity-type vital relays. The CC&CS does not require any computerized equipment. It is fully automatic. The design is based on proven technology using components of well-known characteristics.

3.3.1 Vehicle Protection

Rohr's system at Houston uses a block control design. It is a "sector-block" zone system where the guideway track is divided into eight sectors. Each sector contains a station and the section of guideway leading to that station. The sectors are numbered 1 through 8, in the direction of a vehicle traveling counterclockwise around the loop.

Each sector forms a vehicle protection zone. The system is designed to allow vehicles to proceed from station to station, as long as the next sector ahead has been vacated. Therefore, a train of vehicles will be held at a station with its doors open until such time as the preceding train has moved and left the sector ahead. The word "block" is used at Houston to describe the track between the stations in which operational control circuits are implanted for various speed commands (see Section 3.3.2). The use of "block" in this context should not be confused with zones (station plus blocks) by which vehicles are separated for protection.

For vehicle detection, a direct current of controlled voltage and polarity is applied across the signal collector bar and the negative propulsion return bar. A train detection relay is connected across these collector bars at the opposite end from the dc input. The current collector shoes, one on the negative propulsion return bar and one on the signal collector bar, shunt across these two collector bars, short-circuiting the dc voltage. This causes the detector relay to become de-energized and to indicate block occupancy. The relays are both biased and voltage sensitive, ensuring their response to only one voltage and one polarity.

The track occupancy signal inhibits, via other central control relays, the application of any speed command signals to the track in the block behind for redundant safety protection. This interlock logic is used throughout the system.

The vehicle has six onboard command relays that control the propulsion and braking systems. The absence of a speed command signal (as in a power failure) will automatically open all these relays, resulting in the removal of propulsion and the application of brakes.

3.3.2 Vehicle Operations Control

Within each sector block or zone, the control of vehicle operations is divided into block controls on the track and station controls at station areas.

Each block is further divided into appropriate segments. Each segment has its own track circuit through the use of insulators inserted on the signal rail. The number of segments in each block is determined by the block's location--in a free running area, a switch area, or a maintenance area.

A typical free running area between two stations has segments of 4 mph for leaving the station, 8 mph for a straight run, 4 mph for slowing down, and 1 mph for entering stations. The command codes are as follows:

Speed Command	Command Signal (V)	Signal Polarity
8 mph	15.5 V dc	+
4 mph	.3 V dc	+
1 mph	.3 V dc	-
0 mph	.0 V dc	
Vehicle door open	15.5 V dc	-

The command signal, in volts, appears on the track in each segment to set the appropriate onboard relay for the speed signaled.

The 4 mph speed is used for leaving a station and for slowing down to enter a station; it is also used for entering areas when a slowdown is necessary due to the civil speed limit. The train proceeds at 4 mph to the vicinity of the station, where the speed command is reduced to 1 mph. When the car doors and station doors are aligned, the train is commanded to stop.

A relay on the wayside will close when the electromagnet on the train is properly aligned with the relay. This will start the "station door open" and the "door open" relay contact on the train, which, together with a zero velocity contact, will open the train doors. The setting of the wayside timer determines the station dwell time. When the wayside timer runs out, the "station door open" relay drops, closing the station door and canceling the "door open" signal to the train.

The "station door cycle" relay checks to see that the station gates have operated through their entire cycle, following which the cycle relay applies the 4 mph signal to the curved track section leaving the station. If the vehicle doors have been prevented from closing by a passenger, the vehicle will not respond to the speed command until the doors are closed.

The above description shows that the station door control in the Houston system is complicated; it is an element of a series of controls that enables the system to proceed. Therefore, the reliability of each of the door electronics becomes extremely important for the reliability of the whole system.

2.3 Central Control

Central control is composed of a display of vehicle movement by illumination, an operation selector, and cabinets of vital relays.

The control console also has controls for each station in the passenger service route to provide for one of three modes of operation--AUTO, HOLD, or BYPASS. These controls operate independently of one another, so that different stations may be operated in different modes (i.e., a single station or selected group of stations may be operated in the BYPASS mode so that trains will not stop there, while normal station stops will occur at the remaining stations left in the AUTO mode).

In the AUTO mode, trains will execute a normal station stop, with doors remaining open for the time period for which the timer for that station is set.

With a station set in the HOLD mode, a train may enter the station and the train and station doors will open normally. The hold position of the control lever, however, prevents the station door relay from closing at the end of the timing cycle, so that the train and station doors cannot close. The train will thus remain stopped at the station with train and station doors open until such time as the selector is returned to the AUTO mode.

3.3.4 Data Communications System

An exclusive signal rail and contact shoe carry a dc control voltage for wayside-to-vehicle communication. Vehicle-to-wayside "communication" consists only of the shunting of the signal rail to indicate zone occupancy and the activation of detectors at stations that sense train presence.

3.4 Steering

The Rohr P-series Monotrain has two bogie-guiding arrangements. The end bogies on the "A" and "C" cars have two parallel fixed axles, with four guidewheels at the corners of the bogie. In a curve there is some tracking error for each axle. The two shared intermediate two-axle bogies are articulated so that each axle can be positioned radially on a curve. Six guidewheels per bogie are required to steer the intermediate bogies correctly. The running gear is mechanically suited to bidirectional operation. This capability is not used at Houston.

The guidewheels were initially preloaded to the guidebeam by compressing the wheels 1/16 in. to control hunting and to fix the lateral position of the vehicle more accurately. This is important in stations to control the gap in the walkway. However, the guidebeam began to develop cracks at the flange-to-web juncture, and the guidewheels were adjusted to allow a slight clearance, which proved unsatisfactory because of excessive lateral motion. The guidewheels are currently adjusted to zero clearance, best described as "snug."

3.5 Switching

The guideway switch system used by Rohr for the Houston installation is a segment substitution type. Tangent and curved guidebeam segments are interchanged to complete the desired path by translating them on Thompson round tracks, commonly found in machine tool applications.*

*Thompson round tracks are sliding load-carrying devices consisting of recirculating ball bearing sliders moving along the axis of circular section steel rods.

Because of problems with motor-driven ball screws initially installed, the switches are now manually operated and locked. This method of operation is acceptable to the operators because the switches are only used to add or remove trains to the system loop at the maintenance area.

The guidebeam has mechanical discontinuities at the switch segments, as is necessary with a segment substitution switch system. The guiding forces are imposed by the guidewheels above the centerline of the guidebeam web, which causes a bending movement in the guidebeam flange. At discontinuities in the beam the increased bending stress has caused fatigue cracks at the flange-to-web juncture. It has been necessary to reinforce the ends of all beam segments to control the cracking.

3.6 Propulsion

The propulsion equipment used aboard the Houston tunnel train is designed around traction motors and controls built by General Electric (Speed Variator Department). The system uses three driven bogies per train. The lead bogie on the "A" car is undriven. Each dc compound traction motor drives a differential gear unit through a flexible coupling. The differential is connected by means of a silent chain to the axles of the drive wheels, providing positive and negative traction. Alternating current collected from the power rail is converted to dc through rectification. Speed control is achieved by variation of armature voltage. A single silicon controlled rectifier package per train is used to convert control signals (in the form of low voltage gate pulses) into the corresponding armature voltage.

The General Electric equipment consists of two basic units: the power control unit and the dc motors. Specifications for these items are as follows:

- Compound wound dc traction motor--7.5 hp; 1,750 rpm; 240 V; 27.7 A.

- Speed variator power conversion unit--277 V; 90A; 60 Hz; single phase.

The power convertor converts single-phase ac to controlled dc voltage. The output range is from 0 V to 240 V, with current matched to the motor requirements. Control input consists of two gate pulses, 180° apart, and from 10 to 50 msec in duration. The pulses must be at least 15 V at 15 mA.

Each motor is fitted with a different piece of auxiliary equipment connected to the train speed control system: a tachometer, an overspeed switch that trips at 1,900 rpm, and a Stearns brake. The tachometer is a feedback element in the speed control system. The overspeed switch operates in case of a control system failure that allowed excessive speed. The function of the Stearns brake has been described in Section 3.2.2.

The differential gear units and drive chains provide an overall reduction. Information was not available regarding reduction ratio or overall efficiency.

3.7 Suspension and Guidance

The suspension system of the Rohr P-series Monotrain is appropriate to the indoor environment and operational speed of the system. The vertical suspension system consists of foam-filled load-carrying tires, and one air bellow per axle. The air bellows are inflated at discrete intervals from shop air and monitored by maintenance personnel for correct pressure (unlike some vehicles that maintain suspension air pressure from the vehicle onboard air supply). Naturally, a passive system cannot be used to correct floor height for varying passenger loads.

Positive mechanical guidance is provided by an aluminum extended guidebeam shown in Figure 3-4. Beams are anchored to the concrete floor with a height of approximately 2 5/8 in. The lateral suspension system consists solely of the deflection in the foam-filled guidewheels.

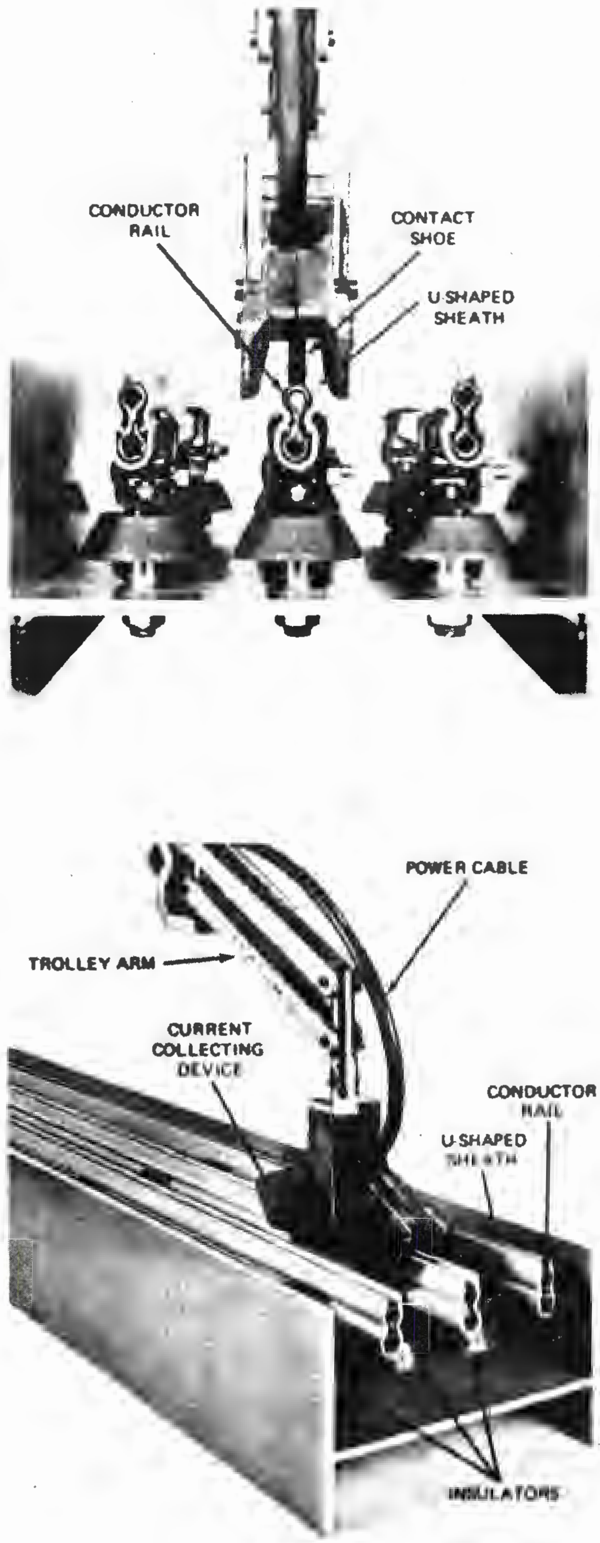

FIGURE 3-4 HOUSTON TUNNEL TRAIN POWER COLLECTOR AND GUIDEBEAM

As a result, the lateral ride quality is largely dependent on the accuracy of alignment of the guidebeam. Additionally, the relatively narrow track of the load-carrying wheels translates floor twist or assymmetrical discontinuities into lateral and roll disturbances in the passenger compartment. Based on our discussions with system operators, it appears that the maximum speed potential of the present suspension system does not greatly exceed the manufacturer's stated top speed of 12 mph.

3.8. Guideway

3.8.1 General Engineering Description

The terminal complex at Houston presently consists of two terminals (A and B located 1,400 ft apart) and a hotel arranged along a linear spine. The surface space between the terminals and the hotel is used for public parking. The tunnel train system provides passenger access by means of an exclusive tunnel right-of-way. Four three-car trains operate on a continuous 6,080 ft loop guideway to serve the four on-line stations within this row. The two sides of the guideway loop, together with a pedestrian path between, take up the entire cross section of the tunnel. The vehicle main suspension rides directly on the floor of the tunnel and the lateral guidance beams are also fastened directly to the floor. The tunnel floor was built using ordinary construction tolerances, which easily account for the poor ride characteristics that have been reported. In the original planning, a leveling topping had been contemplated for the guideway. This was eliminated, however, in an economy drive initiated by the City of Houston early in the project.

3.8.2 Geometrics

The vast majority of the parallel loop guideway is straight. Very short 24-ft radius horizontal curves are used to go around the on-line stations and terminal stations. The profile geometry is essentially flat.

3.8.3 Guideway Structure

Since the tunnel train system makes maximum use of the tunnel right-of-way, it has essentially no separate guideway. The floor of the tunnel doubles as the tractive and support surface for the vehicle, which easily accounts for the poor ride quality. Construction tolerances for tunnel floors are coarse. It was virtually impossible during the early stage of construction to obtain the kind of profile control which is essential to acceptable ride comfort.

The central guidance beam assembly is also fastened directly to the tunnel floor, but apparently no problems have developed from this interface. The guidance beams themselves have reportedly suffered some fatigue cracking, possibly as a result of the lateral forces applied to them.

3.8.4 Environmental Considerations

The tunnel provides protection from the weather and the temperature is maintained at 70 to 72 F. The tempurature in the vehicles is somewhat warmer than the stations and tunnel walkways. The system is virtually pollution free.

3.9 Stations

All Houston tunnel train stations are of the same style. They are located in a broadened area of the tunnel, which is circular in form. (See Figure 3-1 on page 9.) These circular station areas vary in size as follows: Terminal A, 9000 ft^2; Terminal B, 11,700 ft^2; hotel, 7,200 ft^2; and parking, 3,670 ft^2. The stations are accessible by stairways that connect the station areas with the ground level. Escalators and elevators are also provided in the terminal station area.

3.10 Power Distribution

The power distribution system consists of 225 A single-pole breakers and fuses installed at the maintenance area, Terminal B, and the hotel. There are two feeds at the maintenance area and Terminal B, and one feed at the hotel. Contactors are arranged to allow operation of the system even if one of the feeds is taken out of service. All five feeds are 480 V ac, Y-connection three-phase, 60 Hz systems.

The vehicle current collectors are a sliding contact design. Insulated contact heads are mounted on spring-loaded trolley-type arms to articulate and swivel.

The propulsion subsystem on each train consists of a full wave bridge rectifier for the 240 V dc traction motors. Metal casing of the guidebeam serves as the grounding.

4. SYSTEM OPERATIONAL PERFORMANCE

4.1 Operational Characteristics

Currently the Houston airport is operating four of the six trains, with two spares kept in the maintenance area. Each vehicle has a normal capacity of 12 passengers (6 seated and 6 standees). The crush capacity is 6 seated and 10 standees.

The round-trip time is approximately 18 min and the mean headway under four-train operation is 4.5 min. Though physical bunching is avoided by a block signal system, the headway can vary from 2 to 8 min. The line capacity under current operating practice (four-train operation) is 480 passengers/hr with normal loading and 640 passengers/hr with crush loading (10 standees/vehicle). The line capacity for six-train operation is 720 passengers/hr with normal loading and 960 passengers/hr with crush loading (10 standees/vehicle). These capacities are based on an average round-trip time of 18 min.

The maximum speed of the system is 8 mph; the operational speed is 3.7 mph, which includes stops at stations. The system is operational for an average of 18 hr per day, 365 days a year. The system is operated with no schedule adjustment to the demand level. The dwells at all stations are adjusted to 17 sec.

4.2 System Performance

In 1976, the system operated with five trains 85% of the time and with four trains 15% of the time for an average of 18 hr. per day. These numbers have been used to calculate the system performance measures. According to the maintenance staff, the operating fleet was later reduced to four trains mainly because of aluminum guidebeam deterioration.

The annual vehicle hours of travel (VHT) were estimated as 95,600 based on the information given by site operators. The annual vehicle miles of travel (VMT) were estimated from the operational speed, the annual operating hours, and the number of vehicles operated. In 1976, the VMT was 366,000.

Annual system patronage is estimated by Lockwood, Andrews, and Newnam (airport engineers) to be about 1.2 million to 1.4 million. The exact method of estimation is not known.

A passenger survey was conducted by Lockwood, Andrews and Newnam on December 22 and 23, 1976, the days considered to be the most crowded days of the year. The passenger survey was performed by counting the number of passengers that boarded and deboarded the train. Figure 4-1 shows the variations in this number for each day. The highest demand was observed at 5:00 p.m. to 6:00 p.m. on December 23.

An average trip length of one-quarter mile was assumed in estimating the annual passenger miles of travel (PMT). (The average trip length during the peak hour on December 23, 1976 was 0.26 miles). Using the annual patronage of 1.3 million, the annual estimated PMT in 1976 was 325,000. The estimated vehicle load factor is 0.085, which indicates that the average occupancy was one passenger per vehicle.

4.2.1 System Productivity

The measures adopted to describe the system performance are employee-to-vehicle ratio, system man-hour to VHT ratio, vehicle productivity, and labor productivity. These measures were calculated for 1976.

Nine employees were engaged in operating the system in 1976. The average number of trains operating was 4.85, giving an employee-to-vehicle ratio of 0.62. This means that, on an average, 0.62 people are employed to operate one vehicle. Or, 1.8 people are employed to operate a three-vehicle train.

The system man-hour to VHT ratio in 1976 was 0.19. This is equivalent to 0.56 man-hours per train hours of travel, indicating an average of 0.56 man-hours was needed to operate a three-vehicle train for 1 hr (2,000 work hours/employee/year were assumed).

The vehicle productivity is expressed by the ratio of annual patronage to annual VHT. The value in 1976 was 13.6 (patronage/VHT). This is equivalent to the train productivity of 41, or 41 passengers/train hour.

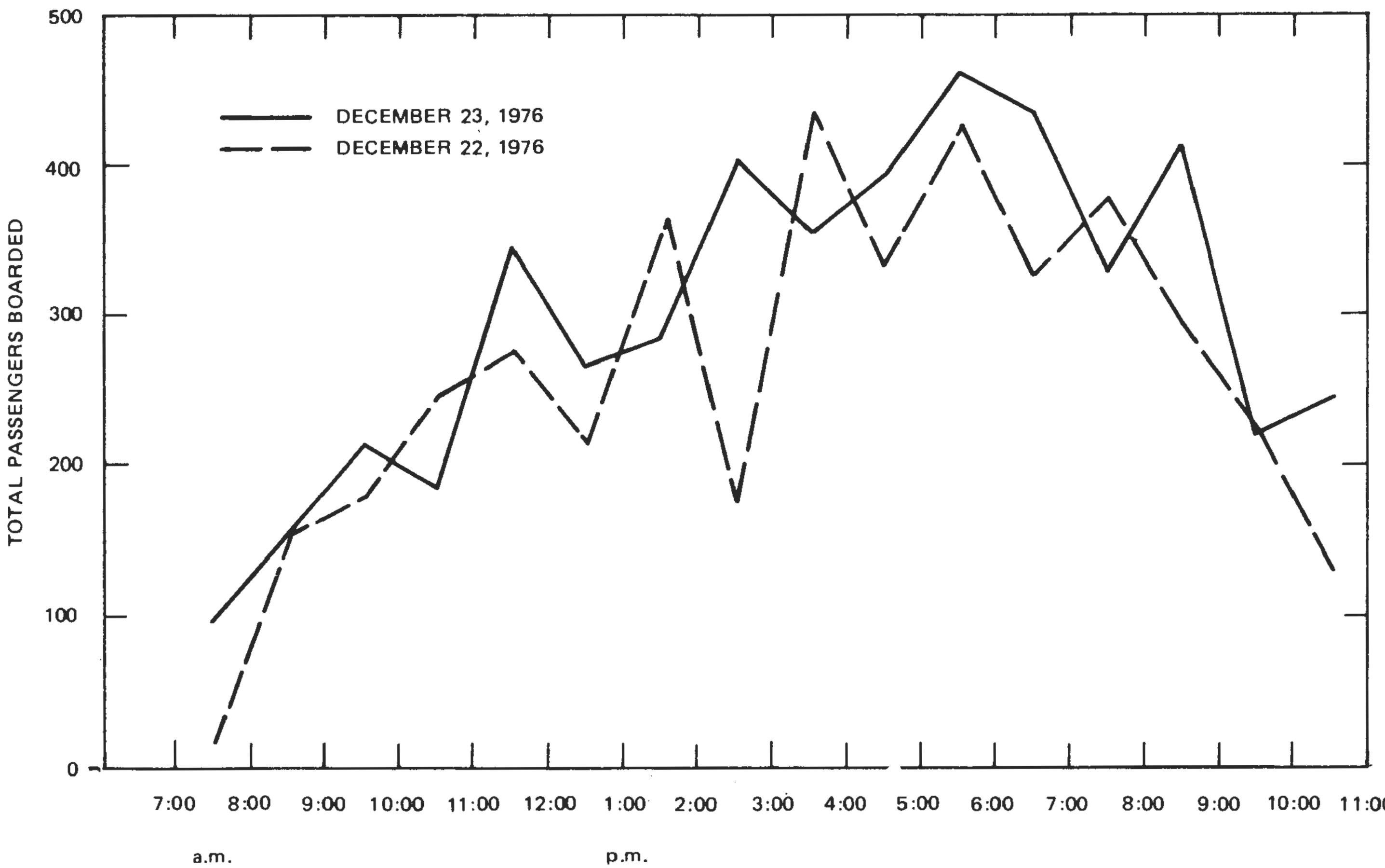

FIGURE 4-1 HOUSTON TUNNEL TRAIN SYSTEM RIDERSHIP

The labor productivity, which is expressed by the ratio of the annual place miles of travel (CMT) to the annual total man-hours, is 244 (1 hr of labor produces 244 CMT).

4.2.2 Comparison of System Performance with System Specifications and Employees' Assessment

The system specifications and operational performance are compared in Table 4-1.

There are some minor discrepancies between the specified requirements and existing operational performance levels; for example, round-trip time appears to be exceeded. However, the system seems to meet the specifications reasonably well.

The maintenance operation staff's opinions on system operational performance are:

- Vehicle operation--Simple to operate and causes no problems. The system is efficient and does the job well.
- Station operation--Gate sensors are not easily adjusted. The noise level of the gates is too high; mentioned as a minor problem.
- Yard operation--Switches cause problems.
- Central control--Satisfactory.
- Failure mode operation--Not too difficult to bring back to normal operation; walkway helps.
- Other--Tunnel geometry causes low speed.

4.3 System Assurance

4.3.1 Maintenance and Reliability

The maintenance program of the tunnel train system is operated by the maintenance crew of the Houston Airport. The crew assigned to the tunnel train system and related works in the parking lot consists of 15 employees (1 supervisor, 7 technicians, and 7 nontechnicians). The airport staff estimates that an equivalent of 9 employees work on the tunnel train system.

Table 4-1

COMPARISON OF SYSTEM SPECIFICATIONS AND SYSTEM PERFORMANCE: HOUSTON TUNNEL TRAIN

System Specification	System Performance
The system to consist of 6 trains with 3 passenger cars each (section VIIC 01. General)	As specified
Under normal loading conditions, each passenger car to be capable of carrying 6 seated and 4 standing passengers, and 10 pieces of luggage (Section VIIC 01. General)	Each car has a capacity of 6 seated and 6 standing passengers.
Trains to travel at a normal speed of 8 mph, slowing down as necessary for curves and station stops (Section VIIC 01. General)	The system has a travel speed of 8 mph at straight sections of guideway†
The total round trip time, including 30-sec dwell at each station, not to exceed 17 min (Addendum to Section VIIC 01. General)	Round trip travel time reported to be 18 min*

*Based on information given by the operator.

†Based on information given by airport representatives.

Source: Lockwood, Andrews, and Newnam, "Technical Specifications for Improvements and Additions to Interterminal Passenger Transportation System (1971)

4.3.2 Maintenance Strategy

Following the initial installation and testing period at Houston, Rohr provided a detailed schedule of preventive maintenance. This schedule described procedures for inspection and maintenance of vehicle and guideway systems. Procedures were to be performed once per shift, weekly, monthly, quarterly, semiannually, annually, and biannually.

The operator chose not to follow the suggested preventive maintenance plan exactly and adopted a strategy described as reactive on-line maintenance. Of the two trains kept in the maintenance yard, one is kept in a ready-to-go condition; the other is usually undergoing some maintenance work.

The maintenance work performed in the yard includes cleaning, checking, and repairing failed vehicles where the failure was not severe enough to block the guideway. It is reported by the maintenance staff that airbags, drive chains, guidewheels, and tires are inspected every day. The guidebeam inspection, cleaning, and repairs are also performed on a daily basis, if necessary.

A failure causing system blockage is detected by the central controller. When a failure occurs, an alarm is given automatically to the maintenance personnel on duty. The maintenance crew drives an electric-powered vehicle to the site, inspects the vehicle, and repairs it at the site. The system is said to have a push-mode recovery capability, but this is not used because the fiberglass body of the vehicle is easily damaged if the vehicle is pushed.

On-line maintenance tends to consume more time in restoring the system than shop maintenance because necessary machines or tools are not available instantaneously at the site.

4.3.3 Record Keeping

A maintenance shop log on daily activities is kept. This shop log contains, in general, the time the maintenance staff reports to work, the time the trains are pulled into the maintenance shop, the type of work performed on the trains, and so on. The maintenance shop log is an activity record rather than a failure record and is not sufficient by itself to determine subsystem mean time between failure (MTBF) or mean time to restore (MTTR). The maintenance staff was unable to keep accurate records for a period sufficiently long to determine subsystem MTBF and MTTR.

4.3.4 Failure Frequencies

Failure frequencies and restore times were obtained from the maintenance staff. The staff made a rough estimate that shutdowns occur twice a week, and minor disruptions four times a day. During a shutdown the whole system is stopped, and passengers are required to either walk or use the backup van. A disruption is a case where a part of the system fails and causes extra delay to passengers in the affected vehicle.

Maintenance staff reports that the station doors have a problem with microswitches causing interruptions whenever passengers hold the station doors open or put luggage between the door leaves. The station doors are also susceptible to foreign objects, which cause them to jump the track. The minor disruptions mentioned above are reported to be due mainly to this station gate-passenger interraction problem. In this study, these disruptions are not included as reliability failures. Failure frequencies and restore times are shown in Table 4-2. The failures focused on in this study are limited to those that may lead directly to unsafe conditions or an accident, those that potentially require removal of the vehicle from revenue service, and reliability failures.

Table 4-2

FAILURE FREQUENCIES AND RESTORE TIMES:
HOUSTON TUNNEL TRAIN SYSTEM

Component	Failure Frequency	Restore Time
Vehicle subsystem		
Door	1/3 months/system	About 1 hr
Propulsion	6 motors/2 years/system	About 1 hr
Braking system	1/week/train	About 1.5 hr
Air bag	2 bags/4 years/system	2-3 hr
Guidewheel	3-4 guidewheels/month/system	1-2 hr
Running tire	10 running tires/month/system	1-2 hr
Guideway subsystem		
Command and control wayside	None	
Guideway (beam deteriorating)	1 replaced/2 years/system	2-3 hr
Power Distribution	4-5 times/4 years/system	2 hr
Switches	Manual operation	Not available
Central command and control	None	
Station gates	1-2 times/year/system	1 hr
Power system	None	

NOTE: Figures based on estimates provided by Houston Airport maintenance staff.

4.3.5 System Reliability

The failure frequencies of each component have been translated into mean time between failures (MTBFs). Table 4-3 shows the estimated MTBFs of the tunnel train system. In calculating MTBF, the daily operating period of 18 hr and the annual operating period of 365 days were used. To obtain the subsystem MTBF, the same failure was counted at different levels. For example, the vehicle door failure was counted at three levels: the component level, the vehicle subsystem level, and the system level. The frequency of failures was given at two levels--the system level and the component level--and two different MTBFs for the system were obtained.

Table 4-3

RELIABILITY, MAINTAINABILITY AND AVAILABILITY MEASURES:
HOUSTON TUNNEL SYSTEM

Component	MTBF* (hr)	MTTR† (hr)	Availability‡
Vehicle subsystem	76/train	1.5	0.98/train
Door	7,950/train	1.0	1.0/train
Propulsion	10,600/train	1.0	1.0/train
Braking system	125/train	1.5	0.99/train
Air bag	63,600/train	2.5	1.0/train
Guidewheel	755/train	1.5	0.999/train
Running tire	246/train	1.5	0.994/train
Guideway subsystem			
Command and control wayside	No failures in the 4 years of operation		
Guideway	13,200	2.5	1.0
Power distributor	5,200	2	1.0
Switches	Manual operation		
Central command and control	No failures in the 4 years of operation		
Station gates	4,400	1 hr	1.0
Power system	No failures in the 4 years of operation		
Total system (includes all component failures)	15.5	1.5 hr	0.91
Total system (based on 2 shutdowns/week and restore time of 2 hr)	63	2.0 hr	0.97

*Mean time between failures = $\frac{\text{operating hours}}{\text{number of failures}}$.

†Mean time to restore. Hours based on estimates by maintenance staff.

‡Availability = $\frac{\text{MTBF}}{\text{MTBF + MTTR}}$.

From the number of system shutdowns (two per week), which was a rough guess made by the maintenance staff, the MTBF of the system was calculated to be 63 hr. However, by combining the number of component failures in a given time period, the MTBF of the system was calculated to be 15 hr. This figure was calculated on the assumption that the daily operating period is 18 hr, the annual operating period is 365 days, with an average of 4.85 trains operating, and that the system experiences only one failure at a time, which shuts the system down. The discrepancy between these two MTBF figures is due in part to staff estimates of unrecorded failures and a limited sampling of component failures.

4.3.6 System Maintainability

The mean time to restore (MTTR) each component and subsystem is shown in Table 4-3. The component MTTR was calculated as an average of the upper and lower bounds when the restore time was given as a range (see Table 4-2). Subsystem MTTR was obtained by dividing the total downtime related to the subsystem during a one-year period by the number of failures in the same period. The restore time of most components is rather long due to on-line maintenance.

System MTTR was obtained from component MTTR and subsystem MTTR. The system MTTR, including all the component failures, is 1.5 hr, calculated on the basis of information given by the maintenance staff. Restore time in shutdowns was reported to vary between one and two hours.

4.3.7 System Availability

The traditional availability for each component and system is obtained from the formula:

$$\text{Availability} = \frac{\text{MTBF}}{\text{MTTR} + \text{MTBF}}$$

The results are given in Table 4-3. The component with the lowest availability is the brake system, at a value of 0.99. System availability was also obtained from the component and subsystem levels of information. System availability, including all component failures, is 0.91; based on two shutdowns per week, it is 0.97.*

4.3.8 Maintenance Facility

The maintenance facility of the Houston tunnel train system is located at the west end of the tunnel. The maintenance tools in this facility are ordinary tools necessary for electronic and mechanical repairs. The central controller is also located in the corner of the maintenance shop.

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*Using an MTBF of 63 and MTTR of 2 (see Table 4-3).

4.3.9 Comparison of Achieved System Assurance with System Specifications and Employees' Assessment

The descriptions found in the system specifications on reliability and maintainability are given in general terms. The reliability of the system as specified in Section VIIC of the system specifications is that system reliability is of the utmost importance, and that design should be accomplished with this goal in mind. The maintainability of the power and command and control subsystems is specified in general terms stressing the importance of accessibility to the equipment. The restore time of the power system is given as 2 hr.

It is the airport representative's opinion that the system manufacturer, Rohr, did a satisfactory job in accommodating the existing tunnel. The reliability of electronic components is said to be excellent. However, the system has some problems, such as:

- Station gate-passenger interaction (see Section 4.3.4).
- Low availability figure (0.91 to 0.97)--It is not known whether or not this figure is due to maintenance methods or inherent design problems.
- Inadequate maintenance personnel.
- The manufacturer is no longer producing parts.
- Guideway switches (see Section 3.5).
- Guideway--Aluminum guideway started to deteriorate toward the end of 1976.

4.4 Human Interface

Access and egress to the tunnel train is by stairs, escalator, or elevator immediately adjacent to the stations. The mean headway is 4.5 min, but actual headway can vary between 2 min and 8 min if a vehicle is delayed. The average waiting time is half the headway, about 2-1/4 min. Frequently, as many as 12 people will be waiting at a station. The image of this many people waiting, when there is no vehicle in sight, seems to influence many people to walk to the next station rather than wait.

Line-haul speed is 8 mph, twice that of a fast walker. However, when acceleration, reduced velocity around curves, and dwell time are taken into account, the mean speed is reduced to 3.7 mph, slightly faster than that of an average walker.

Signs at the station directing passengers to the tunnel train are not clear. There are two terminals--A and B--but they are Stations 1 and 3, respectively, on the tunnel train. Also, Parking Area 5 is at Station 4, but Parking Area 2 is at Station 2. The arrows on the signs are placed incorrectly. None of the signs are in Spanish, although Houston is within 350 miles of Mexico, and some other airport signs are in Spanish. The map above the vehicle entrance is good, although it gives directions to a nonexistent future terminal. It is unfortunate that the station designators inside the vehicles do not light up, because the passengers are often unable to determine where they are. Furthermore, the station names are not clearly identified once the vehicle has arrived. This was the most important finding of Lockwood, Andrews, and Newnam's passenger survey last December. Voice communications are used only when there is a system shutdown.

Only destination, routing, and exit information is given. There is no information on headways or travel times. Special announcements can be made whenever necessary. There is no in-vehicle advertising or entertainment provided.

An emergency button is available to stop the train and to summon an attendant.

4.5 Comfort

The following results related to the comfort of the system were established based on the observations of the assessment team and informal interviews with five randomly selected passengers for their assessment of the system.

Ride quality of the Houston tunnel train is less than satisfactory. The vehicles vibrate during deceleration and around curves, although the trains operate at only four miles per hour around the curves.

There is ample room for six seated passengers and all their luggage, or for six seated passengers and six to eight standees. During periods of peak travel (such as Christmas), the vehicles are frequencly loaded in excess of this capacity, and crowding results. During off-peak hours, passengers can get a sense of privacy by having exclusive use of one car.

The seats have straight backs and are acceptably comfortable. Seats are molded fiberglass with no upholstry for ease of cleaning. Leg room appears adequate for most passengers, with 4 ft 7 in, between the seats. Seats are not always available and standing is often required during peak travel hours. Because vehicles run almost 5 min apart, each one usually loads to capacity when it stops at a station; the remainder of the waiting passengers usually walk. Rarely do they wait for the next vehicle.

The lighting in the vehicles is adequate, as is the air circulation. The temperature inside the vehicles is warmer than the stations and tunnel walkway and is considered by some to be slightly uncomfortable. The noise level was not measured, but the system did not seen to be excessively noisy.

4.5.1 Convenience

For a newcomer to the airport, finding the tunnel train and determing the direction in which to take it and where to exit can be quite confusing because of the unclear nature of the signs. There is no problem with taking baby strollers or baggage on the car. The boarding areas are generally considered to be conveniently located.

An intermediate stop is necessary in traveling between terminals or between the hotel and the parking area or one of the terminals.

Either Travelers Aid or airline personnel accompany handicapped passengers through the airport if they need assistance and bring wheelchairs onto the vehicle. Seeing-eye dogs can be accommodated on the vehicle, although they are rarely brought to the airport. All the instructions are visual, so a visually handicapped person would have to ask for information. All but the very widest wheelchairs fit through the doors. For the occasional exception, or if the passenger is in a hurry, he or she can be wheeled down the walkway. Clearance between the platform and the vehicle is 4 in. (much more than the 1/2 in. recommended) and it could catch cane tips or dangling objects. Ramps and elevators are provided as access to the tunnel trains, and wheelchairs therefore can be accommodated throughout the airport. However, the emergency button is placed near the ceiling so that it will be out of reach of children, but it is also out of the reach of short adults and those in wheelchairs. These passengers could be stranded if caught in a vehicle alone.

The tunnel train is in operation from 6:00 a.m. through midnight. No regularly scheduled flights operate at Houston during the time the system is down.

4.5.2 Appearance and Cleanliness

The 3 ft 6 in. wall separating the guideway from the walkways is considered to be not very aesthetic by some. The surfaces of the vehicle exterior and interior, and the tunnel floor, walls, and ceilings lack color. Interior and exterior graphics and carpeting would improve the appearance of the system.

Janitorial crews keep the areas fairly clean; and the cars are kept quite clean.

4.6 Safety and Security

4.6.1 Safety

No major accidents have occurred on the system since it began operations. Some minor injuries have resulted from the doors closing on passengers, but their actual number is not known.

When the emergency button in any car is activated, or when the car must make an emergency stop for any reason, the silent alarm must be reset manually on the vehicle. This extra safety precaution increases the time required to restore service, but it severely reduces the chances of a serious accident. When there is a disruption in service, a tape recorder activated by one of the maintenance employees plays one of two messages. The first tells people that there has been a break in service, and that it will be restored shortly; the second message, used for longer delays instructs passengers to walk to their destinations. In the event of a shutdown, the hotel has an electric cart that can be used to carry passengers.

There has never been a fire in any of the vehicles, nor have there been any power failures. People rarely, if ever, get on the guideway, because of the walls separating it from the walkway. Vandals sometimes throw objects on the guideway, since the system is unpatrolled at night.

4.6.2 Security

Vandalism is a major problem in unpatrolled areas of Houston Intercontinental Airport, particularly at night and on weekends. The vandals swing on the grabrails and kick in the ventilator screens. This occurs at the isolated turnaround loop past the hotel where the vehicles travel slowly, and the vandals are not likely to be observed. The control boxes are locked to protect them from vandalism.

The tunnel train level of the airport has no scheduled police patrol although officers are stationed at the airport and are available on call.

There are usually sufficient passengers around to discourage criminal activity, and lighting is adequate. The only isolated area is the turnaround loop past the hotel.

5. SYSTEM ECONOMICS

In this chapter the system economics of the Houston tunnel train system are discussed. Included in the discussion are estimated capital costs both in actual year and in 1976 dollars, and annual operations and maintenance (O&M) costs for 1976. Total equivalent annual cost is computed for appropriate service lives and discount rates. Average unit costs of service are computed for train miles, passenger miles, passenger trips, and capacity miles, or place miles, for seated and standing passengers. Methods of analysis are discussed in Appendix B.

5.1 Capital Costs

Detailed historical data on the construction of the facilities for the Houston tunnel train are not available. The construction of the tunnels, access facilities, stations, and maintenance facilities was covered in construction contracts for the airport terminal buildings and the hotel. Also, the transit system now in service was built in two stages: the first stage linked terminal A and terminal B with a portion of unfinished tunnel extending beyond the terminal B station; the second stage linked the first stage with a station beneath a newly constructed hotel.*

Because detailed historical data were not available, it was necessary for the research team to prepare original cost estimates based on a "free-standing," or independent, version of the system. It was thought that these estimates would be more useful to planners than a cost estimate based on an allocation of the costs of the terminal buildings and hotel among all functions served. (See Appendix B for a discussion of the cost-estimating method). The system envisioned for cost-estimating purposes would have simple station entrances at ground level; vertical

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*See Section 6 for a detailed discussion of the development history of the airport.

access equipment to the vehicle level, which is located underground; and somewhat smaller terminal stations than at Houston.[#]

The method used to estimate construction costs is based on dollars per square foot of space. Unit costs for the tunnel and maintenance areas were obtained from the architect. Unit costs for the stations were developed from detailed estimates of the work. Hardware costs were provided by the airport staff.

Volume IV of a series of planning reports contained an estimate that the cost of the tunnel for the second stage of construction would be $680/ft.[†] It did not report estimates for station costs. The volume also contained an estimate that hardware for the second stage would cost $700,000. Airport staff reports that the cost of the system hardware, which included six three-vehicle trains, guidebeams, station gates, the control and communication facility, and power distribution, was $993,000. This figure is regarded as dependable. The year of purchase is reported to have been 1972.

5.1.1 Estimates of Construction Costs

Since directly applicable estimates for construction costs of the different parts of the facilities or the total cost of the facilities were not available from site sources, it was necessary to devise a method of preparing original estimates of floor space required for AGT functions and unit cost factors expressed as dollars per square foot.

Information for these estimates was obtained during a visit to Goleman and Rolfe, of Houston, Texas, the architects of the airport buildings. Construction drawings for the first-stage tunnel, stations, and maintenance shop were obtained together with the following unit costs (in 1969 dollars) for different types of finishes:

[#]Station areas at Houston serve not only the AGT users but also provide space for walking passengers. Thus in a free standing system used exclusively by AGT passengers, the stations could be smaller.

[†]Houston Airport Architects and Airport Engineers, "Plan of Development, Vol. IV: Second Stage" (April 1971).

Type I -- Best finish including lighting, HVAC and vertical circulation = \$27.26/ft^2

Type II -- Finished including lighting and HVAC = \$26.08/ft^2

Type III-- Semifinished including lighting and HVAC = \$21.08/ft^2

Type IV -- Unfinished, bare structure = \$16.08/ft^2.

These unit costs were developed for use by airport management to apportion costs to different areas of the airport and to compute rent or fees for individual airlines. The cost assigned to the train tunnel by the airport authority in the first stage of construction was shown as \$877,628. This is regarded as a dependable figure but does not include the station areas. (To put that cost into perspective, it may be noted that the center walkway is 9 ft 4 in. high, and the guideways are 9 ft 10 in. high. The train tunnel is 23 ft wide.) The cost of facilities with in the terminal was not separated from the cost of the terminal buildings themselves.

The construction costs of the tunnel and maintenance area have been estimated (see Table 5-1).

Table 5-1

ESTIMATED CONSTRUCTION COSTS OF TUNNEL AND MAINTENANCE AREA: HOUSTON TUNNEL TRAIN (1969 Dollars)

	Area (ft^2)	Unit Cost (\$/ft^2)	Estimated Construction Cost
Tunnel and tunnel entrances	55,344	\$26.08	\$1,443,372
Maintenance and storage area	3,680	21.08	77,574

A check was made to reconcile the unit costs for tunnels with an original estimate of cost per foot of straight tunnel construction and the 1969 unit costs cited. The result obtained was approximately

Right-of-way and utility relocation costs were not estimated. The guideway is built underground on undisturbed earth. It is located under parking areas and airport buildings that are not solely used for passenger transport and that were acquired for the primary function of the airport. Consequently marginal cost is taken to be zero.

Engineering and architecture costs include costs associated with the planning, design, and construction supervision of the facilities and have been assumed as 9% of the construction cost of the tunnels, stations, and maintenance facility. This percentage was given by the engineering and architectural firm who was engaged in the airport construction.

The guideway tunnel cost is based on an analysis of historical data and includes the construction cost of the guideway tunnel, passenger walkway, and five tunnel entrances from parking lots. Included are site development and structural costs, architectural finishes, lighting, and electrical and mechanical costs for drainage and HVAC.

The estimate of costs for maintenance and storage facilities is based on an analysis of historical data and includes the construction cost for the maintenance shop and an assigned-parts storage area.

The hardware cost was reported by airport management and is understood to be based on accounting records.

As a check, costs of the present facilities were also estimated on the allocation principle. Only two changes would occur--station costs would decline by $340,500, and engineering and architecture costs would decline by $30,900--a net decline of $371,400 or about 12% of the cost of the independent version of the system.

5.2 Operations and Maintenance Costs

The operations and maintenance costs of the tunnel train system and management costs for 1976 were given by the airport management as $328,930. The breakdown is given in Table 5-4.

Table 5-4

OPERATIONS AND MAINTENANCE COSTS:
HOUSTON TUNNEL TRAIN SYSTEM

	Cost
Custodial labor and supply	$ 31,800
Electricity	24,600
Operations and maintenance	
Routine operations	114,940
Maintenance--train equipment	47,570
Maintenance--train graphics	220
Equipment maintenance	85,990
Electrical maintenance	13,610
Paint and marking	9,690
Structural maintenance	410
Lamps	100
Total	$328,930

It is reported by the airport management that approximately 13% of the total operations and maintenance cost or $42,761, was for management. This amount is included in the total figure cited.

The Houston Intercontinental Airport has a staff of 15 people working on the total air terminal maintenance program. Custodial labor and supply includes the custodial service-related cost for the walkway and the stations. The electricity cost includes lighting, heating, and air-conditioning of stations and electrical energy costs to operate the tunnel train system. Operations and maintenance costs include both labor and material costs; further breakdown of these figures is not available.

5.2.1 Unit Costs of Operations and Maintenance

Unit costs of O&M for 1976 were computed as follows:

Operations and maintenance per train miles traveled (TMT)	=	$2.70
Operations and maintenance per passenger miles traveled (PMT)	=	1.01
Operations and maintenance per passenger trips	=	0.25
Operations and maintenance per capacity miles traveled (CMT)	=	0.07

5.3 Escalation

The conceptual system construction costs and hardware costs are separately escalated to 1976 dollars by using indexes adapted for all sites studied (see Appendix B). The total capital cost in 1976 dollars is $6,807,000, which includes a construction cost of $5,498,000 and a hardware cost of $1,309,000.

5.4 Equivalent Annual Cost

The equivalent annual cost of capital is calculated based on the formula shown in Appendix B. A discount rate of 10% was used.

The service life of AGT components depends on many factors and must be estimated by planners for each new site. To achieve comparability among systems we have employed the same basic service lives for all sites: 15 years for hardware and 35 years for construction. We have also made calculations for optimistic service lives--20 years for hardware and 50 years for construction--to illustrate sensitivity of equivalent annual costs to service life estimates.

Equivalent annual costs of capital for two service life assumptions are given in Table 5-5.

Table 5-5

EQUIVALENT ANNUAL COSTS OF CAPITAL:
HOUSTON TUNNEL TRAIN

	Service Life (years)		Equivalent Annual Cost of Capital (1976 dollars)
	Hardware	Construction	
Basic estimate	15	35	$742,200
Optimistic estimate	20	50	708,300

5.4.1 Total Equivalent Annual Cost

The total equivalent annual cost of capital and operations and maintenance, for the basic service life assumption and in 1976 dollars, is given as the sum of the equivalent annual cost of capital and the cost of operations and maintenance. Thus, total equivalent annual cost is $1,071,130 in 1976 dollars.

5.5 Unit Cost of Service

The unit cost of service prorates the total equivalent annual cost of capital and operations and maintenance over four measures of service--train miles traveled (TMT); passenger miles traveled (PMT); passenger trips (patrons); and capacity miles traveled (CMT) for seated and standing passengers. The following unit costs of service were derived:

Unit cost per TMT = $8.78
Unit cost per PMT = 3.30
Unit cost per patron = 0.82
Unit cost per CMT = 0.24

5.6 Recapitulation

The inputs and results of the economic analysis are given in Table 5-6 and 5-7. Table 5-6 shows all major cost data in 1976 dollars and the equivalent annual cost of capital. Table 5-7 shows the unit cost of service.

Table 5-6

CAPITAL, OPERATIONS AND MAINTENANCE COSTS:
HOUSTON TUNNEL TRAIN SYSTEM
(1976 DOLLARS)

	Capital Cost (Actual Year)	Escalated Capital Cost	Equivalent Annual Cost	Annual Operations and Maintenance Cost	Total Annual Cost
Construction cost	$2,976,500[*]	$5,498,000	$570,100	N.A.	
Hardware cost	933,000[†]	1,309,000	172,100	N.A.	1,071,130
Operations and maintenance cost	N.A.	N.A.	N.A.	328,930	

N.A. = not applicable.

[*]In 1969 dollars. Estimated by SRI based on "free standing" concept.

[†]In 1972 dollars.

Source: operator's record

Table 5-7

UNIT COST OF SERVICE:
HOUSTON TUNNEL TRAIN SYSTEM
(1976 DOLLARS)

	Per TMT[*]	Per PMT[†]	Per Pass.[‡]	Per CMT[§]
Operations and maintenance cost	$2.70	$1.01	$0.25	$0.07
Equivalent annual hardware cost	1.41	0.53	0.13	0.04
Equivalent annual construction cost	4.67	1.75	0.44	0.13
Total equivalent[**] annual cost	8.78	3.30	0.82	0.24

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[*] TMT = Train miles of travel.

[†] PMT = Passenger miles of travel.

[‡] Pass. = Passenger.

[§] CMT = Place miles of travel or unit capacity miles of travel.

[**] Total equivalent annual cost does not necessarily equal the sum of the three items above because of rounding off.

6. SYSTEM DEVELOPMENT PROCESS

6.1 Role of AGT

An underground transportation facility containing an AGT loop and a pedestrian walkway links two unit terminal buildings and a hotel complex at the Houston Intercontinental Airport and will be extended to additional buildings to be constructed in a staged development program. The buildings stand in a straight line at intervals of about 1/4 mile. Because of the great distances between buildings, the AGT system provides an essential transportation service.

Stage 1 included the construction of unit terminals A and B and the connecting transportation route, and the installation of an AGT system. Stage 2 added the hotel complex, extended the transportation facility, and replaced the first AGT system with a second from another supplier. Stage 3 is scheduled to add unit terminal C in 1981, and still another change of AGT hardware is under consideration. A site has been reserved for unit terminal D, and land is available for two additional terminals if desired.

6.2 History and Initiation

During the late 1950s, efforts to develop a much needed second commercial airport at Houston were frustrated by the city's inability to plan and finance land acquisition. This problem was solved by a group of citizens who made private purchases of some 3,000 acres of land and offered the land to the city, at their acquisition costs, on condition that a commercial airport be constructed by 1970. The city purchased the 3,000 acres in 1960 and made additional acquisitions to enlarge the site to 7,300 acres. Availability of this large site gave the city a unique opportunity to plan an entirely new major commercial airport to be developed in multiple stages over a long period of time.

The airport is owned, operated, and financed by the City of Houston. The City Aviation Department has principal responsibility for planning, development, and operations. The City Public Works Department participated in engineering and design. Two consulting groups were retained as airport architects and airport engineers. The latter group is a joint venture called Engineers of the Southwest.

The City Council initiated the airport development planning process in September 1960. Volume I of a series of planning reports, published in October 1961, dealt with broad issues involved in planning the new airport but did not include detailed consideration of the terminal area. Volume II, which described four alternative terminal concepts, was published and presented to the city in July 1963. Consultants recommended the unit terminal concept and the City of Houston adopted that alternative in September 1963. A chronology of airport and AGT development is included in Appendix C.

6.3 Planning and Design

Design criteria established by the city in 1961 emphasized ease of use by travelers, short walking distances, simple airport operation, flexibility, and provisions for staged expansion.

6.3.1 Alternative Terminal Concepts

The formulations and evaluation of concepts included continued liaison and periodic conferences with representatives of airline management, the Houston Airlines Technical Committee, and the Federal Aviation Administration. A survey was made of terminal facilities at 11 major U.S. commercial airports. Discussions were held with representatives of airports in Chicago, San Francisco, Tampa, Miami, and Los Angeles where major planning programs had recently been concluded.

Four terminal concepts were formulated. All included passenger transportation systems and none required passengers to walk more than 550 feet. One concept, generally similar to Dulles International, would have used mobile lounges. Two concepts called "pier" and "satellite" would have used trams to carry passengers between a central terminal and gate positions arranged along piers or in satellites. Descriptions of these two layouts were not found. One illustration used on a report cover suggest that, except for the trams, the pier configuration was conventional in design with several long finger piers. Perhaps the satellite configuration served by AGT systems would have been similar to the Tampa design. However, the Tampa design did not reach final form until about two years after the Houston layout was chosen.

The unit terminal concept provided for staged construction of four substantially identical terminal buildings, each with 20 gate positions, plus a central hotel complex, all connected by a passenger transportation system. Land for two more unit terminals was reserved. At the end of this stage of design the airport architects and airport engineers unanimously recommended the unit terminal concept as the best answer to the established criteria, and the concept was adopted by the city.

Approval of the unit terminal concept in September 1963 initiated a new series of studies and conferences dealing with execution of the concept. These deliberations again included representatives of the federal government, the city, airport management, consultants, airlines, prospective tenants and concessionaires, financial institutions, and other interested parties. A document entitled "Preliminary Terminal Area Design," published by the airport architects and airport engineers in April 1964, describes the design process and illustrates the approved plan. The plan is being executed in a four-stage program as follows:

Stage	Increment	Status (1977)
1	Unit terminals A and B	Completed in 1969
2	Hotel complex	Completed in 1972
3	Unit terminal C	Planned to open in 1981
4	Unit terminal D	Future

The five building sites were designated at the outset and lie in a straight line. Centers of sites are separated from one another by distances of almost 1/4 mile.

The two unit terminals constructed in the first stage include one that was fully developed with 20 gate positions and one that was partly developed with 15 gate positions, plus provisions for 5 more. One includes facilities for processing arriving international passengers, and the other includes airport administrative offices. Each contains two floors for passenger service functions and a below-ground station containing an AGT station and parts of the AGT loop and pedestrian walkway.

Each unit terminal is a "drive-in" facility containing curb space for autos, taxis, and buses; two garage floors above the passenger service areas, plus provisions for addition of a third garage floor; and ground level parking and auto rental space in adjacent lots. A unit terminal is especially convenient for passengers who are driven to and from the airport by friends and relatives, or who use buses and taxis. It is also convenient for travelers who drive and park private autos provided they depart from Houston and return through the same unit terminal.

The existence of multiple unit terminals and a separate hotel complex is relatively inconvenient for persons in several classes, including the following:

- Travelers making round trips who depart through one terminal and return through another if they have parked their cars near their departure terminal.
- Passengers who change planes at Houston and who must make transfers between airlines in different terminals.
- Departing passengers who make last-minute changes of airlines requiring travel to another terminal.
- Airport employees and visitors who have occasion to use more than one terminal.
- Hotel guests and visitors.

All these people must travel between buildings. Some are encumbered with luggage and small children, some are physically handicapped, and some are under considerable pressure to hurry. Under ideal conditions, travel among buildings involves some inconvenience, extra effort, and delay. Without the AGT system the burdens would be excessive for many persons.

The addition of the hotel complex in the second stage of terminal development has encouraged out-of-town travelers to stay at the airport. The hotel offsets one inherent disadvantage of the unit terminal concept by providing a focal point for centralizing certain activities. It encourages special service firms, restaurants, and retail stores to locate at the airport. However, it also increases dependency on the AGT system.

6.3.2 AGT System

The decision to build a terminal complex containing five widely separated buildings carried with it an obligation and commitment to provide transportation services between the buildings. The buildings were designed to incorporate transit stations below ground level. Elevators, escalators, and stairs were installed to serve the stations. Tunnels were designed to include the AGT system and a pedestrian walkway between guideways. Stairs are provided to link the pedestrian walkway and guideways with ground-level parking lots.

The underground transportation facility was always regarded as an essential feature for a terminal complex that would eventually approach one mile in length. However, it could have been omitted in the first stage, and surface transportation via bus could have been substituted. At one time during Stage 1, consideration was given to postponing development of parts of the underground facility between the first two unit terminals. This appears to have been part of a broader exploration of means to reduce the capital cost of the first stage of airport development, and that explanation would be reasonable in light of the great financial burdens commonly encountered in constructing an entirely new airport. The alternatives available for consideration were:

- Make provisions for the tunnel but postpone construction.
- Construct the tunnel shell but postpone finishing the interior and placing the facility in service.
- Construct the tunnel and pedestrian facilities but postpone installation of the AGT system.
- Complete the tunnel, AGT system, and pedestrian facilities.

The last alternative was adopted.

The underground transportation facility appears to have been designed to minimize the width and height of the structure--perhaps as an economy measure. Most of the tunnel is just wide enough for two guideways and a pedestrian walkway. The tunnel is widened at several points to provide space for stairs to parking lots and at portals to stations. The guideway has several features that now appear unattractive: it is narrow, it has numerous short-radius turns, and the running surface for wheels is only a few inches below the walking surface in stations. These characteristics have generated the following severe constraints in selecting AGT vehicles to be employed on the route:

- Short vehicles and low speeds are needed to negotiate the curves.
- Narrow vehicles are needed to operate within the pathway.
- Operation of trains is necessary to achieve desired capacities at acceptable headways.
- Low vehicle floors are needed to provide near level surfaces between vehicles and platforms.

The tunnel design also requires that vehicles normally operate in one direction around a closed loop. It does not provide space for the storage of "bad-order" cars---cars that fail in service. Bypasses are not included to allow multiple-train shuttle operations on one guideway when the other side is blocked. The presence of the pedestrian guideway in the median prevents use of cross-over and turn-back features. All these characteristics tend to generate a requirement for highly reliable hardware, and both the first and second hardware installations have been disappointing in this respect.

6.3.3 Hardware

Two hardware systems have been employed at Houston. The first system was supplied by Barrett Electronics Corporation. It employed battery-powered tugs pulling trains of passenger cars. It began service in June 1969 and was retired in August 1972, after about three years of service. Details of the acquisition of this system and of its design were not found. However, it is known that it was an adaptation of an automated mixed-traffic vehicle (AMTV) system used successfully for transportation of goods in factories, warehouses, and terminals. One important feature of the system was "wire follower" guidance. A wire near the centerline of the guideway carried a signal. Vehicles were equipped to sense the signal and steer the vehicle so as to follow the wire. In normal applications for goods movements AMTVs travel on pathways shared by pedestrians and manually operated vehicles. Tugs are equipped with a sensitive bumper which sets emergency brakes immediately on contact with any obstruction. Stops must be abrupt to avoid injury or damage to the obstruction, and that means that speeds must not be higher than about 1 mph or 1/3 walking speed. Programmed stops and switching between pathways are accomplished by employing wayside signal devices, such as magnets and sensors, and activators on the vehicle.

The low speed used in goods movement would have been unsatisfactory for the trip distances at Houston. A speed increase of about fivefold was needed--from about 1 mph to 6 mph. The higher speed dictated use of an exclusive guideway to minimize the chance of collisions with pedestrians or material objects. The higher speed and additional requirements for safety required new designs for the tug, vehicles, and controls. The battery-powered system is said to have experienced many difficulties, but records were not found. It is known that the original system was considered unsuitable for continued use and expansion in Stage 2 when the hotel complex was added.

In 1968, the city accepted a study dealing with the construction of a hotel complex as the second stage of airport development. The hotel was developed and financed by Host International, Inc., at a reported cost of $10 million. Design of the hotel was reported to be under way in May 1969. Opening was planned for January 1971 but was delayed.

In April 1971, the airport engineers published a report entitled "Plan of Development, Vol. IV: Second Stage" in which the problems of extending AGT service to the hotel complex are discussed. Specifications for the second AGT system were issued on July 23, 1971. Significant changes were not made in guideway geometry either in the existing facility or in the new tunnel. This means that bidders for the second system faced the severe limitations imposed by the geometric characteristics of the original guideway design.

Major participants in the planning and design of the airport and AGT system are listed in Appendix D.

6.4 Acquisition

Procurement procedures used to acquire the first system from Barrett are not known. The reported cost of the hardware was $380,000.

Acquisition of the second system was by competitive bidding, but most prospective suppliers could not fit their hardware into the limited guideway space. Only two potential suppliers responded to the request for bids. Barrett's proposal was disqualified--it was said to have been unresponsive to the specifications and to have been received late. Westinghouse Air Brake Company (WABCO), Monorail Division was the other bidder ans was awarded the contract. This Division was later sold to Rohr Industries, which has provided aid in perfecting the design and maintaining the system.

6.5 Finance

The total cost of the Houston Airport project was reported to be $110 million through the first stage. The separate cost of the terminal complex is not known. The airport was financed by revenue bonds serviced by income from airlines and other tenants. As in all major airport projects, large outlays must be made over a period of years before revenue is produced. The AGT system was financed as part of the entire project and was subject to the same cost "squeezes" as other elements. As indicated above, pressure to economize on construction costs during 1964 may help to account for the limited space provided for the AGT system.

7. CONCLUDING REMARKS

The Houston tunnel train system was installed in 1972 as a replacement of an earlier battery-powered tug system. Thus, it represents a case of retrofitting an AGT system into an existing facility. The tunnel geometry imposed severe constraints on the retrofit AGT system. For example, the small radius of the hotel station restrains the turnaround speed, which results in a lower average line speed for the system. In the proposed extension of the terminal, the airport will have to decide whether to upgrade and extend the tunnel train or install a new system.

Unlike most AGT sites, where the phasing-out of manufacturer involvement has been gradual, the tunnel train system has been maintained and operated by airport maintenance staff ever since the system was accepted. This may account for the fact that the maintenance strategy adapted at the site is somewhat different from that recommended by the manufacturer. Usually, the maintenance procedures recommended by the manufacturer are engineering and hardware oriented, whereas those used by the operator are manpower, staffing, and distribution oriented.

The maintanence crews at the Houston Intercontinental Airport have duties other than maintaining the tunnel train (e.g., maintenance of the parking lots and other airport facilities). Although the tunnel train is a part of the airport facilities, it is not a vital link per se since walking in the basement tunnel is always an option. Therefore, unlike some AGT sites, the demand on systems performance and reliability is not absolutely critical.

The Houston tunnel train provides a good example of the problems associated with fitting an AGT system into an existing environment. The system itself represents the product of a design that uses components with proven characteristics. A more stringent maintenance program may be used to reinforce system performance. In terms of current demand, the system serves its purpose adequately.

Appendix A

AGT ASSESSMENT MEASURES: HOUSTON TUNNEL TRAIN

This appendix provides a detailed check-list of assessment measures associated with the description and performance of the Houston Tunnel Train. The descriptive measures essentially provide the basic facts about the design of the system. The performance measures provide data associated with system operations. The statements under the column heading "user" are qualitative descriptions about the system from user's point of view. The statements or numbers under the heading "operator" reflect the operational features of the system generally in quantitative terms. These were either provided by the system operators or were calculated by SRI team using some basic data provided by the operators. Much of the information presented in this appendix has been extracted from the main body of the report. Some of the information presented in this appendix may not be found in the main body of the report. Such information was either gathered inedpendently or was inferred from the data in the main body of the report.

Appendix A

AGT ASSESSMENT MEASURES: HOUSTON TUNNEL TRAIN

Descriptive	User	Operator
1. System sizing		
Fleet size		
Total		18 vehicles*
Peak-hour operating		12 vehicles*
Off-peak operating		12 vehicles*
Number of vehicles per train		
Maximum		3 vehicles*
Peak hour		3 vehicles*
Off peak		3 vehicles*
Number of stations		4* stations/8 platforms
Guideway configuration		
Closed loop or others		Closed loop*
Length at grade, elevated, etc.		6,080 ft. guideway, underground tunnel
Bidirectional service		No
Station occupancy		1 train (3 vehicles)/station
Employees		9 employees
2. System costs		
Capital costs		(Estimated for a duplicate system, See Table 5-3)
ROW		Not applicable
Guideway		$ 1,443,000 (1969)
Stations (4)		$1,210,000 (1969)
CC&CS, Power, Vehicle		$993,000 (1972)
Maintenance facility		$ 77,500 (1969)
3. Technical description		
System description		
Gradeability		Guideway is flat
Line capacity		480 passengers/hr/lane‡ (4 trains at present)
Seat		240 seats/hr/lane‡
Standee		240 passengers/hr/lane‡
Crush		640 passengers/hr‡
Degree of automation		
Employee-to-vehicle ratio		0.62 employees/mean number of vehicles in operation‡
System man-hour ratio		0.19 total daily man hours/total daily vehicle hours‡
Fare collection	None*	None*
Existing automated operation		
Strategies		
Peak hour, Off peak hour		Unscheduled circulation, no schedule adjustment to demand level
Elderly and handicapped accommodations		Can handle most wheelchairs (up to 4'7" wide)
Mean operational speed	Slow§	3.7 mph average speed**
All-weather capability	Fully enclosed§	System operates in enclosed tunnel
Subsystem description		
Vehicle		
Weight (empty & maximum design)		7200 lb capacity* (3 car train)
Dimensions (length, width, height, wheelbase, etc.)		40 ft × 5 ft × 7.5 ft* (3 car train)
Design life (with average mileage/year)		20-25 years†
Capacity		
Seated passenger		6 seats/vehicle*
Standee passenger		6/vehicle*
Crush		16 passengers/vehicle*

*Data supplied by the manager or operator.

†Estimate by the operator.

‡Calculated result based on given information.

§Data collected by SRI by observation of installation or passengers.

**Estimate by the contractor.

Descriptive	User	Operator
Speed		
Maximum		8 mph[*]
On-board heating		Fan only (air-conditioned tunnel 70-72°F)[*]
On-board cooling		Fan only (air-conditioned tunnel 70-72°F)[*]
On-board illumination	Satisfactory[§]	Incandescent
Command, control, and communications,		
Hardware		Transistors, relays[*]
Software		No software, hard-wired logic[*]
Vehicle control and management		Relay-set[*]
Operational control strategy		Unscheduled circulating trains
Headway protection		Fixed block with train detection relays
Merge strategy		Not applicable
Service policy		Continuous service
Routing policy		Fixed route on loop
Empty vehicle management strategy		Not applicable
Dispatching policy		Not applicable; four trains operate in a loop
Failure management		An electric cart is sent or passengers advised to walk
Steering		Vertical axis guidewheels operating on vertical surface guidebeam[*]
Switching (captive/noncaptive)		Manually operated segment substitution[*]
Propulsion		Thyristor bridge, 3 dc traction motors 7.5 hp[*]
Power		Single phase ac, 277V[*]
Suspension		Air bellows, foam-filled tires, 4-wheel bogies[*]
Guideway		Flat surface with raised, central H-section guidebeam[*]
Stations		On-line, accommodate one train only
Passenger information	Lighted panel indicates station not working	
Braking (normal, backup, emergency)		Dynamic, drum, shaft[*]
4. Service characteristics		
Levels of service		
Comfort		
Temperature		70-72°F (ambient in tunnel)[†]
Humidity		Not measured
Lighting		Not measured
Heating and cooling		None on board
Air circulation		Not measured
Periods of operation		
Hrs/day	18 hours/day[†]	18 hours/day[†]
Days/year	365 days/year[†]	365 days/year[†]
Accessibility or area coverage	Serves terminals, hotel and parking[§]	
Patronage		3,500 passengers/day[**] (1.2 ~ 1.4 million/year)[**]

Performance	User	Operator
1. Sociological		
Levels of service		
Comfort		
Seating room area	Satisfactory[§]	Not measured
Standing room area	Sometimes crowded[§]	Not measured
Seat availability (peak, off peak)	Satisfactory except at peak[§]	
Lighting	Satisfactory[§]	
Heating and cooling	OK[§]	
Air circulation	Satisfactory[§]	
Satisfaction	Could be improved[§]	Unknown
Ride quality	Shaky and bumpy	Not measured
Convenience		
Transfers	None	No transfers
Service Quality		
Frequency of service (peak, off peak, policy, demand actuated)	4.5 min mean headway[‡]	4.5 minute mean headway[†]
Mean wait time	2.3 min	2.3 min
Average trip speed	3.7 mph	3.7 mph

Performance	User	Operator
Maximum trip speed	8 mph	8 mph
Cruise trip speed	8 mph	8 mph
2. Economics		
Capital costs		$3.97 million (1969-72); $6.81 million (1976 dollars)
Operating and maintenance costs		$328,930[†] (1976)
Per passenger mile traveled (5 car train)		$1.01/passenger mile[‡]
Per vehicle mile traveled		$2.70/train mile
Per seat or place mile traveled		$0.07/seat or place mile[‡]
Per passenger trip		$0.25/passenger trip[†]
Maintenance		$1.02/vehicle mile (include operations)
Labor		Separation of operations and maintenance costs not available. See Table 5-4.
Materials		
Operations		
Conducting transportation		
Energy		
General and administrative		
Life cycle costs (equivalent annual cost)		$742,200/yr; 35 years construction life, 15 years hardware life
Travel cost (fare)	None	None
3. Environment/land use/energy/safety		
Environment		
Impact		
Noise (exterior)	Minimal[§]	Not measured,
Air pollution		Virtually none
Aesthetics	Unsatisfactory (see text)[§]	
Urban disruption		Not applicable
Land use		
Guideway space requirements		0.363 acres/mile for guideway alone, ROW~0.8
Stations		0.542 acres/mile of guideway
Maintenance and other facilities		0.141 acres/mile
Energy		Data to calculate Kwh/vehicle mile was not available.
Safety and security (on system versus off system)		
Accidents	None	None
Fatalities	None	None
Injuries	Minor door incidents[*]	Not recorded
Assaults	Almost 0[†]	Few if any
Vandalism	Major problem	Major problem, dollar estimate unavailable
4. Operational/technical performance		
System		
Elderly and handicapped factors	Accommodates wheelchairs[†] up to 4'7" wide	
Accommodations	Satisfactory[§]	
Ease of use	Satisfactory most of the time[§]	
Routing efficiency		Not applicable
Vehicle load factor		0.085 passenger miles/place miles[‡]
Vehicle productivity		13.6 passengers delivered/vehicle hours[‡]
Labor productivity		244 place miles/person hours[‡]
Operating cost productivity		13.35 place miles/dollars of system O&M costs[‡]
Availability		
Subsystem availability		
Traditional availability		0.98/train[‡] (vehicle subsystem), ~1.00[‡] (other subsystem)
Proportion of delay (vehicle-based)		Data not available
Successful trip ratio vehicle-based)		Data not available
Total system availability (traditional)		0.91[‡]~0.97[‡]
Subsystem		
Vehicle		
Acceleration	Slow[§]	3.0 mph/sec[§]
Deceleration (service and emergency)	Accompanied by vibration[§]	3.0, 3.3 mph/sec[*]
Speed		
Line (peak and off peak)	8 mph	8 mph

Performance	User	Operator
Vibration (stationary vehicle)	0	0[‡]
Noise	Minimal[§]	Not measured
Jerk		
Acceleration		1.5 mph/sec^2
Deceleration		1.5 mph/sec^2
Tire life		26,000 miles[‡]
Command and control		
Acceleration		3.0 mph/sec
Deceleration		3.0 mph/sec
Speed		~1/4 mph mph/sec mean deviation from commanded levels[*]
Stopping		0.009 hundredths mile mean deviation from commanded levels[*]
Headway		4.5 minute (mean)
Steering		
Lateral ride quality	poor on deceleration and curves[§]	Not measured
Steering member wear		Not measured
Switching		
Response time		180 sec (original design value, presently manual operation)
Noise	Imperceptible[§]	Not measured
Vehicle vibration		Not measured
Propulsion and braking		
Tractive effort		0.14 lb force/lb mass[‡]
Power distribution system		
Power pickup wear		Not measured
Electromagnetic interference		Not noticeable
Voltage regulation		Not measured
Guideway		
Condition	Satisfactory[§]	None
Roughness characteristics	Less than satisfactory[§]	Not measured
Maximum dynamic load		Not measured
Stations		
Dwell time		17 sec mean time
Throughput		500 passengers/hr/station[‡] (present peak value)
Comfort	Adequate[§]	
Capacity (15 depart/hr assumed)	Satisfactory[§]	1080 passengers/hour (boarding and deboarding)
Information/graphics	Poor[§]	
Access/egress	60 sec[§]	
Train screens		None
Fare collection		
Ease of use	No fare	No fare
Service capacity		
System and subsystem		
Maintenance requirements		Adequate spare parts available
Equipment		No special equipment
Labor		See Table 5-4
Operating requirements		
Labor		See Table 5-4
Reliability		Typically 2 shut downs/week (1976)
Maintainability		1-2 hours Restore Time (1976)
Service life		Assumed 15 years for hardware; 35 years for construction.

Appendix B

METHODS OF COST ESTIMATING AND ANALYSIS

Appendix B

METHODS OF COST ESTIMATING AND ANALYSIS

Objective

One objective of the assessment of six existing AGT systems was to collect and present cost information on these systems in a manner that would be useful to planners of new AGT systems in the Downtown People Mover program and in other urban settings.

Various Problems and Aspects Associated with Cost Analysis

To approach the objective, a number of problems and aspects--both practical and theoretical--had to be taken into account, as discussed below.

Historical cost data obtained from published reports and by inquiries addressed to owners and participants in AGT system development projects are often incomplete or otherwise unsuitable, as guidance or indicators, for planners of future systems. Costs of some items are incorrectly reported or omitted. Separate costs of some items are not obtainable because the AGT facility was built as an integral part of a multipurpose facility. Where necessary, cost estimates have been derived by SRI staff members and consultants.

Urban settings for AGT systems are the main focus of interest in this research but none of the six AGT systems studied is in a typical urban setting--three are in airports, two are in recreation parks, and one is in a multipurpose commercial development owned and operated by private interests. The research staff has taken various measures to recognize possible differences between the actual settings observed and typical urban settings. Planners of new AGT systems are urged to pay particular attention to the stated conditions associated with cost estimates prepared for each site, and to make needed changes in cost estimates to fit the actual conditions of local sites.

Price changes must be taken into account to make cost data from different years useful to planners. AGT systems and their components were purchased or constructed in different years and at different price levels. Escalation adjustments have been made to state all capital cost estimates at 1976 price levels. Capital costs for each system are stated in 1976 dollars.

Total equivalent annual costs is the most convenient format for presentation of cost data on the six systems. However, initial capital costs are incurred in lump sums, and long intervals pass between replacements of capital assets while operating and maintenance costs are incurred year-by-year. To make these estimates commensurate, capital costs have been restated as equivalent annual series amounts for assumed service lives and interest rates. The result is equivalent to the uniform annual payment that would be needed to repay a loan with interest by the end of the series life. Equivalent annual costs of capital and annual operating and maintenance costs can then be added to produce total equivalent annual costs.

Unit costs of service per vehicle mile, per passenger mile, etc. are quite useful in making comparisons. These are computed by dividing total equivalent annual costs by measures of service performed.

Growth or decline in costs of operation and in amounts of service rendered are likely to occur from year to year during the life of each AGT system. For example, patronage and costs may increase for many years, then level off, and finally decline as the AGT system or the entire facility approaches obsolescence. Growth and decline are site-dependent characteristics--the experience of an existing site will seldomly, if ever, apply at another. Therefore, growth and decline have not been treated in this research.

Discussion of Terms and Parameters Used in Cost Analysis

A discussion of several terms and parameters used in the cost analysis is presented below. Values of various parameters used in the study are also mentioned where applicable.

Joint-use and multipurpose refer to facilities and services shared by an AGT system and one or more additional functions. An example is an AGT station located within an air terminal building.

Free-standing and independent refer to facilities and services provided solely for an AGT system such as an AGT maintenance facility.

Conceptual design or duplicate facility refers to a hypothetical free-standing or independent AGT system designed solely for transit service. It is functionally equivalent to the transit portion of a system having joint-use or multipurpose characteristics. This concept allows estimation of costs of an AGT system without the need for division of costs among an AGT system and other functions.

Actual cost is the dollar amount paid for a specified asset or service.

Allocated cost is a division of the cost of a joint-use facility or multipurpose service among numerous functions and is usually based on some estimate of the percentage of use. For example, if an AGT station occupies 1% of the space in a shopping mall, one might say that the allocated cost of the station is 1% of the cost of the entire building complex. Allocation of costs is common in accounting practice, but cost allocations made for one site will seldom be well suited for decision making at another site. Therefore, allocated costs must be used with caution.

Marginal cost is an estimate of the additional cost or cost increment made necessary by the addition of an optional function, such as an AGT station, to an existing or planned facility, such as a hotel or office building.

Duplicate cost is an estimate of the cost of a hypothetical duplicate facility discussed above. In this study it is the estimated cost of duplicating the essential AGT functions observed in an existing joint facility at a hypothetical new site where the AGT system could be independent or "free standing."

Price indices are factors used to adjust estimates of costs of assets acquired in given years to the price levels of a common year--1976 in this research. Indexes and escalation procedures must be used with care to avoid introduction of serious errors. This is especially true when systems having dissimilar characteristics--such as buses and AGT systems--are to be compared. In this work separate indices are used for three cost categories:

- Hardware
- Construction
- Professional and administration services.

The selection of various indices was made in consultation with UMTA and its subcontractors. A brief description of various indices is given below.

Hardware--The Wholesale Price Index for Machinery and Motive Products is used to escalate all hardware costs including vehicles; command, control, and communications; power distribution system; station equipment; and power rails.* Commodities included in this index are:

1. 42%--Electrical machinery and equipment: wiring, integrating instruments, motors, transformers, switchgear, electronic components, and accessories.
2. 14%--General-purpose equipment: elevators, escalators, mechanical power transmission equipment, conveyor belts, monorail conveyors, valves, and bearings.
3. 14%--Tools: metal working tools and machine-shop products.
4. 8%--Heavy equipment: tractors, construction equipment.
5. 22%--Miscellaneous equipment: mining, textile, food, woodworking, printing industries.

Construction--The Engineering News Record (ENR) Construction Cost Index for 20 cities is used to escalate all construction costs including guideways, stations, utilities, maintenance, and support facilities. The components included and their relative weight in the index are (1) base price of structural steel shapes (38%); (2) consumer's net price of cement exclusive of bag (7%); (3) lumber (17%); and (4) common labor rate (38%).

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*The selection of this index is based on MITRE letter to UMTA, # W24-3789, Subject: "Inflation Rates for AGT Socio-Economic Research Program," 27 July 1977.

Table B-1

COST INDICES FOR ESCALATING AGT CAPITAL COSTS

	Hardware (Wholesale Price Index for Machinery and Motive Products)		Construction (Engineering News Record Construction Cost Index for 20 cities)		Professional Services (Consumer Price Index for Urban Wage and Clerical Workers, U.S. City Average)	
Year	Index	Conversion Factor to 1976 Prices	Index	Conversion Factor to 1976 Prices	Index	Conversion Factor to 1976 Prices
1965	--	--	91	2.45	--	--
1966	--	--	95	2.35	97.2	1.75
1967	100.0	1.66	100	2.23	100.0	1.70
1968	103.0	1.61	108	2.07	104.2	1.63
1969	106.0	1.56	119	1.87	109.8	1.55
1970	110.6	1.50	130	1.72	116.3	1.46
1971	115.3	1.44	148	1.51	121.3	1.40
1972	118.2	1.40	164	1.36	125.3	1.36
1973	121.2	1.37	177	1.26	133.1	1.28
1974	136.3	1.22	188	1.19	147.1	1.16
1975	156.2	1.06	206	1.08	161.2	1.06
1976	165.8	1.00	223	1.00	170.3	1.00

Source: N. D. Lea and Associates, Inc.

Professional and Administration Services--The Consumer Price Index for Urban Wage Earners and Clerical Workers, U.S. City Average, All Items is used to escalate all costs for professional services such as A&E, design, project management, systems integration, and acceptance testing.

Service life is the period of service expected of an asset. Service life may be determined by wear or exhaustion of the asset or by obsolescence of the entire facility. Equivalence calculations start with the service life of the AGT subsystem having the longest expected life--usually the structures. Subsystems with shorter service life are assumed to be replaced at the same initial cost, stated in 1976 dollars. The selection of service life is based on experience and judgement.

Two sets of service life assumptions have been made for all systems. One, characterized as "basic," uses 15 years for hardware and 35 years for construction. A second, characterized as "optimistic," uses 20 years for hardware and 50 years for construction. In addition, a third set, characterized as "commercial", uses lives of 15 years for both hardware and construction and was applied to the two recreation parks--King's Dominion and Disney World. These short lives refelct the possibility that obsolescence, rather than use and deterioration, will determine the end of service.

Salvage value is the expected value of an asset at the end of the service life. Salvage values are neglected in this analysis.

Discount rate is the time value of money to the owner of an AGT system or the rate of interest that would be attractive for a given investment in an AGT system. A discount rate of 10% was used in the study, this being a typical discount rate currently prevailing. However, planners should use the rate predicted to be available for the specific case.

Equivalent annual cost of capital, R, is found by the following equation:

$$R = P\left[\frac{i(1 + i)^n}{(1 + i)^n - 1}\right]$$

where

P = capital cost

n = service life

i = discount rate.

Operating and maintenance costs are annual outlays for goods and services required by AGT systems.

Total equivalent annual cost is the equivalent annual cost of capital, R, plus the cost of operations and maintenance.

Cash flow analysis is not employed in this report but would be an appropriate tool for certain purposes. For example, cash flow analysis is required to determine fare structure adequate to repay capital and interest and to recover operating and maintenance costs. If a cash flow analysis is desired, all cash receipts and outlays must be estimated for each time period over the life of the system. For example, actual cash expenditures for interest must be used, rather than the discount rate used in equivalent annual cost calculations.

Some Specific Comments on Capital Cost Estimates

AGT systems include numerous items or groups of capital assets, and there is no uniformity among systems in the breakdown of systems into subsystems, components, and so forth. However, it has been possible, with fair accuracy, to classify assets under three headings--professional and administrative services, hardware, and construction.

Professional and Administrative Services--Detailed historical records of the cost of consultants and administration were usually not found. In such cases these costs were calculated as a fraction of the cost of major assets in consultation with the system designers.

Hardware--Estimates of hardware costs obtained from the AGT sites appear to be reasonably complete and dependable. AGT hardware was usually purchased for cash under one or a few contracts. It is noteworthy that published reports of hardware costs usually cite the price bid by the system supplier, rather than the final contract amount. Consequently, the published figure often omits such elements as the costs of change orders and items furnished by other suppliers. Data obtained from accounting records were usually considered dependable and were used.

Right-of-way was not purchased for any of the systems studied. In each case, the AGT system occupies a small part of a large parcel of land acquired to serve a broad variety of purposes. Right-of-way costs will differ greatly among urban sites, and may be quite substantial in certain cases. Where owners have used the allocation technique to estimate a right-of-way cost to meet accounting needs, that estimate is reported.

Site preparation costs are included in the analysis in those cases where historical data were found. However, where the data were lacking, estimates were not derived by the research staff.

Utility relocation was not encountered as a cost factor in any of the systems studied. Again, urban sites will differ greatly in this respect and gain little from the experience of the six AGT systems treated in this research.

Construction costs for civil works--mainly tunnels, elevated structures, and stations--have presented the most difficult cost-estimating problems. Available historical data of dependable quality were always used. In several cases the cost of major elements of the civil works had never been estimated by the owner (or anyone else) until the restudy stage of this research. This lack of data is understandable. In many instances an AGT facility element was incorporated into the design and construction of another, much larger facility. In such cases there is no theoretically correct way to identify the cost of the AGT facility and, in some cases, no need to make a cost allocation. Only a few owners treat AGT systems as profit centers and have a need to account for the cost of the AGT system.

To overcome the lack of historical data, special studies have been made to derive construction cost estimates. These estimates fill data gaps and present a complete--but qualified--cost picture for use by planners of future AGT systems. Three main approaches are available to estimate construction costs:

- Duplicate Cost Approach. Costs are estimated by assuming free-standing duplicate facility with appropriate dimensions.
- Allocation Cost Approach. Costs are estimated by allocating a suitable fraction of the total cost to AGT system.
- Marginal Cost Approach. Costs are estimated as the additional cost that must have been incurred because of the inclusion of the AGT system.

In the present study, one or the other approach was used where appropriate.

Appendix C

CHRONOLOGY OF EVENTS

Appendix C

CHRONOLOGY OF EVENTS

1957	Ben C. Bolt, President of the Houston Chamber of Commerce, initiates land acquisition idea.
1960	City of Houston purchases 3,000 acres of land for the new airport. City initiates preliminary airport development planning.
1961	City acquires additional 4,300 acres for airport site. Houston City Council authorizes airport design.
1963	City approves unit terminal design.
1964	Preliminary Terminal Area Design approach.
1967	Runways completed.
1968	Barrett driverless electronic train system installed--City approved study for hotel.
1969	Houston Intercontinental Airport opens, September. Initial AGT system opens.
1970	Airport handled 4.5 million passengers.
1971	Host International opens airport hotel.
1972	WABCO AGT system replaces the Barrett system in September
1977	Planning for third unit terminal in progress.

Appendix D

MAJOR PARTICIPANTS

Appendix D

MAJOR PARTICIPANTS

(1) Jet Era Ranch Company*

J. S. Abercrombie
Edgar W. Brown, Jr.
George Brown
Herman Brown
J. F. Coaley
Roy H. Cullen
J. Brown Cutbirth
W. H. Francis, Jr.
W. J. Goldston
E. J. Gracey
J. A. Gray
Claud B. Hamill
W. N. Hooper
Rex E. Hudson
Ralph A. Johnston
Douglas B. Marshall
R. E. Smith
William A. Smith

(2) City of Houston (1964)

Louie B. Welch - Mayor

City Council

Robert S. Webb
Arthur T. Miller
Lee McLemore
Homer L. Ford
Frank O. Mancuso
Bill Elliot
Frank E. Mann
John Goyen
Roy B. Oakes - Controller

Department of Aviation

Joseph A. Foster, Director
Paul Koonce, Airport Director

Department of Public Works

Enos B. Cape, Director

*The Jet Era Ranch Company consists of a group of citizens led by Mr. Ben C. Bolt, President of the Chamber of Commerce. The group assembled some 3,000 acres of land through private purchases and resold the land to the city at cost.

(3) Airline Technical Committee

American Airlines

Braniff International Airlines

Continental Airlines

Delta Airlines

Delat Airlines

Eastern Airlines

Royal Dutch Airlines (KLM)

National Airlines

Pan American World Airways

Texas International Airlines

(4) Airport Engineers

Engineers of the Southwest (1964)

Lockwood, Andrews, and Newnam, Inc.

Bovay Engineers, Inc.

Turner and Collie, Consulting Engineers, Inc.

(5) Airport Architects (1964)

Goleman and Rolfe

Office of George Pierce and Abel B. Pierce

(6) Barrett Electronics Corp.--Supplier of initial system

Westinghouse Air Brake Company (WABCO)--Supplier of second system

(Rohr Industries, Inc. is the present owner of the AGT product line.)

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☆U.S. GOVERNMENT PRINTING OFFICE: 1978-261-264/224