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Technical Assessment of the Transette Transit System

Transportation Systems Center
Cambridge MA 02142

October 1981
Final Report

U.S. Department of Transportation
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16. Abstract

A novel, prototype transportation system called Transette has been installed on the campus of the Georgia Institute of Technology by Transette Inc. Transette is a unique, belt-driven system currently in a loop configuration, employing passive vehicles controlled and propelled by a drive belt system that permits vehicles to move at twice the speed of the belt. This assessment covers the period between May 1978 and November 1979. Section 2 describes the background and events of the development. A technical description of the system is provided in Section 3. Section 4 provides a description of the system operation and performance and Section 5 provides the system economics. Section 6 is the TSC assessment of the system with recommendations of what is needed for a revenue system.

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PREFACE

This report describes an assessment of the Transette system located at the Georgia Institute of Technology in Atlanta, Georgia. The work reported herein was performed between May 1978 and November 1979 and consisted of on-site inspections, technical reviews, and technical interchanges with the system developers.

The assessment was conducted by the Transportation Systems Center (TSC) and is sponsored by the U.S. Department of Transportation, Urban Mass Transportation Administration (UMTA), Office of Technology Development and Deployment through its Office of Socio-Economic and Special Projects.

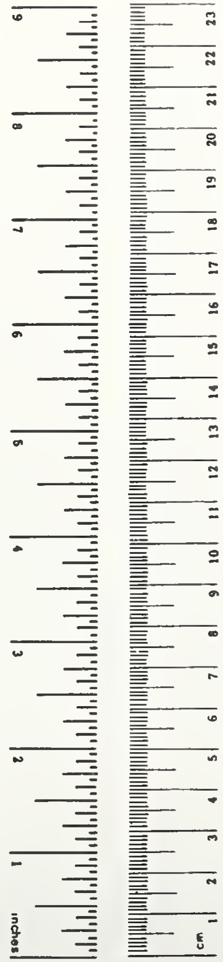
The first five sections of this report are based on data provided by the Georgia Institute of Technology and Transette Incorporated while the conclusions and recommendations represent the evaluation and opinion of the assessment team of the Transportation Systems Center.

Acknowledgement and special thanks are given to Chauncey W. Watt for his contributions in the areas of safety and reliability. and also to Mr. F.J.Rutyna for his overall guidance.

METRIC CONVERSION FACTORS

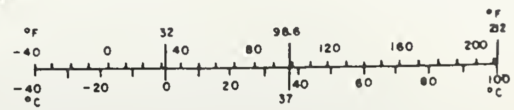
Approximate Conversions to Metric Measures

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	squars kilometers	km^2
	acres	0.4	hectarss	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	qusrts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic ysrds	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Calsius temperaturs	°C



Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimetsrs	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 ysrds	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	scres	
		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	pinta	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



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EXECUTIVE SUMMARY

INTRODUCTION

As part of UMTA's continuing assessment program, the Transportation Systems Center (TSC) of the U.S. Department of Transportation (DOT) has conducted a technical assessment of the Transette System located on the campus of Georgia Institute of Technology in Atlanta, Georgia. Transette is a 0.25-mile (0.4 km) fully-automated, engineering prototype test system, employing passive vehicles. The assessment was sponsored by the DOT Urban Mass Transportation Administration (UMTA) and conducted under the auspices of the Office of Socio-Economic and Special Projects, Office of Technology Development and Deployment. It covers the period between May 1978 and November 1979. This technical assessment was conducted concurrently with the Transette Engineering Modification and Test Program funded by UMTA's Office of Technology Development and Deployment, Office of New Systems and Automation. The engineering modification and test program was completed in November 1979, after which the assessment was completed. A technical assessment of the Transette prototype test system was conducted because Transette was not an operational system at that time. This report represents the status as of November 1979 of the technical development of Transette which has undergone a long development cycle (i.e., since 1974) at a cost of about $685,500.

BACKGROUND

The unique belt-driven Transette system was invented by Dr. J.F. Sutton while employed by Lockheed Aircraft Corporation. Lockheed released the invention to Dr. Sutton, since they were not interested indeveloping automated transportation systems at that time. Subsequently, in 1972, Transette Inc. was established and was issued U.S. Patent No. 3,690,367 for the Transette System.

The Transette system was conceived at a time when active control systems received a great deal of attention. In concept active systems were not overly complex in themselves, but considerable complexity was introduced by the requirements of being fail-safe, the need for redundancy, and the inordinate amount of data transmission. Rather than try to build better active control systems, the Transette concept was an attempt to eliminate or circumvent the need for many of the functions performed by active systems, e.g., no need for data transmission to and from the vehicle.

A great simplification was achieved by placing the speed regulator at the wayside and providing only a longitudinal actuator, i.e., a transmission on board the vehicle. Thus, the vehicle only responds when power is applied, otherwise, it comes to a stop. Hence, the vehicle is passive and does not perform any higher level functions.

Passive vehicles have passive propulsion systems. But vehicles with passive propulsion are not necessarily passive. The distinction is made on the basis of the level of information transmitted to the vehicle and the functions the vehicle performs. A passive vehicle such as Transette is defined as one that only responds to a propulsion signal and does not perform any control determinations such as position, velocity, or accelerations relative to a fixed point in the guideway or relative to another vehicle.

Basic headway control was accomplished by placing two vehicles on a single belt thus giving a mechanical separation. A fixed block control system was superimposed on the entire system to ensure that this mechanical separation could not be violated while a vehicle is traversing from one belt to another.

The concept of an automated system using a totally passive vehicle propelled, guided, and controlled from the wayside is very appealing because of the potential of simplified system operation, enhanced availability, reliability, maintainability, and safety; and reduced cost in comparison to conventional AGT systems.

In June 1974, Georgia Institute of Technology was awarded Grant RDT-74-22600 for $127,400 by the National Science Foundation (NSF) for the installation and testing of the Transette prototype, passive-vehicle Personal Rapid Transit (PRT) system. An additional $275,000 was included in the program by Transette Inc. for fabrication of hardware. The grant was funded as part of the Federal Laboratory Validation Experiment by the Industrial Programs of Research Applied to National Needs (RANN) program of NSF.

The Transette system was designed to automatically control and propel four-passenger, passive vehicles around the guideway by means of a belt drive system that would permit the vehicle to move at twice the speed of the belt. Although the Transette system achieved an operational state, in October 1976, demonstrating the feasibility of the system, it did not do this in an automated mode nor were the vehicles able to operate continuously around the guideway loop. Three problem areas existed that needed to be corrected: 1) belt slipping, 2) mechanical interference at the station carousels, and 3) the inability of the system to operate automatically.

1. Belt slipping problems occurred because the initial design was based on inaccurate data on coefficients of friction and elongation characteristics.

2. Mechanical interference problems were a result of funding limitations which forced the purchase of a station carousel ring significantly different from the original design and, in addition, corrective measures were precluded when interference problems were discovered.

3. The automatic control system, a hardwired solid-state-logic fixed-block control system, was not made operational because of insufficient funds to complete the wiring, functional checkout and debugging of the system.

These problems were corrected by the Transette Engineering Modification and Test Program which was funded in May 1979 under an UMTA Grant (GA-06-0009) for $233,680. This UMTA program was designated Phase IB whereas the previous NSF program was designated Phase IA. The Phase IB program included the following modifications:

1. Incorporating a new belt and a constant-tension, belt take-up system in the drive system to account for load and temperature variations.
2. Increasing the radius of turn from 25 feet (7.6m) to 125 feet (37.9m) and designing a one-piece belt to go around the curve to the south terminal reducing the five main-line drive belts to two.
3. Adding an auxiliary guidance rail to the carousel, altering vehicle geometry, and introducing front-wheel steering.
4. Completing the wiring and checkout of the control system.

TECHNICAL DESCRIPTION

The Transette system is an automated, engineering prototype test system employing passive vehicles (Figure ES-1). All propulsion and command and control functions including speed regulation of vehicles are performed by a wayside system of belts. The loop system, a two way system with carousels operates between two main stations separated by 0.25 mile (0.4km), and includes an off-line station, a control center, and maintenance and storage facilities (Figure ES-2).

The system has two prototype test vehicles, each with a capacity of four passengers. Each vehicle is supported on four pneumatic rubber tires. Transmission of power to the vehicles is provided by a series of power belts and pulleys driven by electric motors. The five inch (12.7 cm) wide belts are made of polyester fabric layers impregnated with polyurethane. The belts slide along stainless steel slider beds mounted on top of the concrete guideway. Drive torque is transmitted to the vehicle via the left rear wheel (rubber tire) of the vehicle which ride on the belt. The left rear wheel transfers torque to the right rear wheel through a 1:2 gear box, thereby driving the vehicle at twice the belt speed.

FIGURE ES-1. TRANSETTE VEHICLE ON THE GUIDEWAY

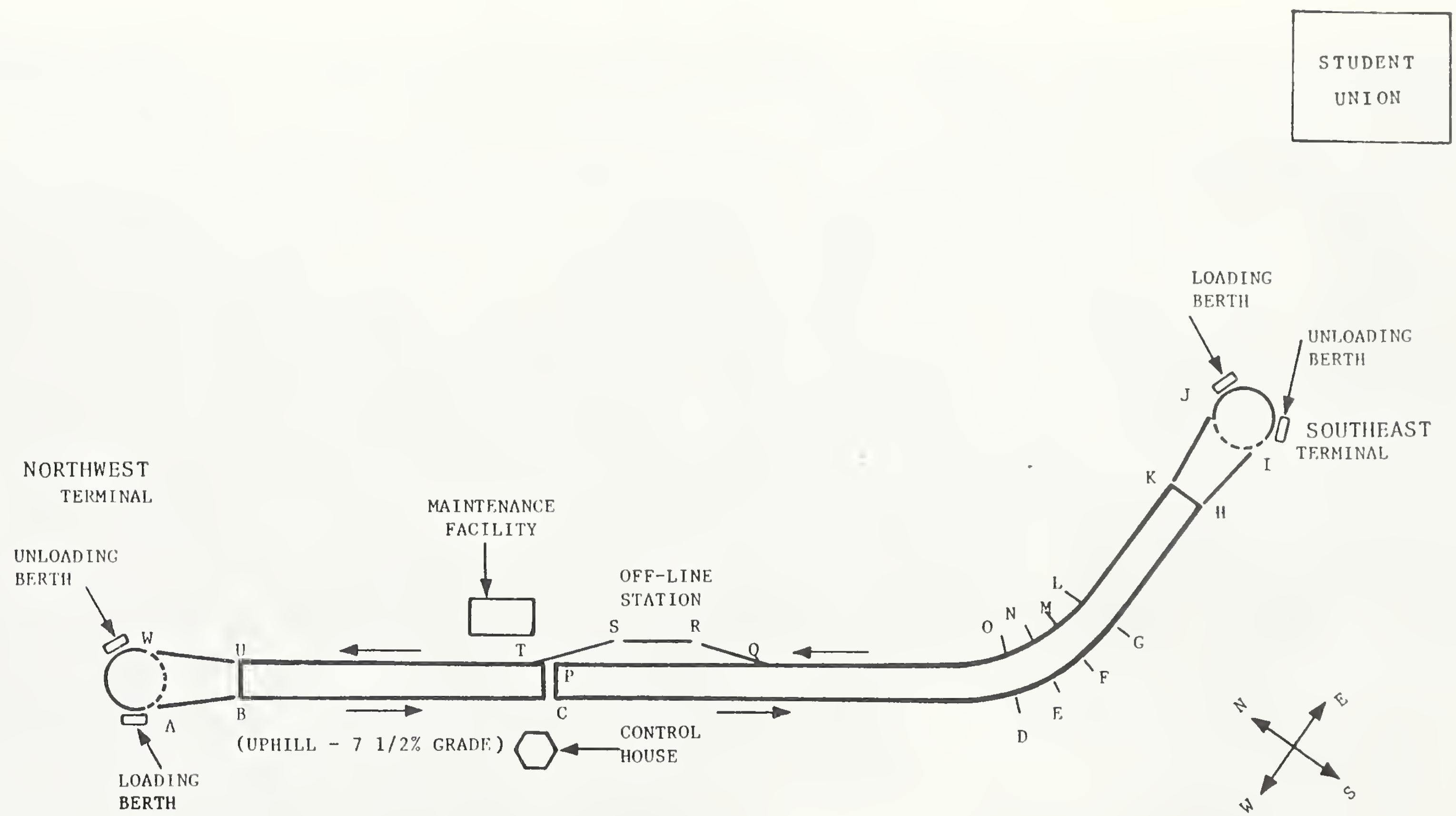


FIGURE ES-2. TRANSETTE GUIDEWAY LAYOUT (SCHEMATIC)

Two carousels, one at each end of the guideway, turn the vehicles around, thus closing the guideway loop. The carousels also position the vehicles at the station loading and unloading berths.

Headway between vehicles is established by placing the vehicles at a fixed distance apart on the moving belt. Automatic control of the vehicles is achieved by superposition of a fixed block control system that de-energizes the belt drive motor if a minimum headway of 15 seconds is violated for any reason. Implementation of this control system is by means of a hardwired system of solid state relays. The system can be operated in either a scheduled or a demand-responsive mode.

Some of the more important technical and operational characteristics of the Transette system are summarized in Table ES-1.

TECHNOLOGICAL ASSESSMENT

The Transette system development was achieved with the expenditure by all contributors of some $685 thousand dollars. The highest system trip reliability achieved during the test program was 0.957 (see Sec. 6.3). This is not adequate for a practical application, especially since the system is synchronous. This reliability in conjunction with the long mean-time-to-restore would result in a low system availability. However, if the corrective actions indicated are made, then the system is potentially capable of achieving a high level of availability.

SAFETY

Transette was designed with safety as a primary consideration. Safety features are inherent in the design. The passive nature of the vehicle with its belt drive system eliminates the hazards of heat, fumes, fire, electrical short-circuit, noise and vibration from an onboard motor. The wayside belt drives are considerably less hazardous than live power rails.

TABLE ES-1. SUMMARY OF TRANSETTE SYSTEM CHARACTERISTICS

Automation	Fully Automated
Type of Service	Scheduled Collection and Distribution or point-to-point demand responsive
Maximum Theoretical Lane Capacity	897 Pass/hr.
Maximum Practical Lane Capacity (80% of theoretical)	718 Pass/hr
Headway (min)	15 Seconds
Maximum Operating Speed	15 mi/hr. (24 km/hr)
Average Speed	12.4 mi/hr (19.8 km/hr)
Average one-way (0.24 mi) Transit Time (includes 15 sec. dwell)	1.55 min
Vehicle Capacity	4 Seated Passengers
Vehicle Weight	850 lbs.
Stations	2 on-line with unloading and loading berths; and 1 off-line, single berth.
Guideway (total at-grade)	2932 ft. (0.9 km)
Switching	mechanically on-board vehicle, wayside actuated
Development Cost	$685,500

Placing vehicles on a belt, in essence, fixes the headway mechanically. However although operation on a single belt has inherent safety built into the design, collisions can occur when transitioning from one belt to another. To ensure against any collisions when transitioning from one belt to another, a fixed-block control system was superimposed providing a safety zone between vehicles. It has been implemented with solid state relays. The performance of the fixed-block control system has been highly satisfactory from a safety point of view. No vehicle collisions have occurred in an automatic mode. However, the fixed-block control system is not implemented in a redundant manner and a possible failure could occur that may result in a collision. Hence, it is recommended that a redundant control system be implemented.

Vehicle braking action is always applied unless propulsion power is applied. This eliminates the need for an interlock between the propulsion and braking systems and ensures that propulsion and brakes can not be applied simultaneously. This is a simple mechanical system with inherent safety designed into it. The propulsion and braking system in the prototype system are implemented in a single drive axle. If, over time, a failure of an axle or keyway occurs, the vehicle will be left without a braking system making a collision possible. Therefore, it is recommended that a dual-drive system be implemented to make the braking system redundant.

As noted in Sec. 6.5.4, proper clutch engagement is necessary in maintaining correct vehicle separation on the belt. In the extreme, an unengaged clutch could result in the "free wheeling" of a vehicle on any grade. While this condition is considered a safety concern for the prototype test vehicles, a new design using a simple automatically engaged and adjusted clutch has been implemented on a test basis and could potentially resolve this problem.

The positively retained front-wheel steering design has a possible single-thread failure mode on the forward outboard guidance wheel. A failure of this guidance wheel could result in loss of steering control. To ensure against this possibility, a second guidance wheel should be added to make the steering redundant.

GUIDEWAY BELT DRIVE

The belt elongation problems were corrected by the introduction of a belt take-up system on the main-line drive. The number of main drive belts was reduced from five to two. A long belt was extended around the curve, which was increased in radius to 125 feet, in one continuous belt by successive chordal turns. The belt take-up system performed extremely well. The fluid couplings in the main-line belt drives and the viscous oil in the tubes surrounding the take-up weights reduced jerk and dynamic loading on the belt as vehicles transitioned from one belt to the other. The damping resulted in a very smooth operation of the system.

BELTS

Four generations of belts were used during the development process. In the event of a break, mechanical splices could not be used on the first two generations developed during the Phase IA (NSF) effort. Bonding, the only means of repairing, these belts would take between 2.5 and 24 hours. This was unacceptable in terms of availability. The next two generations used an "S" weave construction that permitted the use of mechanical splices. This reduced the time to restore a belt break to about 20 minutes greatly improving availability. Numerous splice designs were tested including a series of sewn splices. The sewn splices outperformed the mechanical splices on the long belt, which had the highest applied loads by at least a factor of 4 to 1. But mechanization of sewn splices requires further developments.

The belt-splice problem proved to be among the most difficult encountered during the development process. Since the belt reliability and availability are crucial to the success of Transette, its problems required the utmost attention. A satisfactory belt design for the hill belt, the shorter of the two main-line belt drives, was successfully demonstrated. However, this belt design was not satisfactory for the long belt with its associated higher loads. This suggests that the use of lower design loads is one solution.

A data base applicable to transportation systems was developed, heretofore not possessed by belt manufacturers, that would permit practical design of a fifth generation long belt. Sufficient design alternatives now exist to potentially solve the long-belt problem.

GUIDEWAY

The guideway of the Transette engineering prototype system includes the major design elements of an urban system. Loop operation with two on-line stations, an off-line station, and a 7.5 percent grade were successfully demonstrated. The dual-lane guideway, approximately 1340 feet in length (0.4 km) is entirely at grade. Structurally the guideway is a simple concrete, 4 inch (10 cm) slab that is 8 feet (2.4 m) wide providing two vehicle traffic lanes.

Sensors are placed at 150-foot (45 m) intervals to form the block control system which automatically shuts down the belt if the 15-second minimum headway between vehicles is violated.

CAROUSEL

The vehicle and carousel had an interference problem which was corrected by introducing Ackermann front-wheel steering on the vehicle with an auxiliary guidance rail at each carousel. Overall, the carousel performed extremely well. Indexing of vehicles from unloading to the loading berth was performed reliably.

VEHICLE

The Transette passive vehicles are simple, consisting of an integrated fiberglass body, a chassis with a four-wheel suspension and steering system, and a 1:2 step-up gear drive and slip clutch. Overall, the performance of the vehicle was satisfactory after a number of problems were systematically eliminated.

During the reliability test program, bearing wear of the switching cam actuator was discovered. This caused a series of adjustments to the steering system which resulted in non-positive locking of the steering system as it was designed to do. These maladjustments resulted in three occasions when the steering system unlocked and allowed the vehicle to suddenly turn right. A redesign of the locking mechanism is recommended to achieve a design tolerant of maladjustments.

Numerous clutch adjustments were necessary to obtain smooth operation. Vehicle clutch adjustments were the most significant maintenance item and were counted in the reliability testing thus contributing to the unavailability of the vehicle. To overcome this problem, it is recommended that an automatically adjustable clutch design be implemented. This should keep the average acceleration constant with load variations.

A unique door opening device was designed using a linear actuator, a cable, and pulleys. The lightweight, low cost device represents a simplification over conventional door openers and could prove to be significantly more reliable.

SUMMARY

Although the vehicle was the source of many problems, its simple nature represents a component that can be made adequate provided a sufficient level of additional development. To eliminate major vehicle problems and obtain significant improvements in performance and reliability a dual-drive, dual wagon-wheel steering system with automatic clutch control is being incorporated. Making the wayside propulsion system sufficiently reliable is the key to system effectiveness; i.e., curing the belt-splice problem. To achieve high system availability the propulsion system will have to be made extremely reliable, since the mean time to restore the system when a belt splice failure occurs is about 20 minutes. A significant data base has been developed during the course of the Phase IB program to permit practical design of an operational belt.

1. INTRODUCTION

Changing needs for transportation have necessitated the examination of new transportation techniques and innovative system concepts. Transette is an innovative transit system that uses belts for propulsion and control of passive vehicles. This system has the potential for lower cost and higher reliability than existing transit systems.

The Urban Mass Transportation Administration (UMTA) of the U.S. Department of Transportation initiated a program several years ago to assess and evaluate such systems. The results are intended to assist planners, policy makers, and technical developers to formulate realistic and effective implementations of transit systems. The objectives of these assessments are to:

1. Gather and exchange information on transit technologies to better understand the state of technological advancement and to obtain synergistic improvements for future development.

2. Review problems and solutions encountered during the design, development, implementation, and operation of transit systems in order to improve these processes.

3. Obtain information on engineering, economic, operational performance, and public response which can be used in planning future transit systems.

4. Provide urban planners with information which will enable them to determine the applicability of transit systems to their specific transportation problems.

The assessment of the Transette system was conducted by the Transportation Systems Center (TSC) of the U.S. Department of Transportation (DOT). The work is funded by the U.S. DOT, Urban Mass Transportation Administration (UMTA). The project is sponsored by UMTA's Socio-Economic and Special Projects Office which is under the Office of Technology Development and Deployment.

This report is an assessment of the Transette prototype test system located on the campus of the Georgia Institute of Technology in Atlanta, Georgia. It was conducted concurrently with a Transette engineering modification and test program funded by the DOT's Office of Technology Development and Deployment, Office of New Systems and Automation. The engineering modification and test program was completed in November 1979, after which the assessment was completed.

Because the Transette system is a prototype test system and is not an operational system in passenger service, operational factors were not assessed. Hence, only the technology was assessed. Where possible estimates were made of operational factors.

The Transette assessment covers the period between May 1978 and November 1979. Section 2 describes the background and events of the Transette development. A technical description of the system is provided in Section 3. Section 4 provides a description of the system operation and the system performance. A cost estimate for a deployed system is projected in Section 5. Section 6 is the TSC assessment of the Transette system with recommendations of what is needed for a revenue system.

2. BACKGROUND

The unique belt driven Transette system was invented by Dr. J.F. Sutton while he was employed by Lockheed Aircraft Corporation. Lockheed released the invention to Dr. Sutton for further development, since they were not interested in developing AGT systems at that time. Subsequently, Transette Inc. was established in Marietta, Georgia in 1972, to develop and market the Transette system. Transette Inc. was issued U.S. Patent #3,690,367 covering the Transette system.

In June 1974 Georgia Institute of Technology was awarded Grant RDI-74-22600 for $105,700 by the National Science Foundation (NSF) for the installation and testing of the Transette prototype, passive-vehicle Personal Rapid Transit (PRT) system. NSF awarded two supplementary grants one for $17,000 in September 1975 and the other for $4,700 in February 1977. This brought the total NSF grant up to $127,400. An additional $275,000 was put into the program by Transette Inc. for fabrication of hardware. Grant RDI-74-22600 was cost-sharing to the extent that it provided for the concrete guideway and related appurtenances; Georgia Tech provided the right-of-way, preparation of the right-of-way, and power, and while the actual hardware was made available by Transette Inc. Transette Inc. was under subcontract to Georgia Tech.

The grant was funded as part of the Federal Laboratory Validation Experiment by the Industrial Programs of the Research Applied to National Needs (RANN) Program of NFS. The purpose of this program was to identify and test Federal incentives for improving the climate for technological innovation. It was based on the assumption that the validity of claimed performance is an essential part of the development and commercialization of new technology. That is, it was assumed that performance validation of new technology would reduce, or clarify, the potential risk of investment in the development and marketing of new technological products and processes. The program was designed to determine the effectiveness of providing performance validation for new technology in overcoming some of the barriers to an efficient innovation process.

The Transportation Systems Center (TSC) under an interagency agreement with NSF was to conduct a Test Program to measure the performance and evaluate the system safety. Although the system achieved an operational state in October 1976, demonstrating the feasibility of the system, it did not do this in an automated mode nor were the vehicles able to continuously operate around the guideway loop. Therefore, TSC was unable to make the measurements and perform a complete evaluation.

Subsequently, Georgia Tech submitted an unsolicited proposal to UMTA in March 1977 for further engineering development and testing of Transette. Three principal problem areas existed that needed to be corrected. These were: 1) belt slipping, 2) mechancial interference at the carousels, and 3) the inability of the system to operate automatically. Power is transmitted to the vehicle by a belt drive which employs friction for the transfer of energy. Tangential friction forces are generated between the drive pulley and belt by the interaction of a tension force in the belt and torque on the pulley. These friction forces depend on the coefficient of friction between belt and pulley. Power is transmitted to the belts through a system of pulleys dependent on a high coefficient of friction between the top side of the belt and the pulley lagging material. A rubber lagging material covering the final drive pulleys was used to transmit power to the power belt. Tension in the belts and on the drive pulleys was generated simply by preloading the belts. The load carrying member of the belt was of polyester covered by a textured rubber upper surface and polyurethane on the back surface.

Belt slipping problems between the head pulley and belt occurred because the initial design was based on inaccurate or estimated data on coefficients of friction and elongation characteristics as a function of temperature and load. Under wet conditions, it was found that the coefficient of friction of the upper rubber surface which transmits power to the belt dropped to about 0.1 from approximately 0.5 under dry conditions. At the same time the belts collected more water than anticipated because of the textured upper surface, resulting in considerably higher loads. Those two effects caused belt slipping under wet conditions.

Manufacturer's data on the coefficient of friction between the back side of the belt with the polyurethane cover and the stainless steel slider bed was also found to be in considerable error. The loads introduced by the sliding friction force were significantly higher than anticipated causing some of the slipping between the lead pulley lagging material and the belt. The polyurethane covering material on the back of all belts was removed, exposing a nylon backing material. The coefficient of friction of the belt with the exposed nylon backing resulted in a significantly reduced coefficient of friction of about 0.07.

The remainder of the slipping problem was caused by significantly more stretch of the belts under temperature and load than indicated by the manufacturer. The belt elongation at 70°F (22°C) was not to exceed 1.5 percent. However, 5-7 percent elongation was observed. This resulted in a relaxation of the belt tension and a smaller frictional force.

In addition, at the only bend in the system, short individually powered belts were not installed. Thus, as the vehicle proceeded along the guideway moving from one belt to the next, it came to a gap without a belt and therefore without propulsion. Because the radius at this bend was relatively sharp, considerable vehicle speed was lost thereby preventing the vehicle from running continuously from one belt to the next. The vehicle, however, was able to traverse the gap in one direction. But, the speed mismatch placed undue stress on the belts and caused excessive wear. At the same time the small radius resulted in high lateral accelerations considerably above the comfort limit.

Mechanical interference problems were a result of constrained funding and the availability of a smaller diameter carousel ring at a considerably lower cost. The smaller diameter ring was purchased after the vehicles had been designed and the first two prototype chassis built. As a result a mechanical interference problem occurred between the vehicle side chord and the tangent of the carousel flanged ring. This problem was to have been corrected by geometry changes to the guide wheels. This was not achieved because of funding limitations.

The automatic control system which is a hardwired-logic, fixed-block control system was not made operational because of insufficient funds to complete the wiring, functional checkout and to de-bug the system. All proximity sensors were in place but not connected to the control system.

The Transette Engineering Modification and Test Program was initiated in May 1978 under UMTA Grant (GA-06-0009) for $197,680. This was subsequently supplemented by an amendment to the Grant for $36,000 bring the total to $233,680.

These problem areas were corrected by:

1. Incorporating a belt take-up system in the drive system with constant tension to account for load and temperature variations, and a considerably increased angle of wrap around the drive pulley to compensate for the low coefficient of friction when wet.

2. Increasing the radius of the turn from 25 feet (7.6 m) to 125 feet (37.9 m) and designing a one-piece belt to go around the curve to the East terminal. Thus, the system was reduced from five main-line drive belts to two.

3. Adding an auxiliary guidance rail to the carousel. Vehicle geometry was altered and front-wheel steering was introduced.

4. Completing the wiring and checkout of the control system.

This phase IB work effort was completed in November 1979 and this assessment was subsequently conducted.

3. TECHNICAL DESCRIPTION

3.1 SYSTEM DESCRIPTION

The Transette system is an automated, engineering prototype test system employing passive vehicles (Figure 3-1). All propulsion and command and control functions are performed by the wayside guideway. The passive vehicles have virtually no intelligence and do not perform their own active vehicle control functions. That is, the vehicles only respond to command signals or in this case propulsion power from the wayside. The system was intended to be put into operation transporting students between the Georgia Institute of Technology Student Center and an area of student dormitories. However, technical and financial difficulties have precluded its regular operation. Eight chassis and vehicle bodies were fabricated, but final assembly of the remaining six will not be made until all modification and testing is completed. The loop system operates between two main stations separated by 0.25 miles (0.4 km); an off-line station, a control center, and maintenance and storage facilities are also provided. (Figure 3-2.)

Although the system can incorporate eight vehicles, only two prototype vehicles were completed for testing. Each vehicle has a capacity of four passengers. The vehicles are automatically controlled and propelled by the belt-drive system in the guideway. Drive torque is transmitted to the vehicle via the left rear wheel (rubber tire) which rides on the belt. The left rear wheel transfers torque to the right rear wheel through a 1:2 gear box, thereby driving the vehicle at twice the belt speed. A fixed block control system regulates the vehicle headway by de-energizing the belt drive motor if a minimum headway of 15 seconds is violated for any reason. A 15-second headway between vehicles is established by placing the vehicles at a fixed distance apart on the moving belt. Since there is essentially no relative motion between vehicles on the same belt, the separation, or headway, is automatically maintained.

FIGURE 3-1. TRANSETTE VEHICLE ON THE GUIDEWAY

EASTBOUND ROUTE		
LANE SEGMENT	NOMINAL LENGTH (feet)	VEHICLE SPEED (mph)
AB	35	10
BC	315	12
CH	945	15
HI	45	3

WESTBOUND ROUTE		
LANE SEGMENT	NOMINAL LENGTH (feet)	VEHICLE SPEED (mph)
JK	45	10
KP	943	15
PU	315	12
UW	35	3

STATION ELEMENTS		
LANE SEGMENT	NOMINAL LENGTH (feet)	VEHICLE SPEED (mph)
WA	31	3
IJ	31	3
QR	83	3
RS	70	10
ST	37	12

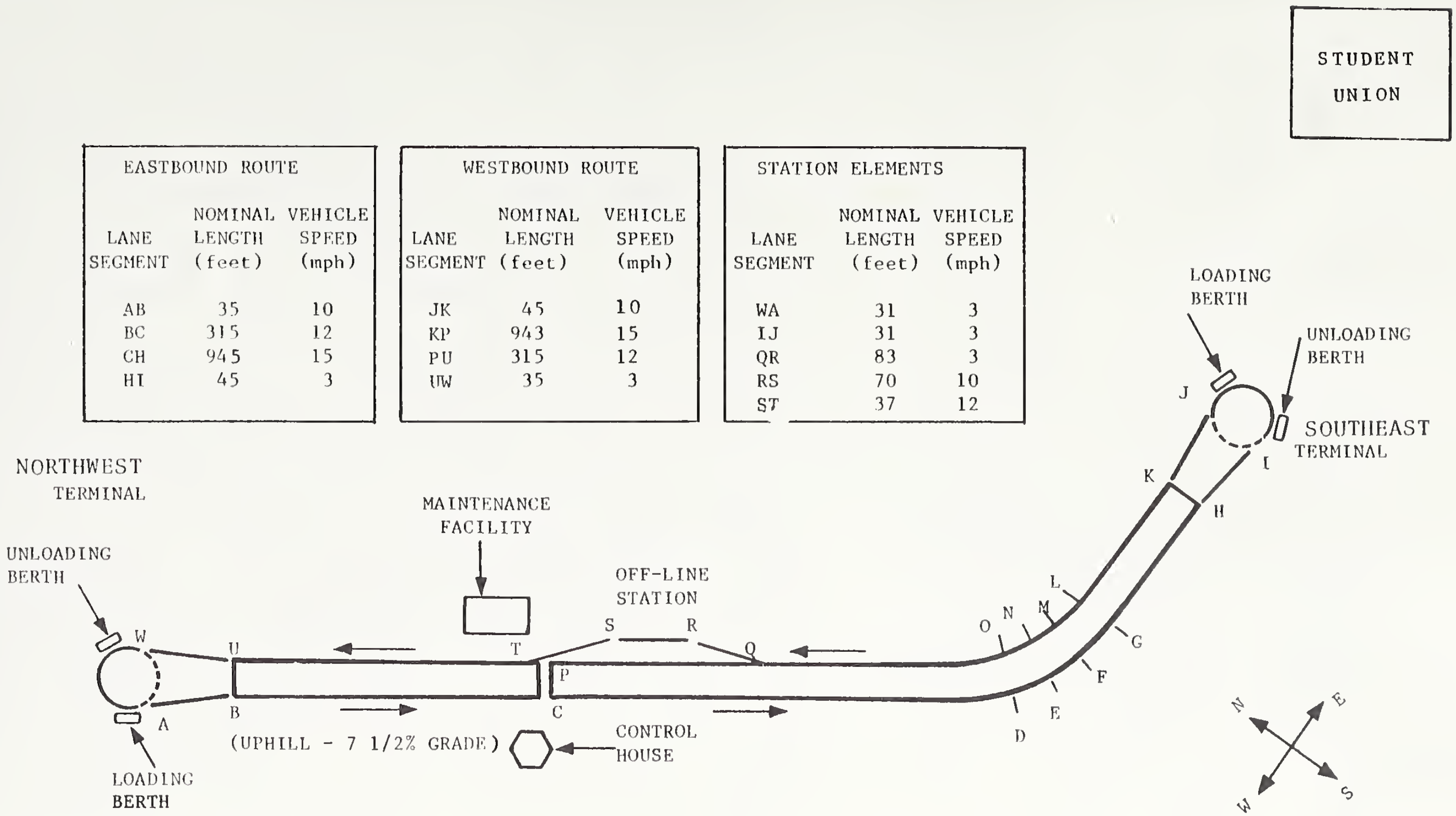


FIGURE 3-2. TRANSETTE GUIDEWAY LAYOUT (SCHEMATIC)

The guideway is entirely at grade and is made of concrete slabs. A guiderail located at the center of the guideway provides for effective front-wheel steering (see Figure 3-1) of the vehicle via side-mounted guide wheels. Switching is actuated from the wayside. A wayside cam plate moves the onboard steering guide wheels into the appropriate switched position to effect switching.

Two carousels, one at each end of the guideway, turn the vehicles around, thereby closing the guideway loop. The carousels also provide vehicle indexing, positioning the vehicles at the station loading and unloading berths.

Automatic system operation is achieved by means of a hard-wired system of solid state relays operating as a block control system. The system can be operated in either a scheduled or a demand-responsive mode.

3.1.1 System Characteristics

The Transette system operates at four discrete speeds. The main line operates at 12 mi/hr on the hill and 15 mi/hr elsewhere. Deceleration and acceleration belts prior to entry or exit from the carousels bring the vehicles down to speeds of 3 mi/hr. and up to speeds of 10 mi/hr, respectively. Indexing on the carousel is achieved at a nominal speed of 3 mi/hr. The speed sequence over the guideway is shown in Figure 3-2.

The average speed is 12.4 mi/hr (18.3 ft/sec, 5.5 m/sec, 19.8 km/h) requiring 2.1 min. to travel the 1340 ft (0.25 mi, 0.4 km) between the west and east stations with station stops, or 4.2 min. to complete the 0.9-mi (0.8 km) loop. Assuming that the unloading of passengers at the unloading berth, the relocation of the vehicle to the foremost loading bay, and the loading of passengers requires 55 seconds, the maximum theoretical one-way capacity of the system is 897 passengers/hour. This is based on eight vehicles with a maximum design capacity of four seated passengers. The maximum practical one-way capacity, considered to be about 80 percent of the theoretical maximum would be 718 passengers per hour.

The Transette System Characteristics

System Performance:

Max. theoretical one-way capacity	897 pass/hr
Max. practical one-way capacity	718 pass/hr (80% of theoretical)
Headway (minimum)	15 sec.
Availability	Test system - Planned use: on demand, 12 hr/day
Type service	point-to-point, demand responsive, or scheduled collection and distribution
Type network	loop
Interior noise	65-72 dBA
Guideway transitions	75-80 dBA
Exterior noise	60-65 dBA

Vehicle Performance:

Average speed	12.4 mi/hr (19.8 km/h)
Max. speed	15 mi/hr (24 km/hr)
Max. grade	7.5 percent
Maximum acceleration	0.13 g
Maximum deceleration	0.13 g
Max. jerk	Not available.
Emergency deceleration	0.13 g
Stopping precision in station	± 1 ft
Degradation if guideway is wet	none
Degradation for ice and snow	little or none
Vehicle design capacity	4 seated
Vehicle crush capacity	4 seated
Energy consumption	Not available

Stations:

Type	2 on-line, with loading and unloading berths 1 off-line, single berth
Type boarding	stepped
Ticket and fare collection	free service planned
Security	none
Boarding capacity	960 pass/hr

Stations: (cont.)

Type	on-line carousel
Debarking capacity	960 pass/hr
Max. wait time	205 sec
Vehicle in-station dwell time	15-55 sec
Station spacing (principal)	0.25 mi (0.4 km)

Individual Service:

Privacy	single party
Transfers	none
Stops	at off-line station on demand
Accommodations	seating
Security	none
Instruction	auditory and signs planned
Comfort	ventilation

Steering:

lateral guidance	front wheel and body steering via 5 laterally-mounted outboard wheels on each side of the vehicle, off-center wheel guidance on a guide rail, steering wheels are also used for switching

Propulsion:

Type	belt drive - single rear wheel riding on top of belt transmits power to opposite wheel riding on pavement through 1:2 gear box - vehicle moves at twice belt speed

Number of Motors -

Main line drive system	2-15 HP (11 kW) electric motors driving belts through fluid couplings. All motors mounted on the guideway

Number of Motors - (Cont.)

Station drive system	
acceleration belts	2-5 HP (3.7 kW) motors
deceleration belts	3-3 HP (2.2 kW) motors
carousels	2-2 HP (1.5 kW) motors
Type power	480 V, 3ϕ, 60 Hz
Brakes:	
Type	transmission design and clutch setting provide automatic vehicle braking at 0.13 g when applied propulsion is removed
Emergency brakes	none
Switching:	
Type	wayside switching at line speed by cam plate which switches on-baord steering wheels
Guideway:	
Type (double-lane)	double lane, at-grade guideway - concrete slab construction
Width	8 ft (2.4 m)
Thickness	4 inches (10 cm)
Total length including off line station	2932 ft (894 m)
Length, loop	2680 ft (817 m)
Max. grade	7.5%
Min. turn radius	57 inches (1.4 m)

3.2 VEHICLES

The vehicles are passive, hence extremely simple in nature. The vehicle body is a fiberglass shell attached to a welded steel frame. Windows are made of ultra-violet absorbing acrylic. A single door sliding open to the rear is located on the right side of the vehicle. A push button-operated electro-mechanical device actuates the door only when the vehicle is in a station area.

The vehicle body is attached to a chassis via a secondary suspension system of four air-bag springs and dampers. The two rear wheels are rigidly mounted to the chassis (see Figure 3-3). The front wheels are castered using an Ackermann steering design. The rear drive axles are connected through a 1:2 step-up gear box which transmit torque from the rear wheel riding on the belt to the right rear wheel riding on the concrete guideway.

Vehicle steering is achieved by controlling the front axle yaw response through a linkage system which connects the tie rod to the front set of guide side-mounted steering wheels, which positively track the guide rail (see Figure 3-4). A set of guide-wheels mounted on both sides of the aft end of the vehicle aid the guidance function. Switching is achieved by actuation of a plate in the guideway that moves a cam on the vehicle disengaging the outboard guide wheel on the left side and engaging the outboard guide wheel on the opposite side. All four inner guide wheels are rigidly mounted, providing positive control of the vehicle during the switching process. In the region where switching is effected, guiderails exist on both sides of the vehicle against which the inner, side-mounted steering wheels can bear, thereby positively restraining the vehicle. The outboard steering wheels are interconnected by a series of links to provide positive locking when switched in either direction.

The vehicle is accessible from the right side through a single electro-mechanically operated sliding door. The door panels are constructed of fiberglass over a steel frame. Tracks at the top and bottom support the doors. A pressure-sensitive, safety door-edge switch causes the door to retract and recycle if obstructed.

The interior of the vehicle with a seated passenger is shown in Figure 3-5. A schematic of the vehicle is shown in Figure 3-6.

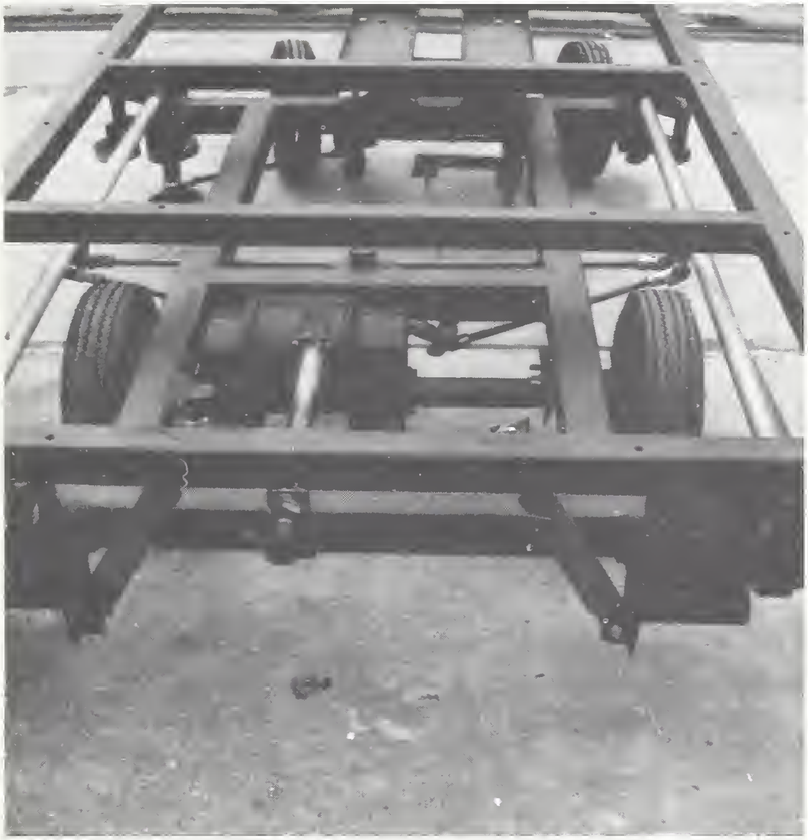
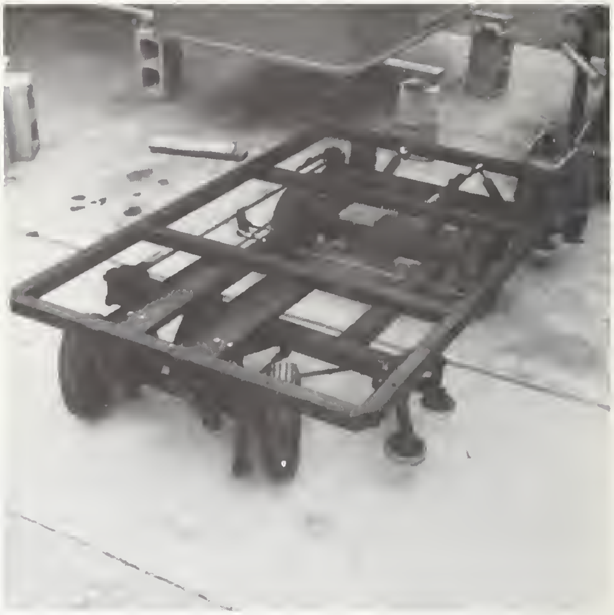


FIGURE 3-3. REAR VIEW OF THE VEHICLE CHASSIS SHOWING GEAR BOX



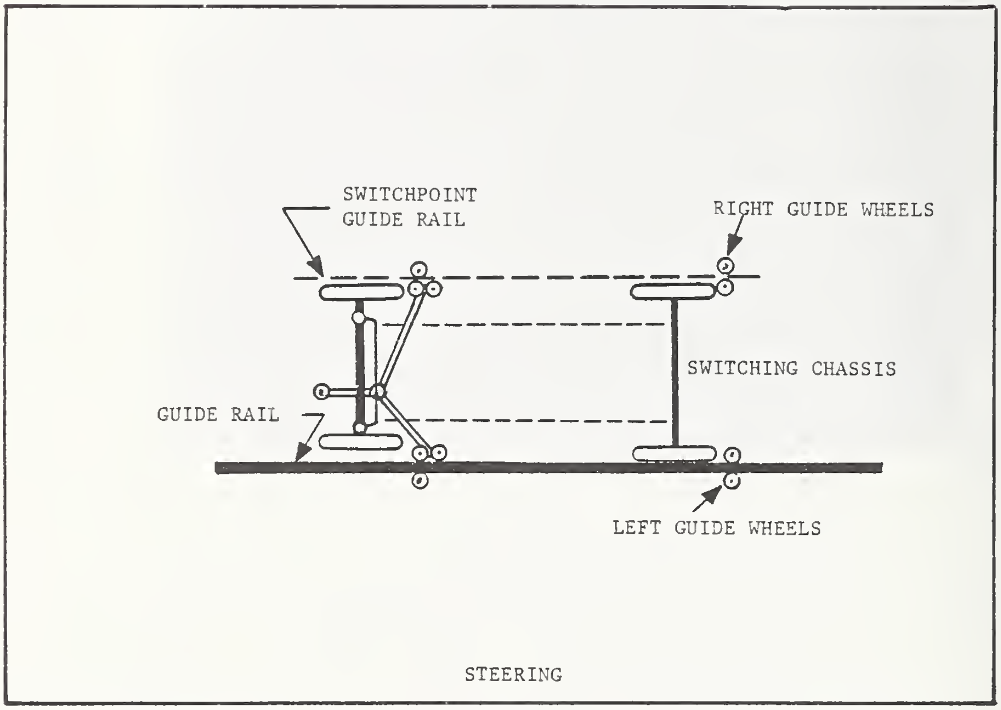


FIGURE 3-4. TWO VIEWS AND A SCHEMATIC OF THE STEERING AND SWITCHING GEAR

FIGURE 3-5. VIEW OF THE VEHICLE INTERIOR

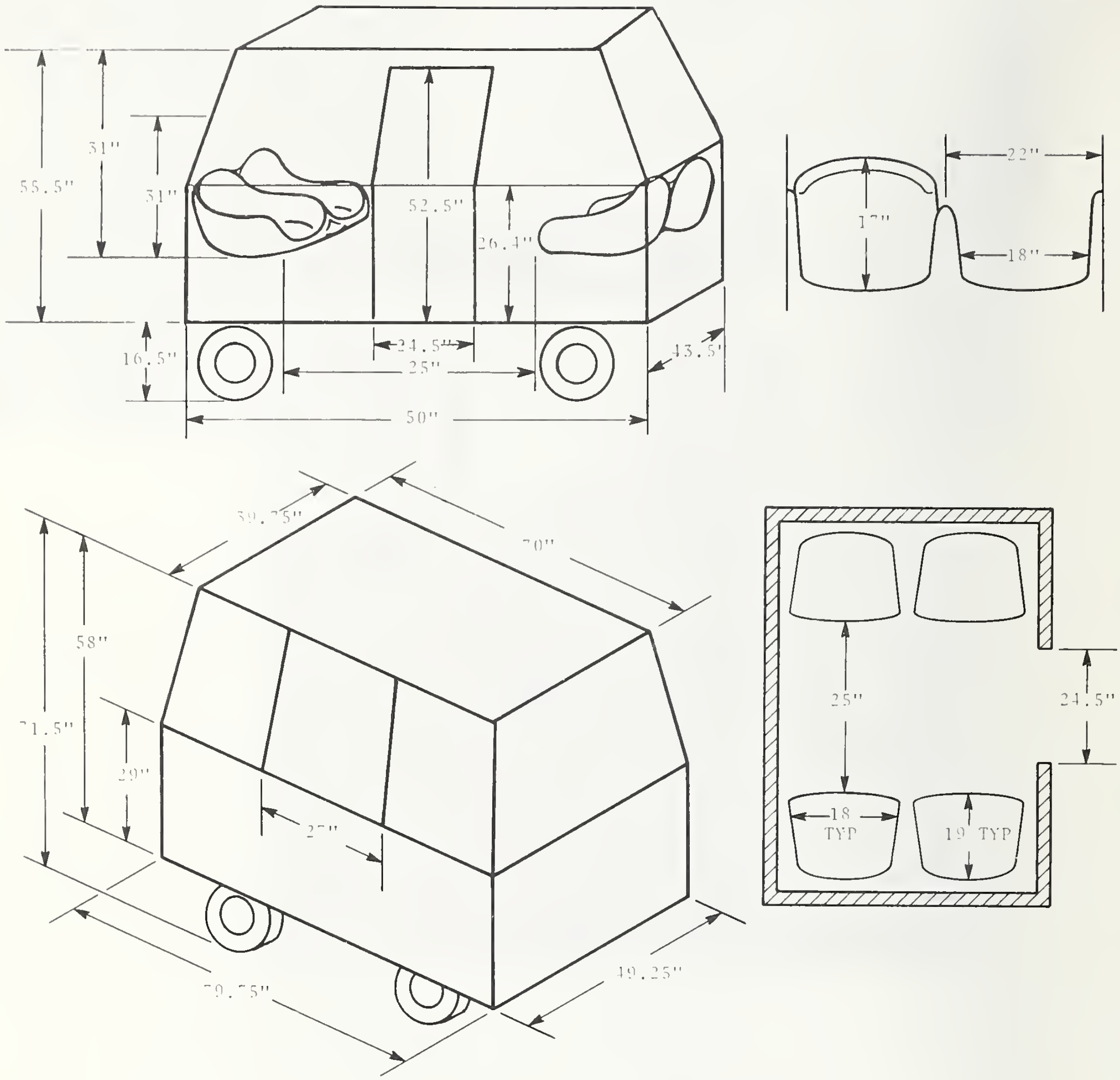


FIGURE 3-6. SCHEMATIC OF THE TRANSETTE VEHICLE

The seats are integrally molded of fiberglass extending the full width of the car. Two individual seats are located at each end of the vehicle, facing each other, providing two forward and two aft facing seats.

3.3 BELT DRIVE

Transmission of power to the vehicles is provided by a series of power belts. The belts are five inches (12.7 cm) wide and one-quarter inch (6 mm) thick. They have two polyester fabric layers impregnated with polyurethane. The belt weighs 0.45 lbs/ft (0.68 kg/m) and the breaking strength is rated at 750 lbs (3300 N). It slides along a stainless steel slider bed mounted on top of the guideway. The left rear wheel of the vehicle rides on the belt. Longitudinal motion along the guideway is given to the belts by electric motors. Power is transmitted to the belts by a system of pulleys. Propulsion power is in turn transmitted to the vehicle by the belts. The left rear wheel of the vehicle translates relative to the belt - very slowly at start-up, then gradually reaches full speed (twice the speed of the belt). The slip clutch on the vehicle permits this to occur.

The belt drive system includes two main drive belts, three acceleration belts, three deceleration belts, and one off-line station belt which is a linear analog to the on-line station carousels. The schematic arrangement of the various belts, pulleys, and turntables is shown in Figure 3-7. The main drive belts are labelled BCPU and CHKP. Each of these belts provides motion in two directions. The belts are passed over a system of pulleys at BU, CP, and HK which permit the belts to pass under the guideway steering rails and return in the opposite direction thereby forming a loop. There is a 125-foot-radius (38 m) curve in the long belt (CHKP). To maintain the long continuous belt and to negotiate the curve a series of pulleys allow the belt to make three chords in each direction on the 125-foot radius curve.

Large suddenly applied loads on the belts occur when a vehicle traverses from one belt to the other. To compensate for these

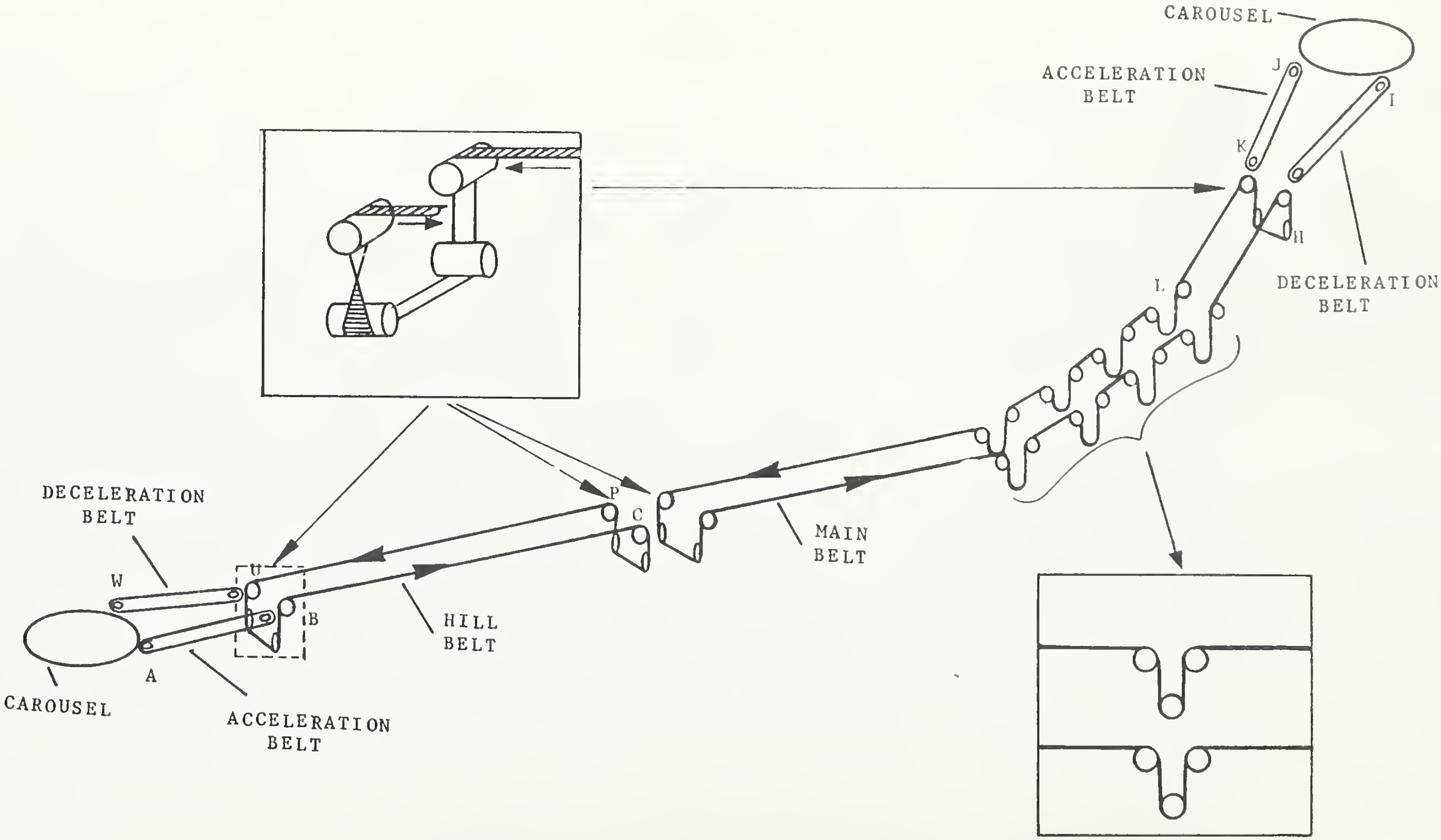


FIGURE 3-7. SCHEMATIC OF THE MAIN LINE DRIVE BELTS AND PULLEYS

suddenly applied loads, a belt take-up reel system that uses counter-weights has been introduced on each of the two main drive belts. Belt elongation due to change of temperature is also compensated for automatically. Figure 3-8 shows a schematic of the belt take-up reel system. A main drive pulley frame is shown with a 15-horsepower (11 kW) electric motor. A take-up pulley is mounted on a trolley that is attached by a cable to a set of weights. The weights are immersed in an oil filled tube to provide damping. The weights attached to the trolley maintain a constant tension on the drive belt. The 15-horsepower, three-phase, 480-volt electric motor drives the headpulley through a fluid coupling and a reduction gear box. The take-up reel system can accommodate up to 50 feet (15 m) of stretch of the long belt.

3.4 GUIDEWAY

The Transette system at Georgia Tech is a dual-lane guideway (see Figure 3-2) with two on-line carousel reversing stations, one at each end, forming a loop system. It also has one intermediate off-line station. The dual-lane guideway, approximately 1340 feet in length (0.25 mi, 0.4 km), is entirely at grade and is laid out primarily on a northwest-to-southeast line. A major feature is the 7.5 percent grade section running for approximately 300 feet (90 m) from the north station.

Structurally the guideway is a single concrete, 4-inch (10 cm) slab that is 8 feet (2.4 m) wide providing two vehicle traffic lanes, (see Figure 3-9). A single lane is nominally 4 feet (1.2 m) in width.

Figure 3-10 schematically shows the location of proximity sensors and oscillators at 150-foot (45 m) intervals, which provide automatic shutdown of the belt if the 15-second minimum headway between vehicles is violated.

3.5 STATIONS

The Transette loop test system has two on-line stations, one at each end and one intermediate off-line stations. All station

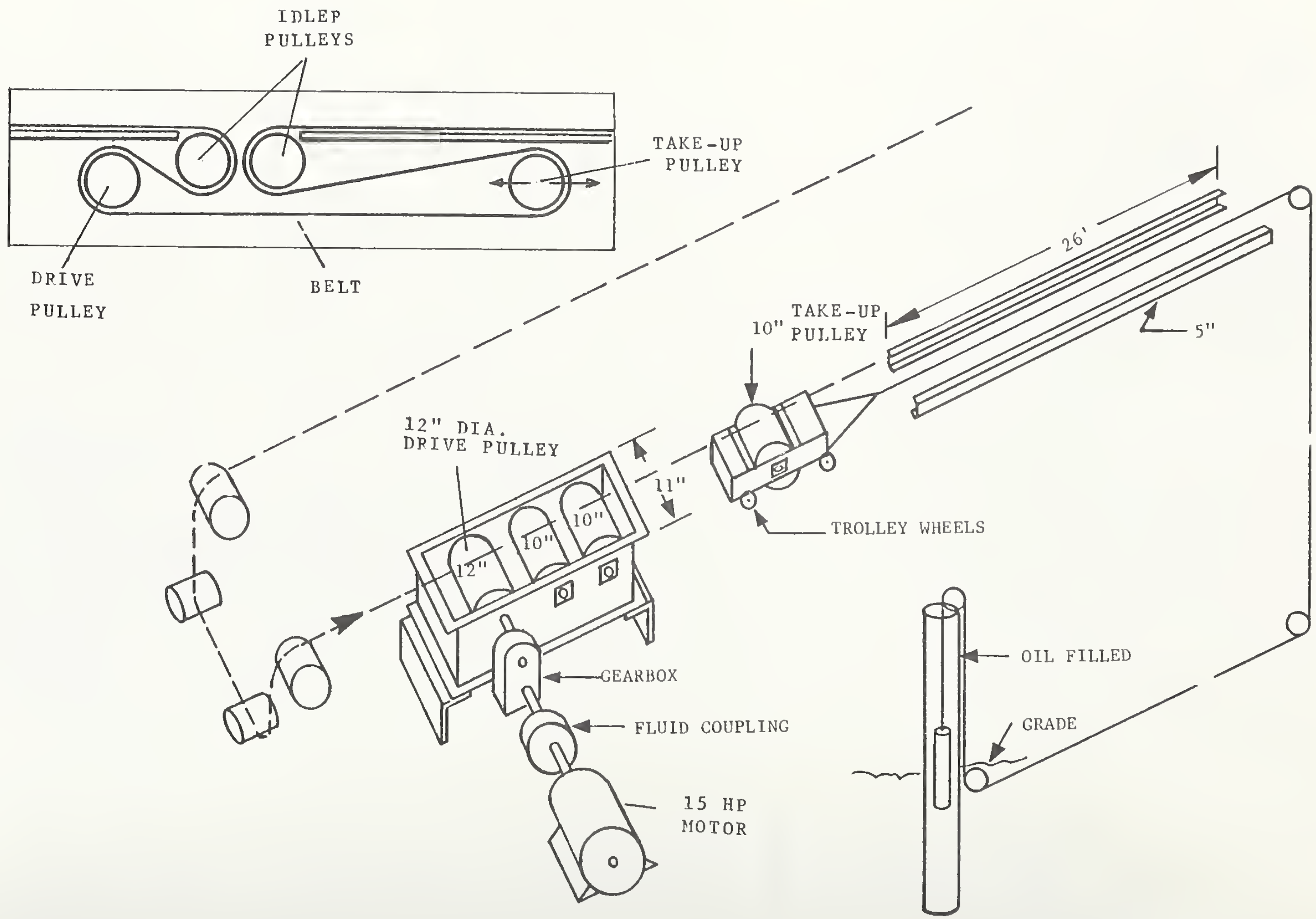


FIGURE 3-8. SCHEMATIC OF THE BELT TAKEUP AND DRIVE MECHANISM.

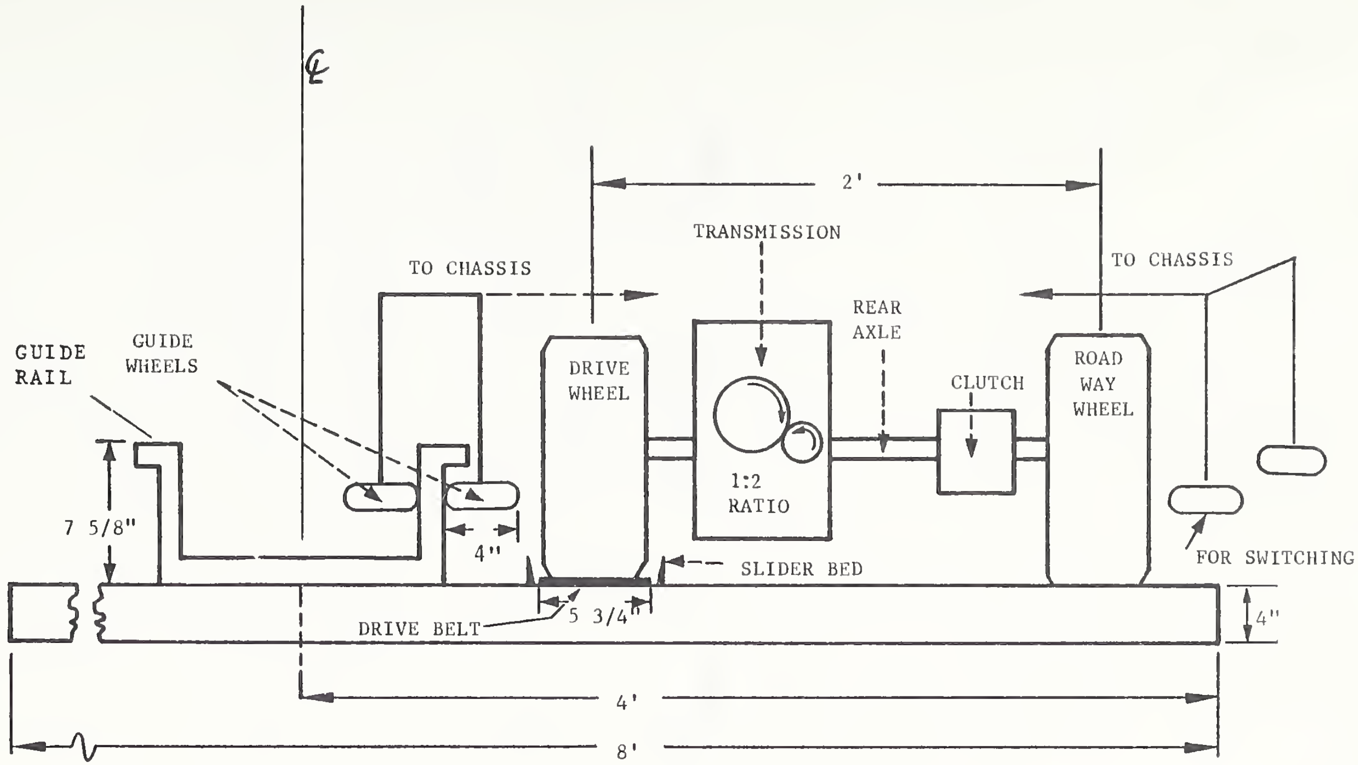


FIGURE 3-9. SCHEMATIC CROSS-SECTION OF WHEELS AND GUIDEWAY

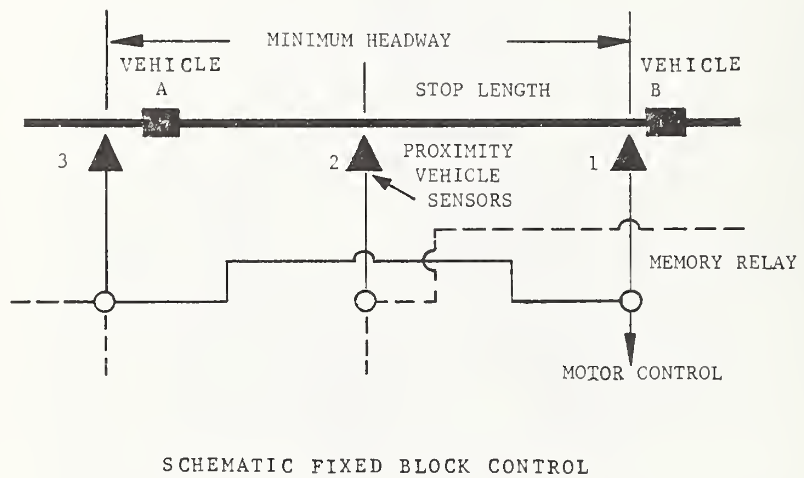


FIGURE 3-10. SCHEMATIC OF THE BLOCK CONTROL

functions are automatic. The on-line stations consist of carousels that move or index vehicles from the unloading position to the loading position and finally move the vehicles on to the acceleration belt. The carousel is a flanged ring mounted on a series of rollers. The carousel is electrically driven by a 2-inch-wide (5 cm) belt that goes around the flanged ring. (Figure 3-11.) Take-up idler pulleys are incorporated between the drive pulley and the flange to adjust the belt tension.

An auxiliary guiderail has been incorporated to steer the front wheels around the carousel. Its centerline is at a radius of 89 inches (2.3 m). This auxiliary guiderail was included to minimize wheel scrub.

As the vehicle approaches a station area, a proximity sensor provides a command to turn on the deceleration belt, the function of which is to reduce the vehicle speed from a line speed of 12 or 15 mi/hr to 3 mi/hr. When the vehicle traverses from the main line belt to the deceleration belt, it will be slowed down and moved forward until the left rear wheel leaves the moving belt and rides up onto the stopped flange of the carousel. The vehicle automatically comes to a stop at the unloading berth because of the lack of application of power. Another proximity sensor is used to sense when the vehicle has reached this position and commands the deceleration belt to stop.

Door opening is initiated by pushing a button inside the vehicle, similar to that of a conventional elevator. Pressing the button initiates a timing sequence which will close the door after a nominal preselected time of 15 seconds, thus allowing unloading of the vehicle. At the end of this time interval, the carousel is rotated, moving the vehicle around until the left rear wheel rides off the carousel and onto the stopped acceleration belt. A third proximity sensor is used to sense when the vehicle has reached this loading position and commands the carousel to stop. A button on the exterior of the vehicle will, when pressed, initiate door opening, a dwell of about 15 seconds, and

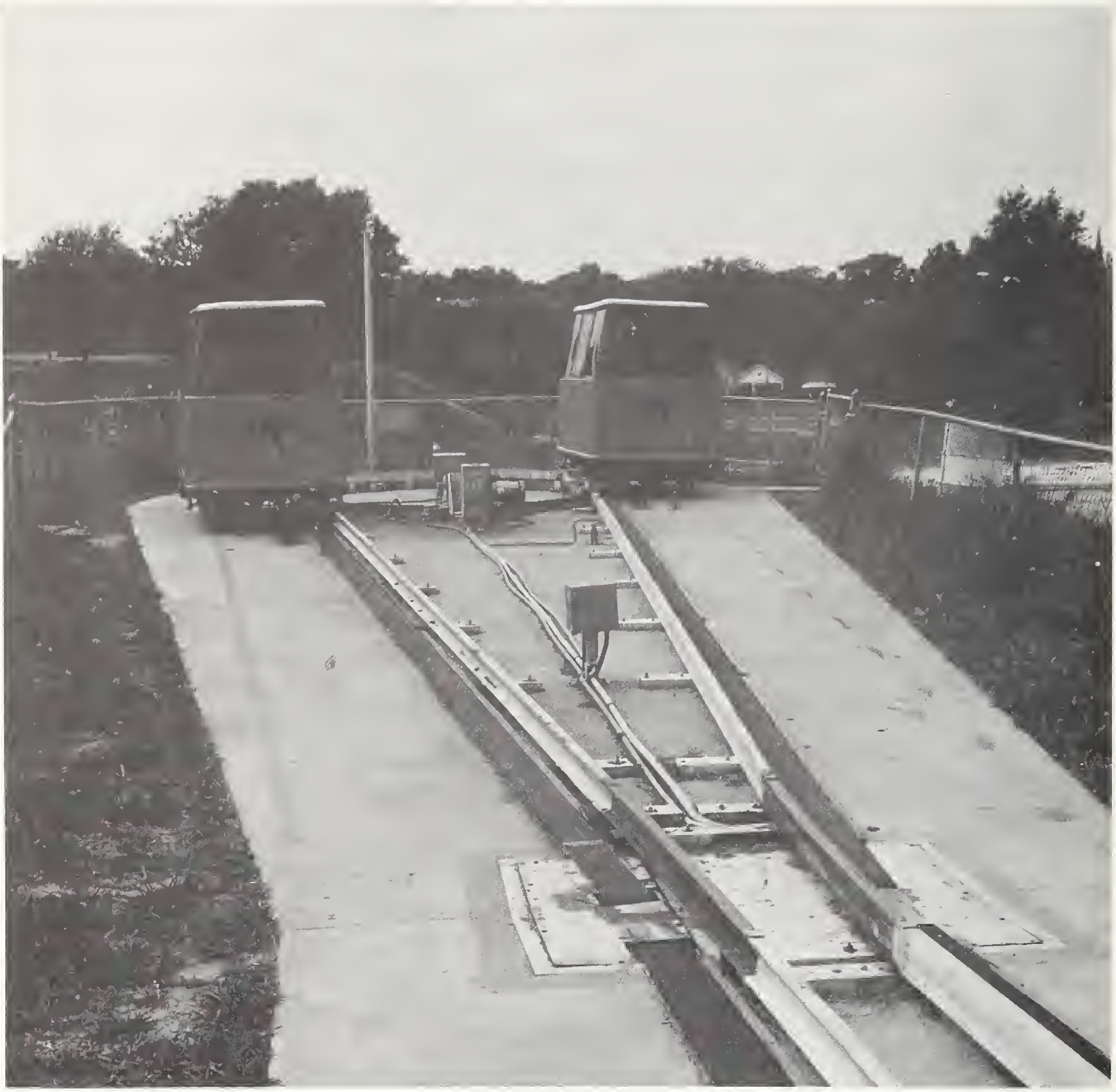


FIGURE 3-11. VIEW OF THE CAROUSEL AND ACCELERATION AND DECELERATION BELTS

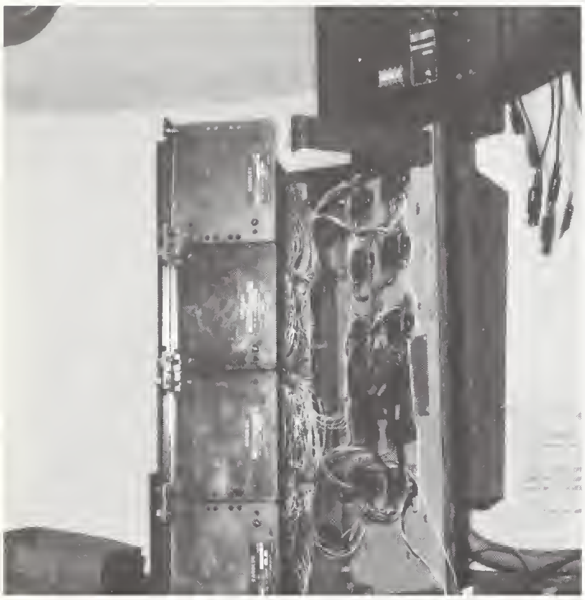
and door closing. After the door closes and is checked, the acceleration belt starts up, moving the vehicle out of the station area and onto the main drive belt. A fourth proximity sensor establishes that the vehicle is, in fact, riding on the main belt and commands the acceleration belt to stop.

3.6 COMMAND AND CONTROL

The command and control system is a hard-wired, fixed-block system with conventional check-in, check-out blocks separating vehicles. The function of this system is to control the sequence of starting and stopping motors driving the propulsion belts and carousels at each station so as to provide controlled movement of vehicles and headway control by shutting down any section of the drive in which minimum headway conditions are violated. All control functions are performed at the wayside in the control house. (Figure 3-12.) There is no communication with the vehicle to command motion. Rather, electric motors are either operating at the prescribed speed transmitting constant motion to the belts or they are stopped. Since vehicles are driven in direct response to motion of the belt, a vehicle will move as long as it is on a belt which is moving and transmitting power to the vehicle. If the belt which the vehicle is on is then stopped, the vehicle will come to a stop. Hence, the Transette system vehicles are passive.

Because vehicles respond to belt motion in approximately the same manner, two vehicles on the same belt with a given spacing interval will essentially maintain that separation when the belt is either moving or is stopped. Hence, the system is synchronous. In order to transmit power over a long distance, the main-line drive system is composed of two belts which are normally both in continuous operation. If, for some reason, the forward-most belt were stopped and a vehicle from the second belt transferred onto the stopped belt, that vehicle would immediately come to a stop. A following vehicle moving along the same path would collide with the first vehicle since the available stopping distance would be short by the stopped vehicle's length. A third

CONTROL PANEL



REAR VIEW OF SOLID STATE CONTROL SYSTEM

SOLID STATE CONTROL SYSTEM

FIGURE 3-12. THE CONTROL STATION AND SOME OF THE EQUIPMENT vehicle's stopping distance would be short by two vehicle lengths etc. Hence, there is a need for a control system to maintain some minimum headway under all conditions.

A fixed-block control system was selected for this purpose because of its simplicity. In the present fixed-block system, proximity sensors are located at 150-foot intervals along the main portion of the guideway. A safety zone of one block is provided between any two occupied blocks for a nominal cruise speed of 15 mi/hr (24 km/h) and a design minimum headway of 15 seconds. Proximity sensor signals (contact closures) are amplified and transmitted by hard wires to the central control house where control unit is located. The fixed-block headway control is, in effect, created by a solid state system of relays.

The system has two modes of operation, a schedule mode and demand-responsive mode. In the schedule mode, vehicles are circulated from station to station at intervals of 2.1 min. This includes a station dwell time of 55 seconds. Entry into the vehicle is initiated by the passenger depressing a button on the exterior of the vehicle which opens the electrically actuated door and starts an adjustable timer that will hold the door open for a preselected time interval; nominally 15 seconds. After door closing and interlock checkout. The acceleration belt is turned on and brings the vehicle up to a speed of 10 mi/hr (16 km/h). When the vehicle reaches the opposite terminal, the vehicle transfers onto the deceleration belt which slows it to a speed of 3 mi/hr (4.8 km/h) and transfers it onto the flanged ring of the carousel, where it stops for unloading. Door actuation for unloading is initiated by a passenger depressing a door-opening button on the inside of the vehicle. The vehicle door-dwell timer holds the door open while the passengers disembark and then closes it. At the conclusion of this operation the vehicle is indexed to the loading berth and is ready to repeat the cycle.

In the demand-responsive mode of operation (not yet fully implemented), the system, when not in use is in a standby state, such that a vehicle is parked at the loading berth of each station, the main-line drive belts are turned off, and the track warning lights are on but not blinking. To activate the system in this mode, a passenger would depress a service request button located in the station. The warning lights immediately start blinking and after 5-10 seconds the main-line drive belts are turned on. Entry to a vehicle is gained in exactly the same way as in the schedule mode, and after the usual door dwell interval, the door closes, and the acceleration belt starts up. Simultaneously, the acceleration belt at the opposite station also starts up, provided the door of the vehicle at the loading position there is closed and the interlock checked, regardless of whether or not a passenger has entered that vehicle. If a passenger happens to be entering the vehicle at just this time, the acceleration belt will come on as soon as the vehicle door does close. In effect, activation of the system in the demand-responsive mode from either station will simply cause two vehicles, each in an end station, to exchange positions at the two ends. As soon as both vehicles have completed their trips and the loading berth at each station is again occupied, the system will automatically revert to the standby state unless in the meantime another prospective passenger has pressed the service-request button. During low traffic periods, the demand responsive mode will conserve power and put fewer cycles on the belts, thereby decreasing operating costs and increasing reliability and system life.

Switching to the off-line station is achieved by movement of a guideway-mounted blade that trips a vehicle-mounted cam that in turn causes the steering control to be transferred from the left side of the vehicle to the right. The switched wheels contact the right hand guideway mounted steering rail which directs the vehicle off-line and into the station. The guideway mounted blade is solonoid actuated and is controlled from the control house.

All communications are via hardwired lines to the control house. A flashing light is to be mounted on the vehicle for either mechanical or security related emergencies rather than voice communications. This approach was to be taken because visual observation is possible over the entire guideway from the control house.

4. SYSTEM OPERATION

4.1 OPERATIONAL DESCRIPTION

Transette is an automated system that utilizes a fixed-block control to maintain headway between vehicles. All vehicle control functions are performed by the wayside control system. The vehicles are controlled by either activating or stopping the individual belt drives. This effects vehicle propulsion or braking. Automatic control is initiated at the control panel shown in Figure 3-12. Each belt can be individually operated and can either be off, on automatic operation, or in a manual backup mode of operation. When all belts are switched on and are in automatic operation, vehicles will circulate through the system automatically. In the event of a failure in the automatic control of a given belt, that belt can be manually operated without any effect on the system operation. However, it should be recognized, that the fixed-block control system which maintains headway would not be in operation and the operator must be ready to stop the belt in the event a vehicle comes to an emergency stop on the belt ahead. If normal operation is experienced and no vehicle stops for an emergency, then vehicles will be maintained at their relative headway by the synchronous nature of the belt propulsion system. Carousels can also be operated manually, but the vehicles will not dwell for disembarkation unless the operator brings the vehicle to a stop at the appropriate location. The operator would have to turn on the acceleration belt after an appropriate dwell for embarkation. Both carousels of the test system were visible from the control house making this function possible.

Schedule Mode

Transette has the capability of operating in two modes, a schedule mode and a demand-responsive mode. In the schedule mode vehicles are constantly circulated from station to station at intervals of 2.1 minutes. To show the process the vehicles go through as they loop around the system, a description will be given of a trip from the north terminal to the south terminal and return. (See Figure 3-3.) Although only two vehicles were operational in the test system, a description of as many as eight vehicles representing a maximum design condition, are described to demonstrate how the vehicle would operate.

When the vehicle arrives at the unloading berth at the west carousel, the door is opened automatically to allow passengers to leave the vehicle. Egress from the vehicle is initiated by the passenger depressing a button in the interior of the vehicle which opens the electrically actuated door and starts an adjustable timer that will hold the door open for a preselected time interval; nominally 15 seconds. At the end of this time interval, the vehicle is indexed around the carousel to the loading berth where the vehicle dwells for a given time interval while passengers enter the vehicle. Entry to the vehicle is initiated by the prospective passenger depressing a button on the exterior of the vehicle which automatically opens the door and holds it open for a preselected time interval; this is analogous to initiating use of an elevator.

Proximity sensors control indexing or rotation of the carousel to preselected locations. The dwell time for loading is also adjustable, but nominally is 15 seconds. After this dwell, the door is closed automatically, and the interlock is checked. Upon receipt of the "OK-tc-proceed" command, the carousel is indexed, placing the vehicle on the acceleration belt.

The acceleration belt, AB, (see Figure 3-2) accelerates the vehicle up to a speed of 10 miles per hour. At the end of belt AB the vehicle is transferred to the mainline drive hill belt, BC, which increases the vehicle speed to 12 miles per hour. After the vehicle climbs the 7.5 percent grade, it transitions to the mainline long belt, CH. On this belt the vehicle speed is increased to 15 miles per hour. In the region DG the vehicle negociates a 125-foot radius curve. At the end of the long belt, CH, the vehicle is put onto the deceleration belt, HI, which slows the vehicle to a speed of 3 miles per hour before it rolls onto the flanged ring of the south carousel and stops at the unloading berth. The door is then automatically opened by passenger initiation, the vehicle dwells for a nominal 15 second interval while the passengers disembark, and the vehicle door closes. The vehicle is then indexed to the loading berth at a speed of 3 miles per hour and the passengers embark after depressing the exterior door opening button. After a 15-second nominal delay the vehicle door is automatically closed, interlock is checked, and the acceleration belt, JK, is turned on which accelerates the vehicle up to a speed of 7.5 miles per hour. The vehicles is then transitioned to the long belt, KP, which propels the vehicle to a speed of 15 miles per hour.

If it is desired to switch the vehicle to the off-line station, RS, a cam plate in the guideway is activated by the control operator which interacts with the switching cam on the vehicle and effects switching. The switched guidance wheels direct the vehicle onto the deceleration belt, QR, which slows the vehicle to a speed of 3 miles per hour. When the vehicle transitions to the stopped belt, RS, the vehicle comes to a stop at the loading and unloading berth. Passengers will embark and disembark as previously described. To reinsert the vehicle from the linear station belt, RS, after the door is closed a series of checks are made including door interlock and a check of the fixed block control system. When an available block or slot is found, a "safe-to-proceed" signal is sent to central control. At this time the belts RS and ST are automatically turned on. The vehicle is accelerated up to a speed of 12 miles per hour before it enters onto the main-line hill belt, PU. Since the vehicle speed on the hill belt is 11 miles per hour no further acceleration occurs. When the vehicle transitions to the deceleration belt, UW, the vehicle is slowed to a speed of 3 miles per hour. The vehicle then rolls onto the flanged ring of the north carousel and stops at the unloading berth to complete the final step of the cycle.

The Transette test system can operate with as many as eight vehicles in the schedule mode for maximum flow conditions. In this case two vehicles would be at each carousel; one in the unloading berth and the other in the loading berth. Four vehicles would be distributed on the hill belt and long belt, two moving toward the east terminal and two moving toward the west terminal.

As the vehicle loading berth at the north terminal completes loading and door-closing and check-out functions, the vehicle would be launched provided the block ahead is clear and a "safe-to-proceed" condition is evident. To launch this vehicle the acceleration belt is turned on. The carousel rotates until the vehicle in the unloading berth has been indexed to the loading berth. A proximity sensor at the loading berth provides a "safe-to-proceed" signal indicating the vehicle ahead has departed and allows the carousel to index. Another sensor located prior to the loading berth provides a signal to terminate carousel rotation. Movement of the vehicle from the unloading berth has left that position open to accept the incoming vehicle. The next vehicle would be launched approximately 15 seconds later. This is sufficient time for the previously launched vehicle to climb part way up the hill. Thus two vehicles could be on the upside of the hill belt simultaneously at a minimum headway of 15 seconds.

At the instant of launch of the first vehicle, a vehicle is simultaneously launched from the south terminal. A similar launch occurs on the launch of a second vehicle. Since it takes longer than 30 seconds to travel from one end of the guideway to the other, the unloading berths will not be occupied after the launch of the second vehicle. If a vehicle enters the unloading berth after the vehicle ahead has been moved to the loading berth, but before it completes the loading cycle, launch of the vehicle ahead will be delayed until the unloading timing sequence has been completed. Therefore, although initiation of launch may be simultaneous, this condition need not persist.

To start the system, four vehicles are positioned by manual control at loading and unloading berths at each carousel and four more vehicles are stored in the off-line station. These four vehicles in the off-line station are inserted onto the guideway sequentially by manual control. Vehicle launchings from the north terminal are released after two vehicles have been launched from the off-line station while the other vehicles are held in the south terminal. The final two vehicles are launched from the off-line station before release of launchings from the south terminal. This is done in a manner that would equally distribute the vehicles around the guideway. When distribution has been achieved, launches are initiated from the loading berths of each carousel and the system is placed under automatic control.

A low-flow, schedule mode is effected with two vehicles, each positioned in the loading berth of each carousel. The timing sequences are based on simultaneous launchings. Vehicles can be inserted in any number up to six from the off-line station to provide intermediate levels of service. Operation in the schedule mode is keyed to simultaneous launchings except in the highest flow mode which can achieve a slight unbalance due to delays in loading. That is, if a door is held open for a period greater than the preselected dwell time, it will not influence a launch at the other end which is based on a schedule. If the door is held open, preventing a launch until the vehicles are all awaiting entry into the unloading berth of the station with the held vehicle, the operator can either allow the vehicle to function automatically with this unbalanced distribution or intervene to balance the distribution again.

Demand-Responsive Mode

Demand-responsive operation is initiated by pushing a button at the loading berth to call for a vehicle, if it is not already there or to initiate the timing sequence of it. In the test system, the calling button is located in the center of the north terminal carousel. When the vehicle arrives a button on the exterior of the door is pressed which will open the door automatically. As previously mentioned this also starts a timer which will close the door automatically. The vehicle is launched after completion of the timing sequence. Operation of the vehicle is then the same as in the scheduled mode. A vehicle will be simultaneously launched from the opposite station to replace the vehicle in use. Alternatively, if a higher demand is experienced vehicles stored in the off-line station would also be used to replace the occupied vehicles. Insertion of vehicles from the off-line station is controlled by the operator. If the system has an adequate number of vehicles in service, sequential launches will move vehicles from station-to-station. However, the system can be left to operate with imbalances. That is, if only two vehicles were in the system they could end up at the west terminal. Thus a 2.1-minute wait would occur if a demand was issued at the east terminal. Maintaining or not maintaining balance and short-wait times is at the discretion of the operator.

The essential difference in operation is that in the schedule mode all main-line belts are operating at all times whereas in the demand-responsive mode, aside from the service difference, only the belts that are needed to move a vehicle from one location to another are turned on; they are also turned off after the belt has been used. Thus, in periods of low demand, potential energy savings may be achieved as well as savings in maintenance costs, and increased reliability, and system life due to fewer number of cycles on the system.

4.2 PERFORMANCE CHARACTERISTICS

A series of performance tests were made to determine the performance characteristics of the Transette engineering prototype system. The general objectives of the test and evaluation effort were to:

1. Measure and assess the accomplishments of the development objectives;
2. Measure to obtain an indication, estimate, or verification of the actual performance capabilities of all items of equipment, subsystem, or system in as realistic an operational environment as possible;

3. Identify operational and engineering deficiencies;

4. Provide data for operational analyses;

5. Verify the maintenance effectiveness; and,

6. Evaluate the safety and reliability of the system in both normal and abnormal environments.

A test plan was developed, against which all measurements were made. Operational and engineering deficiencies were identified by comparing the performance with the system specifications and with requirements of urban systems in general. Adverse weather environments were not simulated but random conditions which occurred were investigated.

A functional test of the system and all subsystems was made to assure proper system operation and safety prior to conducting the performance tests. A single vehicle was first run around the guideway to assure that no interference was present and that all systems and subsystems were functioning properly. All switching, acceleration and deceleration functions were checked. A series of brake tests were performed by stopping the belt at various points along the guideway including the downhill side and observing the vehicle deceleration. All subsystems functioned in accordance with the intended or specified requirements.

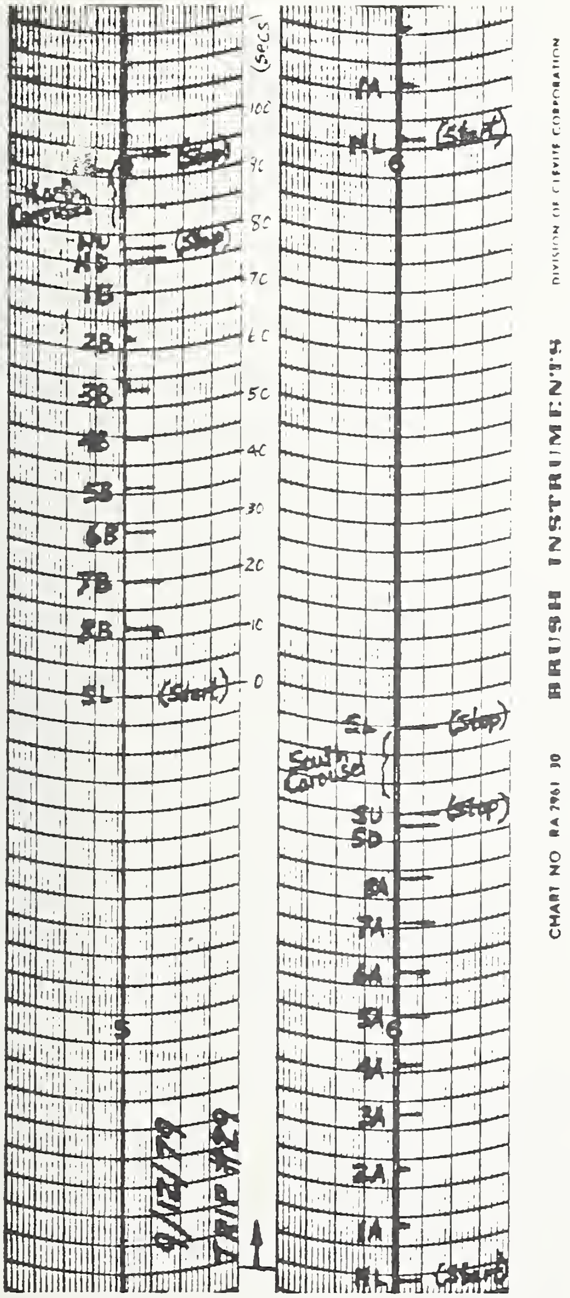
There are no separate brakes in the vehicle, instead the clutch drive system acts as a brake when the belt is either stopped or moving slower than half the speed of the vehicle. Brake actuation is virtually instantaneous and does not require an actuator to effect brake operation. Since the drive system and brake system are one and the same, the added function of disengaging the drive system and assuring this function need not be performed. Hence, the system is less complex than active vehicle automated guideway systems, since the drive system disengagement is automatic with the application of brakes. The converse is also true making restart simple after brake application.

Station operation with a single vehicle was checked. Operation was in accordance with the description provided in Section 4.1. That is, the vehicle slowed to a speed of three (3) miles per hour on the deceleration belt and came to a stop at the unloading berth. The guide wheels on the left side of the vehicle that engage the center guiderail were disengaged by the vehicle mounted cam striking the guideway mounted plate. This occurred after the vehicle auxiliary steering wheels engaged the guideway mounted,auxiliary guidance rail. Once the guidance wheels were disengaged, the auxiliary guidance system steered the front wheels around the carousel while the vehicle was being indexed to the unloading berth. The dwell time for loading and unloading is adjustable from 4 to 66 seconds and was normally set to dwell for 15 seconds.

The door interlock functions were checked. A vehicle could not be moved onto the main guideway with the door open. The safe-to-proceed signal was transmitted prior to the vehicle's start. Operation of the door safety was checked by application of a force while the door was in the process of closing. The door stopped and recycling was observed. Door operation was not checked under snow and ice conditions, but was operated in the rain without difficulty.

Trip Time and Velocity

The vehicle travel time was measured by observing the time of activation of the block control sensors. A sample strip chart recording shown in Figure 4-1 indicates the sensor activation times for two trips of vehicle , each with two passengers. The strip chart is for a round trip starting at the north terminal loading sensor (NL) and proceeding to the south terminal unloading sensor (SU), movement around the carousel to the south terminal loading sensor (SL), a return trip to the north terminal unloading sensor (NU), and finally movement around the carousel to the north loading sensor (NL). Reduced trip time data is included in the insert with distances between sensors and cumulative distances



'TRANSETTE' PROJECT DATA SHEET

Date: 9/12/79

BLOCK		TRAVEL TIME (Seconds)		
Sensor Pair	Distance (Feet)		Car 1/2 Pax	Car 1/2 Pax
		Trip #	29	30
NL-1A	95			
NL- "	95		9.2	9.2
1A-2A	156 1/2			
NL- "	251 1/2		19.0	19.0
2A-3A	158 3/4			
NL- "	410 1/4		28.4	28.3
3A-4A	162			
NL- "	572 1/4		36.9	36.8
4A-5A	148.75			
NL- "	721		45.3	45.2
5A-6A	162 3/4			
NL- "	883.75		53.3	53.2
6A-7A	165			
NL- "	1048.75		61.5	61.4
7A-8A	156			
NL- "	1204.75		69.3	69.2
8A-SD	130 1/2			
NL- "	1335.25		78.3	78.2
SD-SU	4 3/4			
NL- "	1345		80.3	80.2
SL-8B	144			
SL- "	144		11.8	11.8
8B-7B	149.5			
SL- "	293.5		19.9	19.8
7B-6B	165			
SL- "	458.5		28.6	28.4
6B-5B	148.75			
SL- "	607.25		36.1	35.9
5B-4B	162 3/4			
SL- "	770		44.7	44.5
4B-3B	162			
SL- "	932		53.2	53.0
3B-2B	158 3/4			
SL- "	1090.75		61.8	61.6
2B-1B	156 1/2			
SL- "	1247.25		70.0	69.8
1B-ND	83			
SL- "	1330.25		75.8	75.6
ND-NU	12			
SL- "	1342.25		77.8	77.6

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FIGURE 4-1. STRIP CHART OF A ROUND TRIP

from either the north or south loading sensors. The block control sensor locations are schematically shown in Figure 4-2. The variance in travel time between trip 29 and 30 is very small, indicating good repeatability after the vehicle has been run a while and the transmission oil is warmed. The difference in time between a southbound trip and a northbound trip is 2.5 seconds. This is due to the vehicle climbing the hill on the southboand trip and going downhill on the northbound. The travel time for both southbound and northbound trips are plotted in Figure 4-3. as a function of sensor distance.

The average velocity as a function of time for southbound and northbound trips is presented in Figure 4-4. The corresponding sensors and their locations are also indicated. The effect of the 7.5 percent grade is clearly shown when comparing the two curves. Although the vehicle was designed to achieve a maximum speed of 15 miles per hour (22 ft/sec), the highest speed achieved in the southbound direction was 13.7 miles per hour (20.1 ft/sec). This was attributed to slippage of the clutch with a loading of two passengers. In the northbound direction vehicle 1 achieved a maximum speed of 13.5 miles per hour (19.8 ft/sec). This maximum velocity was also below the design velocity of 15 miles per hour.

To show the difference in velocity made possible by clutch settings, the average velocity was plotted in Figure 4-5 for a vehicle loading of two passengers. The greatest time differential accumulated over the entire run was 3.1 seconds, the greatest velocity differential was 0.77 ft/sec.

The question of velocity differential is important because, if there is sufficient time for one vehicle to catch up to another vehicle, or if the vehicle can violate the block control spacing, then the belt and finally the link will shut down. Violation of the block control spacing is more critical since, 1) it has to occur before vehicles can collide, and 2), if this occurs and the belt is shut down, the entire link will shut down because of the synchronous nature of the system.

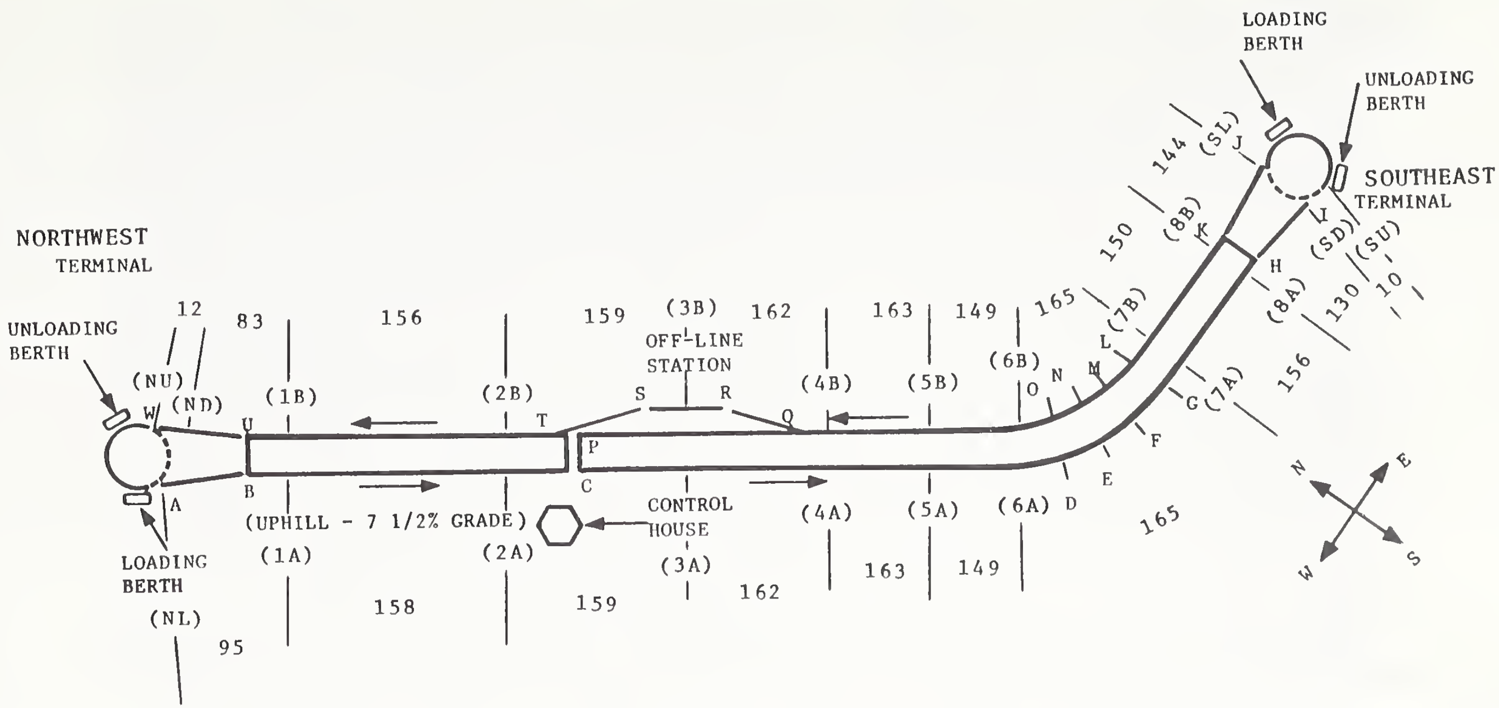


FIGURE 4-2. BLOCK CONTROL SENSOR LOCATIONS

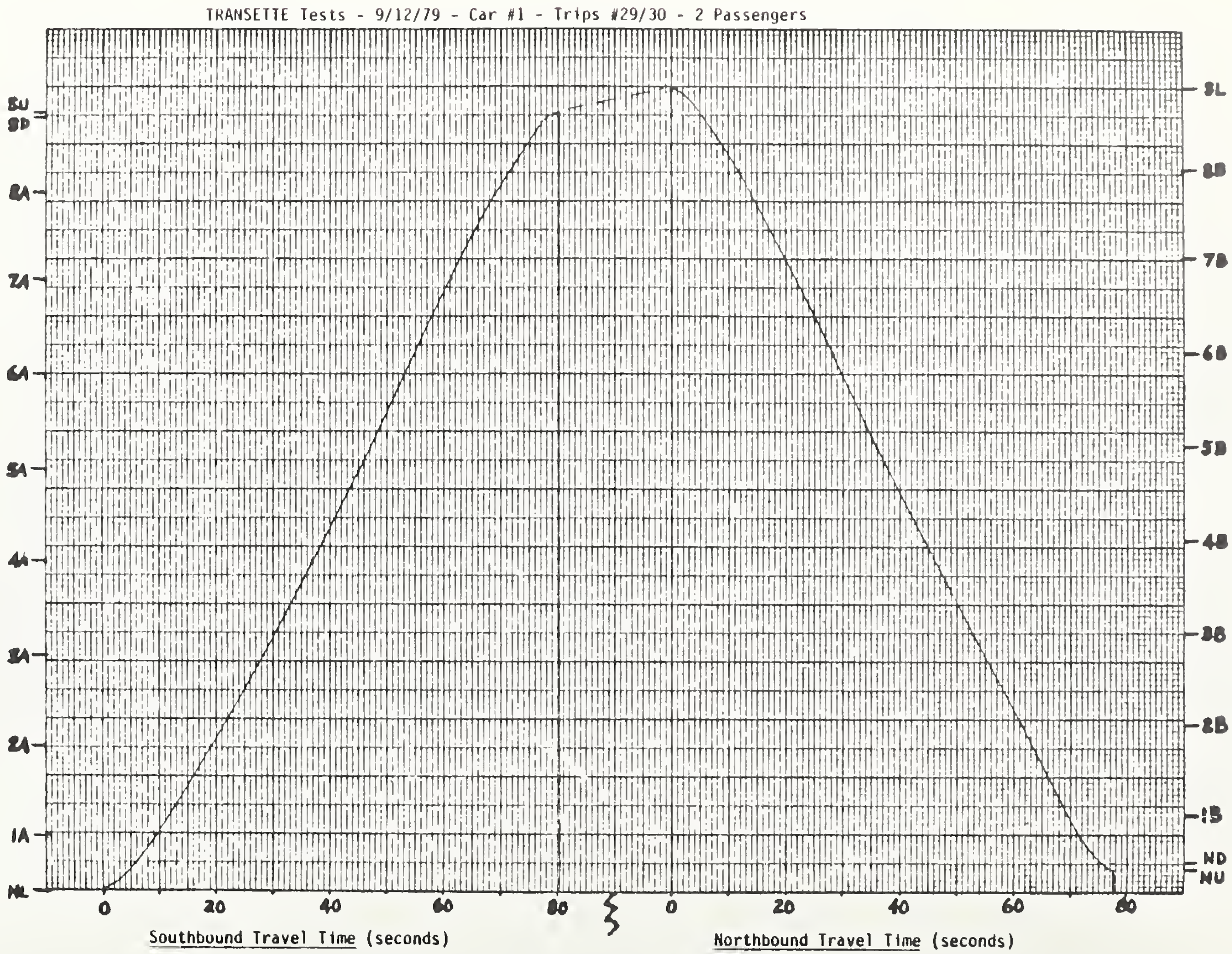


FIGURE 4-3. TRAVEL TIME VS DISTANCE

LOADED - 1 PASSENGER

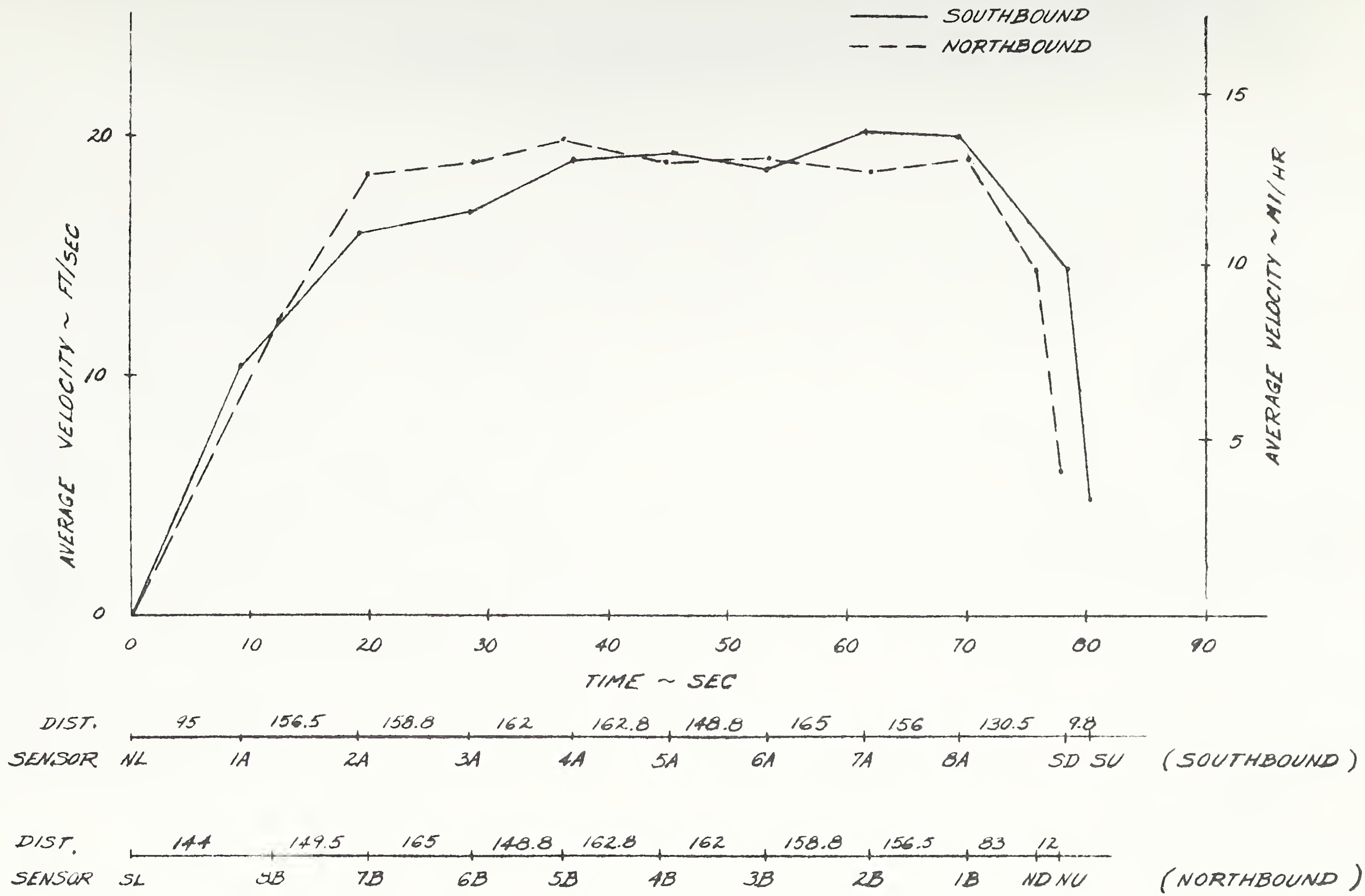


FIGURE 4-4. AVERAGE VELOCITY VS TIME----NORTHBOUND AND SOUTHBOUND

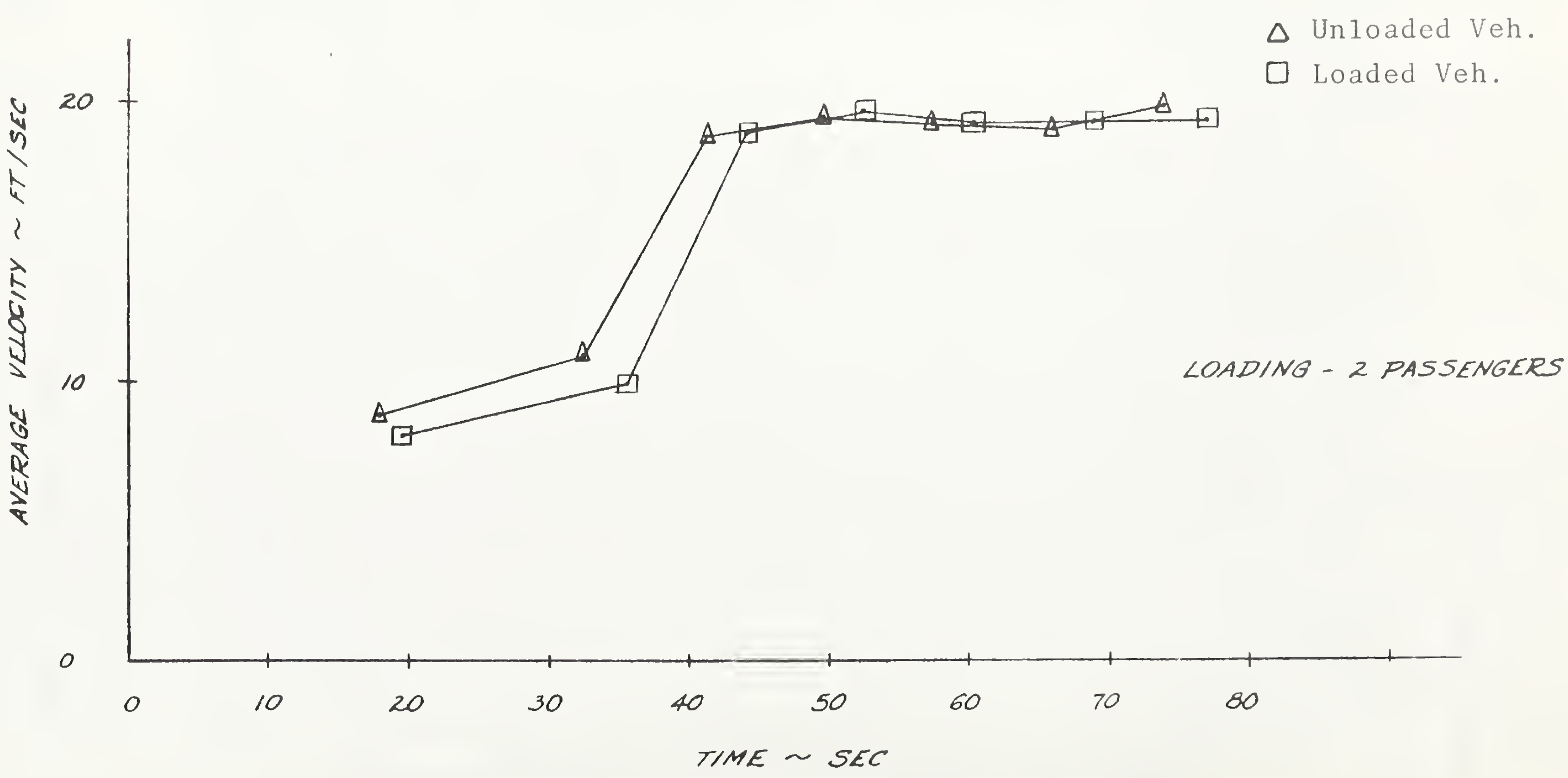


FIGURE 4-5. AVERAGE VELOCITY VARIATION VS TIME

The greatest time differential over one control block (1A-2A) is 1.7 seconds. This is an insufficient differential to allow a following vehicle to violate a block. The cumulative variation of 3.1 seconds is also not sufficient to permit a vehicle to violate a control block. The southbound average velocity versus time as a function of passenger loading is shown in Figure 4-6. The differential time as a function of passenger loading is also insufficient to permit a vehicle to violate a control block. That is, differentials of the order of 2.3 seconds were measured as opposed to a minimum of about 8 seconds required between control blocks. However, if the cumulative variation is examined, a maximum differential of 6.4 seconds was measured. Although this will not violate a control block and bring the link to stop, it is approaching the time of passage of a control block. Therefore, if greater differential times are experienced with the application of heavier loads, links could be shut down. If a link is shut down with two vehicles on the same belt, it will be necessary to go out onto the guideway and physically pull the lead vehicle ahead into the next block in order to restart the system. This would adversely affect availability.

A solution to this problem is to increase the headway. That is, headway is a function of the differential time or velocity experienced in a system. The control block lengths were established at 7.5-second intervals for a speed of 15 miles per hour. This was based on a capacity of 897 passengers per hour. The vehicles actually move somewhat slower and as a result take about 8 seconds to pass each block control sensor. An alternative is to install an automatic clutch control system that can vary the clutch setting as a function of load. Such a subsystem has been installed on Transette's latest chassis development with dual wagon-wheel steering. The latter alternative is the preferred solution since it will allow headways to be established as a function of needed capacity.

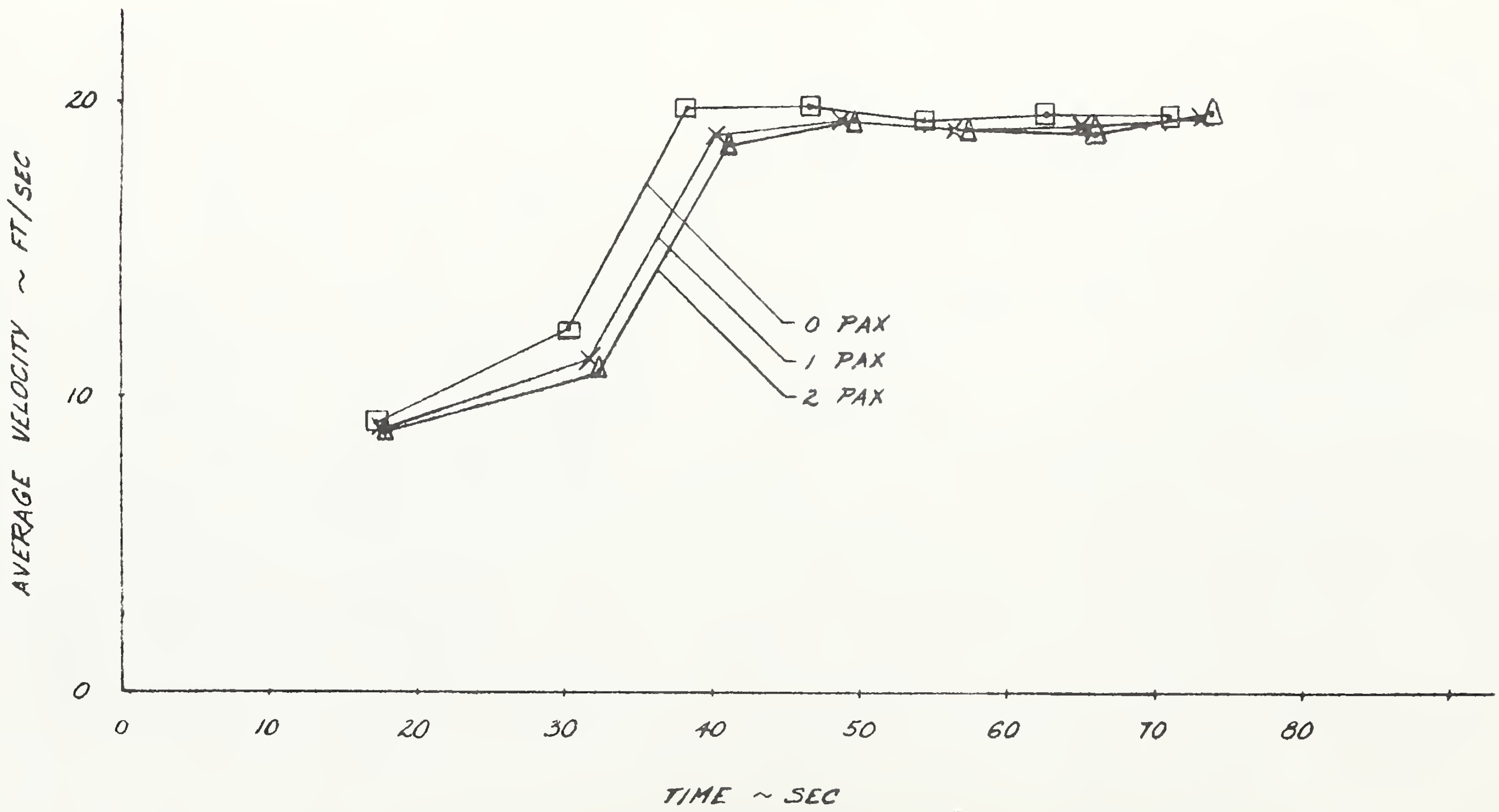


FIGURE 4-6. SOUTHBOUND AVERAGE VELOCITY VS TIME

4.3 SYSTEM DEPENDABILITY AND MAINTAINABILITY

One of the principal purposes of the test program was to determine the reliability of the prototype Transette system, since this is the essential element in understanding the effectiveness of passive vehicle systems. All malfunctions were recorded and their causes determined. Furthermore, it was intended to learn from actual operation where the weak points exist in the system design. The objective was to correct enough defects to permit a full week of operation in the automated mode without any failures.

The following were considered failures of the test system:

1. Belt failures were related to the failure of belt splices. (Failure of the parent material of the belt was never observed.) When they occurred either the southbound or northbound lane was stopped; eventually it led to the entire system shutdown. The belt splice was fixed expeditiously;

2. Tire wearout occurred frequently making replacement necessary;

3. Vehicle derails due to guidewheel failure or linkage maladjustment.

4. Control system failures were primarily malfunctions of the block control sensor, and

5. Propulsion failures, other than belt failures, were due to motor burnout, which was really a secondary failure induced by other causes.

In the test system many stoppages were due to adjustments of the vehicle clutch, the wayside sensors, and the carousels. In general, each adjustment required stopping the vehicle.

4.3.1 Test System Performance

An informal daily log was first used to record data. This was soon replaced by a more detailed and standardized sheet, on which every run was recorded, as well as all events. All dependability data were manually recorded.

The recorded data cover the period from September 5, 1979 through November 23, 1979. The total number of trips around the loop during this test period was 764. The average trip time was 3.5 minutes giving a total system operating time of 764 x 3.5 minutes, or 44.6 hours. The trips are tabulated in Table 4-1.

During this period there were 73 failures and 51 adjustments, either one of which required a stoppage, giving a total of 124 events that required the vehicle be stopped. This gives an indicated Mean Time Between Stoppages (MTBS) of 22 minutes for a one-vehicle system.

The failures that occurred have been largely concentrated in the propulsion and control system. The full details of all the failures and adjustments in the system during the above time period is presented in Table 4-2.

It is interesting to compare the stoppage data for different periods of the test system's operation. Period 1 is defined as the time from September 5, 1979 through October 29, 1979, for on that date the vehicles were disassembled and an overhaul was begun. Table 4-3 shows failures and adjustments for this period. Period 2 is the time from October 29 thru November 23. Table 4-4 shows failures and adjustments for this period. Figure 4-7 shows the Mean Time Between Failures (MTBF) for each period, Mean Time Between Adjustments, (MBTA) and Mean Time Between Stoppages, (MTBS), as well as the same data for the entire period of September 5 thru November 23. As the causes of failures were eliminated, there were fewer failures; and the MTBF for Period 2 was 138 minutes compared to only 26 minutes for Period 1.

The recorded causes of stoppage are ranked as follows by frequency of occurrence:

Adjustments		51
Failures: total		73
Sensors:	26	
Splices	21	
Steering	9	

TABLE 4-1. TABULATION OF VEHICLE RUNS

DATE	AUTO-MATED (1)	MIXED MODE (2)	ROUND TRIPS TOTAL
9/5		19	19
9/6	12		12
9/7	7		7
9/10	10		10
9/11		*4	4
9/12	13	24	37
9/13		13	13
9/14		9	9
9/18		23	23
9/20	3		3
9/21	1	2	3
10/3		6	6
10/5	27	19	46
10/7		7	7
10/15		12	12
10/16	8	5	13
10/17	11	1	12
10/18	9+3*	3	15
10/22	116	15+3*	134
10/23	4	7	11
10/24	40	11	51
10/25	15	19	34
10/29	5	3	8

DATE	AUTO-MATED	MIXED MODE	TOTAL
1/4	9		9
11/15	20	11	31
11/16	7	13	20
11/19	57	44	101
11/20	18	2	20
11/21	53	4	57
11/23	27	10	37

Total Round Trips = 764
Total Round Trips (Auto) = 475
Total Round Trips (Man) = 289

@ Average round trip time of 3.5 min.

Total System Time
= 764x3.5 = 2674 Min.
= 44.6 Hours

Total Belt Hours
(Exclusive of Check Outs):

Hill Belt = 93 Hours
Long Belt = 128 Hours

ALL DATA FROM TRANSETTE LOGS, MANUALLY RECORDED

*All with Vehicle 1 except those with asterisks, which were Vehicle 2

(1) All Sections under automatic control
(2) Some Sections under automatic control and others under manual control.

TABLE 4-2. FAILURE FREQUENCIES TOTAL

SUMMARY OF TRANSETTE FAILURES AND ADJUSTMENTS DURING THE RELIABILITY TEST PERIOD

Period Covered: September 5, 1979 - November 23, 1979
Total number of runs: 764
Average time per run: 3.5 Min.
Total System runtime: 44.6 Hr (2676 Min.)
Total Failures: 73
Total Adjustments: 51
Indicated MTBF, this period: 37 Min.
Indicated MTBA, this period: 52 Min.
Indicated MTBF, this period: 22 Min.

		Failures		Adjustments	
Vehicle #1:	Drive Line				
	clutch	1		28	
	gear box				
	Suspension				
	tires	8		2	
	shocks				
	airbags				
	Steering				
	wheels	1		3	
	guidewheels	8		2	
	tie rods			2	
	Doors and actuators	1			
	Sensor targets			1	
	Total		19		38
Vehicle #2:	Drive line	-		-	
	Suspension	-		-	
	Steering	-		-	
			0		0
Command and Control:					
	Logic				
	Sensors	26		2	
	Wiring				
	Total		26		2
Drive train:	Belts				
	slider beds	4		1	
	splices				
	long belt	13			
	hill belt	2			
	SE accel.	4			
	SE decel.				
	NW accel.	1		1	
	NW decel.	1			
	Total		25		2
	Motors and drives	1	1		
	Pulleys	1			
	Totals		1		
	Carousels				
	motors				
	drive belts	1		2	
	other			7	
	Total		1		9
	TOTALS		73		51

TABLE 4-3. PERIOD 1

SUMMARY OF TRANSETTE FAILURES AND ADJUSTMENTS DURING THE RELIABILITY TEST PERIOD

Period Covered: September 5, 1979 - October 29, 1979
Total number of runs: 489
Average time per run: 3.5 Min
Total System runtime: 28.5 Hrs
Total Failures: 65
Total Adjustments: 30
Indicated MTBF, this period: 26 Min
Indicated MTBA, this period: 57 Min
Indicated MTBS, this period: 18 Min
System: Derailments - 6

		Failures		Adjustments	
Vehicle #1:	Drive line				
	clutch	1		19	
	gear box	-			
	Suspension				
	tires	7			
	shocks	-			
	airbags	-			
	Steering				
	wheels			2	
	guidewheels	5		2	
	tie rods			2	
	Doors and actuators	1			
	Sensor targets			1	
	Total		17		26
Vehicle #2:	Drive line				
	Suspension				
	Steering				
Command and Control:					
	Logic	-		-	
	Sensors	25		1	
	Wiring	-		-	
	Total		25		1
Drive train:	Belts				
	slider beds	3			
	splices				
	long belt	10			
	hill belt	2			
	SE accel.	4			
	SE decel.				
	NW accel.	1		1	
	NW decel.	1			
	Total		21		1
	Motor and drives	1	1		
	Pulleys	1			
	Total		1		
	Carousels				
	motors				
	drive belts	1		2	
	Total		1		2
	Offline switch	-		-	
	TOTALS		66		30

Source: Transette Log Sheets

TABLE 4-4. PERIOD 2: SUMMARY OF FINAL WEEK

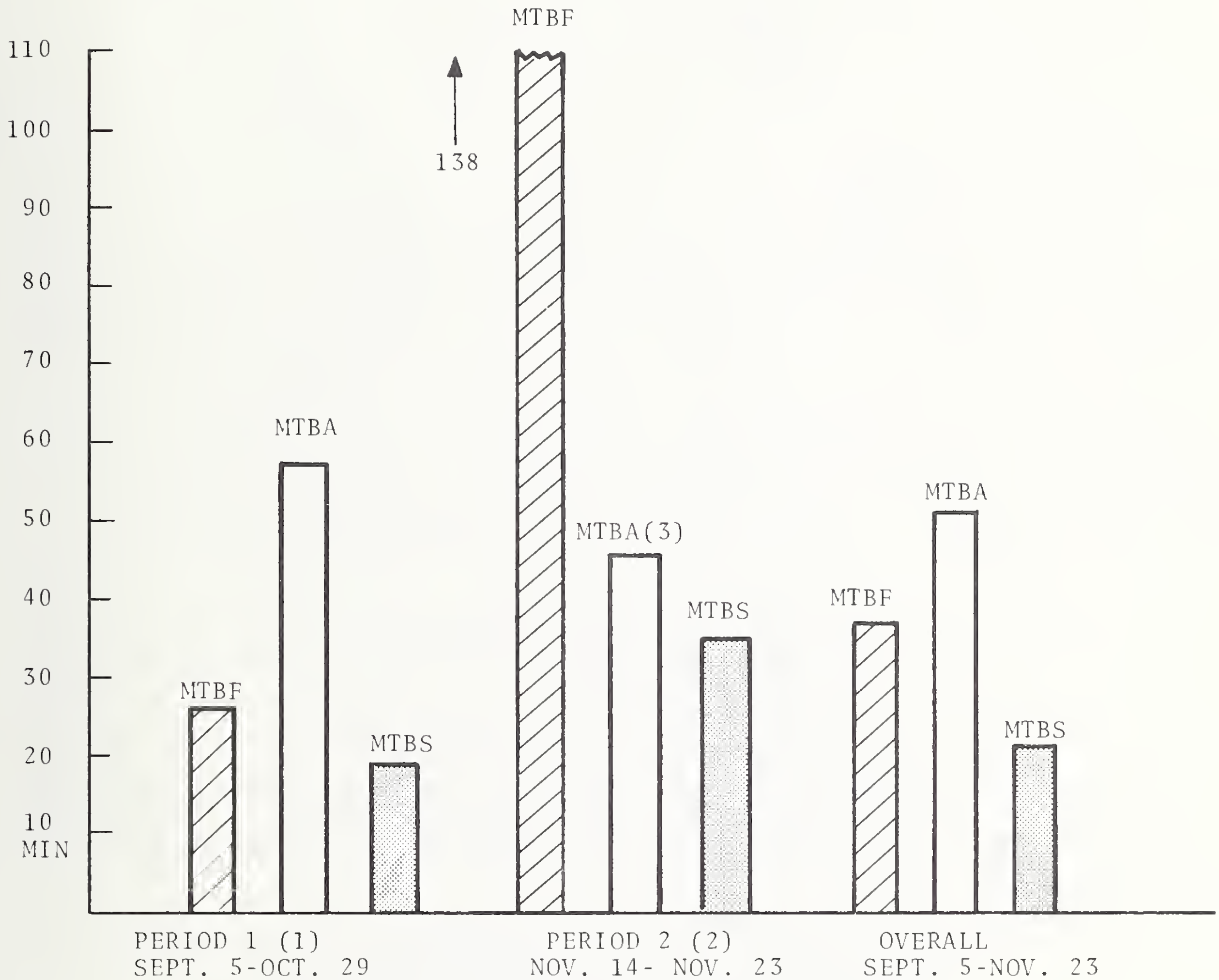
SUMMARY OF TRANSETTE FAILURES AND ADJUSTMENTS DURING THE RELIABILITY TEST PERIOD

Period Covered: 1979 - November 14-23
Total number of runs: 275
Average time per run: 3.5 Min
Total System runtime: 963 Min (16 Hrs)
Total Failures: 7
Total Adjustments: 21
Indicated MTBF, this period: 138 Min
Indicated MTBA, this period: 46
Indicated MTBS, this period: 35

		Failures	Adjustments
Vehicle #1:	Drive line		
	clutch		9
	gear box		
	Suspension		
	tires	1	2
	shocks		
	airbags		
	Steering		
	wheels	1	1
	guidewheels		
	tie rods		
	Doors and actuators		
	Sensor targets		
	Total	2	12
Vehicle #2:	Drive line	-	-
	Suspension	-	-
	Steering	-	-
		0	0
Command and Control:			
	Logic		
	Sensors	1	1
	Wiring		
	Total	1	1
Drive train:	Belts		
	slider beds	1	1
	splices		
	long belt	3	
	hill belt		
	SE accel.		
	SE decel.		
	NW accel.		
	NW decel.		
	Total	4	1
	Motor and drives		
	Pulleys		
	Carousels		
	motors		
	drive belts		
	other		7
	Total	7	21

Note - Does not include preventive maintenance actions

Source: Transette Log Sheets



(1) - AT THE END OF PERIOD 1 THE VEHICLES WERE OVERHAULED.
(2) - DURING PERIOD 2 THE OVERHAULED VEHICLES WERE FREE OF DERAILMENT PROBLEMS AND OF FAILURES DUE TO GUIDE WHEELS AND LINKAGES. PREVENTATIVE MAINTENANCE WAS ALSO DONE ON PULLEYS AND BELTS WHICH REDUCED FAILURES.

FIGURE 4-7. CHARTS OF MEAN TIME BETWEEN FAILURES, ADJUSTMENTS, AND STOPPAGES

Suspensions	8
Slider beds	4
Drive motors	1
Drive pulleys	1
Carousels	1
Clutch	1
Doors	1

4.3.2 Maintainability

The data from the operational logs seldom include any clear indication of time to fix or repair. For example, eight tire changing episodes are included in the log resulting from blowouts or flat tires. No serious effort was made to standardize tire changing procedures to minimize downtime, and other things were often done during the downtime occasioned by the tire change. The time involved in each episode can be derived as follows:

2 changes @ 1 hour each
2 changes @ 11 minutes each
1 change @ 25 minutes
3 changes with no time recorded.

No quantitative conclusion can be drawn, therefore, from the Transette log data. Qualitatively, however, it is clear from the test operation that:

a) any propulsion failure involving the belts or their drives required a complete system shutdown;

b) tire failures required removal and replacement of the vehicle or shutdowns.

The number of failures of wayside mechanical equipment must therefore be minimized, and the goal for the system must be high wayside reliability.

4.3.3 Availability

Availability of a system is a measure of its capability to perform its intended function when called upon to do so. That is, the availability of a system is the probability that it is operating satisfactorily at any instant when used under stated conditions.[1] The total time under consideration includes operating time, active repair time, and logistic time. This measure allows realistic assignment of responsibility in the event of an unsatisfactory condition. If an improvement in intrinsic availability (the built-in capability of the system to operate satisfactorily) is required, responsibility can properly be assigned to the design, maintainability, system operational characteristics, or management and logistic delays.

Availability in itself is not entirely meaningful in this context, since Transette is not an operational system, but rather is a prototype test system. It can however, serve to point out those elements of the system which need improvement. Sufficient data was not collected to determine the Mean Time to Restore (MTTR) with an adequate level of confidence since the test period was not long enough. Based on the limited data an MTTR of 8 minutes was estimated. A 20 minute MTTR for belt splice faults was used in this estimate. Shorter times were used for stoppages due to adjustments.

The calculated availability, A, is defined as:

$$A = \frac{\text{Scheduled Operating Time - Downtime}}{\text{Scheduled Operating Time}}$$

where downtime = No. of stoppages X MTTR of Period 2

$$A = \frac{963 - (28 \times 8 \text{ min.})}{963}$$

$$A = \frac{963 - 224}{963} = \frac{739}{963} = 0.77$$

[1]Reference [1]: Reliability Engineering; edited by William H. Van Alven, Prentice-Hall, Inc., 1964.

where: Operating Time = 963 min.
No. of Stoppages = 28
Estimated MTTR = 8 min.

Specifications for operational transit systems usually call for a minimum availability, A, of 0.98. If it is assumed that the operating time is 963 minutes and the number of stoppages is 28 (that of the vehicle demonstrated in Period 2) an availability (A) of 0.98 would require a mean time to restore (MTTR) the system of

$$0.98 = \frac{963 - (28 \text{ X MTTR})}{963}, \text{ MTTR} = 0.7 \text{ minutes.}$$

This MTTR is extremely short and difficult to achieve.

The most common failure was the belt splice. Any splice failure, whether it was a mechanical splice or vulcanized splice, was replaced by a mechanical splice. On the average, each required about twenty minutes to repair. Although this time could be reduced by about half with some mechanization and organization, it would lead to a requirement fewer than two 10-minute stoppages in 963 minutes or 16 hours for the system. Thus it is apparent that eliminating the cause of failure is a better way to achieve high availability rather than by attempting to decrease the mean time-to-restore (MTTR) below the 10 minutes considered reasonable.

4.4 HUMAN FACTORS

The human factors aspects of the evaluation were determined from the point of view of the passengers, operators, and maintenance personnel. The evaluation was performed utilizing the Guidelines for the Design and Evaluation of Human Factors Aspects of Automated Guideway Transit Systems (UMTA-MA-06-0081-79-1).

Boarding and Alighting

The door opens automatically or semiautomatically after the vehicle has stopped at the unloading berth. Only the semi-automatic door opening is currently implemented on the prototype test vehicles. It requires the passenger to push a button on either the exterior or interior of the door to embark and disembark. The single door slides rearward exposing a doorway opening of 24.5 inches. This door opening is adequate but not excessive. To enter, the passengers must step up 16.5 inches from the ground or 6 inches from a planned station platform. The passenger must stoop because the floor to ceiling height of the four passenger vehicle is only 55 inches and must be entered in much the same way as a conventional automobile. The ceiling and floor are padded with carpeting. The top of the doorway which is only 52.5 inches from the floor however, is a painted steel member which could cause head injuries. Padding would greatly reduce this hazard. The low ceiling height is intentional having been designed to be uncomfortable for standing, thus forcing passengers to sit; receiving more secure and comfortable ride than standing, since seated passengers can be exposed to higher deceleration levels than standing passengers without causing movement and unbalance. Larger movements are applied on standing passengers requiring more muscular restraint - hence less comfort.

Passenger assists were not present in the vehicle. Assists such as flexible grab straps could greatly facilitate passengers movement in a stooped posture in the vehicle or to sit down or get up. These straps should be mounted 36 inches above the floor to be accessible to seated passengers.

A door safety edge has been incorporated which is an electrically operated pressure sensitive element. In the event of a person or object in the doorway the door will automatically open and recycle. However, even in the event of loss of power the door can be slid open. This capability acts as an additional safety device that does not permit a door closing force of greater than 30 lbs. This safety device is mechanical and is dependent on friction to transmit the door closing force.

Vehicle Interior Design

The vehicle is designed to seat four passengers; two facing forward, and two facing aft (see Figure 3-6). Ample room is available in the seats (18 x 19-inch seat pan), between adjacent seats, and between the two sets of seats for legs (25 inches, and packages. A height of 39 inches from the seat pan provides clearance even for males in the 97.5th percentile.

The seats and body are made in an integrated mold; eliminating rough edges or protruding fasteners which could injure passengers. However, the armrest separating the seats has a very small curve radius. This could cause injury, particularly to the lower end of the spine (coccyx), as passengers attempt to sit down. Furthermore, this small radius also presents a potential hazard in the event of an emergency stop. A larger radius curve would reduce this hazard.

The acrylic window behind the seat is sloped such that the head of an average height passenger would just touch it when in a leaned back position. In the event of an emergency stop or an accident it is very likely that the forward two passengers would hit their heads. Although the window is acrylic and would deform to some extent, it would not eliminate the hazard. A headrest, however, would provide adequate protection and is necessary to protect passengers from potential head injury. The acrylic window would however, prevent shiplash injury to the neck. It functions as a headrest although it is not padded and could result in injury to the head.

At present there is no interior lighting. Lighting is provided by exterior lamps along the guideway. A 12-volt battery is onboard to operate the door. Plans have been made to add an electric alternator which would be sufficient to provide interior lighting, power for the door, air conditioning, and heating but it was not implemented on the prototype vehicles. It is recommended by the Guidelines for the Design and Evaluation of Human Factors Aspects of Automated Guideway Transit Systems that station lighting provide 50 foot-candles of non-glare illumination in the boarding and unloading areas and that guideway lighting provide at least 30 foot-candles of non-glare lighting in the interior with no more than 30 percent variation. Because of shadows and vehicle motion the exterior lighting source provides more than a 30 percent variation on the interior.

No heating is provided in the prototype vehicles. The trip length at the test track is sufficiently short (approximately 80 seconds in one direction) so as not to require heating. Heating could be provided by electrical heater supplied by the previously mentioned alternator and supplemented with a closed, heated station.

Cooling was more of a problem in the warm, southern climate of Georgia. No air conditioning system was provided. However, ultra-violet absorbing acrylic windows were incorporated to reduce the heating. In addition, a blower was added for ventilation that was powered directly by the drive axle. The tinted windows were quite effective in reducing the heating of the passenger compartment. Although the ventilation system was disconnected throughout most of the testing the comfort level was equivalent to a shady environment.

Emergency Conditions

The door is the only entry or exit to or from the vehicle. In an emergency the door can be slid open from either the inside or outside with a force not greater than 30 pounds. There is no lock on the door that needs to be released. The door over-ride force is adjustable. Having the capability to slide the door open in an emergency is an asset. The door edge has sufficient exposure to be pushed without the need for an exterior handle.

Although there is no lock, the door slides forward to close and therefore would not open in the event of a collision. Because of the low vehicle weight and low speed the impact energy is insufficient to open the door in the event of rear end collision. Maintaining the passengers inside the vehicle in the unlikely event of a collision is a basic tenet of transit vehicle design, but allowing them to escape easily is also a major consideration. This stems from the fact that the most dangerous hazard is not collision, but a fire from within the vehicle that results from uncontrollable combustibles carried on by passengers. However, by making it easy to escape without the need for a door lock release, a security hazard has been created. An unwanted person could enter the vehicle at will, even possibly while it is in motion at slower speeds. Television monitors could guard against such action. A passenger could also open the door while the vehicle is moving, since there is no interlock other than in the station. This has created a great deal of controversy among the Georgia Tech and Transette design teams.

The window could be made removable providing a second means of exit in the event of emergency. This would allow a door lock without the possibility of entrapment. However, a window is more difficult to remove and can not be easily used by handicapped and elderly. Hence, there is a preference for a closed door without a locking device,which could be jammed.

There is no communication system between the passenger and operator although one was contemplated. It is desirable to have some form of communication, preferably some form of intercom to allow voice communication. Therefore, a passenger would not be able to escape from the vehicle while it is moving without risk of injury if a communication system is not added.

The vehicle is fabricated with epoxy fiberglass, foam-filled sections which are not fire retardant. The glazing material is an acrylic which is highly impact resistant and does not shatter into sharp-edged pieces when it breaks but does melt at about 450°F. Although the fire hazard is extremely low due to passive nature of the vehicle, the fire hazard due to combustibles carried on board by passengers is not low. Therefore fire retardant material or an active fire extinguishing system are necessary. A thin glass layer could be applied to the acrylic window that would make it fire-resistant, resistant to scratching (reducing maintenance), and yet retain its impact resistance. The absence of an electrical motor and electrical power pick-up greatly reduces the external fire hazard, making Transette potentially significantly safer than active AGT systems.

Station

In the current test program, stations are non-existent. From the passenger's viewpoint a platform with a step height into the vehicle of 6-8 inches and a covering over the vehicle and passenger waiting area are necessary. An enclosed station with heating and air conditioning are desirable futures.

4.5 ADVERSE WEATHER OPERATION

Operation under adverse weather conditions was tested including snow, ice, rain. Ice and snow testing was not extensive. It was done after natural precipitation which was not very frequent or long in duration, but for Atlanta, the accumulation was considerable. A definitive series of tests was not performed, but sufficient testing was performed to indicate the performance characteristics under adverse weather.

Ice and Snow

Two conditions are important for operation in an ice and snow environment 1) the ability of the vehicle and the system to maintain operation once precipitation has started, albeit even in a degraded mode; and 2) the ability to start up a system after it has been idle and accumulation of precipitation has occurred. The latter test is primarily a test of snow removal capability.

To determine the system performance characteristics under dry conditions without precipitation, the system was tested at a variety of cold temperatures down to 20°F. Vehicle acceleration was somewhat erratic or "jerky" until the first two runs had been completed. After this, the oil in the transmission was warmed sufficiently to provide smooth performance. These accelerations are noticeable but not objectionable. Belt operation was not measurably different from dry, warm conditions.

An ice test was performed to test the system start-up characteristics. Ice up to one-quarter inch in thickness was formed artificially over the belt by running water over the hill belt and the guideway at a temperature of 20°F. The ice on top of the belt was a clear ice with an undulating surface which varied in thickness between 0.125 and 0.25 inches. The guideway had smooth patches of clear ice with a thickness up to 0.125 inches. When the hill belt motor was started, the belt did not move. Power was left on until a circuit breaker was thrown. The motor torque was insufficient to overcome the bonding of the belt to the slider bed. Therefore, the belt was lifted manually to break this bond. Not much effort was required. The hill belt was again turned on and the belt moved. The ice remained bonded to the belt while on a straight surface, but was thrown off the belt at the turn-around. A pile of ice accumulated at the turn-arounds and was simply shoveled away. In effect, the belt acted as an ice conveyor. The belt system performed a remarkable job of cleaning the ice from the top of the belt. A piece of ice did stick to the bottom of one belt and caused local untraining and a small belt tear. The torn section was removed and the belt respliced. The ice test was repeated several times. It was found that when the ice remained on top of the belt, as it would with freezing rain, and the belt did not bond to the slider bed, the belt could be safely operated, thus removing the ice. However, if rain occurs first and the temperature drops below freezing the belt should be operated continuously to prevent ice accumulation on the bottom of the belt. Otherwise, some type of a heating system would be necessary to melt the ice from the bottom of the belt prior to operation. An alternative is to manually break the bond along the entire guideway as was done with the test system.

The vehicle was able to climb the 7.5 percent grade with the drive wheel operating on patches of glare ice. Some wheel slippage did occur, but the vehicle operating capability was not seriously degraded -- a small reduction in speed was evident. This test was performed with only one passenger on board. Braking tests on ice were not performed. These should be done to determine what portion of the fixed block control unit is used to stop with maximum vehicle load.

The No. 1 vehicle was operated continuously in a small 2.5-inch, wet snow storm in February. The snow was estimated to have a water content greater than the 30 percent. As was the case with ice, the snow was rejected from the belt. The drive wheel in contact with the guideway for the most part melted the snow. No serious performance degradation was evident. Belt performance with the second generation belt was normal. In addition to this, the No. 1 vehicle was operated after an 8-inch, wet snow had fallen during the night. Snow was not removed from the guideway, but some of the snow was shoveled from the belt. The vehicle operated over the snow, which was compacted to a thickness of about 2.5 inches on the guideway. The vehicle climbed the hill (7.5% grade) more slowly and had a significantly rougher ride, but the vehicle did continue to operate.

Rain

Belt performance in rain with the second generation belt was not a problem. The different belts used during the development process are described in Section 6.5.1. The textured rubber surface retained water that was shed into the pit as it passed over head and idler pulleys. Although these made an increase in the belt loading and near doubling of the coefficient of friction to 0.14 over dry conditions, the drive motors were not overloaded. However, with the introduction of the third and fourth generation belts which had considerably higher dry coefficient of friction (0.25) and considerably higher water retention, the drive motor capability on the long belt was exceeded. A current of 16 amperes was needed to drive the belt under dry conditions; whereas, a current of 28 amperes was used in rain. Operation with the fourth generation belt could be continued with an increase in long-belt motor horsepower, it was concluded that a more desirable approach would be to develop a fifth generation belt with lower coefficient of friction and less water retention characteristics. Section 6.2 Subsystem Assessment discusses this in more detail.

5.0 SYSTEM ECONOMICS

The Transette System is an engineering prototype system and as such has not developed any operational cost data. Engineering development cost data however is available.

5.1 DEVELOPMENT COST

The Transette engineering development has been conducted in phases previously indicated in Section 2.0. The Phase IA effort funded by NSF demonstrated feasibility, but did not provide sufficient funds to make the system totally operational. The Phase IB effort funded by UMTA brought the engineering prototype system to a state where the system was completely operational and performance characteristics could be determined. The Phase IA development cost $402,000. The NSF contract with Georgia Tech for site preparation and feasibility testing amounted to $127,000. Transette Inc. had supplied the vehicles and hardware and installation labor at a cost of $275,000. The Phase IB development cost $283,000. UMTA provided $233,680 for hardware modifications and testing and Georgia Tech's contribution was $49,420. The total engineering development cost to date is $685,000.

Phase IA	
NSF Test site preparation and feasibility tests	$127,000
Transette Inc. hardware and labor	275,000
	$402,000
Phase IB	
UMTA hardware modifications and testing	$233,680
Georgia Tech	49,420
	$283,100
Total	$685,100

6.0 TECHNOLOGICAL ASSESSMENT

6.1 DEVELOPMENT APPROACH AND PHILOSOPHY

The Transette system was conceived at a time prior to TRANSPO 72 and the Morgantown PRT when studies of Personal Rapid Transit (PRT) that addressed the issues of synchronous versus asynchronous longitudinal control were being investigated. Among the types of longitudinal control considered, active control systems received overwhelming attention. These active systems were divided into wayside functions which were primarily related to determining the position of vehicles as they progressed along the guideway and on-board functions which were related to using this transmitted position information to regulate the speed and acceleration of the vehicle. In concept active systems were not overly complex in themselves, but considerable complexity was introduced by the requirements for fail-safe safety systems superimposed on the longitudinal control, the need for redundancy and the large amount of data transmission. Rather than try to build better active control systems, the Transette concept was an attempt to eliminate or circumvent the need for many of the functions performed by active systems, where possible, or to at least greatly minimize their complexity.

A great simplification was achieved by placing the speed regulator at the wayside and providing only the motor or, longitudinal actuator on-board the vehicle. Thus, the vehicle only responds when power is applied otherwise, it comes to a stop. Hence, the vehicle is passive and does not perform any higher level functions.

Basic headway control was accomplished simply by placing two vehicles on a single belt providing a mechanical separation. Thus, if the forward vehicle stopped because the belt stopped so did the following vehicle. This, however, did not account for transitions from one belt to another. That is, if two vehicles were traveling on a single belt and the foward vehicle transitioned to a belt ahead that was stopped,it would come to a stop; the following vehicle would perform similarly, but would collide with the forward vehicle due to the loss in stopping distance associated with vehicle length. To eliminate these transition problems a conventional fixed-block control system was superimposed that maintains one block between two vehicles at all times.

The unique drive system is extremely simple. It is a belt-drive system that powers one rear wheel on the vehicle which in turn propels the vehicle at twice the speed of the belt. The unique drive system incorporates both propulsion and stopping capability in a single system without the need for even the complexity of conventional brakes and the eventual need to replace brake pads. The transmission drive primarily consists of a 1:2 gear box and a clutch. The mechanical advantage is such that the vehicle will remain stopped with a maximum load on a 7.5 percent grade. Furthermore, the vehicle will always come to a stop when power is not applied. The vehicle only moves when power is applied to the drive wheel on the belt which turns at half the speed of the driving wheel on the concrete. By incorporating both propulsion and brakes in one mechanical device without the need for any actuation precludes the need to check and provide an interlock to insure that propulsion and brakes are not simultaneously applied.

Although two vehicles were on the same belt, small differences in velocity would occur due to differences in loading that directly influence the slip of the clutch. A weight actuated automatic clutch compensator was designed, but was not used on the prototype vehicles for simplicity and because sufficient distance margin existed in each control block to not cause a shutdown as a result of the small vehicle closing speed. As predicted, no shutdowns were experienced because of headway violations. But, in retrospect, numerous manual clutch adjustments were made that caused undesirable delays. That is, these manual clutch adjustments would be precluded with automatic clutch control.

Simplicity, however, is not without its price. Systems that are synchronous suffer from a serious disadvantage. That is, if a vehicle failure occurs on the guideway the entire system will eventually be shut down resulting in low availability. Therefore, to avoid or minimize this effect in a synchronous system either the system must be restored rapidly or failures must occur infrequently. In other words, the MTTR (Mean Time to Restore) must be very low and the MTBF (Mean Time Between Failures) must be very high in order to achieve high system availability. Based on the types of failures experienced in the prototype system, a very low MTTR appears difficult to achieve. Thus, the principal effort has been devoted to achieving a very high MTBF. This approach is better than the former since it attempts to eliminate delays rather than minimize them. What remains to be seen is if a sufficiently high reliability (MTBF) can be achieved. No apparent technical reason exists for not being able to achieve this end provided sufficient development is performed.

The concept of an automated system using a totally passive vehicle propelled, guided, and controlled from the wayside is appealing from the point of view of simplified operation, enhanced availability, reliability, maintainability, and safety; and significantly reduced cost in comparison to conventional AGT designs. The Transette passive vehicle system has resulted in numerous potential benefits for an operational system:

1. The passive vehicles eliminate the hazards of heat, fumes, fires, electrical short-circuit, noise, and vibration from an onboard motor.

2. The passive vehicles greatly reduce the weight per passenger-mile conserving energy and reducing pollutants.

3. The low-weight of passive vehicles results in reduced capital costs for fabricating the vehicles and the guideway and also reduces tire[2] and guideway wear and the associated guideway maintenance.

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[2] Reference [2]: "The Friction of Pneumatic Types," by Desmond F. Moore, Elsevier Scientific Publishing Co., 1975.

4. The passive vehicles allow the design of simple, reliable systems. Light-weight construction results in reduced maintenance due to infrequent failures and low component weights.

5. The belt drives are much less hazardous than live power rails.

6. The belt drives preclude the need for power collectors and power collector shoes since the need for electrical power for propulsion on board the vehicle is unnecessary.

7. Electromagnetic interference (EMI) from power pick-ups is eliminated. The latter is important to onboard electronic control systems which in this case do not exist. This system also does not add to the general level of EMI in the environment.

8. The belt drive provides an added measure of safety beyond the fixed block control system in that it essentially does not permit one vehicle to overtake another since both are propelled by the same belt and headway is mechanically fixed.

6.2 DEVELOPMENT PHASES

Transette, in a prototype test form, has the above characteristics. It has gone through two developmental phases. Although the first phase (Phase IA-NSF) was intended to demonstrate feasibility, it was underfunded and the prototype phase was not completed. Concept feasibility was demonstrated, but performance capability was not. At the conclusion of the first development cycle (Phase IA-NSF) the system was not completely functional, did not have a complete and functional automatic control system, and numerous questions concerning its performance capabilities were unanswered. In particular, there was no information on the reliability of the system. Although the system is simple in concept and potentially low in cost, high reliability is the key to high system effectiveness. This is particularly true because of the synchronous nature of Transette.

The second development phase (Phase IB-DOT) completed the prototype development. This resulted in two fully functional vehicles, capable of operating automatically around the entire guideway, including the carousels. It must be clearly understood that this second development phase, however, did not make the system operational. On the contrary, Transette is still not operationally ready. Before the system is implemented in an urban environment, it will be necessary to conduct a Phase II engineering development program that would verify the system's operational capability and incorporate the improvements indicated by the previous two development phases.

Several problem areas still exist in Transette which require modification before the system can be considered operational. Improvised solutions made it possible to test the prototype, but such solutions are not necessarily the best from a reliability viewpoint. For example, to solve the carousel problem, an auxiliary guidance rail approach was taken which resulted in Ackermann steering of the front wheels and a simple axle drive rather than the preferred dual-axle drive and dual-wagon wheel steering approach. More will be said about this below.

The remainder of Section 6 will be devoted to a technology assessment of the Transette system on both a system and subsystem level. Improvements will also be discussed that might be made during an engineering development program.

6.3 RELIABILITY

The test program attempted to operate the system continuously to build up operating time and generate some reliability data. No prior reliability analysis had been possible because of the small budget of this project from the start. As a result much of the test program provided a real-time analysis of failure modes and effects. The data collected have been valuable to the developers, because weak spots in the implementation of the system were identified. It is quite clear that design improvements must be made to several elements of the system and that these improvements are now identified. There is no apparent technical reason why they cannot be made. The number of runs achieved and the number of failures experienced were presented in Section 4.3.

In summary, the following conclusions can be drawn from the failure data developed during the test program:

1) Vehicles were the source of 26% of the failures and required 87% of the adjustments.

2) The wayside was the source of 74% of the failures and required 13% of the adjustments.

This compares with the Morgantown AGT system (using active vehicles) in which 54 percent of the unscheduled maintenance actions resulted from vehicle troubles, and 46 percent from wayside troubles (Morgantown). As was stated in Section 4.3, the overall Mean Time Between Stoppages (MTBS) for the duration of the test period was 22 minutes. Assuming an exponential reliability model and using the 22-minute MTBS, the probability of making the 1.55-minute trip from one end of the loop to the other without a stoppage is approximately $(e)\ \frac{-1.55}{22}$ or 0.932 (For single vehicle system)

If the results of Period 2, the last part of the reliability test, are used the probability of successfully completing the trip is about $(e)\ \frac{-1.55}{35}$ or 0.957. A minimum vehicle MTBS for a successfull revenue system must be at least 16.3 hours which implies a probability of successfully completing a trip of $(e)\ \frac{-1.55}{16.3\text{x}60}$ = 0.998 for a 1.55 minute trip. This is based on an availability of 0.98 and an MTTR of 20 minutes. Transette should at least be brought up to this level to realize a practical revenue system.

If the various failure and adjustment problems were systematically eliminated, as indicated in Table 6-1 the resulting Mean Time Between Stoppages would be greater than 28.5 hours. Alternatively, this would result in the probability of successfully completing a trip of about 0.9991 which is above the required minimum of 0.998. Technically this appears feasible but remains to be demonstrated.

TABLE 6.1. SYSTEMATIC ELIMINATION OF FAILURE AND ADJUSTMENT MODES

CONDITION	EVENTS REMAINING FAILURE	ADJUSTMENT	DOWNTIME EVENTS	MTBF	MTBS
COUNTING ALL	65	30	95	26 Min.	18 Min.
1. Eliminate All Clutch Adjustments	65	11	76	26 Min.	22 Min.
2. Condition #1 and Eliminate Flat Tires	58	11	69	29.5 Min.	25 Min.
3. Condition #2 and Eliminate Guide Wheel Problems	50	9	59	34 Min.	29 Min.
4. Condition #3 and Eliminate All Other Steering Problems	49	5	54	35 Min.	32 Min.
5. Condition #4 and Eliminate All Sensor Problems	24	3	28	71 Min.	61 Min.
6. Condition #5 and Eliminate Belt Splice Breakage	3	2	8	9.5 Hr	3.6 Min.
7. Condition #6 and Eliminate Other Drive Problems	1	0	1	28.5 Hr	28.5 Hr
8. Condition #7 and Eliminate Door Problems	0	0	0	>28.5 Hr	>28.5 Hr

Initial Downtime Events: 95
Initial Failures = 65
Initial Adjustments = 30

6.4 SYSTEM SAFETY

Transette was designed with safety as a primary consideration. Safety features are inherent in the design. The passive nature of the vehicle with its belt drive system eliminates the hazards of heat, fumes, fire, electrical short-circuit, noise and vibration from an onboard motor. The wayside belt drives are considerably less hazardous than live power rails.

As previously discussed, placing vehicles on a belt, in essence, fixes the headway mechanically. As long as they are on the same belt, the vehicle separation will be maintained regardless of the speed of the belt. This is considerably different than a typical AGT system with an active vehicle where any vehicle can move independently on the guideway and its position and speed relative to other vehicles must be safely regulated.

Although operation on a single belt has inherent safety built into the design, collisions can occur when transitioning from one belt to another. To ensure against this a fixed block control system was superimposed providing a safety zone between vehicles. It has been implemented with a network of solid state relays. The performance of the fixed block control system has been highly satisfactory from a safety point of view. No vehicle collisions have occurred in an automatic mode. However, the fixed block control system is not implemented in a redundant manner and a possible failure could occur that may result in a collision. At the test track the back-up is visual observation from the control house. This may not be possible in an operational system; thus, there is a need for a redundant implementation of the fixed block control system.

As previously indicated a braking action is always applied to the vehicle unless propulsion power is applied. This eliminates the need of an interlock between the propulsion and braking systems and ensures that propulsion and brakes cannot be applied simultaneously. This is a simple mechanical system with inherent safety features designed into it. However, the propulsion and braking system in the prototype system are implemented in a single drive axle. If, over time, a failure of an axle or keyway occurs, the vehicle will be left without a braking system making a collision possible. Therefore, it is recommended that a dual-drive system be implemented making the braking system redundant.

The steering system has evolved from a positively retained body steering design to a positively retained front-wheel steering design. The latter has a set of wheels both foward and aft. If a failure occurs in the aft wheel set, little or no effect will be noticed depending on the alignment of the rear drive axle. The largest effect is the possibility of the front guidance wheels binding, thereby slowing or stopping the vehicle. However, if a failure occurs on the front guidance wheels, particularly on the forward outboard wheel, steering control would be lost and the vehicle could leave the track resulting in an accident. To ensure against this possible single-point failure mode, the factor of safety can be increased significantly by using locking bolts to hold the guidance wheel on, or a second steering wheel may be added to make the steering system redundant.

Careful consideration in future engineering development should be given the safety areas discussed above. Further considerations may arise if an operating system is elevated; that is, evacuation of passengers from a stalled vehicle onto an elevated guideway must be examined from a safety point of view.

An at-grade guideway requires protection from human or vehicular intrusion. This security situation plagued the test system, since students were constantly walking the guideway inspite of signs and flashing lights. One student was hit by a vehicle during testing, but was not injured. The student admitted that it was his fault and that he was negligent for not observing the warnings. What should be understood is that the test track has been used as a walkway during off test hours because it is the only paved walkway between the Student Union and some dormitories. This practice has unfortunately carried over during testing inspite of warnings.

6.5 SUBSYSTEM ASSESSMENT

6.5.1 Guideway Belt Drive

The Phase IA (NSF) development resulted in a belt drive system that relied on preloading the belts. The Habersett Belt Co. guaranteed a maximum belt elongation of 1.5 percent over the ambient temperature range, approximately 20°F to 110°F. The manu facturer's data on elongation as a function of load and temperature was significantly different from observations. [As much as 7.5 percent elongation was observed, resulting in considerable belt slipping.] Furthermore, the manufacturer's data on the coefficient of friction was also considerably in error resulting in higher loads and temperatures than predicted. This was particularly true under wet conditions. Deposits of polyethylene from the belt backing material were found on the stainless steel slider bed which further increased the coefficient of friction, especially under wet conditions. Therefore, a second generation belt was created by removing the polyethylene backing material. This lowered the coefficient of friction on the dry stainless steel surface from 0.15 to about 0.07.

In wet conditions the belt loading was increased because the textured upper surface retained water, effectively increasing the unit weight of the belt. Water was shed at the extremities of the belt as it passed over head and idler pulleys. This characteristic would only minimize the belt loading after precipitation had stopped or in light rain conditions where the precipitation rate was lower than the rate of shedding water. In addition, the coefficient of friction would increase to about 0.14, further increasing the belt loading.

To account for the greater elongation, higher tension loads were applied to the belts. This further aggravated the elongation problem. No problems were experienced with belt training over crowned pulleys, but initial preloading of the belt was not an easy task. Considerable time was required to retrain the belts. This added considerably to belt splice repairs.

The higher applied loads also resulted in higher shear loads on the head-pulley lagging material. Lagging material was used to increase the coefficient of friction of the head pulleys to minimize the angle of wrap. The lagging material used was nothing more than a piece of belt bonded to the outer rim of the pulley so that the upper, rubber textured surface was on the outside. The bond proved inadequate resulting in unbonding after only a short period of time.

The belt in the guideway curve (see Figure 3-2 D to G and L to O) was segmented and unpowered. The vehicle was intended to roll around the 25-foot radius curve from inertia. The segmented belts were removed because they caused the vehicle to slow down too much. The vehicles were able to traverse the turn when going south toward the Student Union, but were unable to traverse the curve in the opposite direction. This was attributable to insufficient distance to accelerate the vehicle prior to the curve when traveling northbound. The small 25-foot radius turn caused the vehicle to experience a significant lateral acceleration and significant loss in velocity. Because of the velocity mismatch the vehicle experienced a considerable jerk when it reached the other belt. The belt similarly experienced a high dynamic load, causing a belt splice problem and head-pulley lagging unbonding problem.

These problems were corrected in the Phase IB (DOT) development by the introduction of a belt take-up system which applies a constant belt tension through a set of weights. The main drive belts were reduced from five to two, and only these have take-up systems. The take-up system was only used for the two main drive belts. The acceleration and deceleration belts, on the other hand utilized preloading. The preloading technique, in this case, was satisfactory because the short lengths of belt (approximately 40 feet) did not elongate enough to unload the belt and cause slipping.

The belt take-up system on the main line drive belts performed extremely well. Fewer belt training and splice problems were experienced. The fluid coupling in the main line belt drives and take-up system greatly reduced jerk and dynamic loading on the belt as vehicles transitioned from one belt to the other. The function of the fluid drive coupling was to limit the torque and hence the power in the belt. Although not absolutely necessary, the acceleration and deceleration belts would experience lower levels of stress if fluid couplings were used in their drive systems.

The belt take-up system also acted as a jerk limiter for vehicles traversing mainline belts. A viscous oil in the tubes surrounding the take-up weights provided damping to the belt take-up system. This damping resulted in a very smooth operation of the system.

The belt take-up system did not require any significant maintenance. It was necessary to change the bearings on the long belt, head-pulley from a two-bolt mounting configuration to a three-bolt because bolts had come loose after some 40 hours of operation and were showing signs of significant shear levels indicating higher applied loads than the design loads.

The cable on the lower pulley of the take-up weight system was found to have come off on a few occasions making it somewhat harder to lower and raise the weights when repairing belt splices. This problem also caused the weights to hang up a few times, thereby unloading the belt. As a consequence this usually resulted in failure of a belt splice. Therefore, it is necessary to correct this defect by adding a guide to the lower pulley to ensure that the cable stays on the pulley when unloading belt for inspection or repair.

The long belt on the mainline was brought around the 125-foot radius curve in one continuous belt by successive chordal turns. The chordal turns were accomplished by running the belt over pulley frames which turned the belt through small angles. The vehicle wheel describes a radius while traversing the curve radius. This applies a lateral force to the belt. The lateral force resulted in a belt kick-out, or crossover problem, on the inner radius. The corrective measure was to mount clips on the guideway to guide and constrain the belt. Although this does the job, it frays the edge of the belt during vehicle traversal. It was found that the two inside pulley frames were mis-located by approximately two inches. Thus the vehicle wheel would move completely off the belt kicking out the belt for a short time. Consequently, it is necessary to relocate these two pits for a completely satisfactory solution. In addition to this correction, a wider belt, perhaps as much as eight inches wide, would be desirable to increase the lateral stability of the belt and to keep the curved trace of the wheel more centered on the belt. Although a wider belt was thought to be desirable prior to entry into the Phase IB (DOT) development, it was not possible to make this change without incurring major costs; that is, all pulleys and frames would have to be changed.

The lagging material supplied for the drive pulleys by Bandag Tire Co. performed well. No failures or problems were experienced with the vulcanized, siped lagging material. No wear was evident after about 600 vehicle trips, indicating this is not likely to be a high maintenance item. However, because friction does exist, wear undoubtedly takes place. The number of vehicle trips prior to replacement should be determined.

Belts

Four generations of belts were used during the development process. The first belt was manufactured by Habersett Belt Co. under a Swiss license. This belt was a polyethylene impregnated, polyester fiber belt with a top cover of highly textured rubber and a bottom cover of polyethylene. As previously indicated the coefficient of friction on the stainless steel slider bed was considerably higher than expected, about 0.15, and was even higher in wet weather. This resulted in a large number of belt splice breaks. Therefore, the polyethylene back cover material was removed, lowering the coefficient of friction to about 0.07.

Although the back belt fibers were exposed and slid along the slider bed which collected considerable dirt and debris, little or no noticeable wear was evident. The belt edges under normal tension curled up leaving only about two inches in the center in contact with the slider bed. The belt has a tendency to clean debris from the center and deposit it along the edges. For the most part only the weight of the belt acts on the slider bed thereby applying a small load (0.45 lb/ft). The exception is when the vehicle's driven wheel is on the belt, which then locally adds the normal weight of the wheel to the belt. In wet conditions the upper textured surface of the belt captures a considerable quantitiy of water increasing its weight per unit length above the dry weight. Overall the belt performance was good, having a low wear and no breakage of the parent belt material. It did nowever suffer from a serious belt splice break problem. The belt manufacturer guaranteed bonded splice joints that would be equivalent to the parent material, but was unable to produce a joint that was in excess of 65 percent of rated load.

The method of splicing this belt was to bond the belt with a bonding agent suplied by the Swiss manufacturer. The splice was a lapped, skived joint (i.e., each end was tapered). Curing of the bond required a minimum of 45 minutes with at least one hour of cool-down. The total minimum time including skiving and releasing the belt tension was 2.0-2.5 hours depending on the location of the splice break. However, splices made at this fast curing time generated only 65 percent of the maximum expected belt load rating of 750 lb. Good bonds generating approximately 85 percent of the maximum belt rating of 750 lbs., required roughly 24 hours to cure. The variation in performance of these good bonds was relatively small. But, the variation in two-hour bonds was considerable. Two-hour bonds were considered temporary and were only used to put the system back into operation.

A two-hour down time, however, was unacceptable from the standpoint of system availability. Mechanical belt splices were not possible with this belt because of the weave construction. A single mechanical splice was tried and pullout was immediate.

During the first part of the Phase IB test program belt splices became a serious problem when a large number of belt splices started breaking and new 24-hour belt splices were achieving only a 450-lb breaking strength. At first it was thought that the bonding material purchased from the Swiss manufacturers was defective. But after considerable investigation of that bonding material and several other bonding materials, it was decided that the problem was not with the bonding material. Several cleaning agents and skiving techniques were also investigated. It was determined that the inter-layer bond between the rubber and polyester fiber belt had deteriorated over the three-year time span and had caused a chemical reaction with the splice bonding material. After a considerable effort, a chemical cleaning agent was found that would permit bonds of 85 percent of the rated load. Although the fatigue life was relatively poor, the load carrying capability of the belt was adequate, albeit marginal under wet conditions. However, this did not cure the availability problem. It was subsequently decided to change the belt to a design which would permit the use of mechanical splices.

The requirements for the third generation belt were:

1) a belt with sufficient load carrying capability for all loading conditions;

2) a low coefficient of friction on the bottom surface that would be insensitive to temperature and weather conditions;

3) a high coefficient of friction on the upper surface consistent with a head-pulley lagging material to minimize the angle of wrap;

4) a small expansion coefficient; and

5) a quickly spliceable belt to maximize availability.

The belt selected was the Unilok belt manufactured by Georgia Duck and Cordage Mill. The basic stress members were a polyvinlychloride (PVC) impregnated, polyester-filament, solid-woven, single-ply carcass. The upper and lower covers were made of PVC and spun polyester fiber. The more common name for polyester yarn is Dacron (Dupont's trade name). Because no previous breakage problem had been experienced with parent belt material, a polyvinylok, type PVK-150, was selected with the 150 lbs/inch of width maximum load capability. This belt has a thickness of 13/64 inches, weighs

0.54 lbs/foot, and has an ultimate tensile strength at rupture of 1500 lbs/inch of width. The minimum recommended pulley diameter was four inches. But, all drive pulleys were changed to a 12-inch diameter because of drive friction considerations. A mechanical alligator splice clip was utilizable with this polyvinylok belt.

The coefficient of friction of this belt was found to be too high, causing the burn-out of a drive motor. Georgia Duck and Cordage Mill was requested to produce another belt but without the bottom cover. The manufacturer produced a fourth generation belt without an upper or bottom PVC cover; leaving the PVC and spun polyester fibers in contact with the slider bed. The coefficient of friction of this belt was considerably reduced, but above the manufacturer's expectations and above the coefficient of friction of the second generation belt. To accommodate this increased load, the main-line drive motors for both the long belt and the hill belt were changed from 10 horsepower to 15 horsepower.

In wet weather conditions the belt absorbs and retains so much water that the power to move the long belt is roughly doubled from that of dry conditions. That is, 29 kW are needed to move the long belt in wet conditions, whereas 16 kW are needed in dry conditions. This represents a small overload to the motor. The application of a vehicle on the long belt in wet conditions would greatly overload the motor causing circuit breakers to trip. Therefore, the long belt is not usable in wet weather. No problems were experienced with the shorter hill belt in wet weather other than increased power consumption. However, because of the shorter length and fewer idler pulleys, the hill belt motor was not overloaded and had sufficient capacity to power a vehicle at-speed up the 7.5 percent grade. Therefore, a higher horsepower drive motor for the long belt is one solution.

A second solution is to go to a fifth generation belt with an upper cover, but without a lower cover. The upper cover would minimize the amount of water collected on the upper woven surface and wicked down to the fiber interstices. The upper cover would of course not prevent water from entering the belt through the lower surface. This could be prevented by a suitable lower cover material. Finding such a material does not seem likely. Although the current belt sheds water, there is a greater quantity of water retained than the second generation. The suspected reason is the difference in weave construction. The second generation belt had a very close weave construction as opposed to the more open polyvinylok design. Revising the belt carcass construction to a more close weaved design does not appear to be consistent with the requirements for mechanical splices. Shortening the belt is, of course, the converse of increasing the horsepower. Sufficient data was generated during the development program to adequately design a fifth generation belt.

Mechanical belt splices greatly reduced the time required to splice belts from about 2.5 hours to about 20 minutes. However, numerous splice failures occurred because of clearance problems and edges that would catch the alligator clips. Mechanical alligator fasteners would not fail entirely (see Figure 6-1). Rather edges of the clips would be torn up making it necessary to replace the clip prior to failure. Nonetheless considerable time was spent during the development program replacing splices. The splice problem was considered to be the single most difficult problem during the Phase IB development program.

It was not possible to put a cover of either PVC or rubber over the alligator fastener because of clearance and several small four-inch diameter idler pulleys that remained from the Phase IA activity. On the hill belt and acceleration and deceleration belts no failure of the mechanical fasteners was observed, only edge catching failures. However, on the long belt several pullout failures were observed indicating an excessive load for the splices. As previously indicated, one potential solution is to make the belt wider; increasing the load carrying capability of the splice. In the test system this would mean a change to the entire belt drive system. An accompanying change to the vehicle wheel width would also be necessary because a stress distribution concentrated in the center of the belt could still possibly over-stress the splice. An alternative is to increase the belt thickness and the load carrying capability of the belt and splice. This would require changing the 4-inch diameter idler pulleys to 6-, 8-, or 12-inch diameter and could possibly mean changing the four pits to accommodate the larger pulleys. This change would have the least impact on the overall system, but may not facilitate the belt kick-out problem at the curve. Lowering the load on the long belt is yet another alternative.

Although the mechanical splices serve to improve the availability problem and have been demonstrated to last through at least a day's operation, they did not prove to be the long-term solution on the long belt which the belt manufacturer claimed. To achieve a long-lived splice with the Polyvinylok design several designs of sewn splices were tested. Sewn splices were butted together and either stitched across the belt or the stitch was crossed over at the butt. In all cases PVC covers were used to protect the threads from abrasive or catching damage. The PVC covers were vulcanized over the splice joint making it a long term process, i.e., about 2 to 5 hours. Stitched splices across the belt were done with a conventional leather sewing machine. Stitched, crossed-over splices were done by hand and took roughly two hours to make. The stitched splices considerably out-performed the mechanical splices on the long belt by at least a factor of 4 to 1. However, all stitched, crossed-over splices failed within about forty hours of operation. Some pull-out failures were observed indicating stresses higher than the bond strength and locking strength of the belt. The majority of failures were however, associated with overstressing of individual threads which further weakened the splice and led to its ultimate failure. It would appear that bending stresses of the individual threads were too high. Some degree of success has been achieved with a stitched splice across the belt. This splice has not failed and is still operational at the end of the Phase IB development testing. Further testing is needed to determine how long this splice will last before failure.

A few mechanical splices on the hill belt are original indicating that making the load smaller is a definite alternative to solving the splice problem. The fourth generation belt has been demonstrated to be satisfactory for the shorter hill belt and has been tested with the maximum possbile loading of two vehicles. Because the applied loads on the long belt were greater than the belt splice capability and because several alternatives were tested, a data base was developed that would now permit practical design of a fifth generation belt for the engineering prototype system, and as a matter of fact, for any other system. Tradeoffs of length of belt, load, and cost per foot of belt are now possible. A fifth generation belt is needed to resolve the problems associated with the long belt. The fifth generation belt would be a polyvinylok type construction with a load rating of 315 lb/inch of width. Its thickness would be 17/64 inches and would weigh 0.705 lbs/ft. Note that the load carrying capability is increased by a factor of 2.1 and the weight by only 1.3. To maintain a low coefficient of friction the spun polyester fiber back impregnated with PVĆ would be used directly on the slider bed without a back cover. The upper covers would be of a textured rubber to decrease the water absorption and provide a higher coefficient of friction for the drive pulleys and for the vehicle/belt interface. The increased load capability would permit the use of mechanical splices and would greatly enhance the life of a splice.

In summary, the belt splice problem has proven to be among the most difficult encountered during the development process. Since the belt reliability and availability are crucial to the success of Transette, its problems required utmost attention. A satisfactory belt design for shorter lengths such as the hill belt was successfully demonstrated. However, this belt design was not satisfactory for the long belt with its associated higher loads.

A data base was developed, heretofore not possessed by belt manufacturers, that should permit practical design of a fifth generation long belt. Although this fifth generation belt has not been tested and further problems could be discovered, enough alternatives exist to potentially solve the long-belt problem. As a result of this program belt technology for transportation applications has considerably matured.

6.5.2 Guideway

The guideway of the Transette engineering prototype system includes the major design elements of an urban system. Loop operation with two on-line stations, an off-line station, and a 7.5 percent grade have been successfully demonstrated.

The at-grade guideway is a simple eight-foot wide, four-inch thick concrete slab with a center-mounted guiderail. Based on the judgement of the assessment team the estimate of the ride quality was moderate. The principal causes for the moderate ride quality were poor concrete surfacing, small wheel diameter, and a short wheel base. The concrete was screeded laterally rather than longitudinally; resulting in a somewhat rough surface. Furthermore, two large patches were put into the guideway when a large steam pipe and drainage culvert were put under the guideway after it was constructed. A few significant guideway perturbations resulted. These considerations affected heave and pitch. The small twelve-inch diameter trailer wheels were used for convenience in fabricating the body and chassis and for their availability. Future vehicles will utilize larger diameter wheels and a longer wheel base to minimize the effects of guideway perturbations.

Thermal expansion joints were placed in the guiderail at 60-foot intervals. They presented no problems, indicating an adequate design over the temperature range of approximately 20^{o}F to 110^{o}F. The four-inch guiderail channel depth did not permit sufficient clearance with the 60 p.s.i. tire pressure. At certain locations on the guideway the vehicle will bounce and rub on the upper flange of the guiderail. This contributes to moderate ride quality and to noise. In the future the guiderail channel would be made at least seven inches in depth allowing the use of larger primary suspension wheels and larger steering wheel and support components.

The lateral ride quality component was poor and was attributable to small radii turns (25 feet) of the curve and at the acceleration and deceleration belts and main belt transitions. Cost dictated the use of these radii. It was thought that at speeds less than 15 mph, the lateral ride quality would not exceed the ISO 2631 standard. After the Phase IA development was completed, it was clear that the lateral acceleration on the curve was in excess of 0.15 g's. Subsequently, the curve radius was increased to 125 feet. This lessened the severity of the curve. However, the transition into the curve could be considerably smoother. The application of spiral transitions at the acceleration and deceleration belts would also enhance the lateral ride quality.

The vertical ride quality component is good except at the bottom of the hill belt in the region of transition from the main belt to the deceleration belt. At this point the vertical component is noticeable but not too severe. To correct the test track, considerable filling and concrete construction would be required over a length of track of some 40 feet.

6.5.3 Carousel

Prior to the start of the Phase IB development, the carousels were functional, but an interference problem existed with the vehicle. This occurred because the carousel was fabricated with a smaller diameter than the design diameter. The availability of two scrap steel rings at a very low cost were the motivating factors. At the time of this decision the vehicle chassis were fabricated. The interference problem was slight, necessitating a push to get the vehicle around the carousel. Furthermore, a drive slippage problem also existed. To correct these problems, three design alternatives were investigated: 1) making a larger diameter carousel, 2) introducing Ackermann front-wheel steering with an auxiliary guidance rail, and 3) introducing dual, wagon-wheel steering with a smaller turning radius.

The first alternative would have required significant landscaping work on the north carousel and would have been the most expensive alternative. No changes to the vehicle were necessary.

The third alternative, although perhaps the best solution technically, had the greatest technical risk and would have required a considerable amount of time to develop. The second alternative would do the job at the lowest cost in terms of both time and money. Technically this front-wheel steering solution was not as good as the dual, wagon-wheel steering from a number of considerations. First and foremost, the front-wheel steering approach required the steering to be switched from the left-hand guidance rail to the unguided right-hand side at each carousel. This is a function that does not need to be performed with the dual, wagon-wheel steering approach. The increase in number of functions was tantamount to a decrease in reliability. Secondly, when the vehicle steering has disengaged the switching arm, the vehicle is not positively retained. The vehicle is positively guided by the auxiliary traction rail which is engaged by another set of wheels prior to disengaging the switching arm. Although the vehicle is not positively retained, safety is not a real issue, since the vehicle moves around the carousel at three miles per hour, and since the forces are directed inward toward the carousel keeping the left rear vehicle wheel on the prime mover carousel ring. The dual wagon-wheel steering system, on the other hand, is positively retained at all times by a continuation of the guidance channel except when switching to an off-line station. In this instance both approaches are positively steered during off-line switching and are equivalent. Finally, the front-wheel steering approach has a multiplicity of wheels that are maintenance problems and potential reliability problems. The vehicle-mounted switching cam which strikes a guideway-mounted cam plate produces the highest noise level source (approximately 92 dBA) measured over the entire guideway. The dual, wagon-wheel steering approach on the other hand has a multiplicity of links, but in this case the wheels are almost always in contact as compared to the front-wheel steering approach which has wheels and cams switching at each carousel from lock to unlock and back to the lock position and are engaging the guideway with high impulsive forces. Therefore, implementation of the dual wagon wheel steering system is recommended to alleviate the problems associated with a smaller than necessary carousel ring.

The smaller diameter carousel ring resulted in tire scrubbing and a clutch adjustment problem since a 1:2 ratio of the inner to outer wheel track radius was not present. Because this ratio was not maintained it was necessary to allow some slippage in the clutch while the vehicle traveled around the carousel. If insufficient clutch slippage was allowed, the rear tires would scrub. However, the clutch slippage necessary to permit traverse of the carousel resulted in a slower acceleration up the hill with increasing loads. This manifested itself in numerous adjustments of the clutch to achieve the best performance. Therefore, a device to automatically adjust the vehicle clutch is recommended. Proper alignment of the front steering wheels was somewhat of a problem initially and resulted in considerable wheel wear. This required the replacement of several tires. It is not expected to be a continuing problem, but one that might be solved with the use of a proper alignment tool.

The carousel ring drive surface is approximately three-quarters of an inch above the concrete surface. Since three wheels are on the concrete and one wheel is on the carousel ring the vehicle rides on three wheels and is canted. Depending on the weight distribution, the vehicle would either be canted forward or aft. This affects the traction effort and velocity of carousel traversal. It also contributes significantly to tire wear. A corrective measure is the addition of either a fiberglass or concrete pad for the two outboard wheel tracks.

The carousel drive system was modified to eliminate drive slippage. A belt drive on the vertical member of the carousel ring was added along with dual, take-up pulleys. Overall, the carousel performed extremely well. Indexing of vehicles from unloading to loading berth was also performed very well. Any problems associated with the carousel operation were not the fault of the carousel but rather of the vehicle with the exception of the height mismatch problem discussed above.

6.5.4 Vehicle

The Transette passive vehicles are simple, consisting of an integrated fiberglass body with a semiautomatic or automatic door, a chassis with a four-wheel suspension and steering system, and a 1:2 step-up gear drive and slip clutch. Overall the performance of the vehicles was satisfactory after a number of problems were systematically eliminated.

From a human factors point of view the four-passenger design is satisfactory regardless of the lack of airconditioning. Sufficient space is available for four passengers. The integrated, individually partitioned seats and the nature of their design make them comfortable for a very broad range of people including 10th percentile females and 90th percentile males. Handicapped and elderly were not tested. Elderly would not have a problem except on the initial step into the vehicle of 14 inches. Some type of a platform was planned and is necessary for the stations. An 8- or 9-inch step should be installed which would be consistent with other public facilities. The test system was not designed to accommodate wheelchairs. A ramp up to the edge of the vehicle would present some type of problem for ambulatory people in that the vehicle has stooping accommodations and entry would likely result in a large number of people bumping their heads initially. After a learning period this would be eliminated or at least minimized. The step into the vehicle almost entirely precludes this problem.

Because the measurement system failed, quantitative ride quality measures were not taken and therefore could not be compared with ISO 2631. Qualitatively the ride as previously indicated was based on the judgement of the assessment team was moderate. This is attributable to a narrow, short-wheel base vehicle with small-diameter wheels intersecting with a concrete guideway that was screened laterally rather than longitudinally. The treatment resulted in a rough guideway with short-spaced undulations. The air-bag springs and oil-filled shock absorbers eliminate the major high frequency accelerations. However, the lower frequency pitch and roll oscillations are noticeable, but not objectionable. The lateral ride quality component is the most noticeable. The Phase IA 25-foot radius curve resulted in a very high lateral acceleration. This was subsequently corrected in the phase IB effort by utilizing 125-foot radius, thereby greatly reducing the lateral acceleration. The transitions into and out of this curve are noticeable. A spiral entry and exit and superelevation would enhance the ride quality, but at a considerable expense. The transition radii at the acceleration and deceleration belts with the main belt are also small and result in noticeable lateral accelerations. Spiral transitions would decrease this component. The vertical radius at the bottom of the 7.5 percent grade in the northbound direction is also relatively small and results in a noticeable vertical acceleration. The vertical curve radius should also be increased. The tire diameter is thought to be too small. A larger diameter tire would provide a larger elliptical contact area and decrease the effect of guideway roughness. Future vehicles are expected to have larger diameter tires and a longer wheel base. The longer wheel base will improve both pitch and heave.

The door operates in both an automatic and semiautomatic mode. The door opening device is unique and inexpensive. A linear actuator is used with cables and pulleys to open and close the door. A friction element provides a door override capability for safety. This is in addition to the electrically actuated door safety edge that reverses the motor direction. If the door closes on a person, a load of up to 30 pounds will be applied if the door safety edge fails to function. Therefore, if there were an accident or a fire onboard, a person could simply push open the door; albeit with some difficulty.

Although several techniques were investigated, a door locking mechanism was not incorporated. It was thought that it would be in the best interest of the passengers to be able to overcome a door in any emergency. Whereas this principle appears sound, care must be taken to insure that door forces in the event of a collision do not open the door and allow the passenger to be ejected from the vehicle. Because the door opens rearward, a "brick-wall stop" would only serve to keep the door closed and the passengers in the vehicle. If a vehicle were struck by a following vehicle the door could be thrown open, but this is unlikely at these low speeds. It would be necessary to run tests to determine the elasticity of the body shell and chassis. A further difficulty with this approach is that a passenger may force the door open and jump from the moving vehicle.

The door opening device is operated by a 12-volt battery that is easily accessible from a shelf under the rear of the vehicle. Although a battery charging alternator was not added to the vehicle, it was intended to introduce an alternator driven by the rear-wheel drive.

To select the mode of door operation (automatic or semiautomatic) it is necessary to operate a switch under the rear of the vehicle, on the battery shelf, where the door opening electronics are mounted. Thus, demand responsive operation cannot be selected without this maintenance action. The door opening delay can be varied for automatic door operation. This is done by manually adjusting a potentiometer.

The cost of the parts for the door opening device was approximately $400. Assembly time was not extensive. The cost even in limited production is estimated to be under $1500; considerably under the cost of available door openers. The linear actuator used a set of spur gears for gear reduction. These gears generated considerable noise. Helical gears are available with these linear actuators that would greatly reduce the noise level. This would eliminate the one undesirable feature. Overall this lightweight, low cost door opener design is novel, offering an advance in the state-of-the-art.

The steering and suspension components presented a number of vehicle problems and required a significant amount of maintenance. Throughout the performance test program and into the early part of the reliability program, systematic maintenance of the vehicle was not performed. Steering sustained considerable wear and damage. Suspension wheels also showed significant wear and cuts. Tire wear was caused primarily by the carousel. As the number of cycles on the system increased, rubber particles were accumulated on the guideway around the carousel. This was a result of tire scrubbing that was caused by insufficient clearance of the steering control rod to permit the wheels to achieve an angle tangent to the carousel curve radius. At least 5 degrees difference was found between the steering angle and the tangent. With a correction of the steering angle tire scrubbing and wear was not measurable over the remaining test cycles.

Vehicle binding on the south carousel occurs even with a perfectly aligned vehicle steering system because of imperfect alignment of the deceleration belt with the carsouel circumference. This lateral misalignment is about one inch. The binding was further accentuated by a bent caster on the rear of the No. 1 vehicle that forced the vehicle rear into the carousel. The function of the rear caster was to keep the rear wheel on the carousel. The vehicle was tested without this caster and tracked well; indicating that the forces were directed inward as anticipated. This binding problem would be precluded with the dual, wagon-wheel steering design previously discussed.

The steering system was designed to positively retain the vehicle by means of a set of wheels on either side of a 4-inch channel. The outboard wheels are used for switching, in addition to guidance, and therefore are movable. To ensure that the switching wheels are moved synchronously and are down and properly locked in place, a system of cross-linked connecting rods was designed to connect the outboard switching wheels on each side of the vehicle with the cam actuator. A set of feedback rods was included to insure the system is positively locked. The feedback rods were attached to different parts of the fore and aft steering wheel side connecting shaft to introduce a torque. This torque must be overcome to switch the wheels. The cam actuator interacts with fixed blades at each carousel and a movable blade at the off-line station to effect switching.

This system worked well throughout the Phase IA effort and the performance test portion of the Phase IB effort. However, during the reliability testing, bearing wear had occurred on the switching cam actuator to the point of allowing over one inch of play. Because the system was designed to account for a considerable amount of play, and because only small adjustments were made to the cross-linked connecting rods over time, gauge dimensions were not used during the course of these adjustments. But, because of the excessive play in the cam, excessive adjustments were made to the connecting rods resulting in the bending of both the fore and aft steering wheel side connecting shafts and the locking feed back connecting rods. Furthermore, these adjustments did not allow the bell crank to go beyond center to provide the initial lock. The result of these maladjustments and bent links was that the steering wheels on the No. 1 vehicle were not properly locked in place although it required a larger manual effort than usual to switch and lock the wheels.

During the reliability test program there were three occasions where sufficient vertical force was generated on the front steering wheel to move the wheel up and allow the front of the vehicle to suddenly turn right. On two of these occasions the No. 1 vehicle struck a sensor and on another it struck the fence. The rear set of guide wheels did not move and kept the aft end of the vehicle locked to the guiderail. At first it was thought that irregularities in the guideway were the cause and were subsequently smoothed out. However, after the second and third occurrences which followed within a very few runs the vehicle was disassembled and a systematic investigation revealed the above maladjustments and cam wear. The vehicle was corrected and adjusted in accordance with gauge dimensions. From that point in time the vehicle's performance was normal and without failure. Although this was a serious problem, it is considered not to be a fault of the design but of maintenance practices. With use of gauge dimensions and reasonable maintenance this is unlikely to recur. However, to ensure this will not recur a redesign of the locking mechanism is recommended to achieve a design tolerant to maladjustments.

The problem does however, point out a possible single-point failure mode. If the outboard steering wheel on the left side of the vehicle were hit by an object in the guideway or the bolt that holds the wheel on fails in some manner losing the wheel, then an accident may occur. This element is critical because the front wheels are steered by the two inboard guide wheels and the outboard switching wheel. Without the outboard steering wheel, steering control would be lost. To ensure safety,the front switching wheels could be made redundant. Then loss of any one wheel would not cause loss of steering. If loss of the aft switching wheel occurs there is likely to be little or no effect because the front steering wheels will direct the vehicle in its track and maintain the drive wheel on the belt. In this event the vehicle might experience a slight wandering motion that would be of no consequence.

The wear on the forward switching wheel is considerably higher than on the aft switching wheel; a factor greater than 2:1. The forward switching wheel provides a steering force, but this force is not sufficiently large with this light weight vehicle to account for the wear. The wear is thought to result from the scrubbing action on the switching wheel that occurs because of the vertical motion of the chassis. One possible way of eliminating this problem would be to caster the switching wheels. Such a mechanism would complicate the steering system and would itself require maintenance. Therefore, the trade-off between increased complexity and frequent replacement of wheels should be carefully examined. A softer switching wheel which would permit greater slip is another alternative. Minimizing the vertical motion by introducing solid rubber wheels and using a longitudinally screeded concrete or smoother steel guideway is yet another alternative.

Performance anomalies were evident in operation on and around the carousels and during acceleration up the hill from the north carousel. The vehicles would move slower or have a tendency to pause at some points of operation. These were accentuated by passenger load variations. As a result, numerous clutch adjustments were necessary to obtain smooth operation. Vehicle clutch adjustments were the most significant maintenance item. To make these adjustments, it was necessary to stop the vehicle and manually adjust a screw on the aft end of the chassis. These stoppages were counted in the reliability testing and contributed to the unavailability of the vehicle.

The reason for these speed performance anomalies was attributable to the smaller carousel radius than called for in the original design (see carousel discussion above) that did not allow a 1:2 ratio of vehicle outer driven wheel radius to the drive wheel radius. Since the step-up gear ratio is 1:2, slip must occur either at the outer wheels or in the clutch. If the clutch were adjusted for proper acceleration up the hill with three equivalent passenger weights on board, then insufficient clutch slip would cause the outer wheel to scrub. Performance with one passenger was very good, achieving smooth operation after the first four runs which allowed the clutch oil to warm up. Performance with two passengers was satisfactory with few difficulties. In this case, the vehicle time to go up the hill is significantly increased (see Figure 4-5). Performance with three was considerably worse. With four passengers, the vehicle either just barely makes the hill, taking simply three to four times longer than the two passenger case, or it will not go around the carousel. A very precise clutch adjustment is needed to operate the four-passenger case.

The original Phase IA design had included a design for an automatically adjustable clutch with load variations to insure that maximum accelerations are not exceeded and to keep average accelerations constant. Cost considerations precluded its implementation. Therefore, implementation of an automatically ajustable clutch in Phase IB was to be accomplished only if time and money would permit. It was not done for vehicles 1 and and 2. This was however, implemented on the new pallet-chassis vehicle with dual wagon wheel steering, but was not tested for either performance or reliability. Implementation is by a relatively simple "C" spring design and should be extremely reliable.

In addition to this problem with the vehicle drive system, several leaking oil seals were observed. The helical step-up gears with their associated end thrust were replaced by spur gears, thus eliminating the end thrust and the oil seal leakage problem.

The brake system depends on mechanical inertia which is always present in the 2:1 step-up gear-box, that is, an input of work is required to move the vehicle. Otherwise the vehicle will remain stopped or if moving will slow and come to a stop. In effect, the brakes are always on except in the instance the brakes are disconnected. A keyway on the clutch drive shaft failed. The vehicle in effect lost its brakes and rapidly coasted into a station. To prevent a recurrence the keyway was made significantly larger and longer. It is expected that such an event will not recur once the upper load level has been determined. This however, is a single-thread failure point that may be hazardous if proper attention is not given. For an operational system, acceptance testing should incorporate a load test to ensure that this critical single-thread keyway will not fail. Keyways can be made redundant, but the drive shaft itself would still remain a single-thread element. Therefore, a sufficient factor of safety is perhaps the most practical approach. A solution to this, is to introudce redundant drive systems as has been implemented on the new pallet-chassis with dual drive and dual wheel steering.

The fiberglass vehicle body was not designed for fire safety. A fire retardent chemical must be added to an operational vehicle. Furthermore, an active fire extinguishing system such as Halon 1301 may also be incorporated to account for carry-on materials that can be ignition sources. The integral body shell and seat design does make it easy to clean the vehicle, thus increasing the likelihood of eliminating such ignition sources. Vandalism, (i.e., setting of fires in the vehicle) can only be countered by an active fire extinguishing agent.

In summary, the vehicle was a source of numerous problems which have, during the course of the Phase IB effort, been systematically eliminated. The corrected vehicle is thought to represent a significant improvement - especially in terms of reliability. The test system has served to indicate what improvements need to be made to achieve a given level of performance. To fully eliminate all vehicle problems and obtain significant improvements in performance and reliability in an operational system, the improvements incorporated in the new pallet-chassis system such as the dual drive, dual wagon-wheel steering, and automatically adjustable clutch should be incorporated. These however, must be tested in an operating environment prior to implementation of an operational system.

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