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TRANSPORTATION SYSTEMS TECHNOLOGY: A TWENTY-YEAR OUTLOOK

TRANSPORTATION SYSTEMS CENTER
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16. Abstract

In this report an overall technology assessment of new and improved transportation systems is given. A broad survey has been made of new systems concepts for passenger and freight transportation in urban and interurban applications. Results of the findings are reported and projections of expected innovations and improvements are made along with discussion of some of the major limitations to wide scale applications over the next two decades. Recommendations for research and development emphasis in some of the more promising areas are given where possible although full analysis of cost factors and comparative analysis of competing systems were beyond the scope of this investigation.

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PREFACE

This report would not have been possible to prepare without the assistance and cooperation of many staff members at the Transportation Systems Center. Major contributors to the effort included the following:

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George Kovatch
Project Manager

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LIST OF ABBREVIATIONS

ACI	Automatic Car Identification
BART	Bay Area Rapid Transit
CARD	Civil Aviation Research and Development
CBD	Central Business District
DMS	Dual Mode System
DOT	Department of Transportation
FHWA	Federal Highway Administration
FTL	Fast Transit Link
FRA	Federal Railroad Administration
GVT	Gravity Vacuum Tube
HSGT	High Speed Ground Transportation
LADOA	Los Angeles Department of Airports
LIM	Linear Induction Motor
MAC	Major Activity Center
MGS	Moving Guideway System
MIT	Massachusetts Institute of Technology
MMS	Multimodal System
MU	Multiple Unit
NECTP	Northeast Corridor Transportation Project
OECD	Organization for Economic Cooperation and Development
OHSGT	Office of High Speed Ground Transportation
PAS	Public Automobile System
PRT	Personalized Rapid Transit
SES	Surface-Effect Ships
SPP	Speed-Payload Product
TACRV	Tracked Air Cushion Research Vehicle
TACV	Tracked Air Cushion Vehicle
TALUS	Transportation and Land Use Study
UMTA	Urban Mass Transportation Administration

1. INTRODUCTION

1.1 BACKGROUND

This study was undertaken by the Transportation Systems Center at the request of the Office of Systems Analysis and Information in support of the 1972 National Transportation Needs Study. The request was coordinated through the Office for Systems Development and Technology, which provided its funding. Preliminary planning was documented in PPA OP01 and detailed in a Technical Project Plan dated December 17, 1970.

The major goal was to prepare an Intermodal Technology Assessment leading to a final report which documents transportation systems and technology status and forecasts possible future developments.

1.2 PURPOSE OF THIS REPORT

This report documents the findings of the technology survey made of various new transportation systems, the analysis performed on some associated critical questions, and the forecast of possible future developments. It is written in a generally non-technical form, with highlights of future possibilities given where appropriate.

1.3 APPROACH AND METHODOLOGY

The approach taken in this study was first to divide the broad transportation field into areas which reflect some of the most pressing problems for which technological change is important. The source of these priority questions was a TPI policy memo dated May 22, 1970. This was summarized to produce the following priorities:

1. Urban Passenger Transportation

    a. Provide alternatives to the automobile in urban areas during peak hours and increase demand for these alternatives.

    b. Reduce automobile air pollution in key urban areas.

    c. Increase efficiency of peak hour movement of people traveling by automobile in urban areas.

2. Interurban Short Haul Passenger Transportation

    a. Improve high speed intercity short haul transportation for passengers.

3. Urban/Interurban Goods Movement

    a. Improve efficiency of intercity and urban area goods movement.

4. Interurban Long Haul Passenger

    a. Increase efficiency of air travel while maintaining air safety levels.

Against these priorities the various new systems concepts and proposals were reviewed. For example, for the first priority area, Urban Passenger Transportation, transportation requirements were considered and categorized into three main types: 1) Major Activity Center requirements, 2) Community level requirements, and 3) Metropolitan service requirements. Major Activity Center requirements are characterized by the need to transport moderate volumes of people over short distances. Community level service typically must handle low demand levels in low population density areas over medium urban distances. Metropolitan service requirements, similar to commuter service, are typified by heavy volumes of people moving in corridors between suburbs and major activity centers.

A number of new transportation systems have been suggested to meet these requirements. Moving Guideway Systems and Public Automobile Systems would serve Major Activity Centers. Personalized Rapid Transit Systems and Dial-A-Ride systems offer potential for Community level service. Dual Mode Systems, Fast Transit Links and Personalized Rapid Transit Systems would serve Metropolitan Level requirements. Results of the investigation of each of these system types are given in the next chapter.

The methodology used was primarily of a survey type with a qualitative analysis of the information collected. Approximately 1000 documents, including technical reports and new system studies, were reviewed. Telephone contacts and personal interviews were held with systems analysis groups and equipment manufacturers. Limited quantitative analysis was performed to verify key conceptual questions. Weekly technical briefings were presented by project staff personnel and invited specialists to expose other team members to findings for further discussion of various technical aspects of the study. Individual findings were documented in twenty-three working technical memoranda covering the systems and technologies surveyed. These served as the basic technical data for the preparation of this final report.

1.4 COVERAGE

Emphasis in this study was placed first on urban passenger transportation followed next by interurban short haul passenger transportation. Goods movement was treated only in a cursory manner.

For urban passenger transportation a large number of new or modified systems have evolved over the past decade. Information on some 330 has actually been catalogued. These systems are in various stages of development ranging from concept only to operational. Several of these were reviewed and analyzed in some detail for this study. Others were only considered as members of a class of system. The results of these analyses are given in Chapter 3. For interurban passenger applications there were considerably fewer new and significant concepts to investigate. Findings on these are presented in Chapter 4. The freight systems survey findings are covered in Chapter 5. Some critical supporting technologies are discussed in Chapter 6.

It was not possible to consider costs to any significant degree within the scope of this investigation. Also it was not the goal in this study to perform comparative analyses of competing systems, so no selection or recommendation of the "best" system for a specific application is given.

Air transportation was not specifically considered here because results of the recent Joint DOT-NASA study on Civil Aviation Research and Development (CARD) were recently reported.

2. SUMMARY OF FINDINGS AND RECOMMENDATIONS

In this chapter the various systems proposed to satisfy future transportation requirements are identified; their applicability, state of development, and limitations and problem areas are summarized. Some general recommendations regarding the scope of future efforts are presented.

2.1 FINDINGS

2.1.1 Personalized Rapid Transit (PRT) Systems. Personalized Rapid Transit Systems were considered in "pure" or "modified" forms. A "pure" Personalized Rapid Transit System is considered to consist of small vehicles which transport passengers non-stop from origin to destination on a network of exclusive right-of-way guideways. Stations are off-line so that passenger loading and unloading does not slow down or interfere with traffic on the main line. The control of a PRT system is necessarily automatic, employing a combination of vehicle sensors and on-board controls, generally under the supervision of a central computer. A "modified" PRT would employ larger vehicles and would operate under various strategies accommodating larger numbers of passengers at the expense of non-stop individual service.

The Personalized Rapid Transit (PRT) concept is attractive for service at the Community and possibly the Metropolitan level. Its service potential is vastly superior to conventional public transit and could revolutionize urban transportation. There are, however, several formidable technical obstacles to "pure" PRT system implementation making it more realistic as a long term possibility. Twenty years or more might be needed to realize its full potential. A "modified" PRT system could be realized within a decade with some combination of operation at headways greater than the minimum vehicle stopping distance, sharing of multi-passenger vehicles, passenger transfers between lines, and walking distances greater than a quarter mile. The level of service would be significantly lower than that of a "pure" PRT system but greater than conventional transit.

It was found in this study that to advance the development of the PRT concept, additional research is needed in the following areas:

- Techniques to reduce guideway interchange land requirements.
- Testing public acceptance of short headway and small vehicle automated operation.

- Testing public acceptance of operation in small tunnels.
- Reduction of noise generated by vehicles on open guideway sections.
- Examination of the relationships between short headway operation and safety.
- Investigation of the relative merits of various network configurations and operating strategies.
- Study tradeoffs among vehicle fleet size, line velocity, waiting times and other system parameters.
- Analysis of cost-effectiveness of PRT alternatives.

2.1.2 Fast Transit Link (FTL) Systems. Fast Transit Link Systems operate within a Metropolitan area on exclusive guideways for trips covering a significant distance relative to the community's size. They link Major Activity Centers to the suburbs or to other Major Activity Centers. Depending on the community, these may involve trip lengths up to 60 miles or more.

A number of vehicles can provide Fast Transit Link (FTL) service. Current rail systems can meet capacity and speed requirements with proper engineering design and adequate maintenance of vehicles and track. Development of active suspension systems and lightweight vehicle designs would provide comfort and performance significantly greater than that now achieved. A problem of present day rail systems is the large amount of wheel noise generated. Extensive research could result in significant reductions in the noise level. Presently rail FTL systems are uneconomical for service with small passenger loads. Development of a class of vehicles that are economical in this type of service would be advantageous. New vehicle designs allowing a more even distribution of weight would reduce the necessary massiveness of elevated track structures.

New wheeled vehicle concepts being proposed for FTL systems include monorails and automatic bus-like vehicles. These claim a number of advantages over rail systems, such as lighter, less expensive guideways, quieter operation, and higher ride quality. The validity of these claims has yet to be established.

Operation of vehicles in underground subway-like tubes offers complete isolation of the vehicle from the environment. This has advantages of weather protection, vandalism prevention, and elimination of undesirable impacts on the community. Tube vehicle systems are capable of extremely high speeds (several hundred miles per hour) if the tubes are evacuated. Tunneling costs however are too high at present to encourage rapid development of these systems. Reduced costs and increased construction speeds of tunneling could facilitate their introduction in the next two decades.

Tracked air-cushion vehicles and magnetically supported vehicles offer potential for FTL service. Both are capable of high speeds and smooth rides. Guideways can be less massive for either of these vehicles than for wheeled vehicles because of the even load distribution. The air cushion is noisy and requires continuous power to maintain it. Magnetic-suspension is still in the concept stage in the United States but in prototype form in Europe. Considerable development is required before it becomes a reality.

2.1.3 Moving Guideway Systems (MGS). Moving Guideway Systems are distinguishable by the motion of the guideway or parts of the guideway. Passengers or capsule vehicles are propelled along on the guideway surface. Two principal concepts are moving walks and passive capsules. Both are attractive alternatives for Major Activity Center transportation.

The principal function of moving walks is to transport pedestrians over very short distances. Present moving walks are limited to speeds slower than normal walking speed. Several new concepts promise speeds of 10-20 mph. Passive capsule schemes permit longer trips at higher speeds and are applicable to larger Major Activity Center application. Work is needed on hardware development, reliability testing, passenger safety, and human engineering testing for many of the proposed systems. It seems certain that few of the new moving guideway systems will be constructed through private initiative due to high costs and uncertain development status.

2.1.4 Dual Mode Systems (DMS). Dual Mode Vehicles operate as conventional vehicles on ordinary highways or streets and as completely automated systems on special, exclusive right-of-way guideways. In some proposed systems, the guideway would provide power and automatic control and guidance. In others, vehicles would be self-propelled but under automatic control.

Dual Mode Systems have their best potential in high speed, medium to long distance Metropolitan service where high line-haul volume is not required. They are particularly attractive where access to the line-haul facility is not otherwise provided by public means. They have limited applicability in Community service where exclusive guideway spacing would be similar to that of present-day commuter railroads or expressways. Discharging dual mode vehicles onto the street system of Major Activity Centers is to be avoided.

Subsystem developments such as vehicle separation and merge control have not advanced to the level where close headway operation can be handled. Short headway operation would be needed to carry more than a few thousand vehicles per hour. The attainment of necessary mechanical and electrical reliability will require much additional work. Rapid, compact, vehicle diagnostic equipment for detecting vehicle irregularities and potential failures is also needed to aid in guideway access control.

2.1.5 Dial-A-Ride Systems. The Dial-A-Ride concept exemplifies demand-responsive systems in which vehicle routes are derived in response to trip requests and are not prescheduled. Trip requests are made by telephone to a central dispatcher. The desired origin and destination is stated and the most eligible vehicle is assigned to pick up the caller. The vehicles could operate on existing highways and roads or in conjunction with automated guideways.

Dial-A-Ride Systems have potential for Community level service especially in situations where travel demands are low. Experimental systems using manual dispatching are being tried with some degree of success but all have been rather primitive to date.

Dial-A-Ride Systems can be rather quickly implemented but fully automated dispatching and communication systems need actual testing in the field. Further work on the following would enhance its implementation in more areas:

- Development of optimum procedures for manual scheduling and dispatching.
- Development of a system simulation model to aid in the evaluation of alternative vehicle configurations, service options and cost-effectiveness.
- Development of scheduling algorithms for use on small computers.
- Development of reliable digital techniques for communication between dispatching center and vehicle.

2.1.6 Public Automobile Systems (PAS). Public Automobile Systems include small vehicles located throughout an area at closely spaced stands. The passenger would walk to the stand, acquire the vehicle, and drive to his destination. There he either turns it in at the nearest public automobile stand or keeps it for his next trip.

The Public Automobile System could best serve large Central Business Districts. The system is not well suited to Major Activity Centers which are either very small, contain only one activity, or where parking is difficult; nor is it suited to wide-area, low-density community service because of large fleet requirements, low utilization rate, and redistribution problems.

It appears that existing technology is adequate to implement this concept.

2.1.7 Interurban Short Haul Passenger Systems. High-speed ground systems can provide transportation on short haul inter-city trips (50-400 miles) at speeds around 150 mph currently with potential to 300 mph in this decade. Ground systems are able to make frequent stops economically and can operate directly into large metropolitan centers. They are constrained to operate on fixed guideways which reduces their flexibility. The most likely means of achieving high speed ground transportation are by high speed rail, air cushion, and magnetically suspended vehicles.

For speeds up to 200 mph rail systems appear to be a logical choice. An extensive track network is already in existence, although considerable upgrading and repair is needed for higher speed operation. The development of active suspension systems, further knowledge of wheel-rail interactions, and the construction of light weight, high-performance vehicles may well result in significantly higher speeds than are now thought feasible. These would also reduce the degree of track reconstruction required to attain high speeds and would result in a much greater level of ride comfort than is now possible. The ability of a rail vehicle to switch from one track to another gives it a degree of flexibility in network operations that air cushion vehicles and perhaps magnetically suspended vehicles do not possess.

Air cushion vehicles offer a possible alternative for intercity short haul trips. Differences of approach exist regarding guideway configuration and air cushion design. At high speeds flow interactions between the air cushion and the on-rushing atmosphere could affect the cushion operation and limit top speeds. High speed tests of cushion are needed to investigate this and the general characteristics of stability and ride quality. Linear induction motors, the most likely source of propulsion for air cushion vehicles, require further test and examination.

Magnetically suspended vehicles are another alternative for high speed ground operations. They may well be less sensitive to guideway irregularities than air cushions. They can be operated in evacuated tubes and may be capable of higher speed operation, at normal pressures, than air cushion vehicles, since they are not susceptible to flow interaction problems. Some proposed configurations have lower levitation power requirements than for air cushions. The lift and propulsion elements could conceivably be combined into a single unit, simplifying vehicle design. The concept is still in its early development and work is required to assess its practical feasibility. Consideration should be given to design of a guideway that could be used with either air or magnetically suspended vehicles to minimize alterations in testing and operating both concepts.

Electric power pickup at speeds much in excess of about 150 mph poses a problem. Further work in the areas of contact and non-contact power pickup are required before electrically powered high speed ground systems can become a reality.

2.1.8 Urban/Interurban Freight Systems. Transportation companies are recognizing the advantages to be gained by integrating modes, where transfers at modal interfaces can be worked out. This has stimulated the development of standardized containers which simplify the transfer of goods between ships, truck, and trains. Container usage has grown rapidly during the past few years and indications are that it will continue at a rapid pace. There are many applications for automation technology in container operations. Reduction in manpower requirements in physical handling, documentation, and control can produce economies which should reduce the total cost of goods distribution and speed up the distribution process.

Truckers have recognized the individual shipper needs and have introduced many specialized vehicles such as refrigerated trucks, tankers, etc. Recent law changes in many states allow twin trailer combinations to operate. The added capacity and economy resulting from this has the additional benefit of allowing movement of more diverse goods by truck. As trucks and trailers increase in size, new size and weight standards will be needed for safety and efficiency.

A technological advance in engines for large trucks is needed to minimize air and noise pollution. Diesel and gas engines appear to have a limited potential for improvement in these areas, thus increasing the importance of new technologies such as gas turbines. Gas turbines are cleaner and less noisy than diesel or gas piston engines, and can achieve lower operating costs on long distance non-stop high speed hauling. For stop and go operation, typical in urban areas, present turbines are not efficient. Nevertheless, developments are promising and their use is expected in this decade.

Railroads are particularly suited for long haul, heavy load operations. Rail operations have been characterized by the introduction of specialty cars for different types of cargoes, heavier loads in cars, and heavier and more powerful locomotives that enable longer and heavier trains to be moved economically. Unit trains carrying cargo such as coal and petroleum are being used increasingly because of their economy. Piggyback and container operations are also increasing. The increased weights and speeds of trains are resulting in more rapid track wear. Development of new rail vehicles that distribute the weight over more wheels should help reduce this problem.

Automation of car identification and handling in classification yards has the potential of considerably reducing the time in transit for shipments. Electrification can result in significant long term economies in areas of heavy traffic.

Marine systems transport a wide variety of cargo, but the greatest tonnage is in petroleum, iron ore, grain and chemicals. Increased ship speed, increased payload, faster turn around times, and greater distance capability result in increased economies. Tankers on the order of 1,000,000 dead weight tons are contemplated. Foreign ship builders are constructing 90 ft draft tankers. Port limitations currently prohibit such large vessels from operating in the United States but developments in the next two decades may change this situation. Higher speed vehicles such as hydrofoils and surface effect ships are being developed. Future developments depend on power plants with low weight-to-horsepower ratios. Nuclear power plant developments may contribute here in the next two decades. Marine automation promises to make navigation safe and precise. Automation will reduce manpower requirements both on the ship and in port operations.

Pipelines account for about 1/5th of the freight movements at costs of fractions of a cent per ton-mile. Where volume is large and fixed, pipelines provide an excellent resource for transporting certain products. Computers are being used in pipeline operations to control valves, schedules, and accounting. The trend is toward larger diameter pipes to take advantage of an economy of scale. Pipelines do not contribute to noise or air pollution, but concern for environmental impact in case of rupture or other failure has arisen. New methods of transporting goods through pipelines are being examined. Certain dry bulk products like grains can be combined with water and carried through the pipe in a slurry form. This increases processing costs but overall costs may still be less than competing transport methods. Capsulization of materials is also of interest in geographic areas which are difficult to traverse by other modes but many technical problems remain to be solved.

2.2 RECOMMENDATIONS

Summarized below are the general recommendations resulting from this study.

2.2.1 New Systems Inventory and Technological Forecast. An activity should be established in the Department to systematize the process of cataloguing technical data on new transportation systems. The technological forecast begun in this study should be updated periodically.

2.2.2 Perform Comparative System Analyses. Comparative cost and performance analyses should be undertaken on those promising new transportation systems identified in this and subsequent studies to determine systems with wide applicability and with high benefit-cost ratios. Demonstration projects should be identified where warranted based on these comparative analyses and prior to making major funding decisions.

2.2.3 Research and Development Programs. Initiate or continue research and development on pacing technologies and new systems to increase the likelihood of successful implementation of the promising candidate systems identified in this report.

3. URBAN PASSENGER SYSTEMS

3.1 INTRODUCTION

All evidence suggests that mere extensions of existing systems will not meet long term urban ground transportation requirements. The widespread use of the automobile has caused driving patterns to become dispersed over large areas. The suburbs have grown tremendously and are continuing to expand outward from central cities. The reliance on the automobile for most personal travel is understandable because of the immense flexibility it provides. However, when large numbers of vehicles converge on the same area at the same time highway systems bog down. Public transit also has limitations. It functions best for high-demand, point-to-point travel and not for travel in low density areas. Public transit operators have seen their profits turn to deficits during the 1960's. The railroads have either eliminated or nearly eliminated passenger trains because of operating losses motivating the Federal Government to authorize establishment of a quasi-private corporation to continue service to passengers on important interurban links. Urban commuter links were specifically excluded from this system, however. The daily commuter continues to face cutbacks or complete elimination of service. The commuters desire for suburban living is the principal cause of loss of service due to unprofitable transit operations. When transit service is cut it works particular hardships on the young, the aged, the handicapped, the poor, and those who choose to be non-drivers.

The manner in which the central urban areas and the suburbs have developed has created a need for three basic types of transportation service (Figure 3-1):

1. Metropolitan service for travel within and across relatively compact portions of metropolitan regions

2. Major Activity Center service for travel within high-density, multipurpose centers including airports, universities and major business and office districts

3. Community service for travel within "communities" or groups of communities constituting a major and somewhat self-contained part of a metropolitan area

Metropolitan Systems. Systems which provide service in regions of contiguous urban development are referred to as Metropolitan Systems (Ref 3-1). Here there are moderate-to-high densities of activity and development, usually organized in relatively continuous corridors along existing major transportation

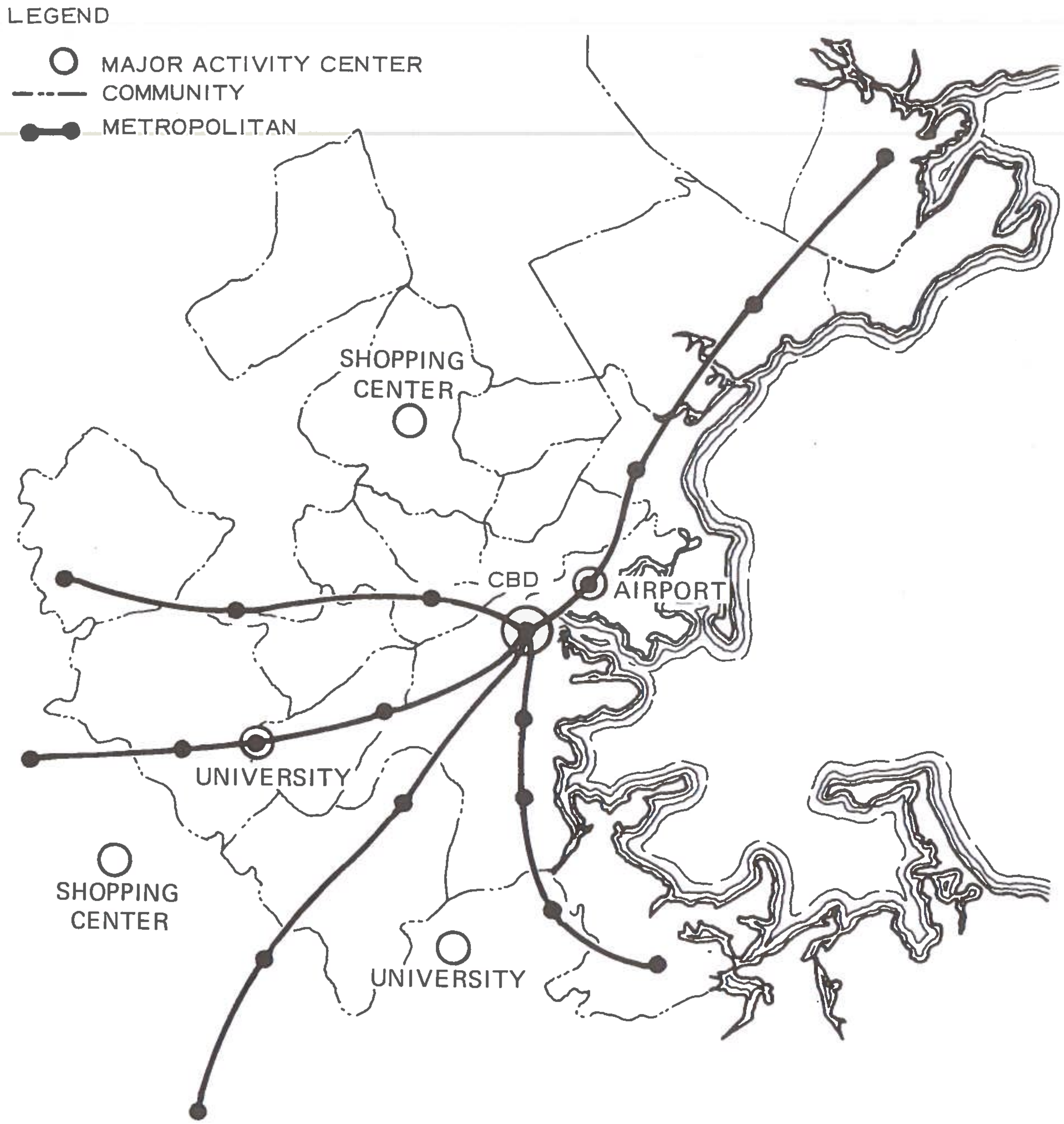

Figure 3-1. Service Areas

facilities. While the continuous nature of the region requires frequent access to transportation facilities, the distances involved demand relatively high travel speeds. These two conditions often work against one another.

Metropolitan systems strongly influence urban forms and patterns. The level of service can be characterized generally as "high-speed, fast-link." Many intraurban trips of this type ramain within the built-up metropolitan area itself, and a separate "metropolitan system" of transportation is required to serve this kind of travel. Auto-highway, rail rapid transit, express bus, and some commuter rail facilities now meet this travel need.

The basic functions of a metropolitan system include: (1) connection of community systems to each other and to centers of employment, education, entertainment, and shopping, (2) connection of community systems to interregional transportation systems, and (3) provision of direct connection between centers and facilities along the Metropolitan system. Relatively high speeds must be obtained to serve these metropolitan functions. This means that future metropolitan movements probably must continue to be met by some combination of auto-freeway, rapid rail, and express bus transit services. Exclusive rights-of-way or preferential use of mixed-traffic facilities may be necessary to achieve this high travel speed.

Major Activity Center Systems. A great need is emerging for the development of transportation systems that can effectively move large numbers of people and goods within large, high-density complexes (Ref 3-1). Transportation in Major Activity Centers is now accomplished by walking, driving, conventional bus, rail transit, taxis, and limousines. None of these is particularly well suited to the task. Each has major shortcomings. When distances, environment, personal capability, and weather permit, walking is normally the most efficient and effective form of movement. High-density complexes exist today primarily in the form of central business districts, colleges, research and medical parks, major airports, and entertainment centers. They are also developing around major freeway interchanges and outlying regions where shopping centers, office, hotel and industrial complexes are being created.

New or improved transportation systems are needed in many Major Activity Centers to allow them to grow beyond normal walking scale, to provide "bad weather" alternatives to walking, to support a greater mix of activity, to reduce the need to accommodate automobiles within centers, and to improve the environment for walking and for the conduct of basic activities. The lack of good systems for the movement of people within such areas contributes to the decline of many existing centers, forces very expensive (and sometimes inadequate) planning for others, and prevents the sound and attractive development of new complexes.

The basic functions of Major Activity Center systems are: (1) collection and distribution of persons traveling to and from the area by auto or by longer distance elements of the overall urban transportation system; (2) transportation to and from work, school, shopping, or recreation of many persons residing or visiting in the area; (3) terminal-to-terminal transfers (airline, bus, or rail); and (4) movement between functions and activities within the area.

In some situations, Major Activity Center systems may use normal street rights-of-way and compete with street traffic, particularly in initial stages. However, where higher volumes, higher speeds, and improved transportation compatibility are required, exclusive rights-of-way and special equipment will probably be needed.

Community Systems. The large bulk of urban travel--whether to work, school, shopping, or even for recreation--consists of short trips carried over Community systems.

For purposes of analyzing new transportation system needs, any area not served directly by Metropolitan or Major Activity Center systems must be included within Community (lower-density) areas. Actually, densities vary substantially and are sometimes quite high. Not all high density areas will be served directly by fast-link Metropolitan or Major Activity Center systems. Fast-link systems will be largely dependent on Community systems for the collection and/or distribution of their users.

Community systems will serve both subareas of larger metropolitan complexes and the large number of smaller cities unable to support Metropolitan systems (Ref 3-1). Community system needs are consequently very large. If, in urbanized areas of up to 650,000 population, Community system needs are defined as all trips of less than four miles, fifty percent or more of all trips fall in this category (Ref 3-2).

The basic functions of community systems are: (1) transportation within the community for all trip purposes, and (2) provision of connections with metropolitan systems.

To varying degrees, most of the functions of Community systems are now being and would continue to be performed by conventional auto-highway systems. However, depending on land use patterns, population densities and characteristics, and the quality of service provided, these functions also can and should be served by some form of transportation that would be available to and usable by all.

Because of the nature of functions to be performed, it is expected that Community systems primarily will use public street rights-of-way for movement. However, special, exclusive rights-of-way may be provided in some situations.

In short, Community systems should combine many of the characteristics of local bus and taxi service but be improved to operate on short headways or be demand-responsive, be capable of some integration with site and building development, and meet the internal or short-distance transportation requirements of neighborhoods and communities of moderate or higher density.

Many of the problems of Community systems are quite similar, regardless of densities. These include the relatively short length and scattered destinations of most trips, difficulties in providing the door-to-door or nearly door-to-door service that may be needed or desired, and difficulties in attaining acceptable travel speeds. Another problem currently affecting Community systems stems from the general lack of fast-link systems.

The implementation of new Community systems is likely to be quite difficult in most of the intensively and relatively fully developed areas established before World War I and the Great Depression. Existing street systems are likely to be congested and inadequate. They contain few, if any, potentials for new land development or for the acquisition of new rights-of-way. Although densities range from moderate to high, travel patterns are widely dispersed and desired movements may be quite difficult to accomplish. However, this is a generalization and every community should be analyzed independently.

How can these varying requirements best be met? The ideal would be a door-to-door single-vehicle service which would be available on demand. This is exactly what the automobile provides and what new forms of transit have to compete with. The automobile cannot be outperformed by any existing transit system! Nevertheless, rush-hour traffic, the automobile's pollutants, and the high proportion of non-drivers create a demand for alternative forms of transportation. We are challenged to provide transportation which can serve the entire urban market at the level of service of the automobile. The characteristics required basically are that the system be fast, comfortable, safe, economical and reliable.

Speed is relative. It is not as important for short trips as for long trips. In fact high speed cannot be obtained in high activity centers due to close station spacing. For line-haul rapid transit speed is important. However, line speed is only one part of the total door-to-door travel time which is the most critical element in choosing a mode of travel. Total travel time includes all time spent walking, waiting, transferring and riding. Minimizing the total door-to-door travel time for the traveler should be a consideration in system design.

Comfort is also dependent on the extent of the trip. For suburban or line-haul trips, a seat should be provided for all passengers. For very short or Central Business District trips, standing can be tolerated. The number of transfers can also be considered a function of comfort, i.e., the inconvenience of changing vehicles, walking or moving from one platform to another, often on different levels. Clean vehicles and pleasant surroundings are also important as are terminal capacity, smoothness of ride, and the lack of objectionable odors and noises (Ref 3-3).

Clearly the system must be safe. Extensive backup systems will probably be required to guarantee a minimum accident probability. The security of a passenger from criminal acts must also be considered.

Out-of-pocket trip cost is also a critical element in the choice of mode of travel. These costs include fares, tolls, and parking charges. The cost of owning and operating an automobile should not be included in the individual intraurban trip cost since the average driver either does not know or does not consider these expenses in the cost of each trip.

Reliability refers to the degree to which the system adheres to schedule. The system is susceptible to delay or breakdown due to weather, vehicle failures, accidents, labor disputes, power outage or shortage, unexpected demand, etc. The system must operate on-schedule for it to be competitive.

The transportation system affects non-users as well as users through the environment. At the very least, the system should be aesthetically acceptable, pollution-free, quiet and non-barrier forming.

There is no question that aesthetic values will help determine the acceptance of any new transportation system. Aesthetic values are qualitative and therefore cannot be precisely judged. Basically, the transportation system should blend with the city or the countryside, preserve scenic values, and be as unobstrusive as possible. In so doing, the aesthetic quality may conflict with other desirable system characteristics, such as economy and system size needed to accommodate demand.

With the current furor over automobile pollution, it is clear that any new urban transportation system will not be able to use vehicles that pollute the atmosphere. For automobiles this probably means operating with some form of electric power. For large transit systems serious consideration is being given to air suspension and linear electric motor propulsion.

Noise is an irritant to residents near a transportation system. Ground noise levels can be reduced somewhat by elevating the system; they can be reduced more significantly by depressing the system; they can be almost completely eliminated by enclosing the system; and they can be eliminated entirely by putting the system in tunnels underground. To do the latter is expensive. To elevate or enclose the system could compromise the aesthetic criteria of the community.

A transportation system whose right-of-way acts as a physical barrier to a community is to be avoided. The preservation of travel patterns and channels of communication already developed must be allowed to continue to the greatest extent possible. Planned systems should be examined for their potential impact on social and cultural structures.

Any new transportation system must exhibit enough desirable characteristics to attract patronage sufficient to become economically viable. It is unlikely that any new system will be implemented with questionable economic prospects.

On the other hand, a system now must not have adverse impacts on the environment in order to be politically acceptable. Regardless of the economic feasibility of any system, it has little chance of implementation if it has severe environmental drawbacks.

Many new transportation system ideas have been proposed. The Applied Physics Laboratory of Johns Hopkins University has compiled a list of some 330 systems and concepts proposed by companies and individuals.

Many of these new systems were investigated during this study and were found to possess a high degree of technical possibility for solving some of the major urban transportation problems. A continuing effort is needed to make available new systems data as it is developed and to provide guidelines for evaluation of future proposed systems.

3.2 PERSONALIZED RAPID TRANSIT SYSTEMS

Introduction. A Personalized Rapid Transit (PRT) System is considered here to consist of small vehicles operating on a network of guideways on an exclusive right of way, which take passengers non-stop from origin to destination. Stations are off-line so that a vehicle picking up or dropping off passengers does not slow down or interfere with traffic on the main line. Control is automatic, employing a combination of vehicle sensors and on-board controls, generally under the supervision of a central computer. A passenger entering a PRT station either finds a vehicle waiting for him at a boarding dock, or summons one off the mainline or from a parking area by pressing a call button. The car door opens automatically to receive the passenger (or passengers, if travelling in a party). All passengers in a pure PRT are seated. The lead passenger presses a button code for his destination, causing the vehicle doors to close and the acceleration process to begin. The car merges with line traffic and is routed to its destination without stopping at any intermediate stations. On approaching its destination it is switched off the main line and decelerated to a stop at the station. Doors open and passengers disembark.

PRT vehicles now being contemplated seat 4-6 passengers with room for small parcels or luggage. Each passenger can travel alone in a car or, if he prefers, in the company of others. The average occupancy of a PRT is expected to be similar to that of any automobile, about 1.3-1.7 passengers per car. The car typically is small, 8-10 feet long, 5-7 feet wide, and weighs about 1500 pounds, i.e., less than a small European automobile. Consequently, the guideway is considerably narrower than that for conventional transit and requires less land. The supporting guideway structures are also less massive. Since costs of land, structures, and tunnelling (if any) account for as much as 3/4 of total transit system investment costs (Ref 3-4), PRT systems have a potential for reducing investment costs per mile of guideway.

The PRT concept has evolved as a logical answer to certain requirements which a transit system must satisfy to compete effectively with the auto in the city. In order to provide a level of service comparable to, or better than, an auto, a transit system should be designed so that no one should have to walk more than 2 blocks to reach a station. Two blocks is often taken as the maximum walking distance (Ref 3-3, 3-4). Stations, therefore, should be not more than about 1/4 mile apart (assuming 8 blocks per mile). If stations are so closely spaced, any system which requires all vehicles to stop at all stations will be too slow. Indeed, assuming 1/4 mile station spacing, an acceleration (deceleration) limit of 3 feet per second/per second, and 30 second station dwell times, the average velocity is absolutely limited to 12.6 mph* (Figure 3-2). In practice the average velocity would probably fall considerably below 12.6 mph. On the

*See Appendix.

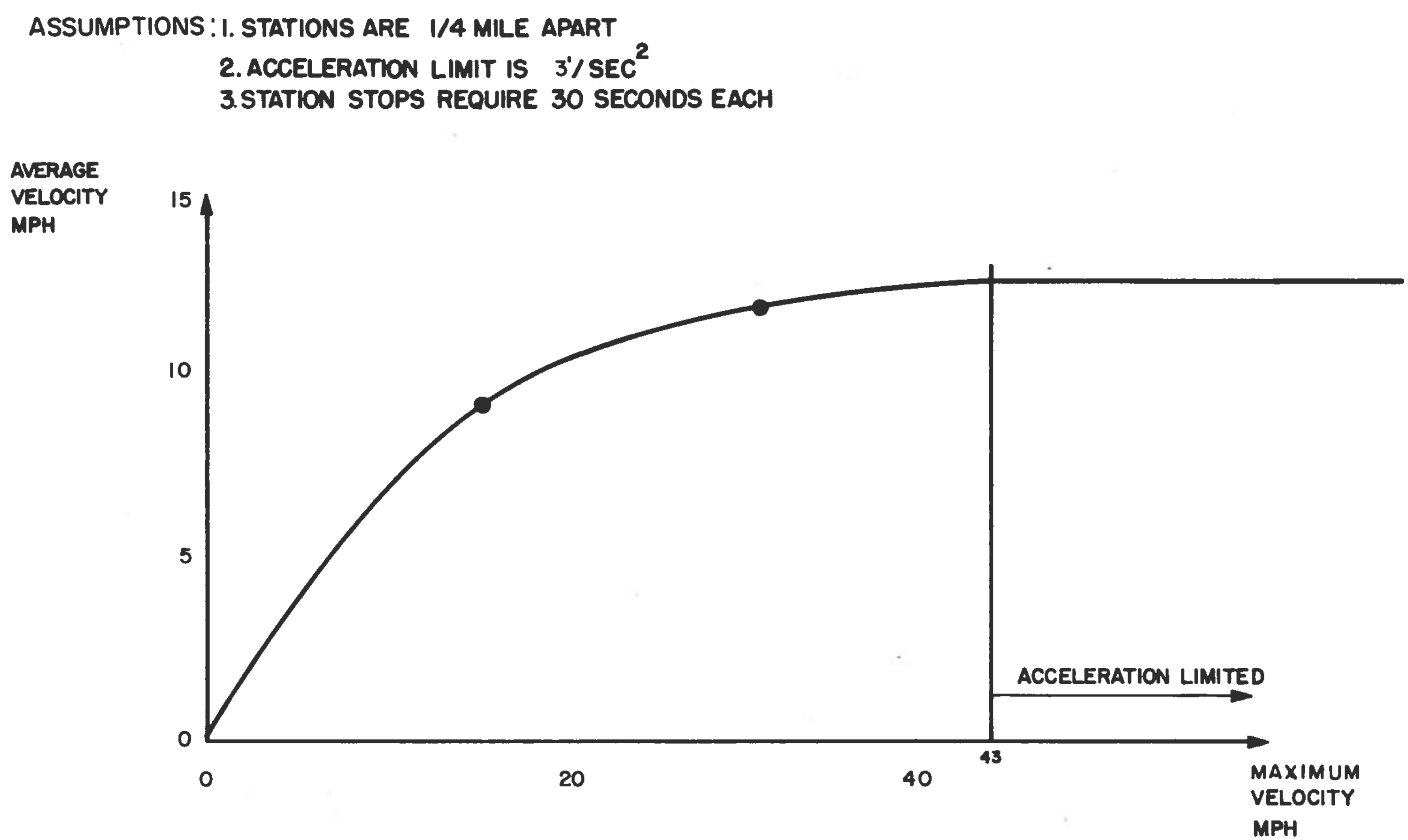

Figure 3-2. Average Vs. Maximum Velocities of a System With On-Line Stations

other hand, to compete with the automobile it is usually assumed that an average speed of 25 mph or more would be required, so that some sort of off-line station arrangement would become necessary.

If passenger transfers are acceptable then a combination of local and express service could provide the required high average velocity. Transfers, however, are undesirable from the passenger's point of view, inasmuch as they are inconvenient and lengthen trip time. In order to avoid transfers it is necessary to have service between every pair of stations. Since the number of pairs is large, whereas the number of passengers wishing to travel between any pair is small and unevenly distributed over time, the logical conclusion is that the vehicle fleet should consist of many small vehicles and should be operated on demand. Finally, it would be prohibitively costly to employ human operators for each vehicle in the fleet, so a totally automated system is required.

A PRT system would offer many of the conveniences of an automobile, without the attendant congestion and pollution. It would be faster than an automobile during rush hours. It would free the commuter of the chore of driving, and would make high quality transportation available to those who cannot drive. It would require far less walking than any conventional public transit system. In fact, for most applications, it would offer a level of service higher than any of the other proposed public transit systems except for the so-called "dual-mode PRT" (which would operate in an ordinary automobile mode off the guideway).

The other side of the coin is that PRT could be expensive (although reliable cost estimates are not yet available) and aesthetic, human, and technical problems are formidable. However, PRT is in many respects such an attractive concept and such a logical adaptation of modern technology to passenger needs that major research to resolve the problems is called for. In the following paragraphs, some of the major problems on which effort must be expanded to achieve true PRT operation will be outlined in the approximate order of importance.

<u>The Placement Problem</u>. Placement is the biggest single problem in the PRT concept, i.e., where to put it. A PRT network in an urban area would require a grid of guideways spaced as little as two blocks apart. As many as 16 stations and an equal number of interchanges might be required in each square mile (assuming a square grid and 1/4 mile between lines). The guideways and vehicles would be much smaller and more attractive than in conventional transit. Nevertheless, a dense above-ground network of them could not be inserted into a city without massive aesthetic repercussions. In time, the pressure of accommodating to the network might force an evolution in city architecture. It

could, for example, accelerate the trend to multi-level planning and eventually lead to the formation of multi-level cities, with pedestrians, automobiles, and mass transit operating at separate levels. A multi-level city would minimize interference between pedestrian and vehicular traffic, allow concealment of unsightly structures, and might therefore be desirable in the long run. In the short run, however, where guideways would have to be inserted into an existing architectural environment, the aesthetic cost would be high.

Claustrophobia in Underground Systems. An alternative to placing the network above ground would be to put it into tunnels. This would be expensive, although costs would be brought down by improvements in tunnelling technology which are likely to occur in the next few decades. Even a breakthrough in tunnelling, however, would still leave a major human-factors problem, namely, that riding in a small underground vehicle induces feelings of claustrophobia in some people. Even with careful lighting and attention to tunnel human factors design, a certain proportion of the public would be unwilling to use the system. For these, an alternative above ground mode such as a bus network, would have to be provided even though the alternative might carry only a small fraction of the total passenger volume. In any case, it is desirable to have more than one mode for greater reliability, greater choice of features, etc.

The Interchange Problem. The most difficult part of the network placement problem, at least for an elevated system, is the location of the interchanges between grid lines. The turning radius at an intersection is limited by human tolerances for acceleration and depends on vehicle velocity. In order to fit into existing city streets the turning radius would have to be kept down to 20-50 feet (comparable to the turning radius of an automobile). To achieve such a small turning radius, the turning velocity has to be kept between 7-13 mph, even if the turn is steeply banked (20%). Vehicles would therefore have to take turns at low speeds. This would complicate the control problem, but would not seriously affect trip time, as the number of turns in a single trip need not be large. Even with reduced speeds and sharp turns, interchanges would occupy large areas. Reduction of this area must have priority in any transportation development program. The following approaches hold promise for reducing interchange land requirements:

1. The use of low-cross-section overhead monorail or cable-type guideways (similar to present gondola ski lift systems). These also have the advantage that banking is accomplished automatically. They do, however, have crosswind and sway problems.

2. The use of vertical switching and overhead (as opposed to alongside) access lanes.

3. The use of one-way routes to simplify interchange topology

4. The possible use of mechanical transfer devices, such as vehicle elevators, to eliminate the need for cloverleaf type interchanges.

Until a compact interchange is developed, the pure PRT grid concept is not practical in the urban environment. An interim approach would require passengers to transfer between vehicles of intersecting lines at most intersections. A possible solution is to cover the city area with a network of intersecting but physically unconnected loops.

Capacity Limitations. One of the main technical difficulties with the PRT concept is the attainment of enough passenger-carrying capacity. The capacity of a single PRT line is limited by the headway between vehicles which must be maintained, firstly, for safety, and secondly, for speed-changing and merging maneuvers. Overall, the capacity tends to decrease sharply with increasing speed at speeds above 15 mph.

The biggest practical factor limiting capacity is the need to maintain safe headway, and the most effective way of increasing capacity is to reduce that headway. Next in importance as a means of increasing capacity is the use of speed-change lanes or of complex operating strategies such as bunching, train operation, or gap control. The effect of these strategems is to reduce the average component of headway that must be reserved for speed change and merging maneuvers.* However, speed change lanes are expensive. For example, at 45 mph or more and 1/4 mile station spacing, the length of speed-change lanes required to accomplish speed-change maneuvers entirely off-line can be greater than the length of main line guideway. The use of complex operating strategies, on the other hand, complicates the necessary control apparatus.

The more ambitious PRT designers (Ref 3-5) are aiming at k-factors of 1.6 - 2.5 at speeds of 30-60 mph. The resulting line capacities for PRT operation are less than about 1500 passengers per hour at the lower speed and 500 passengers per hour at the higher speed. These capacity figures are adequate for handling the average component of peak hour demand in a majority

*Questions of line capacity and its dependence on operating strategies, k-factors, speed change lane lengths, etc., are examined in detail in the Appendix.

of urban situations. However, they are far from adequate for handling the departures from averages that usually occur. Consequently, presently contemplated pure PRT networks would not meet the overall requirements of any but the least demanding urban applications.

A grid of single lane PRT lines operating at k-factors greater than 1, speeds of 45-60 mph, average spacing between lines of 1/4 miles and average trip distances of 2-3 miles would have enough capacity to handle the average component of peak-hour passenger volume for population densities up to 20,000 per square mile. That density figure is higher than the average population density of all U.S. central cities except New York. In other words, such a grid could satisfy the average peak-hour requirements for most community and feeder systems. By reducing speeds to 15-30 mph and employing double-lane guideways, population densities in excess of 40,000 per square mile could be served. The last figure approaches the population densities of Central Business Districts (CBDs) of cities such as Pittsburgh.*

The weakness of such a grid would appear in its ability to service the concentrated trip sources and in its response to unexpected overloads which are likely to occur in any extensive area. Cinemas, large office buildings, and railroad terminals are examples of concentrated trip sources. Capacities of 6000 passengers per hour would be desirable for the absorption of a fullhouse cinema crowd of 3000. With preplanning, an adequate capacity could be ensured by connecting a sufficient number of lines (around 4-6) to the nearest station and by reducing line speeds near the station during peak periods. A more difficult situation, however, would arise if the cinema were planned after the completion of the PRT network. In that case necessary rearrangement and reinforcement of the network would be inordinately expensive. The most difficult overload situations would result from unexpected events that drew unusual crowds.

In short, the PRT grid operating at k-factors greater than 1 and employing simple operating strategies would have poor overload characteristics and would be inflexible to unexpected changes in travel patterns.

To turn the pure PRT concept into a practical scheme with wide potential for urban application, maximum line capacities would have to be increased by an order of magnitude over presently contemplated values. Capacity increases of 100% might be sufficient at low speeds, but increases of 1000% or more might be required at the higher speeds. Such increased capacities would be needed only over localized portions of the network for short times to handle overloads.

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*See Appendix for more detailed analysis.

Conceptually, the least restrictive and therefore most attractive solution to the capacity problem is to reduce k-factors below unity. Indeed, with k-factors of 0.1-0.3 permitted, the PRT concept becomes a flexible scheme with wide urban potential; with k-factors greater than 1.0, the PRT concept has a more limited potential.

The prevailing opinion is that technical problems of achieving reliable operation at k-factors less than unity are massive, but probably could be solved given enough money and time. In addition to the technical problems, there would be problems of public acceptance. Hopefully, public acceptance could be gained by pilot programs demonstrating reliable operation.

In view of the attractiveness of the small k-factor solution, it should become a focus for research and development. In particular, the relationships between k-factors and safety are not well understood and should be studied.

A second way to increase capacity is to use more complex operating strategies, such as bunching, train operation, and gap control (as opposed to simple strategies, such as the synchronous slot strategy). Operation of vehicles in bunches or trains of about 10 vehicles each would, in some applications, produce large increases in capacity. Complex strategies are, however, more difficult to implement, more inflexible and usually are costly in waiting time and user convenience.* Nevertheless, it will probably prove to be efficient to use them in conjunction with small k-factors. The details of these strategies, yet to be worked out, comprise one of the areas requiring research and development.

In the shorter term, capacities could be increased by using larger vehicles of 12-passenger capacity or more to handle peak loads. This would represent a departure from pure PRT operation and entail much more sacrifice in passenger convenience. It would detract from the PRT's ability to compete with the automobile. It should, therefore, be regarded as an interim solution.

It is generally desirable to employ speed-change lanes in a network with off-line stations to simplify operations and/or to increase capacity. Acceleration lanes account for a substantial part of the cost of guideways at speeds above 30 mph. Because their lengths vary inversely with the acceleration limits permitted, the human-factors aspects of acceleration deserve careful study. Human tolerances for acceleration, under the special conditions of PRT operation, should be measured. Preferably, their

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*Capacity increasing strategies generally require passengers or vehicles to queue.

frequency distributions (by population) should be ascertained. Means of increasing acceleration tolerances, such as automatically positioned restraining devices, safety bars, etc., should be investigated.

Station Capacities. PRT stations would require 4-8 times as much space as conventional subway stations per passenger carried.* This disadvantage would be offset somewhat by the fact that PRT stations can be proportioned to demand more easily than conventional train stations. (Even the smallest train stations much be able to accommodate the longest trains. Suburban train stations therefore operate at low capacities per unit area.) PRT stations can, furthermore, be subdivided to fit available land parcels. Nevertheless, the cumulative cost of stations including ancillary automatic docking and control equipment would be much higher (per passenger carried) than in a conventional system because more stations would be constructed.

Most PRT stations would be smaller than conventional stations (but many PRT stations would be needed). The exceptions would be stations at high density centers such as airline and railroad terminals and large office buildings. Entire floors would have to be reserved for PRT operations. Although PRT stations in high density centers would be large, they would require less space and be more economical than present automobile parking and access facilities.* It would, however, be difficult to fit large PRT stations into buildings not designed for them a priori.

Station costs depend greatly on the efficiency with which docking space is utilized. This in turn depends on having fast docking devices, efficient layouts of guideways for maneuvering within stations, efficient vehicle operations (boarding times, waiting times, etc.), and a judicious design of storage areas for waiting vehicles.

System Operations, Command and Control Strategies. The component technologies needed to implement a PRT system are for the most part within the advancing state of the art. That is not to say that a great deal of development will not be needed, but rather that the required development is more in the nature of getting adequate reliability at reasonable cost than setting new performance standards. On the other hand, the problem of getting the parts to perform as an integrated system is beyond the state of the art and poses difficult questions of system operation, coordination, and selection of system strategies. In particular,

*See Appendix

the following questions have not been answered satisfactorily by any of the current designers and will require considerable basic research:

1. How should vehicle arrivals and departures be timed and motions controlled to prevent excessive waiting at switches? More generally, how are traffic jams to be avoided while operating the system near its capacity?

2. How should empty vehicles be redistributed throughout the system? What fraction should be on the guideways and what fraction in parking areas for efficient operations?

3. How can forecasts of passenger movements, taking into account seasonal and diurnal variations, special events, etc., be incorporated into operation strategies?

4. What are the best tradeoffs between fleet size, line velocity, vehicle size, station size, etc.?

5. To what extent should control be centralized and to what extent localized? What is an efficient hierarchical structure for the command-control system?

6. What sorts of preprogrammed contingency and breakdown plans should the system have?

It can be inferred from studies such as Refs 3-4, 3-7, 3-8 and Appendix that system costs are very sensitive to changes in command-control strategies, in fact probably more so than to changes in component technologies. Consequently, it will not be possible to estimate system costs reliably until the above questions are resolved.

<u>Communications and Control Technology</u> (Refs 3-9, 3-10, 3-11, 3-12, 3-13, 3-14, 3-15). The most difficult technological PRT requirements are in the areas of communications and control, where a great deal of development work is still required. As in most of the technological areas, equipment with sufficient speed and accuracy could be built. The problem is one of getting enough reliability at reasonable cost.

At present, manufacturers are leaning to inductive-loop (Refs 3-5, 3-16) and/or photoelectric (Ref 3-6) position-sensing systems. Combinations of time and, in some cases, ingenious position (Ref 3-17) coding are employed; i.e., the information content of a message depends on the time of transmission, or the position of the vehicle in relation to sensors on the guideway at the time of transmission. At present, data on the relative merits of various communications and coding schemes from the point of view of reliability under extremes of operating conditions, channel capacity limitations, cost, etc., are inadequate.

Most designers are planning in an empirical way on redundant use of computers, processors, and memory components for increased reliability. However, definitive analyses of computer reliability in real-time operations and the effects of computer interconnection on reliability have yet to be made in the PRT context.

Obstacle detectors would be desirable for high speed operations on uncovered rights of way. Reliable detectors have not, however, been developed.

There are a large number of headway protection schemes in prototype development. Usually there are block-control schemes, employing fixed electrical blocks on the guideway (Refs 3-16, 3-18), moving virtual blocks or "slots" created electronically (Ref 3-19), or position-comparison schemes implemented via a central computer (Ref 3-5). There are not enough performance data on the various schemes to permit comparison.

Short-headway operations require precise control of acceleration and braking. Redundant brakes and motors mounted in parallel, combined with feedback monitoring or performance are called for. Only one or two manufacturers have made starts in this direction.

Guideway Technology. The following types of guideways are being designed:

1. Support: overhead/underfoot

2. Suspensions: pneumatic tires/air cushions/steel wheels-on-rails.

Some manufacturers plan to enclose their guideways to protect them from ice, snow, and foreign objects. Others prefer to rely on track heaters and hazard detectors (still to be developed).

The relative merits* of the various manufacturers' alternatives depend on the technical setting, and no one approach can be said to be uniformly better than another. For example, underfoot pneumatic-tired systems are preferable where a dual mode capability is required; overhead monorails are the easiest to cover and protect from environmental hazards; air-cushioned suspensions

*See Appendix

are potentially quieter than the others (in low-pressure, light vehicle applications) and less demanding of track-alignment at high speeds.

It appears that various kinds of guideways will be required, depending on local conditions. It seems premature, therefore, to select some and discard others at present. It would be desirable, in the near future, to develop at least one representative guideway concept in each category.

Several manufacturers are actively developing and refining onboard switches. Not enough effort, however, has been expended on the problems of switching at high speed, and, (as previously mentioned) on the design of compact intersections. Development of these two problem areas should be stimulated.

Problems of guideway dynamics, which are serious in most guideway systems, are less important in PRT systems because of the low speeds and lighter vehicle weights.

Suspension Technology. Some manufacturers (Ref 3-5) are developing small air-cushion suspensions for PRT use. Air-cushion suspensions are advantageous at speeds in excess of 100 mph, where they reduce wear at the guideway-suspension junction and diminish the need for precise guideway alignment. At the lower speeds contemplated for PRT systems, however, these advantages are not very important.

More important are the possibilities of reduced noise and omnidirectional maneuverability at stations and switches. However, the elimination of contact noise at the guideway-suspension interface is offset by the hiss created by escaping air. It has not been established how serious a problem this will be. The advantages of omnidirectional maneuverability have yet to be demonstrated.

The ride quality obtainable from a suspension system depends primarily on the springing employed. In principle, rubber-tired systems should be capable of providing as smooth a ride as air suspensions.

Air-cushion suspensions have the disadvantages of requiring power and periodic maintenance for their operation. They do not (in the form now being contemplated for PRT use) have a dual mode capability. They are more limited in the kinds of propulsion they allow. Their advantages should, therefore, be more clearly documented than they have been so far, before their widespread adoption is encouraged. Similarly, the reasons for considering magnetic suspensions for PRT use are not well understood at present for lack of data.

Propulsion Technology. The conventional rotary electric motor is quite adequate for the propulsion of rubber-tired vehicles, although improvements in speed control are desirable, particularly for A.C. motors. However, air-cushion suspensions require propulsion means which do not rely on traction. The main choice at present is between linear induction motors (LIMs) (Ref 3-20) or air-reaction (jet) propulsion.

The LIM with its primary winding mounted on the guideway has no moving parts and is therefore simpler to maintain than a rotary motor. However, since it does not have a force-multiplying transmission, it must develop much higher forces than a rotary motor. Consequently LIMs tend to be heavy and expensive. The larger and more poorly controlled air gap of the LIM reduces efficiency and produces force fluctuations. In transportation use, foreign objects on the guideway could get into the air gap and cause extensive damage. The chief justification for developing large LIMs therefore is for use with air suspensions, where rotary motors cannot be used. Where rotary motors can be used, the advantages of the LIM are unclear.

Air-reaction systems using high pressure air are too noisy for use in ground transportation. One way of reducing noise is to lower the pressure and apply it over a larger area. One manufacturer (Ref 3-21), for example, employs a large number of low-pressure air valves under a completely passive vehicle to supply both propulsion and levitation. Such air reaction systems are potentially attractive. However, more information on their operating characteristics is required before they can be evaluated.

3.3 FAST TRANSIT LINK SYSTEMS

Inroduction. Fast Transit Link (FTL) Systems operate within a metropolitan area on exclusive guideways, providing transportation on trips covering a significant distance relative to the community's size. They link Major Activity Centers to the suburbs or to other Major Activity Centers. Examples are connections between Central Business Districts (CBDs), shopping centers, suburbs and airports. Depending on the community, these may involve trip lengths up to 60 miles or more. The purpose of the FTL is to cover these lengths in a reasonably short time, economically, comfortably, and safely.

Rationale for FTL Concept. A number of motives exist for installing an FTL system. A community may desire to promote its growth and to do so in certain patterns. Or, a community may wish to provide satisfactory transportation for those residents not adequately served by other forms of transporation. A community may also use it to alleviate a severe automobile congestion situation, in which case it will have to attract motorists.

If a goal of an FTL is to lure motorists, then its speed should at least equal, and preferably exceed significantly, the average automobile speed experienced on the journey. Competing with the car is made more difficult for three reasons. First, the FTL generally has a number of station stops along the route at which it must come to a halt, wait while passengers load and unload, and accelerate back to cruise velocity (of course, the automobile generally has to make a number of stops, too, in traffic). Secondly, the FTL is a point-to-point system, and its passengers must get to it from their origins, and then, from it to their actual destinations. This adds significant time to the overall journey, a penalty which the automobile may largely avoid. Finally, waiting time is a part of the overall journey time, and the automobile is ready to begin a journey with virtually no wait time. Thus, it is highly desirable for an FTL to reduce the time required for its portion of the trip wherever such reductions are possible. The above statement is true even if attracting motorists is not the primary goal of the FTL.

Limiting Factors in FTL Trip Times. The time involved in making connections on either end of an FTL trip is a function of: (1) the means of transportation used in these other portions of the overall journey; (2) the spacings between FTL stations on a route; and (3) the spacing between routes. Increasing the number of stations on a route reduces the time required for access to and from the FTL but increases the time involved in the FTL trip. Increasing the number of routes reduces access time still further but involves additional, costly construction. The optimum design conditions depend on the individual communities considered.

Waiting time for an FTL can theoretically be eliminated as a problem, since present day technology permits headways equivalent to about 90 seconds. So, in principle, a system could be built that would require, at the most, a 1.5 minute wait or 0.75 minute on the average. In actuality, a number of economic and operational problems may preclude service at this frequency.

The time involved in a trip is affected by the following four factors: average cruise velocity, accleration/deceleration rates, station spacing, and station dwell time. These interrelations were calculated and are shown in Figure 3-3. The individual effects of these variables on time required for a 20-mile trip are shown in Figures 3-4 and 3-5 for the following base conditions: average cruise velocity = 80 mph; acceleration/deceleration = 0.14 g; station spacing = 4 miles; and station dwell time = 30 seconds. Numerical values are shown in Figure 3-4 and percentages (or sensitivities about base conditions) in Figure 3-5. For comparison, the time required for a 20-mile trip on a typical conventional transit system (32 minutes) is also indicated.

From the plots, it is evident that the braking and acceleration rates have relatively little effect on trip time, especially for values of 0.1 g (a very comfortable and easily attainable figure) and greater. The calculations assume an infinite value of jerk, but a realistic, acceptable jerk rate will have little effect on the results.

Station spacing is an important factor at spacings much less than 4 miles, and not nearly as important at spacings greater than this. The longer trip times associated with spacings in the 1-2 mile range may not be too much of a problem since spacings this close will most likely be associated with routes of rather short lengths. From Figure 3-4, a 10-mile trip with 1-mile station spacings would require 17 minutes, and a 5-mile trip would require 8.5 minutes. Station spacings of 4 miles or greater would be associated with longer routes, perhaps 20 miles or more. In this case, the system can utilize most effectively its speed capability.

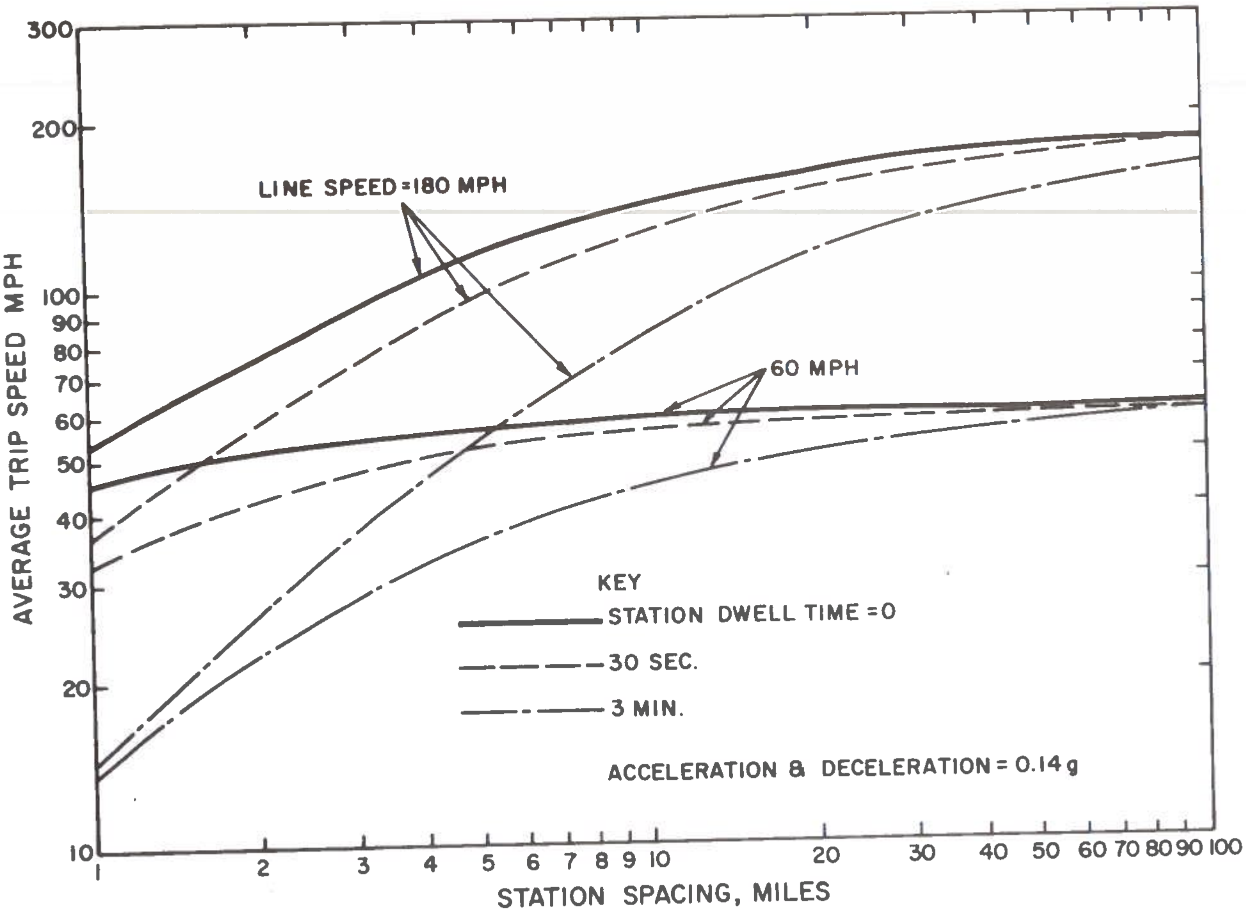


Figure 3-3. Parameters Affecting Average Trip Speed

Cruise velocity is a significant factor until speeds in the neighborhood of 120 mph are reached. Above this, increasing speed is of little benefit. For high speeds to be practical at all (say above 80 mph), larger station spacings are a necessity (e.g., 4 miles or more).

The last factor to be considered is station dwell time. Dwell time is the time required to unload and load passengers in a station. Large values of this parameter significantly increase trip times. Therefore, dwell times should be minimized. Thirty-second dwell times are adequate in many instances for passengers to enter and depart a vehicle, based on present experience. This value does not degrade system performance too severely.

A problem with most FTL systems is their routing inflexibility due to fixed guideways. Once installed, they are essentially permanent fixtures. Therefore, in view of the considerable expense

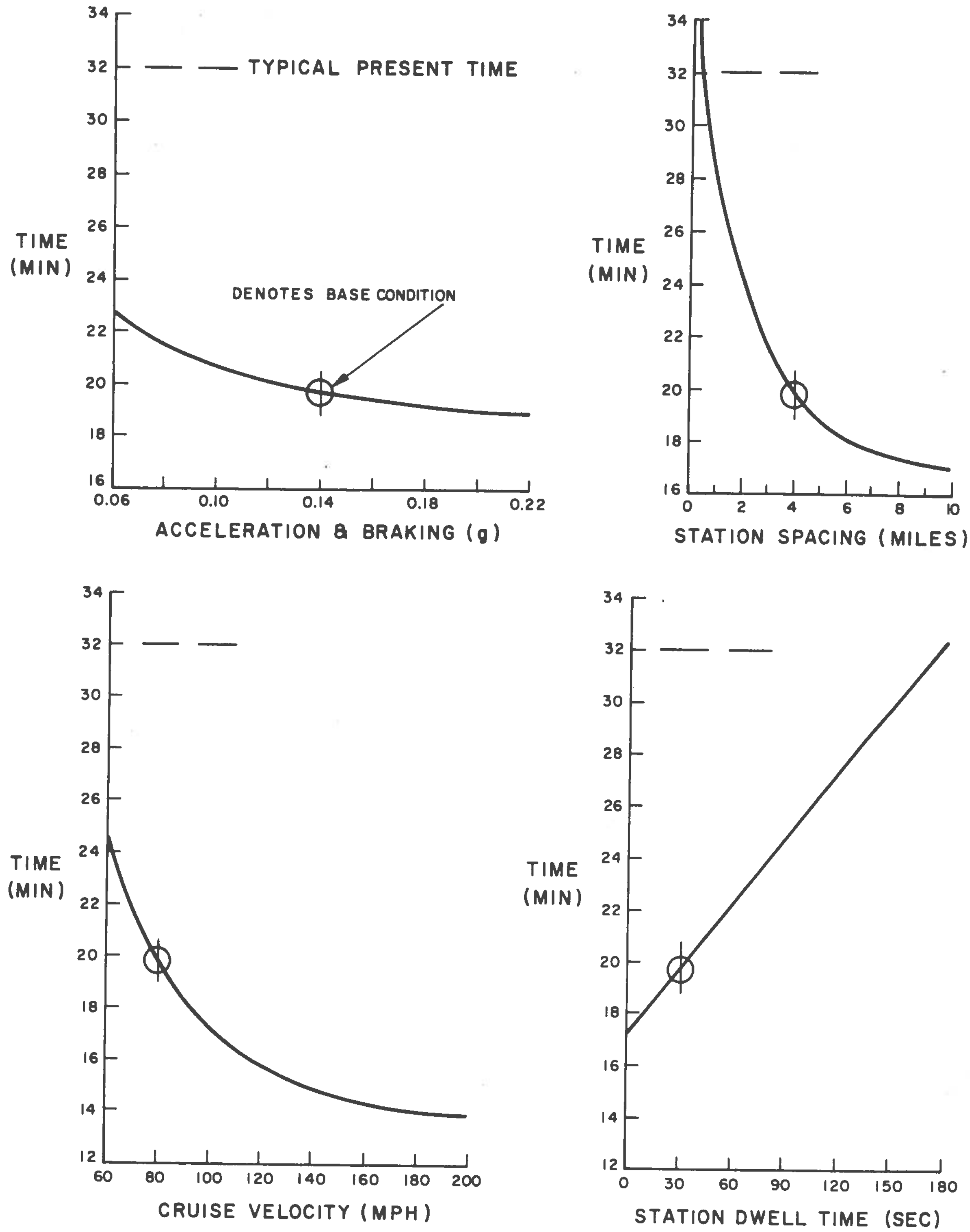


Figure 3-4. Effect of Various Parameters on Time Required for 20 Mile Trip. (Base condition: acceleration = 0.14 g, station spacing = 4 mi., cruise velocity = 80 mph, station dwell time = 30 sec.)

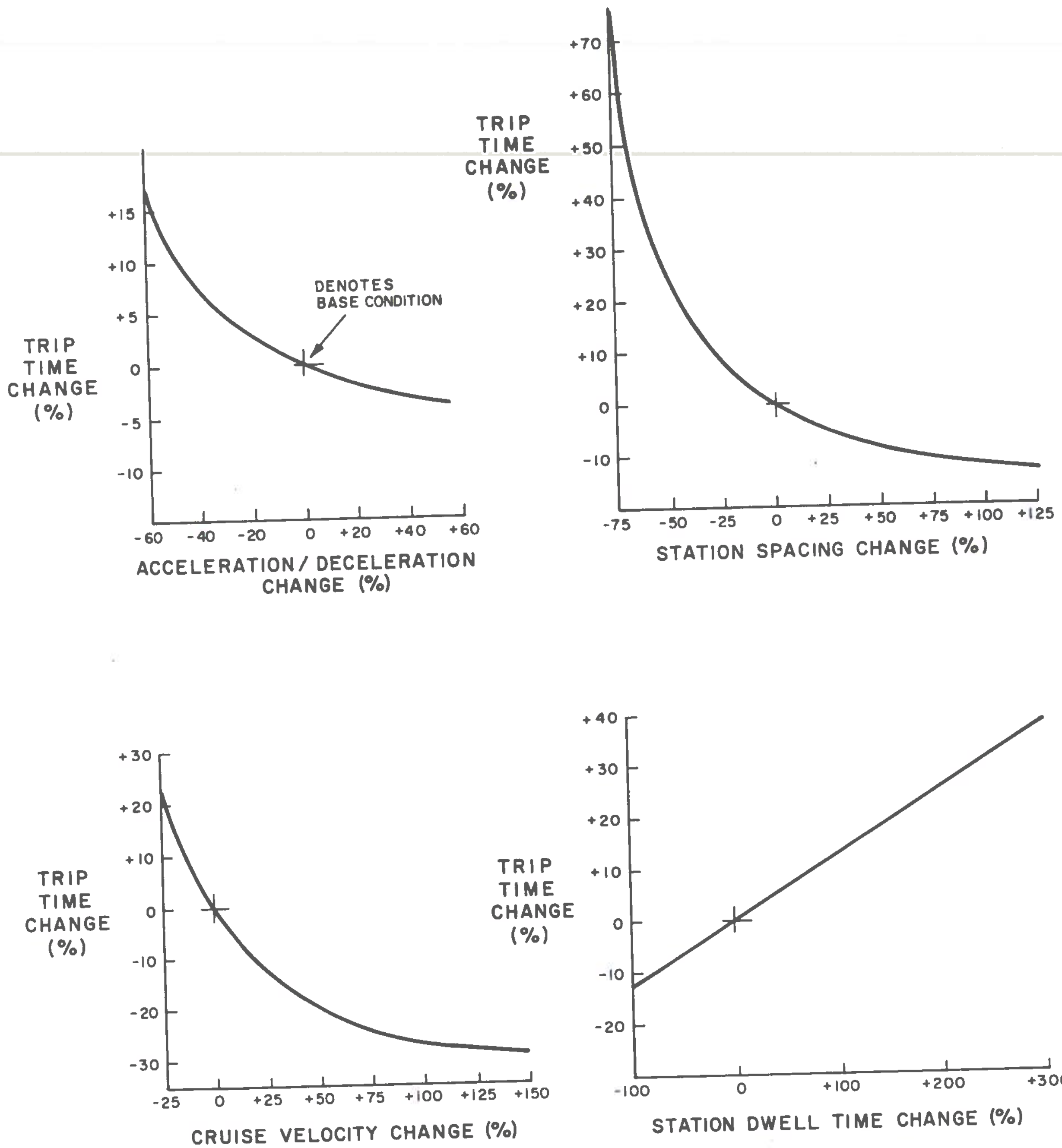


Figure 3-5. Effect of Various Parameters Shown in Figure 3-4 on Time Required for 20 Mile Trip. (% change of parameter vs. % change of trip time.)

of installation, the system must be carefully planned in advance. This means its objectives as well as the desired future growth and development of the community must be well understood. Most probably, compromises will have to be made between the desired extensiveness of coverage and that feasible due to available resources. Because of high installation costs of the guideway, attention should be paid to designing cheaper guideways and to designing guideways that are to some degree portable, to allow for possible routing changes at some time in the future. Portability will be advantageous in allowing a community to temporarily adjust to changing conditions or to investigate the behavior and effectiveness of an FTL system before it commits itself to a permanent installation. A number of FTL concepts will now be considered.

New, Wheeled-Vehicle FTL Concepts. The guideways are the most characteristic and distinguishing features of the new, wheeled-vehicle FTL concepts. The new systems are generally elevated in order to avoid grade crossings and to be able to use existing rights of way currently in use by other forms of transportation. In general, a vehicle can be supported from above, its side, or from underneath. Figure 3-6 shows a number of proposed support arrangements.

A guideway supporting a vehicle from below (e.g. a supported monorail, road-type guideway) requires the least structural height for a given clearance above the ground. The road-type version is perhaps the easiest type of guideway on which to run wide-tracked vehicles (which have greater stability). Also, in case of emergency, passengers could perhaps use the guideway to escape from the vehicle and reach points of safety. The running surface of this type of guideway is directly exposed to the weather, and a de-icing capability may be required. This type of guideway helps protect the vehicle from vandalism, since it is between the vehicle and the ground. But, if something were thrown up onto the guideway, it could very possibly come to rest on the running surfaces and create a hazard to the vehicles.

An overhead guideway requires the most structural height for a given vehicle clearance above the ground. It generally has a narrow-width track, which allows vehicles to sway more due to side winds and buffeting from passing vehicles than would a wider track. However, this sway can be used to advantage on curves, where the vehicle will tend to bank and reduce the lateral forces on the passengers due to the curve. The guideway running surface can be completely enclosed from the weather and well-protected from vandalism. The vehicle is exposed to vandalism from the

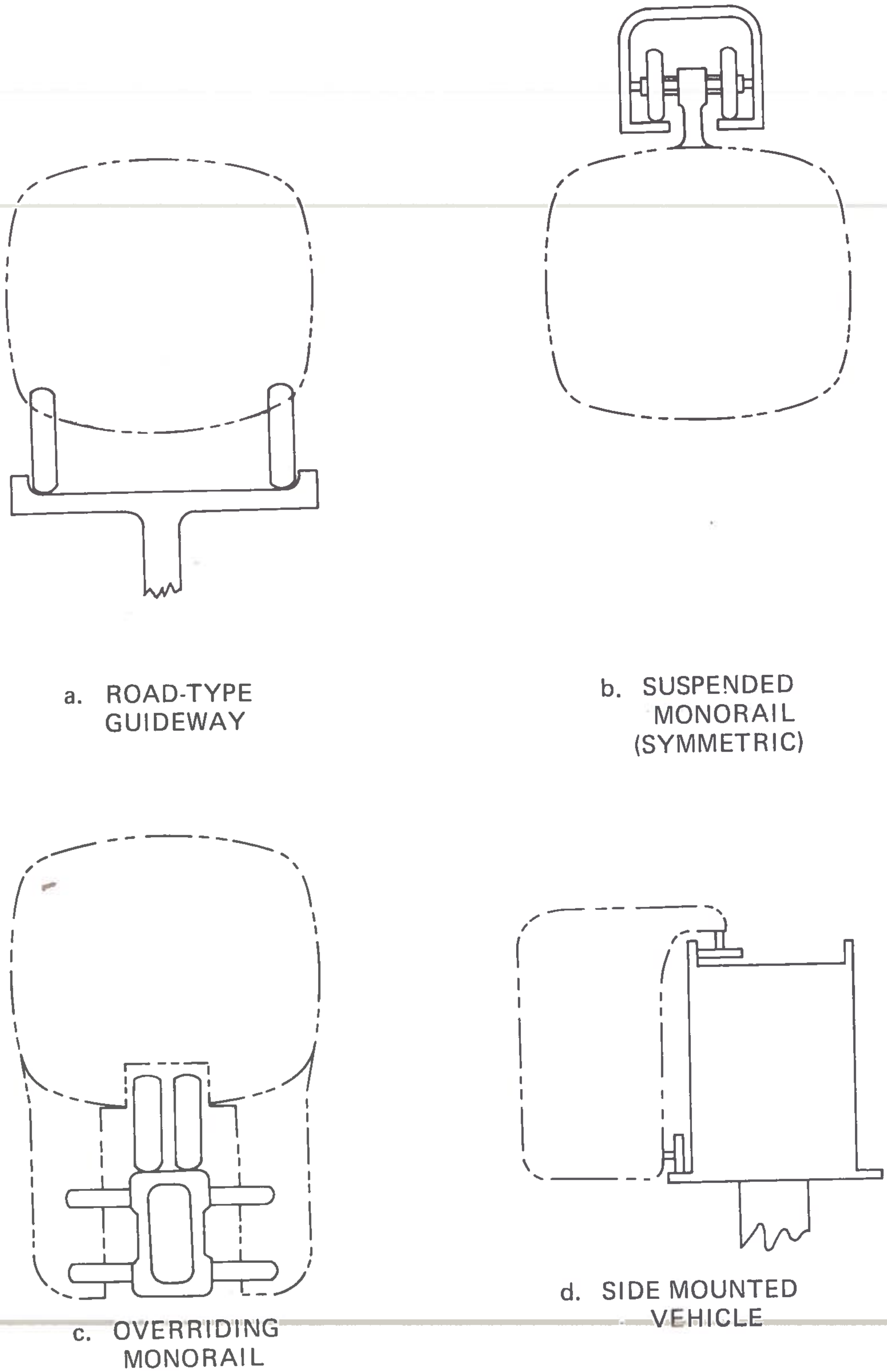


Figure 3-6. Some Basic Wheeled Vehicle Configurations

ground, however. This guideway arrangement lends itself to both rigid and flexible tension-cable construction. In case of emergency, passengers would have to reach the ground directly from the vehicles since they could not walk along the guideway.

A side-mounted suspension requires a structural height intermediate between the preceding concepts. It provides a wide track for vehicle stability, but the vehicle suspension system may be more complex than with other guideway concepts. The guideway can easily be hung on the sides of buildings, bridges, etc., and it can be narrower than other guideway concepts. Loading and unloading of passengers may be restricted to one side side of the vehicle only. In an emergency passengers could probably not use the guideway as an escape route unless the interior of the beam were designed as an escape passage.

The Westinghouse Electric Corp. has developed an FTL vehicle system running on a road-type guideway called the Transit Expressway (Figures 3-6a and 3-7). They have operated a demonstration model near Pittsburgh for some time (Ref 3-22). The vehicle uses an automotive-type suspension system, and is supported by rubber tires running on concrete surfaces. Vehicle operation is automatic. In projected commercial service, ultimate passenger capacity would be about 30,000 per hour per lane (Ref 3-23).

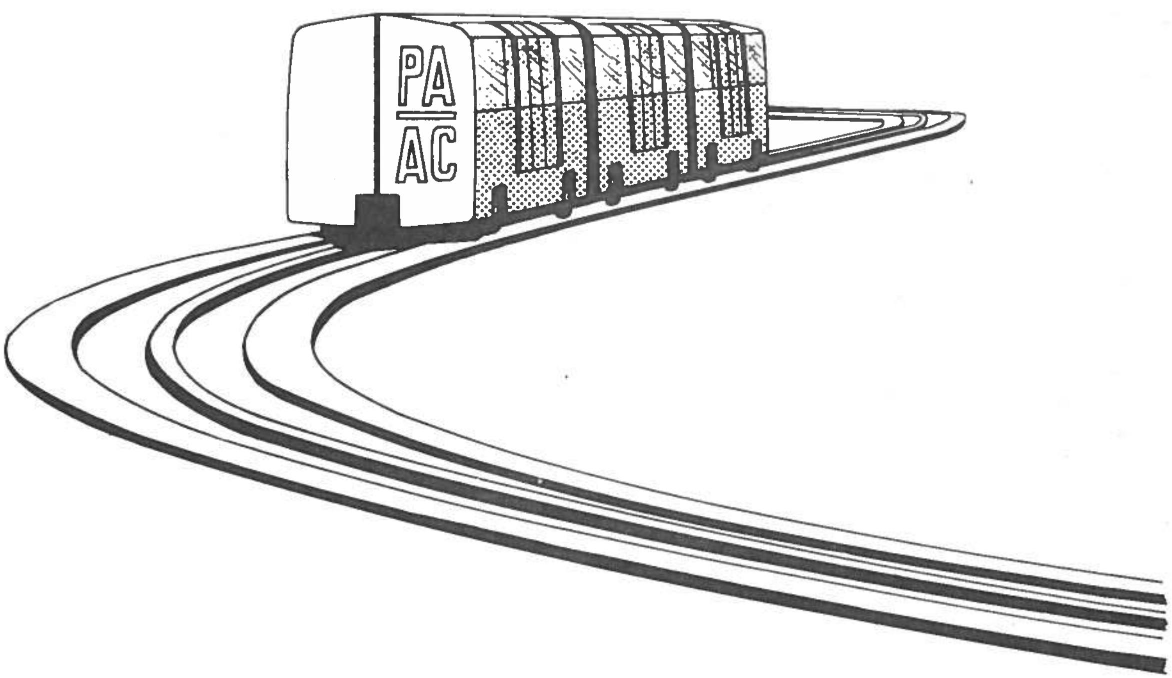


Figure 3-7. Westinghouse Transit Expressway (Source: Ref 3-22)

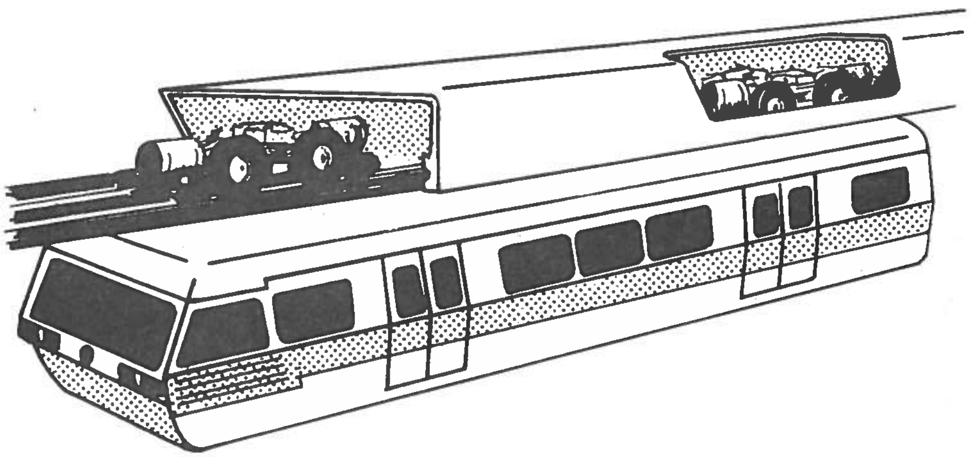
An example of the suspended monorail concept (Figure 3-6b) is the SAFEGE System, developed in France (Ref 3-24). Essentially, it is a narrow gauge, rubber-tired railway with the cars suspended below the tracks. Noise level, although minimized by the use of rubber tires, is further reduced in this design because the wheel motors operate inside the hollow beam that forms the guideway. A full-scale test track, including grades and switches, 0.6-mile in length was constructed in Orleans, France.

The General Electric Aerial Transport System (Figure 3-8), an adaptation of this, has been licensed by GE for development in the United States (Ref 3-24). System capacity is about 45,000 passengers per hour per track.

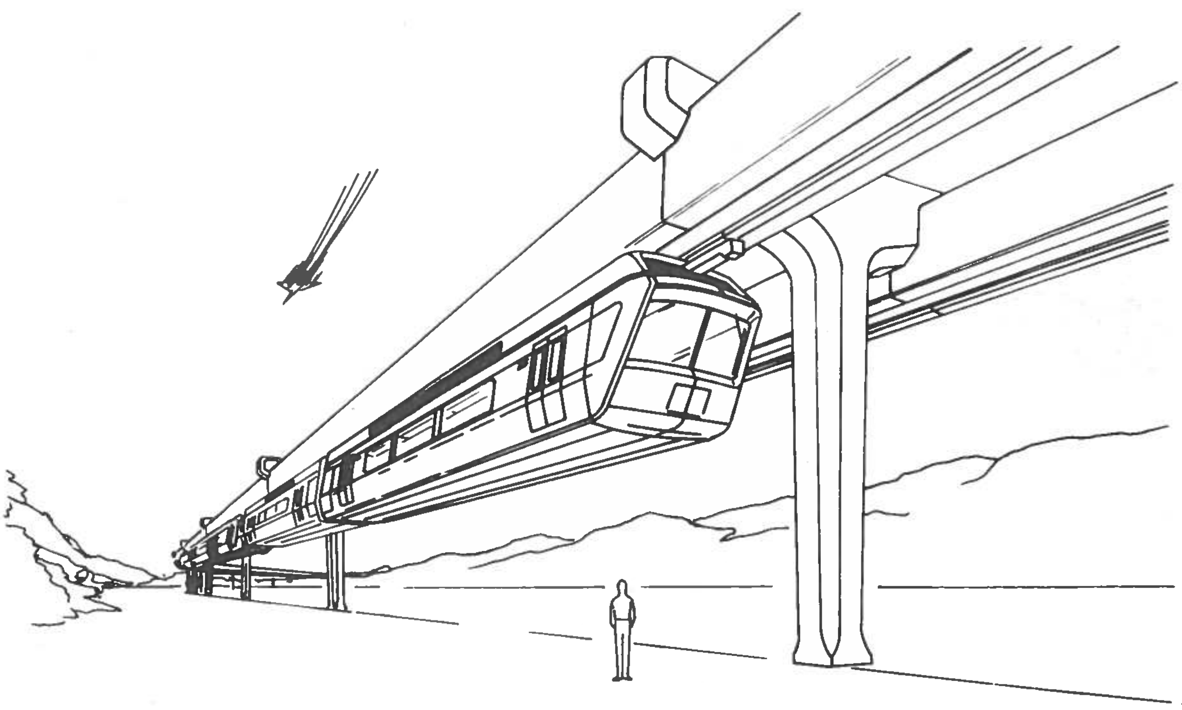
Another suspended monorail, the Aerial Transit System, proposed by Aerial Transit Systems, Inc. (Figure 3-9), consists of lightweight vehicles supported from above by pneumatic-tired trucks that travel along a flexible steel I-beam (Ref 3-25). The guideway consists of two of these I-beams (for 2-way traffic) supported by interconnected cables that are suspended from towers having a nominal spacing of 1200 feet. The long tower spacing allows considerable flexibility in crossing adverse terrain. Rivers, canyons, bluffs, etc., can be traversed more easily than with a system that requires typical elevated guideway tower spacings (60 to 100 feet). Numerous cable structures have been used in transporting goods and passengers in the past, and tension-cable structures of the type proposed have been built to support pipe lines. However, this particular cableway is unique for a passenger transportation system. The developer claims it has a relatively low installation cost and that it is portable. This would allow relocation of the system at practically the cost of labor alone. The suspended cableway stretching across the landscape may provoke complaints about its appearance. Passenger capacity of the system is not large, and appears to be limited to about 3800 people per hour per track.

An example of a supported monorail system is the design developed by Alweg (Figure 3-6c). A double-track Alweg system was used to connect downtown Seattle, Washington, with the Century 21 Exposition. Two trains of four cars each were used in a shuttle operation. Each train carried 460 passengers and covered the 1.3-mile trip in 96 seconds.

The newest commercial supported monorail is the 8-mile line between downtown Tokyo and Tokyo International Airport. This predominately double-track line originates from the fifth floor of the terminal building adjacent to the Hamamatshu-cho Station of the Japanese National Railways. The route traverses a wide

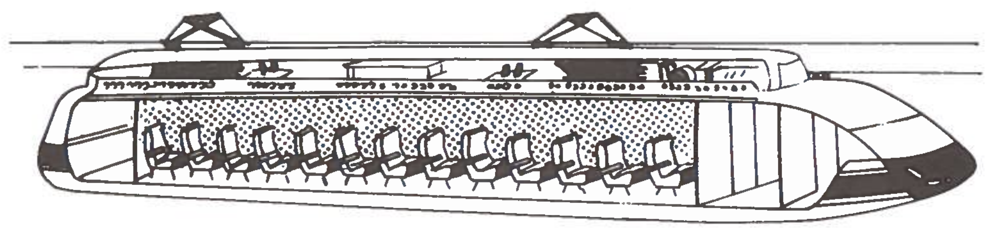


a. Cutaway View of Track and Propulsion Unit

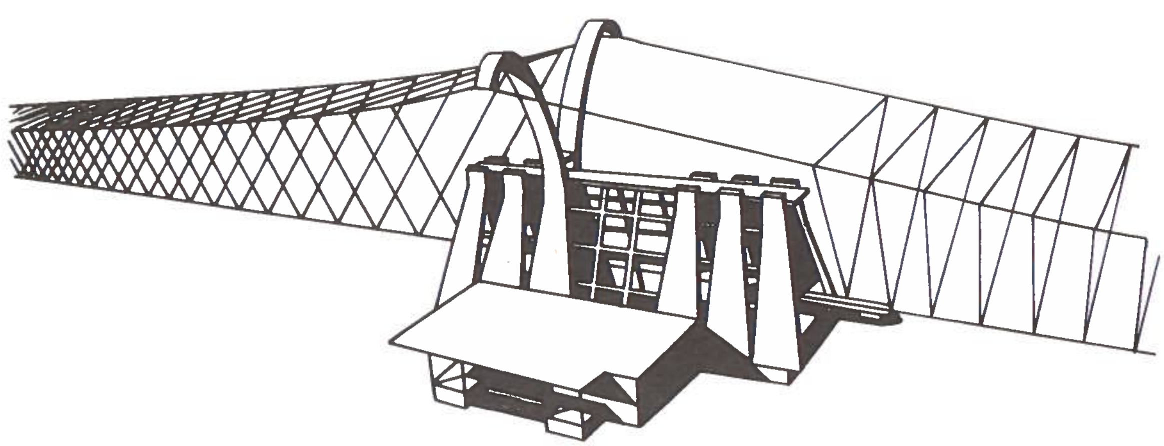


b. View of Installed System

Figure 3-8. Artists' Views of the General Electric Aerial Transport System. (Source: Ref 3-24)



a. Cutaway of Vehicle



b. View of Guideway and Station

Figure 3-9. Artists' Views of Aerial Transit System.
(Source: Aerial Transit System, Inc.)

variety of terrain, passing over land, shallow waters, and through tunnels. Normal service frequency is one train every 5 minutes, but this is reduced to one train every 7 minutes when required. Normal running time for the 8-mile trip is 15 minutes.

The Scherer Monobeam is a side-mounted suspension concept (Figures 3-6d and 3-10) that permits transit vehicles to be suspended on both sides of a single beam structure for simultaneous travel in opposite directions (Ref 3-26). In the Monobeam suspension concept, the cars have steel wheels riding on steel rails. The truck assemblies on the lower rails include traction wheels, lateral stabilizer wheels, suspension springs, and load-leveling devices for controlling the vertical position of the car. The truck assemblies on the upper rail contain lateral guide wheels and a lateral suspension spring.

Railroad FTL Systems. Rail systems (commuter trains) are currently in use as Fast Transit Links. They possess a number of advantages and disadvantages. Their actual and potential speed capabilities are more than adequate for nearly every conceivable FTL situation, but these capabilities are rarely exploited to full advantage. Rail systems can be quite insensitive to weather and can carry very large numbers of passengers (40,000 or more per hour per lane). Considerable rail trackage currently exists in many cities that might be incorporated in part into FTL systems. Problems with rail systems include their present generally poor standards of service, high cost of operation under existing work rules, external noise, and inflexible routing. The present design trend of large, heavy vehicles does not favor frequent service at low passenger loads.

A brief discussion of several existing (or about to exist) rail FTL systems follows. Only the more advanced (in terms of equipment and operation) American systems are included.

The Long Island Railroad carries some 260,000 weekday passengers and 72 million annually. On its 334 route-miles it hauls more passengers than any railroad save the Penn Central (Ref 3-27). 620 new M-1 cars are being delivered from Budd, delivery having started in October 1968. They carry about 120 passengers each and have a top speed of 105 mph. They suffered from initial problems of low reliability due to the lack of prototype debugging

Figure 3-10. View of Scherer Monobeam Guideway
(Source: Ref 3-26)

which resulted from short delivery time schedules (Ref 3-28). Sections of the Long Island right-of-way far from New York are not electrified and, therefore, the development of dual propulsion trains has been pushed. Budd GT-1 and GT-2 prototypes which combine electric propulsion with diesel or gas turbine propulsion in the same car, have been operated experimentally during 1970. The GT-2 has dual turbine/electric operation through the use of an alternator-rectifier hookup to the turbines and the provision of third-rail shoes and standard traction motors. If successful - and results so far are termed promising - such cars could have much wider usage in commuter or interurban service than any of the other forms tried so far.

The Penn Central has ordered from G.E. electric multiple unit (MU) commuter cars designed to operate between New Haven and New York, (Ref 3-29). These cars, also slated to be operated over the Hudson-Harlem Division of the Penn Central, are scheduled to begin service late in 1971. They are not unlike the Metropolitans of the Long Island R.R., and represent no advance in the state-of-the-art.

For completeness, the sophisticated trains of the Bay Area Rapid Transit (BART) system must be mentioned. Although they are only 80-mph cars, they embody extensive automatic operation and are entirely new. They have been tested exhaustively in contrast to other recent systems and should develop a better service record as a result (Ref 3-30).

Another recent set of cars designed for suburban-commuter rapid transit involves the new equipment now in service on the Lindenwold line into Philadelphia (Ref 3-31). There are two configurations of 75-mph cars, with fully automatic train operation and automatic fare collection. They operate as single-car units or as multiple cars in trains. The Lindenwold Line cars are Budd manufactured with GE Automatic Train Operation (ATO) equipment. The only manual operations normally performed by the train attendant are opening and closing of the doors at stations, followed by pushing a button to energize the ATO system and start the train. From this point the cycle is automatic until the train stops at the next station.

Evaluation of Rail FTL Systems. Achievement of high average cruise speeds is dependent upon both the road bed and the vehicle suspension. Where a new road bed is installed, it may be possible to provide gentle, high-speed curves. But if sharper curves must be included, or if presently existing track with sharp curves is to be utilized, then the vehicles must have the ability to go through curves at significantly greater than normal speeds, or, to compensate, a very high cruise speed for straight stretches (accompanied by high acceleration ability), or both. To pass through turns at higher than normal speeds without causing passenger discomfort (generally the limiting factor), a suspension system capable of aligning the vehicle to the proper bank angle is necessary. This may be accomplished by a passive pendulous suspension, as has been used on the Spanish Talgo trains (Ref 3-32) for several decades and was tried briefly in this country in the early 1950s. It is currently being tried again in this country in the Turbo Train. This system is somewhat limited in overspeed through curves because it reduces the vehicle's resistance to overturning and because rather large lateral displacements of the vehicle's center of gravity are necessary for higher speeds. Thus, the allowable widths of the vehicles needed to maintain adequate clearances are limited.

For greater speeds and more positive control of the vehicle's motion, an active suspension system may be necessary (Ref 3-30, 3-33, 3-34). This would force the vehicle to bank in a way that would eliminate or reduce the lateral acceleration on a passenger while passing through a curve. An active suspension can also increase a vehicle's resistance to overturning when passing through a curve by moving its center of gravity towards the center of the curve. Another advantage of active suspension systems is that over straight track they can provide a significantly smoother ride than conventional, passive systems. Vehicle swaying and pitching due to track imperfections and irregularities can be diminished considerably by an active suspension. (See Section 6.3 for further discussion.)

It is desirable to have the weight of vehicles as low as possible. The present use of long cars tends to concentrate weight at a few points on the tracks where the wheels make contact, making massive and expensive track supports necessary. The situation is more severe with aerial track structures. Shorter, lighter weight cars reduce the stress and consequent wear on rails and wheels, reduce the requirements imposed on suspension systems, and reduce the necessary strength and associated massiveness of aerial guideways. Lighter weight vehicles also reduce the power necessary for acceleration and the energy that must be dissipated during braking. Some current rapid-transit vehicles achieve weights under 1000 pounds per passenger with full loads of seated passengers. It would be desirable to reduce this to approximately half to bring it down to the range of automobiles and buses. Present rapid-transit vehicles can achieve weights in the neighborhood of 500 pounds or less per passenger if loaded to the bursting point with standees, but this does not represent a satisfactory level of service.

For high speed service, a low center of gravity is desirable to increase stability against overturning or swaying due to track imperfections, curves, and cross winds. Low centers of gravity are achieved by reducing the overall height of the vehicle (important in increasing stability in cross winds), by concentrating as much weight as is practical near the bottom of the vehicle, and by reducing the distance between ground and vehicle bottom. The independently-wheeled Talgo Train has a floor only about 1.5 feet above the ground, as compared with the approximately 4 feet of conventional rail vehicles.

Propulsion and braking of rail vehicles at the speeds of interest are adequately accomplished by wheel traction. Power for propulsion can either be produced on board or collected from the wayside. On-board power sources are generally restricted to diesel engines or gas turbines. Diesels have the benefit of considerable experience and good fuel economy under a wide range of operating conditions but are mechanically complicated and heavy. Gas turbines are light weight and mechanically simple but suffer from somewhat poorer fuel economy. Both diesel and gas-turbine units must carry a supply of fuel, and this can cause a fire hazard in case of a mishap. They also are not suitable for use in underground areas.

The gas-turbine engine currently being tried on rail vehicles is the non-regenerative version. This type is simpler in construction and less expensive than the regenerative type but less efficient. Regenerative turbines are currently being developed for highway and marine use, and it is expected that they might be advantageous on rail vehicles also. Evidence indicates that fuel consumption may be decreased by as much as 40% under some conditions by using a regenerative turbine (Ref 3-30, 3-35).

Wayside-collected electric power has the advantage of low noise, negligible local pollution levels and no-onboard supply of flammable fuel. Such systems work well at speeds of interest in FTL systems. Collection can be either by overhead pantograph or shoe-on-rail techniques. The overhead pantograph, though high above the ground and thus generally safe from accidental human contact, may pose aesthetic problems. The shoe-rail technique does not encounter the overhead clutter problem but power conductors are near the ground and accidental human contact is possible. The power conductors can be protected to a degree by partially covering them with insulating materials, as is done on the BART system, but the hazard still exists. A disadvantage of wayside-collected electric power is the high cost of electrification of the track. A large traffic volume is necessary to compensate for this cost, but where the volume is available this method can be extremely economical.

Railroad wheel noise can be a severe problem with rail vehicles (Ref 3-36, 3-37). It occurs partially because of wheel resonance and partly because of wheel-rail abrasion. The forces the wheel experiences cause it to vibrate like a drumhead. Solutions appear to be in the form of interruption of the vibration paths, the absorption of the vibrations before they are amplified by the wheel, and the reduction of the forces causing the vibration. (Section 6.3 carries a further discussion of the subject.)

Another way of reducing the noise level is simply to muffle it. Since car bodies are wider than the track gauge, it might be feasible to extend the car body down over the wheels, very nearly to the track, thus enclosing the wheels and their noise as much as possible. And sound barrier fences along the roadbed have been found to be quite effective on the BART system in isolating wheel-rail noise from the surroundings (Ref 3-38).

The entire subject of wheel noise is at present only partially understood. Present approaches are largely intuitive and empirical, and their success suggests that satisfactory results could be obtained if more were known about the subject.

Tube Vehicle Systems. Tube vehicle systems are potentially the fastest of the ground transport systems. They have been studied at the conceptual level for many years, supplemented by limited laboratory experiments.

A number of factors make them potentially very attractive for high-speed ground transportation (200-500 mph):

1. Insulation from adverse weather conditions

2. Controllable environmental effects

3. Security from vandalism

4. The possibility of evacuating the tube, resulting in low aerodynamic drag, and consequently low power requirements.

Tube systems strongly suggest the use of underground operations, particularly in cities and suburbs, to capitalize on the containment of unsightly and noisy effects. Although tunneling is more costly than above-surface installations, this cost will be offset at least in part by lower land-acquisition costs. It is also possible that tubular guideways will slope downward between stations to take advantage of gravity for acceleration and deceleration. One of the advantages of using gravity is that the accelerations and decelerations produced by it are not sensed by the passengers.

During normal operation of an evacuated tube system, tunnel pressure may be maintained by vacuum pumps. Controlled air leakage into the tunnel may be used for maintaining comfortable temperature within the tunnel. In emergencies it may be necessary to repressurize the tunnel rapidly to pressures which will not endanger passengers.

Tube vehicle systems can be suspended by steel wheels on rail, by an air cushion (including ram wing), or by magnetic levitation. Pneumatic tires are not well suited for the speeds of interest (200 to 500 mph) and, at the higher end of the speed range, steel wheels on rails may also run into difficulties. At these higher speeds, air-cushions or magnetic levitations may be the best choices. However, air-cushion suspension may not be practical in systems operating in tubes evacuated for high speed operation. While magnetic levitation thus appears to have the greatest potential for high speed operation, it also is the least developed. Research is being done under sponsorship of the Federal Railroad Administration to determine if the scheme is really practical in terms of power requirements, performance, magnetic shielding of passengers and guideway regularity.

Some propulsion methods available for tube vehicle systems include: linear induction motors (LIM), internal propulsion systems, hydraulic jet propulsion, pneumatic, and electric traction motors driving wheels.

One design approach (Refs 3-39 and 3-40) using the LIM is to externally mount the LIM primary element on the roof of the vehicle and have it straddle an aluminum rail secondary element attached to the roof the tunnel.

The internal propulsion scheme (Refs 3-41, 3-42, and 3-43) is based on propelling the vehicle through a nonevacuated tube so that the air is transferred from front to rear by a flow-induction device. The "pump" generating the desired thrust utilizes a bladeless propeller in a pusher configuration. The bladeless propeller (Figure 3-11) transfers energy from a "primary" flow to a contiguous "secondary" flow, through the work of the pressure forces which the two flows exert on one another at their interfaces.

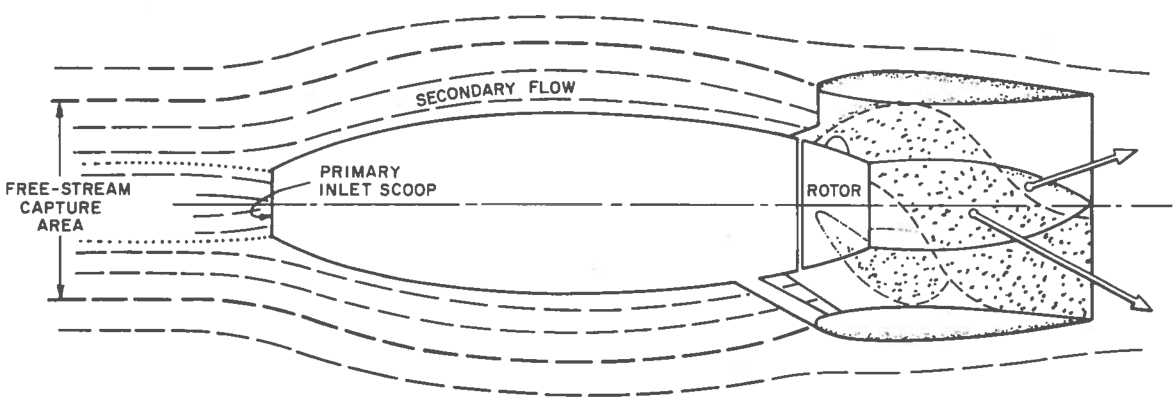


Figure 3-11. Schematic of a Bladeless Fan
(Source: Ref 3-42)

The primary fluid in this arrangement is the air which is taken in through a scoop, energized in a gas generator, and discharged through skewed nozzles on the periphery of a rotor into an annular interaction space between the rotor and a shroud. The rotor spins freely and is driven solely by the reaction of the issuing primary jets. The net work done by the pressure forces is the energy which is transferred from the primary to the secondary fluids by pressure exchange.

Hydraulic-jet propulsion (Ref 3-44) is a method of propulsion in nonevacuated tubes in which the only equipment needed on the vehicle is a row of hydraulic "buckets" fixed in a straight line along its bottom. Hydraulic jets mounted in the tube are aimed in the direction of vehicle travel so that they impinge on the vehicle's "buckets" and provide propulsive force. The jets must be turned on and off in succession as the vehicle passes, but this appears to be within the present capability of hydraulic technology. The arrangement is essentially a linear development of the impulse turbine (Figure 3-12). In hydraulic-jet propulsion there is a fixed relationship between train velocity and water pressure, determined by the density of water (Figure 3-13). Achieving the necessary pressures is within current technology, and they are of a magnitude which gives a small jet and an economic pipe size. Furthermore, the major elements of a hydraulic-jet propulsion system (such as pumps, high-pressure pipes, and hydraulic-jet and bucket technology) are all available and in wide commercial use for other purposes.

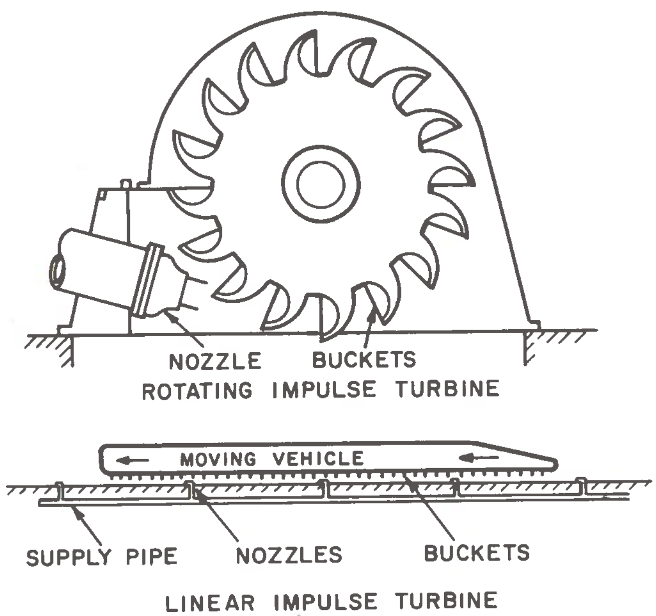


Figure 3-12. Hydraulic Impulse Turbines
(Source: Ref 3-44)

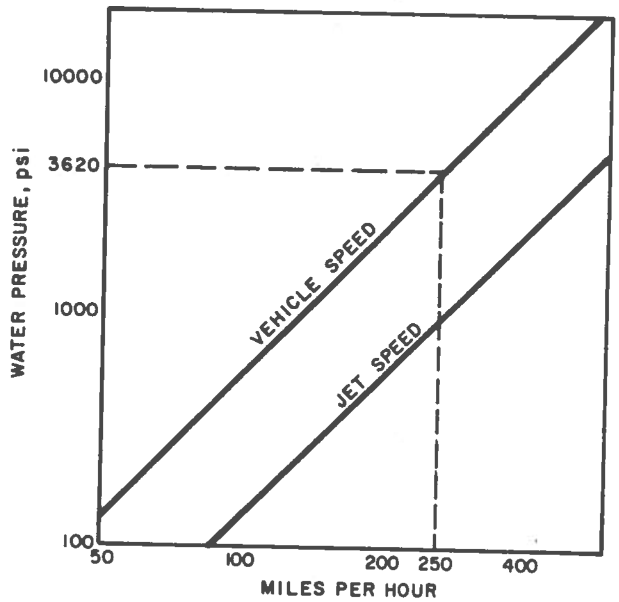


Figure 3-13. Water Pressure Vs. Vehicle Speed (Source: Ref 3-44)

The urban Gravity Vacuum Transit (GVT) System, proposed by Tube Transit Corporation, is a passenger transportation system that uses pneumatic pressure and gravity to propel trains through evacuated underground tubes (Ref 3-45, 3-46). These tubes are evacuated by electrically-powered pumps located near the stations. The trains, which are cylindrical and pressure tight, are accelerated and decelerated through tubes by gravity and controlled admission of atmospheric air pressure. The trains are supported and guided by wheels that ride on rails inside the tubes. A feature of the concept is that it employs gravity for roughly two-thirds of the total propulsive energy requirement.

The operation of the GVT system is based upon using two stations, one at each end of an evacuated tube. The tubes curve downward between stations for gravity boost. While a train waits in the station, the tube is evacuated. Then the entrance door to the tube opens and the train is sucked in. Air pressure behind the train and gravity accelerate it to a high speed, after which it coasts awhile in a level section of the tube. Deceleration for the next station is accomplished by compression of the air ahead of the train and by gravity, as the tube slopes back upward. The tube exit door then opens and the train passes out of the tube and enters the station.

A variation of pneumatic propulsion is the use of steam, proposed by the Susquehanna Corporation (Ref 3-47). In this system, a vehicle is propelled through a sealed tube by steam in back of it at 4 pounds per square inch. Steam pressure in front of the vehicle is about 0.5 pound per square inch. The estimated top speed is 400 mph. The steam in front of the vehicle will condense on the tunnel walls, substantially reducing aerodynamic drag.

TRW proposes using present-day dc traction motors to propel a vehicle in a partially evacuated tube at speeds near 200 mph (Ref 3-48). The vehicle would have a steel-wheel-on-rail suspension system and would be essentially present day state-of-the-art. This system also uses gravity to assist in the acceleration and deceleration of the vehicle.

Air Cushion Vehicles. The Tracked Air Cushion Vehicle (TACV) is attractive for FTL service. The basic principle involved is the use of an air cushion to suspend the vehicle above a guideway. This essentially eliminates all friction between the vehicle and the guideway surface, offering much more propulsion efficiency. One further important benefit from this type of suspension is a better ride quality without unusual or severe guideway smoothness requirements.

TACV has been shown to be applicable to a broad range of ground transportation systems. To illustrate specific characteristics for a particular application, the proposed Los Angeles Department of Airports (LADOA) high-speed access system will be used. This system would run from the San Fernando Valley to the Los Angeles International Airport, a distance of about 16.5 miles. A dual-track guideway, running mainly above an existing freeway, was planned. Top speed of the vehicles would be about 150 mph and an average speed of about 70 mph would be achieved with one stop in route. An explanation of the large difference between the top speed and average speed of the system points out a problem with this class of system. Because of the topography and geography of the only practical route, many guideway curves exist. These result in speed reductions to maintain passenger comfort within acceptable limits. The overall effect is to require operation below the design speed for most of the route. Other significant characteristics of the LADOA/TACV system are nominal vehicle capacity of 60 to 100 passengers for headways of three to six minutes. Traffic growth predictions indicate that the head-training of two lower capacity vehicles may be necessary if headway cannot be practically and safely reduced to two minutes or less.

Fluid support of vehicles operating close to the surface of travelways offers the attractive potential of fast, smooth rides with accompanying economy in propulsive power. A potential significant advantage of the air cushion vehicle over its wheeled counterpart is its ability to operate on a cheaper guideway. The guideway is generally the most expensive part of a ground-transportation system, and the air cushion promises to reduce these costs by relaxing the guideway technical requirements.

First, the air cushion spreads the weight of the vehicle evenly; the guideway need not be designed to take the concentrated stress of wheels. Second, the inherent smooth riding ability of the cushion reduces the surface evenness requirements on the guideway. These and other benefits of air cushions, such as lowered maintenance requirements for vehicles and guideways, would accrue to both high and low speed transport. For the present, technical development is primarily concentrated on TACV for high-speed transport of passengers. Disadvantages of air cushion support include the power required to maintain the air cushion and the noise caused by it.

The development of an operational TACV system requires, along with the air cushion, a host of other technological developments. These developments fall into three categories:

1. Technological developments peculiar to air cushion vehicles

2. Developments generic to levitated (including magnetic levitation) ground transporters (nontraction propulsion)

3. Developments generic to high-density, high-speed traffic systems (automation, safety equipment).

The last two categories are included because the TACV is an important pacing development in new types of ground transportation. The driving motivation behind the development of new guideway technology is cost. Tunneling is costly and, because land acquisition can also be expensive, the elevated guideway is generally considered the most economical.

In addition to structural problems, the major engineering concerns associated with TACV guideways include:

1. Methods for switching vehicles off the guideway. (For a high-speed, high-traffic-density line, this is a very significant problem.)

2. Methods for mounting and alignment-maintenance of the reaction rail (if a linear electric-motor is used for propulsion).

3. Methods for providing wayside power at high voltage and high current levels.

A TACV propulsion system must provide non-traction thrust. Aircraft propulsion systems would appear to be the most applicable; however, they are generally ruled out for reasons of noise and air pollution. LIM is, at present, the most likely TACV thruster and is under extensive engineering development (Refs 3-49, 3-50 and 3-51).

The LIM concept presents the TACV designer with the choice of placing the secondary element in the guideway or on the vehicle. With the LIM secondary (which is merely a conductor) on the vehicle, the primary windings are placed in the guideway. This arrangement has the advantage of not requiring propulsion energy on the vehicle but has the major disadvantage of very high cost for the long primary required. Unless the aggregate length of the vehicles on the line is an appreciable fraction of the line's length, a short primary on the vehicle appears to be the most technically feasible and economic arrangement.

Extensive TACV research and development programs have been underway for some years. In Europe, a French program conducted by the Societe de l'Aerotrain started in 1965. A propeller-driven vehicle on an inverted-T guideway was first developed, followed by a jet-propelled vehicle operated on the same track. Two operational-type vehicles were then developed. One is an 80 passenger vehicle propelled by a shrouded turboprop engine at speeds up to 186 mph. The second is a 40 passenger vehicle powered by a LIM and capable of 110 mph. Testing of these two vehicles was initiated in late 1969.

In the U.S. much research and study of TACV and its technology has taken place, primarily under the auspices of the FRA/OHSGT. MIT was placed under contract in 1965 to study high-speed ground transportation and since then has continued with analytical and experimental work on vehicle dynamics and air suspension systems. NASA has worked with OHSGT, using NASA test facilities for TACV aerodynamic and dynamic tests plus air cushion research. Extensive system engineering studies have been conducted by TRW, starting in 1967. This represented the first overall TACV system study done in the U.S.

A LIM test vehicle, produced by the Garrett Corporation, has been obtained by the FRA and will be operated on a test track at the DOT Test Facility near Pueblo, Colorado. This car, running on conventional rails and capable of speeds over 200 mph, was delivered to Pueblo in May of 1971.

The Urban Mass Transportation Administration (UMTA) is pursuing the development of an urban TACV. They plan to award one or more design contracts for a vehicle of the 150 mph class in 1971, with the test site to be selected at a later time. This program is designed to determine the operational feasibility of the TACV in this speed regime, and in addition, accelerate the application of such systems in urban environments.

Magnetic Levitation. Magnetic vehicle suspension, discussed further in Section 6.3, could be applied to FTL systems. It potentially offers a quieter operation than an air cushion and could operate with an order of magnitude less power. It may also be less sensitive than the air cushion to guideway irregularities.

Magnetic suspension is still in a very early stage of development. Prototype testing of vehicles is going on in Germany and Japan, and feasibility studies are underway in this country.

3.4 MOVING GUIDEWAY SYSTEMS

Introduction. Within Major Activity Centers (MACs) there exist many transportation requirements which are not being met. Moving Guideway Systems (MGS) have been proposed to meet these needs.

Currently, much of the travel in these MAC areas is by walking. In some Central Business Districts, rapid transit service is available but in most cases travel is by automobile, taxi, streetcar and bus, which compete for space on the often-congested streets.

The transportation requirements within MACs have been estimated by Stanford Research Institute (Ref 3-40) as varying from 2000 to 8000 persons per hour per link for most applications, based upon 80 percent utilization. An exception would be in a university situation where peak loadings, at a rate of 18,000 to 60,000 persons per hour, are possible. Average trip lengths in MAC areas range from 1000 feet, for walking trips, to 1/2 mile, for vehicle trips. Very few trips would be longer than 1 mile because of the limited size of MAC areas. Moving guideway systems are well suited to serve these transportation needs.

MGSs are those in which a passenger or a vehicle is propelled by the guideway surface or moving parts within the guideway. There are two principal concepts: (1) the moving walk; and (2) the passive capsule. Representative examples of each are discussed below.

Moving-Walk Systems. The simplest of these systems is the constant-speed walk. Constant-speed moving-walk systems (Figure 3-14) can transport pedestrians horizontally or on slight inclines at speeds ranging from 1 to 2 mph. They represent the only specialized form of people-moving equipment that has been designed, constructed and tested extensively in numerous installations throughout the world. A length of 1000 to 1500 feet has been generally quoted as a practical upper limit for a single moving walk, based on friction levels and power requirements. The system speed is restricted in order to keep velocity differential for boarding passengers low. Since the system speed is lower than the average pedestrian walking speed (3 mph), the usefulness of this means of transport is very limited.

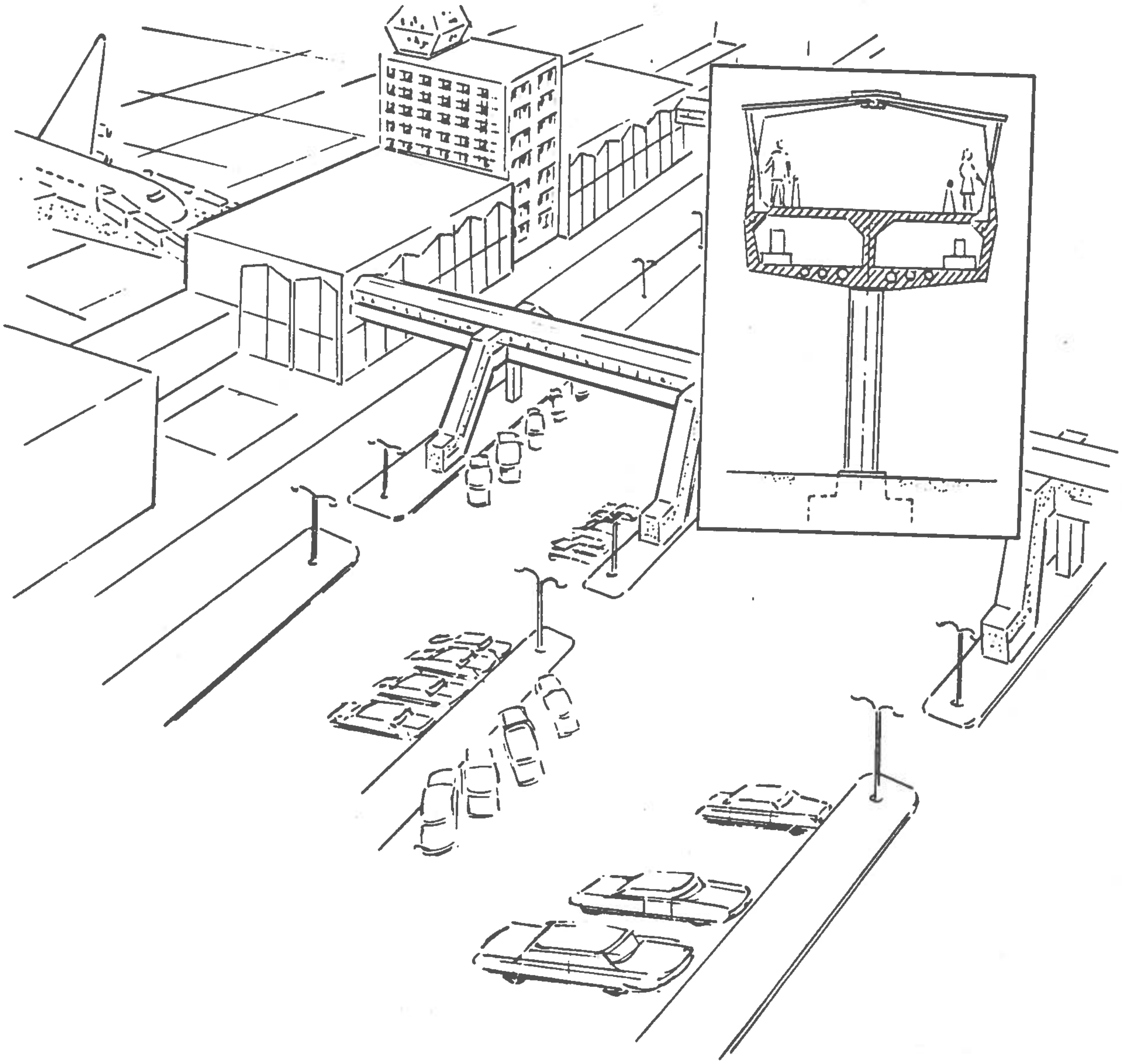


Figure 3-14. Application of Constant Speed Walk (Source: Stearns Manufacturing Company)

In order to raise travel speeds of the passenger, several schemes have been suggested for accelerating the passenger to speeds of 4.5 to 5.5 mph. One scheme (Figure 3-15) proposes a linear series of belts, each moving faster than the preceding one, to accelerate the passenger from the speed of the entry belt (about 1.5 mph) to the speed of the main belt. Another scheme proposes to use an elastic apron consisting of alternating ribs which move forward horizontally, drop away and return

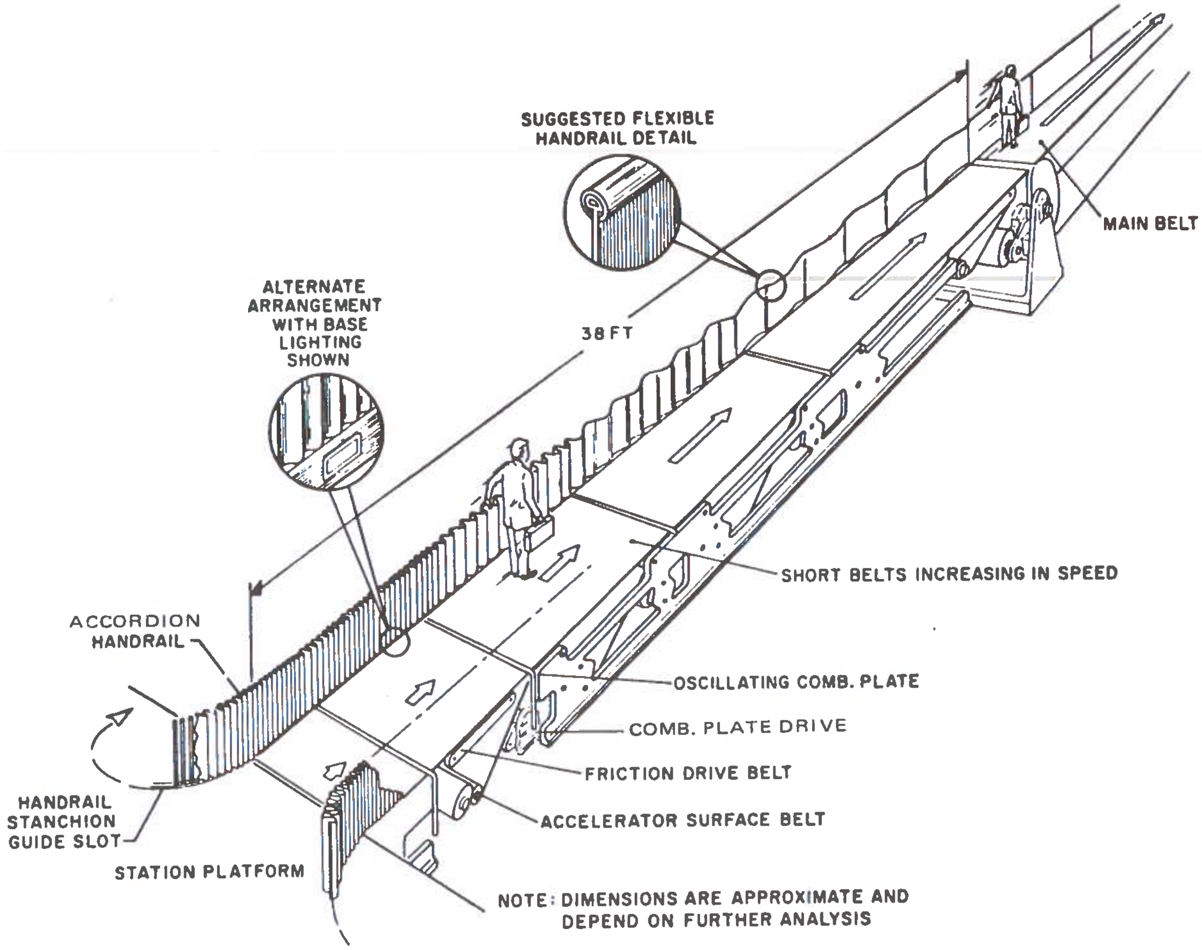


Figure 3-15. Proposed Configuration of a Linear-Array Moving Walk (Source: Ref 3-52)

to their original position for the next forward motion (Figure 3-16). The effect is a uniform acceleration of the passenger during which no discrete changes in velocity or vertical motion should be felt. A third scheme utilizes a deforming mesh which is wide at the entrance point and narrows laterally as it stretches axially (Figures 3-17 and 3-18). As this deformation occurs, the passenger is accelerated. Still another scheme (Transveyor/Transdhec) proposes a variable-pitch screw to accelerate a platen from the entry velocity to main line speed (Ref 3-53)

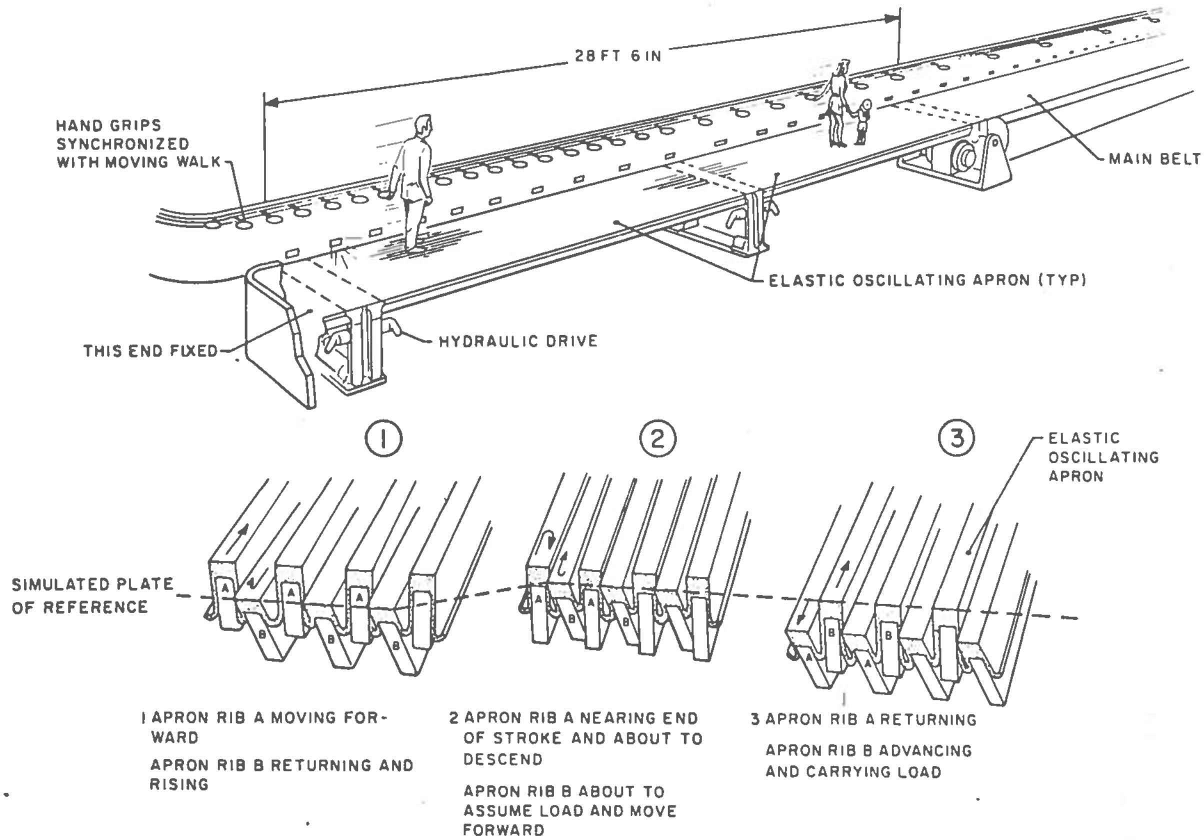


Figure 3-16. Constant Linear Accelerator
(Source: Ref: 3-52)

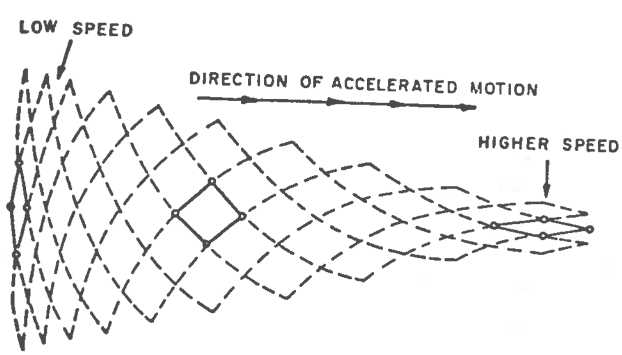


Figure 3-17. Deforming Mesh Principle
(Source: Ref 3-39)

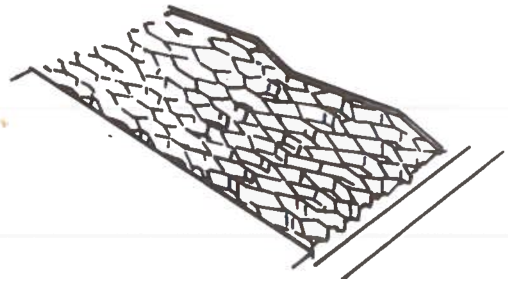


Figure 3-18. Illustration of Mesh Material
(Source: Ref 3-52)

Most of the moving-walk systems proposed are end-loading. The capacities of end-loading systems are limited by the rate at which people can board. This number is independent of walk speed and is in the range of 3000 to 3600 persons per hour per passenger width of walk. Walks seem to have a practical width limit of two passengers due to the desirability of providing handrails or hand supports for the accelerating passengers. End-loading systems, therefore, are limited to capacities in the 6000 to 7200 persons per hour range. This would be adequate to meet most MAC requirements. If sufficient space is available, parallel walks could be added to increase capacity.

Another method of increasing capacity uses intermediate side loading points (Figure 3-19). Side loading can be

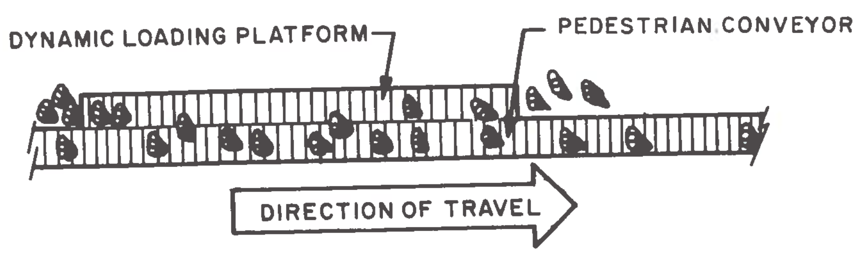


Figure 3-19. Side-Loading System
(Source: Ref 3-40)

accomplished by accelerating the passenger up to the speed of the main walk on a parallel system, with a transfer then necessary from the parallel walk to the main walk for the line-haul travel. As passengers board at end-loading points and are accelerated to the speed of the main walk, the distance between them increases, creating gaps. If these gaps can be filled by persons boarding at intermediate access points, the main walk capacity can be increased. However, this introduces the "post" problem. Posts comprise the barrier between the main walk and the parallel walk (Figure 3-20). Passengers who do not transfer quickly enough in the loading/unloading zone will strike these posts. Care must be taken in the design of the system to minimize the likelihood of serious injuries that may result from this impact. The use of wider walks in the decelerating stage will be necessary to prevent overcrowding and serious injuries due to crushing. The associated lateral maneuver required of the passenger may not be as easily accomplished as it may appear, especially for less agile passengers. Furthermore, the provision of hand supports for all decelerating passengers will be difficult.

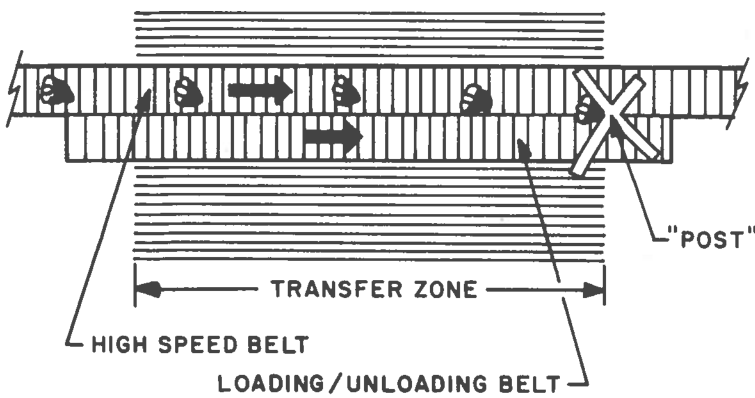


Figure 3-20. The "Post" Problem
(Source: Ref 3-40)

Accelerating walks will allow the pedestrian greater travel range than possible or acceptable by walking. By combining his own speed with the moving walk speed, a pedestrian could reach a walking velocity approaching 9 miles per hour. This is higher than can be attained by auto drivers in some Central Business Districts today. Accelerating walk systems appear capable of meeting virtually all MAC travel-capacity requirements except in the dense Central Business Districts or in high-peak demand situations.

However, there are numerous technical problems surrounding accelerating walk systems. The construction of a deforming mesh that would not catch objects (heels, shoelaces, umbrella tips, etc. and would not be objectionable to the passenger (squirm of surface material underfoot, forces in two directions) has yet to be proven. The maintenance, life span and the replacement of oscillating, elastic-rib aprons appears to be a serious problem. The movement of persons across interfaces between belts, the matching of speeds on acceleration systems, the speed variations of long, continuous belts due to elasticity and non-uniform loading problems are quite significant.

More developmental work seems necessary before accelerating walks are ready for implementation, not the least of which is the testing of the pedestrian's tolerance and acceptance of the different acceleration schemes. In addition, mechanical testing of all subsystem components must be accomplished to insure reliability and safety.

For still higher speeds, intermittent-stop systems have been proposed (Figure 3-21). These systems employ continuous belts

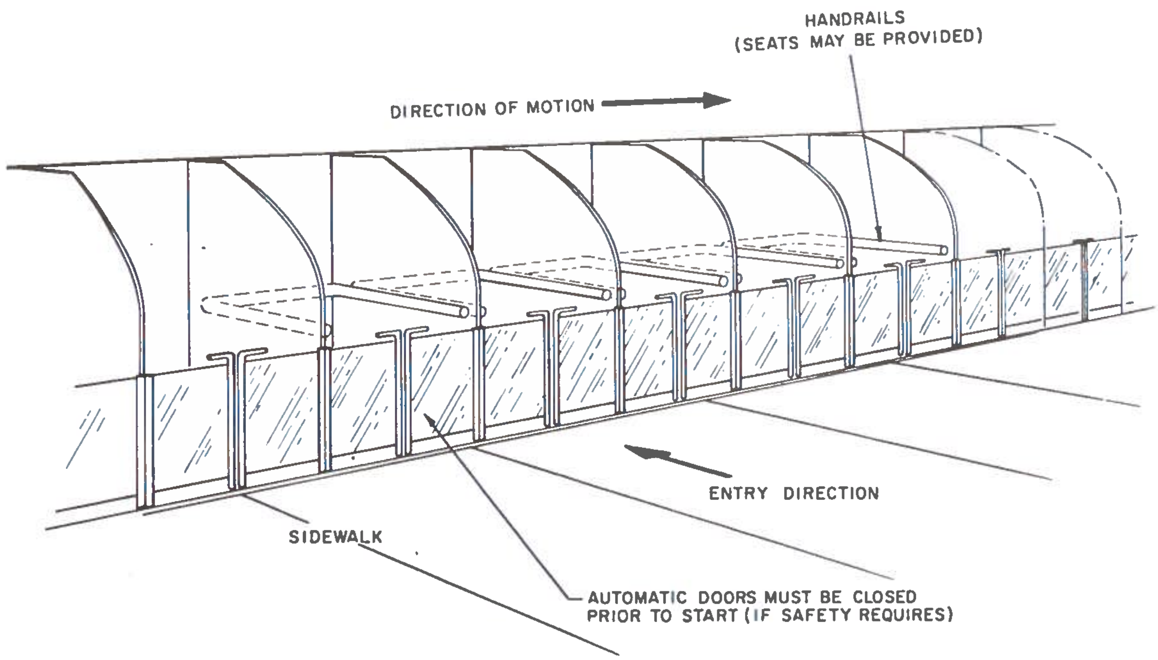


Figure 3-21. Possible Configuration for the Intermittent-Stop System (Source: Ref 3-53)

which stop for loading and unloading, accelerate to line speed (perhaps 15 to 25 mph), travel some given distance and decelerate to another stop. For such speeds, passenger compartments would be desirable. This scheme could carry 20,000 to 30,000 persons per hour. The intermittent-stop belts have the advantage of providing accessibility over the entire length of the system and increases the pedestrian range considerably due to the high line speeds. Because of the relative simplicity of this system, it appears to have fewer problems than the continuously operating belts. The handling of the passenger compartment, if utilized, might pose the most severe difficulty for the system.

One other scheme proposes a platen to accelerate the passenger from entry velocity to line speed, at which point the passenger transfers from the platen to the constant speed walk (Figure 3-22). The principal difference between this and the continuous-entry acclerating schemes described previously is the higher speed of the main walk (20 mph). Although the accelerating platens are used for main-walk access and egress, they could also be used for interline transfers. If the main walk were filled, the capacity would be approximately 35,000 persons per hour, allowing 3 feet of belt per passenger. The possibility of interline transfers makes this the only moving walk or belt system which could be easily envisioned as a

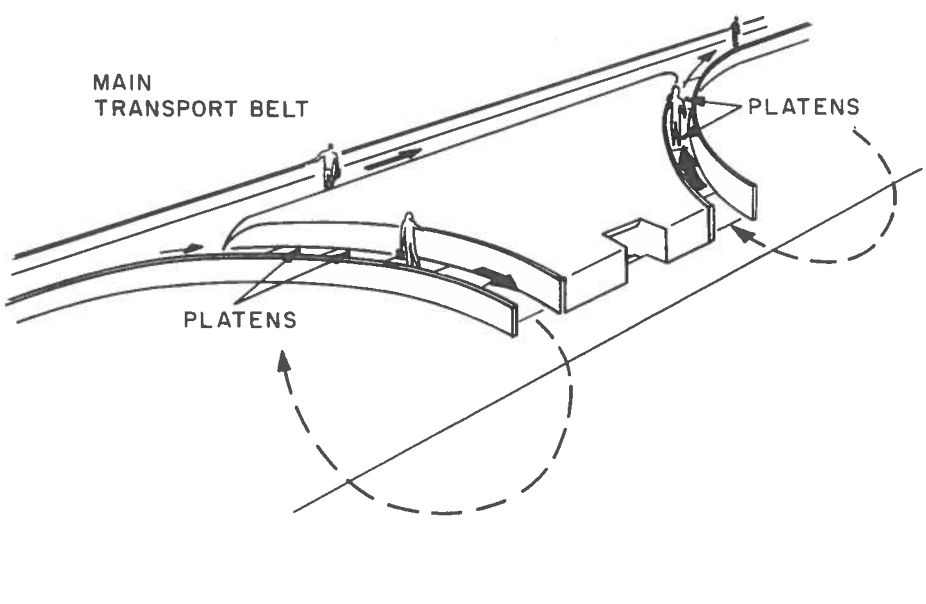


Figure 3-22. An Accelerating Platen System Using the Bouladon Integrator (Source: Ref 3-52)

complete, integrated network for MACs. High speed and frequent access points make this a high-capacity, people-moving system. However, there are some technical problems. The accelerating-platen idea is unproven. As with all moving-walk systems, the length of each belt is limited by horsepower requirements and friction levels. Passenger transfers across the interface between belts at 20 mph appear to be a problem as would the precise matching of speeds between adjacent belts. Prototype development underway in Europe should answer most of the mechanical questions concerning accelerating platens and high-speed belt operations. A parallel effort should test the human engineering aspects of the system and public acceptance.

Passive Capsule Systems. A variation of the intermittent-stop system is the passive vehicle concept wherein vehicles slow down but do not stop at stations. A parallel moving walk or turntable in the station moves at the same speed as the capsule, allowing passenger transfer at zero relative velocity. One manufacturer proposes rollers for accelerating the capsules from a 1.5-mph station speed to a 15-mph line-haul speed and for negotiating curves; belts are used for the straight line haul segments (Figure 3-23). Capacities for this system would be no higher than for end-loading systems due to the slow station speed. For six-passenger cars the capacity is 6750 persons per hour. The high-line speed of the system allows longer trip

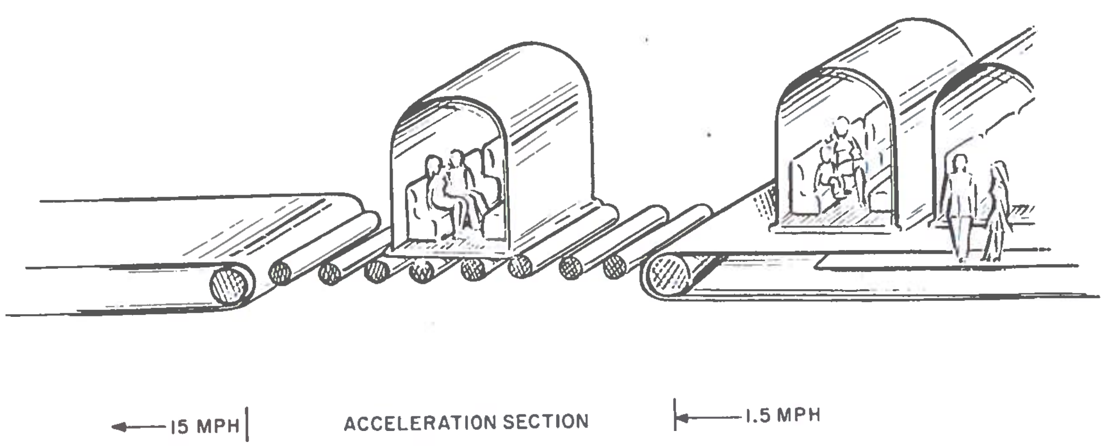


Figure 3-23. A Passive Capsule Proposal: The Carveyor Concept (Source: Goodyear Tire and Rubber Company)

distances, and the provision of seats provides a more comfortable ride. The system is capable of negotiating sharp curves at high speeds, which none of the previously mentioned walk or belt systems are able to do. Since there is no interface problem between belts or rollers, the system can be as long as desired.

Other passive capsule schemes propose propelling the capsules by means of cables (Figure 3-24). Cable systems do not offer any capacity advantage over the moving belt schemes, but the integrated network capability is a particular advantage when combined with 15-mph (or higher) line speeds and off-line stations. In this configuration, they are really PRT systems and are more properly evaluated as such because the problems relate more to control than to mechanical operation. Many ski lifts employ this means of transportation today. The only major complication with this system would be the automated switching development.

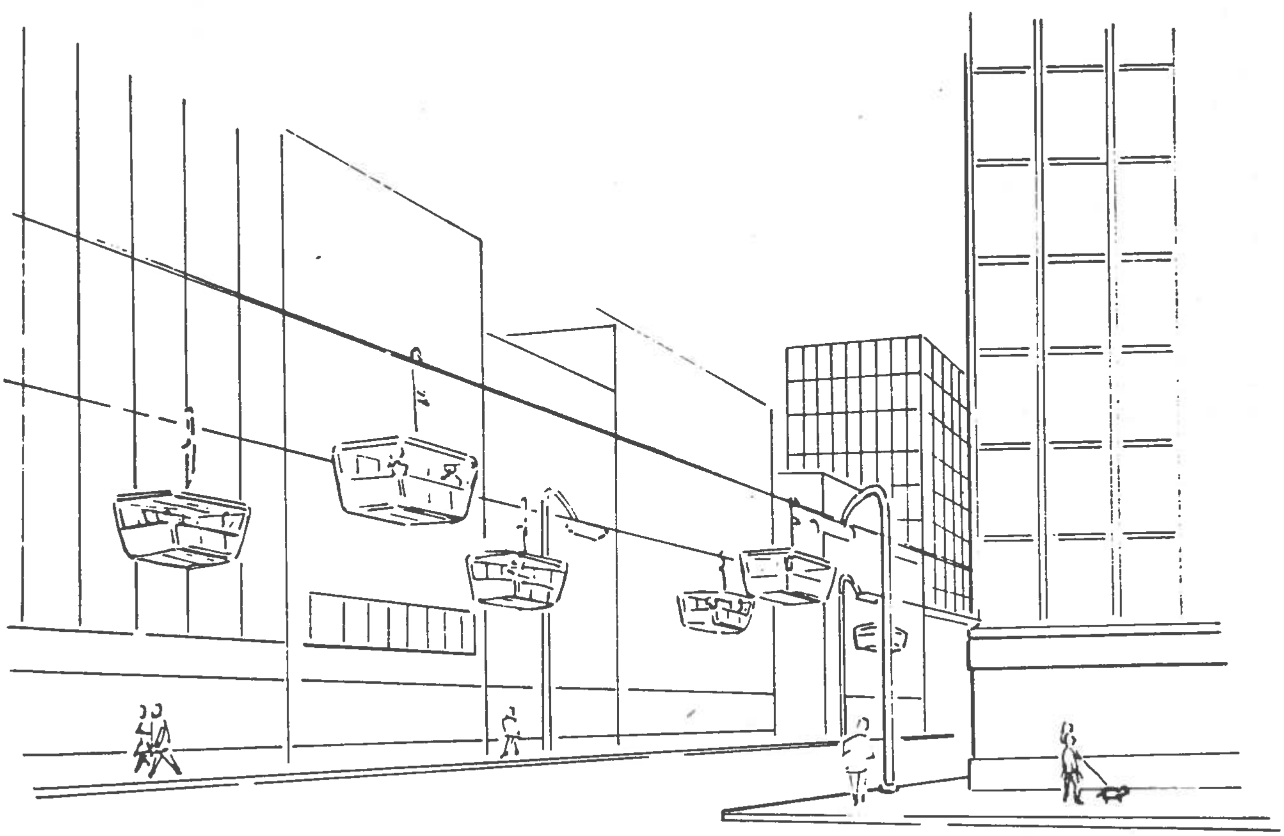


Figure 3-24. Cable Car System (Source: All American Engineering Company)

Costs of Moving Guideway Systems. Capital costs supplied by the system manufacturer or proponent must be viewed with caution since few have advanced beyond the concept stage. The consulting engineering firm of Jackson and Moreland, in a study for the Boston Redevelopment Authority (Ref 3-52), estimated equipment costs for a 3000-ft end-loading system for six different moving guideway systems to be:

System Description	Total Estimated Equipment Cost	Capacity (pph)	Speed (mph)
I - Multiple Belts in Linear Array	$2,653,200	4,400	4.4
II - Constant Linear Acceleration*	$2,902,000	4,400	4.4
III - Variable Platen Length**	$2,403,000	4,400	4.4
IV - Side-Loading Oscillating Elastic Apron***	$1,969,000	12,000	4.4
V - Moving Belt Gondolas***	$2,469,000	3,600	4.4
VI - Bouladon Integrator	$1,969,000 (Estimated to be same as for IV)	12,000	10-20

* Oscillating-rib-apron scheme discussed earlier
** Deforming-mesh scheme discussed earlier
*** Not specifically discussed in this report

Equipment costs are only a small portion of total installed costs, however. For example, total costs for the multiple-belt linear array were estimated at $7,488,400 for a 1300-ft installation in downtown Boston.

For these high installation costs MGSs offer many potential benefits. They require exclusive rights-of-way which separate pedestrian movements from vehicular movements. The pedestrian-vehicle conflict is thereby eliminated, increasing the safety of the pedestrian and facilitating vehicular flow through the MAC. This in turn allows higher average vehicle speeds, reduces the number of potential vehicle stops, and thereby reduces the amount of pollutants emitted from the vehicle exhaust systems.

If the moving guideway system forms an integrated network, it may eliminate the need for automobiles for many MAC trips. The land requirements for parking lots and garages would be reduced, allowing better utilization of valuable real estate. The existence of such a system in any MAC would enhance its attractiveness and increase land value.

Environmental Considerations. The exclusive right-of-way width required is quite narrow, ranging from approximately 4 feet for a moving belt to perhaps 10 feet for a passive capsule system.

For all but the shortest installation, MGSs require a second level for the separation of guideway from regular pedestrian movements. An aesthetic infringement occurs when this second level is elevated. It is aggravated when the right-of-way is enclosed, as most would be for operating and passenger-comfort reasons. It would be further aggravated if the moving guideway is an integrated system whose links must also be grade-separated and thus necessitating a third level.

If the space for these systems is available, the system would probably blend well with the surroundings. But a substantial amount of construction with its associated annoyances would be necessary.

Moving guideway systems would be quiet since all motors are underground or enclosed, emitting very little if any external sound. Since motors would be electric, there would be no pollution created at the installation site.

Conclusions Concerning MGSs. The slow, constant-speed belt may serve in limited applications but is of little usefulness in MACs as an alternative to other forms of public or private transportation.

Accelerating walks and passive capsule schemes have excellent potential for transportation service in MACs. Accelerating walks are best suited for serving short trips and small MAC areas. Passive capsules are best suited for longer trips and larger MAC areas. However, more work is necessary in the areas of hardware development, reliability testing, passenger safety and human engineering testing for many of the proposed systems.

All end-loading walks and most passive capsule schemes are limited to capacities of approximately 6000 to 7200 persons per hour which is adequate for most MAC requirements.

Few moving guideway systems will be constructed through private initiative due to high initial costs and uncertain state of development. The potential client is naturally hesitant about spending large sums of money on the development of a system which may have mechanical or human acceptance problems. The passive capsule concept, with propulsion provided by belts or rollers, would be the easiest to implement by virtue of operational experience at amusement parks and expositions. For shorter MAC trips, accelerating walk schemes offer promise.

3.5 DUAL MODE SYSTEMS

Introduction. Dual Mode Systems (DMS) operate as conventional automobiles or buses on ordinary highways or streets and under complete automatic control on special, exclusive right-of-way guideways. The concept has been discussed and studied for at least two decades, but it has not been implemented anywhere. In some proposed systems, the guideways would provide power to each vehicle, in addition to control and guidance. In others, vehicles would be self-propelled but still under automatic control.

Implementation of DMSs should be made in an evolutionary manner to take advantage of the large investment already made in automobiles and highways. Some proposed systems would use conventional automobiles without modifications. These would be carried on standardized pallets which circulate under automatic guideway control. Automobiles would be loaded and unloaded automatically or be driven on and off under vehicle power.

The associated technological evolution of the automobile would include the staged addition of electronic information displays in vehicles, automatic speed control, automatic headway control and other automatic features. Highway modifications would include inductive loops or electronic guidewires installed in existing roadbeds. In later stages, a power conductor would be added.

Dual Mode Automobile Systems would have the comfort, convenience and diverse origin/destination service of the automobile without requiring a transfer between vehicles. They could provide faster line haul service with higher reliability and safety due to the automatic surveillance and control. The driver would be relieved of the stress of driving and the nuisance of stop-and-go traffic. Higher system capacities could be obtained for a given land area because lane width could be reduced and close headway spacing could be consistently achieved. Variability in driving caused by environmental conditions, such as fog, could be removed through automatic operation.

The high capacities which can be achieved through use of very small headways may not be practical for real situations, such as heavy commuter service. Through-city service, however, may prove useful. Universal application of the DMS is, therefore, not expected. Parking in congested downtown areas also will provide a significant limiting factor to the wide use of the DMS, particularly for private vehicles. A practical service may be provided by public vehicles restricted to guideways in downtown areas, but allowed off the guideway outside.

Special attention will have to be devoted to the automatic checkout of vehicles entering the guideway network. All precautions must be taken to preclude the entry of unreliable or unsafe vehicles because even a single breakdown could effectively shut down a major portion of the system. Removal of disabled vehicles must be accomplished quickly. This is not a simple procedure and has received little attention from system proponents. For publicly owned vehicles and automated pallets, the problem of redistribution of empty vehicles to meet individual demands would have to be solved. The automated pallet system has the advantage of eliminating vehicle checkout requirements. Some proposed DMSs will now be discussed.

Electronic Highways. In 1958, Zworkin and Flory discussed a scheme for the development of a DMS evolving from existing automobile/highway systems (Ref 3-54). In their proposal, various driver aids would first be installed in vehicles to improve driver/vehicle performance. Next, subsystems would be added to vehicles to automate speed control, headway control, etc. Finally, highways would be modified to include guide wires and third rails for vehicle guidance and power collection.

Fenton and Olson recently reported on the state of the art in electronic highways (Ref 3-55 and 3-56), indicating the need for various subsystems including:

1. Automatic longitudinal control
2. Vehicle-spacing detection
3. Communications
4. Automatic lateral control
5. Automatic merging control
6. Controlled lane changing
7. Vehicle propulsion
8. System decision-making capability
9. Compatible manual mode
10. Automatic vehicle checkout
11. Evolutionary developments.

In reviewing the state-of-the-art, several areas were cited as requiring further research and development. The best merging-and-spacing control strategy must be determined because this factor strongly effects the actual capacity of the system and, in turn, determines cost effectiveness.

Practical demonstration of a complex network of automated vehicles under computer control is needed. Theories have been worked out in part but experiemental data are not available. Design decisions concerning the allocation of central and local computer control must be made. For example, complete central computer control can provide better system flow control, but at the expense of complexity and sensitivity to system breakdown. Local computer control would minimize costs but would lose the benefit of control optimization over a wide area. Some combination of central and local computer control would probably maximize the benefit/cost relationship.

MIT/Carnegie Mellon Vehicle. In 1968, MIT began development of a test facility to retrofit a 1967 Ford Mustang with components needed for dual mode operation (Refs 3-57, 3-58 and 3-59). This system was later moved to Carnegie-Mellon University. A side-arm power pickup was used (Figure 3-25). This arm connects near to the vehicle's center of gravity to provide the highest degree of stability in the skidding mode. The arm configuration allows operation in a power pickup channel, which opens downward, thus protecting it against hazards such as ice and snow. Switching is accomplished by connecting the arm on the side of the vehicle corresponding to the desired direction of movement and

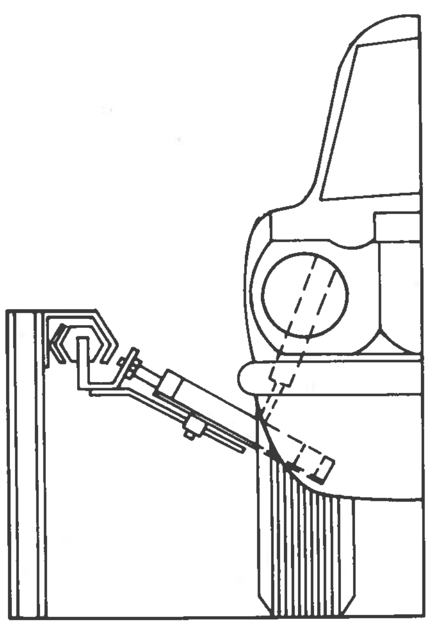


Figure 3-25. Dual Mode Automobile Guideway Connection (Source: Ref 3-59)

disconnecting the other side. At stations, the arm swings down below ground level to minimize problems of interference in that critical area.

The Alden StaRRcar. One of the pioneers in DMS's development is William Alden, of Alden Self-Transit Systems Corporation. His original StaRRcar (Self-Transit Rail and Road Car) consisted of a small, two-passenger electric car capable of travelling at 60 mph on an automatic guideway (Figure 3-26). The guideway was slotted, minimizing the danger of foreign objects interfering with vehicle operation. Rubber tires provided the traction. The onboard switching mechanism would grasp either a right turning or left turning rail at each intersection.

A later version of the StaRRcar is operational on a short test track under single mode automatic control (Figure 3-27). Current designs employ six-passenger vehicles, although larger 15-passenger vehicles (with 9 standees) are planned. Propulsion is supplied by a 30-hp, constant-speed, synchronous electric motor. Coupling of the drive train to the rubber-tired wheels is through a hydraulic, variable-speed transmission. Power pickup is provided by conventional brushes on a third rail. Vehicle steering is automatically controlled by two guide wheels running against curbs of the guideway.

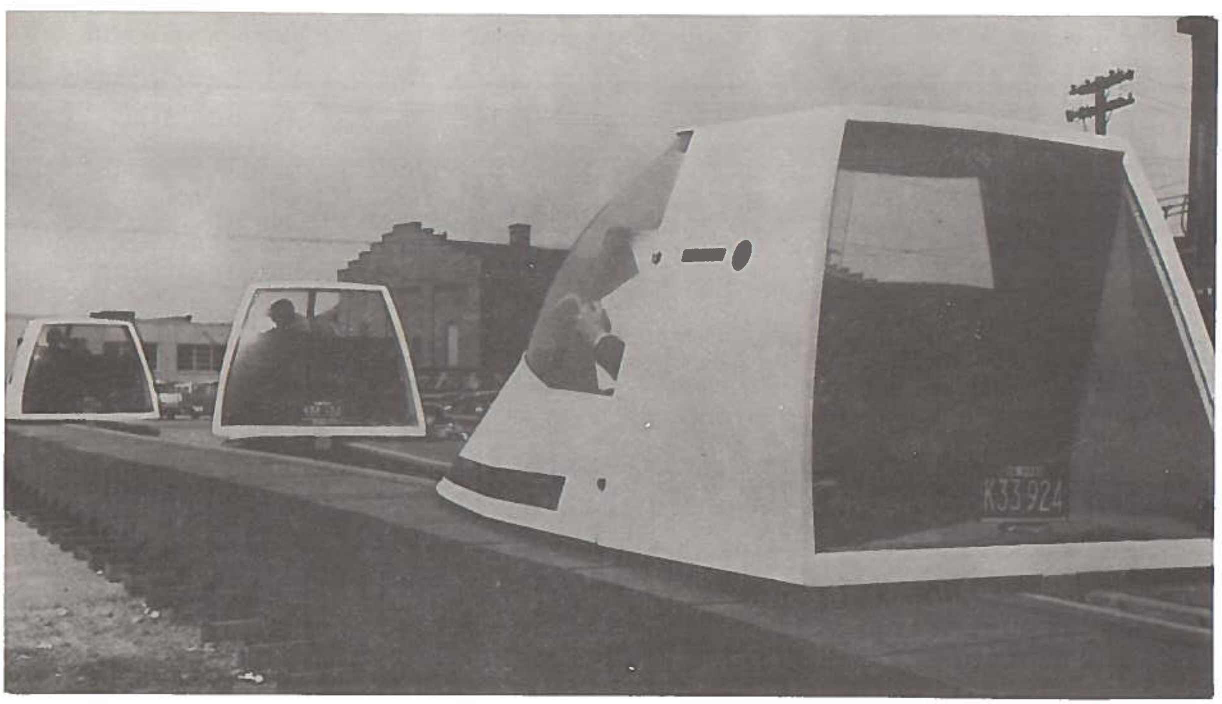


Figure 3-26. Original StaRRcar (Photo: Courtesy of Alden Self-Transit Systems Corporation)

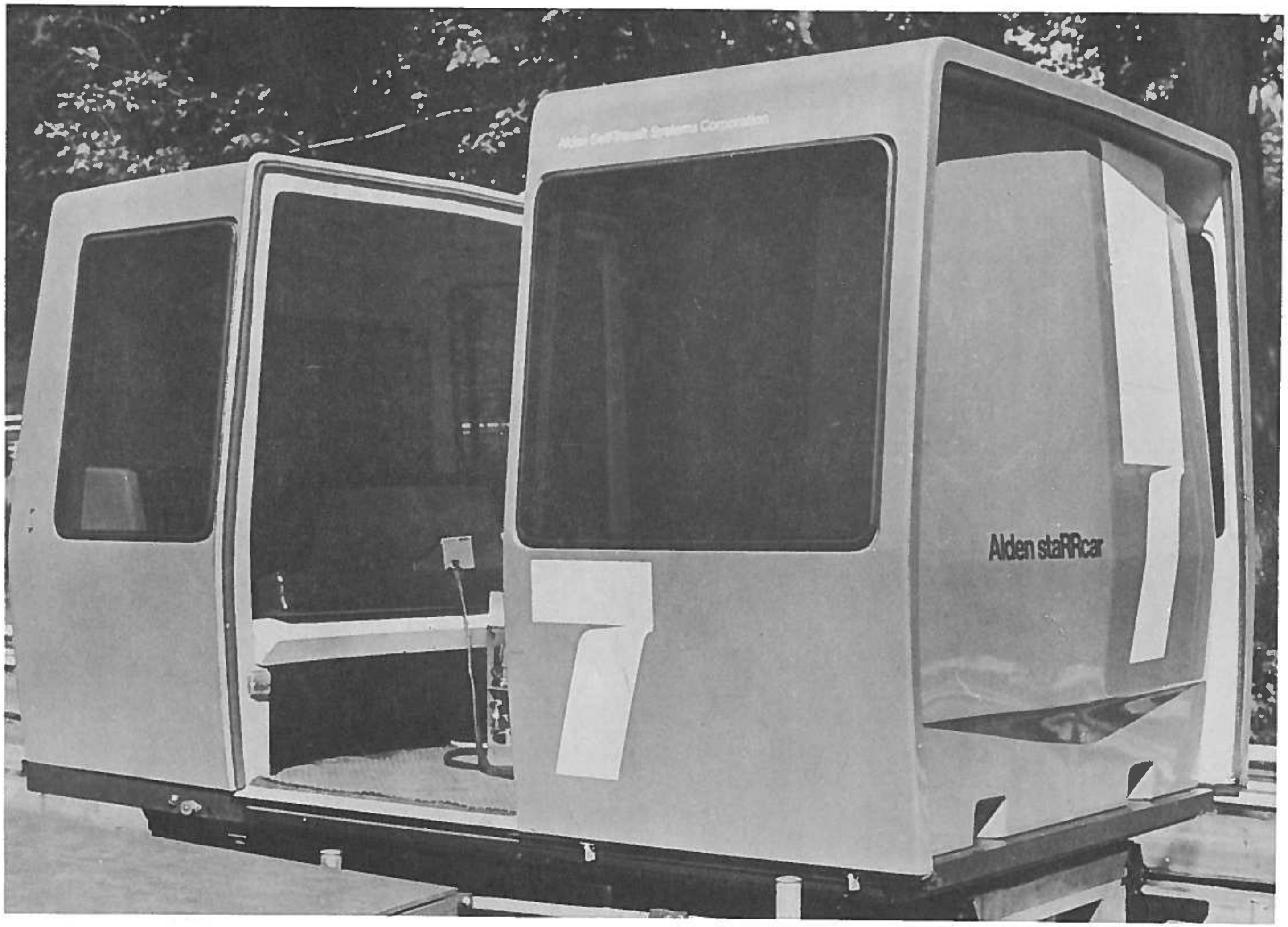


Figure 3-27. Current Version of StaRRcar (Photo: Courtesy of Alden Self-Transit Systems Corporation)

The Urbmobile. Cornell Aeronautical Laboratory has proposed a small four-passenger, electrically propelled vehicle called an Urbmobile (Ref 3-60). It would operate on exclusive guideways under automatic control and on streets it would operate under manual control. The total urbmobile system includes four major parts:

1. Terminal and parking facility
2. Vehicle
3. Guideway
4. Automatic control.

Urbmobiles would enter the guideway system at discrete access points and would be guided and propelled automatically to a destination in the system. Each vehicle would use synchronous rotating machinery of ordinary squirrel-cage motor design. Conventional pneumatic tires would support the vehicle during street operation. During automatic operation, it would be supported by steel wheels on guideway tracks. Batteries would be carried for power. These would weigh either about 850 pounds (lead-acid variety) or about 200 pounds (sodium-sulphur variety). Battery development would dictate the final design.

Additional components required to make the system operate include:

1. Trolley arms to connect vehicle and guideway
2. Steering connectors
3. Absorbing bumpers for low-velocity impact
4. Brake solenoids
5. Onboard display for destination selection
6. In-vehicle switching mechanism.

Safety protection devices would require further study to protect, for example, against acid burns in case of battery breakage in an accident.

The Multimodal System (MMS). TRW systems, Inc., has proposed a MMS (Ref 3-61) for door-to-door service, incorporating:

1. A deterministic control system
2. A functional train-headway policy

3. High-speed switching

4. A unique station layout.

MMS is a pallet-type system in which an automobile driver maneuvers his vehicle onto an automatically controlled, enclosed pallet operating on high-speed (up to 150 mph) interurban guideways. Load capacity of the pallet vehicle is projected to be about 18,500 pounds, with propulsion provided by 220-hp motors. These pallet vehicles may look something like those pictured in Figure 3-28. Design dimensions of the TRW pallet are 25 ft by 8 ft by 8 ft. Power would be supplied from a third rail, with auxiliary batteries on the vehicle for low speed or emergency operation.

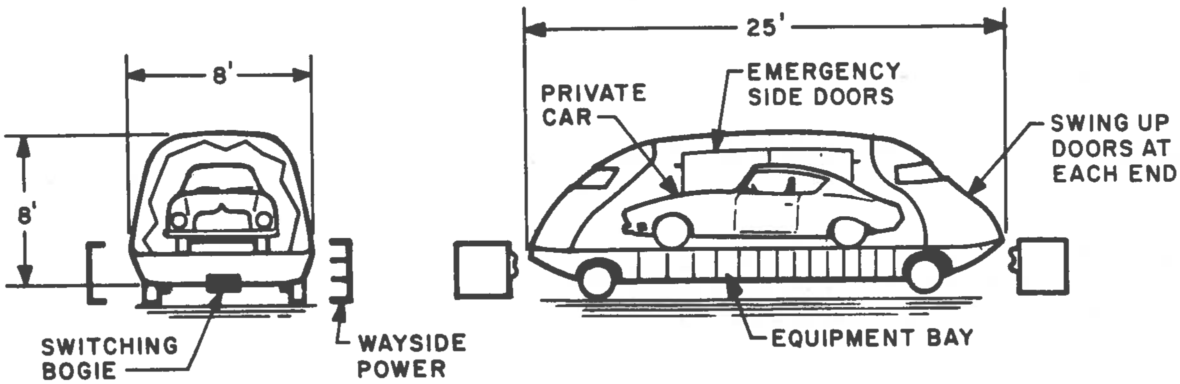


Figure 3-28. The TRW Multimodal System

In pallet design, the problem of heating and cooling passengers must be addressed since it is not expected that the automobile engine would be kept running while on the pallet. Space requirements at stations would have to accommodate loading and unloading of vehicles. Depending on operating strategy and the number of vehicles handled, several times as much space may be required at stations than needed for passengers alone.

The 1970 Ford Study. In 1970, Ford Motor Company established a consortium of participants to demonstrate dual mode technology. Ford's R&D planning division is to provide program management; its car division is to provide the vehicle design; Bethlehem Steel is to construct the guideway; Detroit Edison is to handle power distribution; and TRW Systems, Inc., is to develop the command and control system. Prototype design is underway and should be ready for test on Ford's demonstration track by 1973. Public demonstration would follow if Federal support is provided.

Dual Mode Operating Strategies. Synchronous moving slot strategies have been proposed for DMS operation. It is thought possible, theoretically, to carry upwards of 8000 vehicles per hour per lane at 60 mph (Ref 3-62); however, this has not been verified. Various guidance schemes have been proposed, including inductive-loop guidance, mechanical (servo-controlled) linkages and "rabbit followers" (on small pallets).

In control studies, link or simple networks are generally considered rather than total area networks; thus, effects of system loading are ignored. One example worked out by Ford Motor Company covered the Transportation and Land Use Study (TALUS) area around Detroit, a five-county district over which a 200-mile network was superimposed (Ref 3-63). Using 1966 data, both existing and proposed networks were compared. The study pointed out the need for more intensive tests with real area-wide data.

<u>DMS Capacities</u>. The capacity of a DMS is dependent upon the headway allowed by the operating strategy. If the headway is set at the emergency braking distance (k = 1)*, then the capacity would be only 1310, 20-ft vehicles per hour at 60 mph with a 0.5g braking rate (see Figure 3-29). For virtually zero headway (i.e., vehicles almost touching bumpers, k = 0), the capacity is 15,800 vehicles per hour at 60 mph. Today there is no assurance that such low k-factors could be technically achieved in actual practice or that they would be publicly accepted if they were possible. Hence, the practical achievement of high vehicle flow rates remains a question.

There are other factors which may limit capacity such as station size, sharp curvature and turning movements. These may restrict not only system capacity but, in some cases, line capacity as well.

<u>System Costs</u>. Rough estimates of the cost of DMS can be obtained from work done by General Motors (Ref 3-64), General Research Corp., and MIT (Ref 3-65). General Motors estimated the cost of equipment, control and construction of a rail pallet system to be in the range of \$5 to 8 million per mile and the electronic highway to be \$3 to 4.5 million per mile. General Research and MIT estimated the cost of an automotive DMS to be \$2.9 million per mile. These figures are presented only for information and are not intended to represent the relative or actual cost of an installation. There are many unknowns which can substantially alter the relative cost between alternative DMSs. For a given city, the alternative system may not be placed in the same location. The land costs could be the largest of the

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$$*k = \frac{\text{Headway (feet)}}{\text{Emergency Braking Distance (feet)}}$$

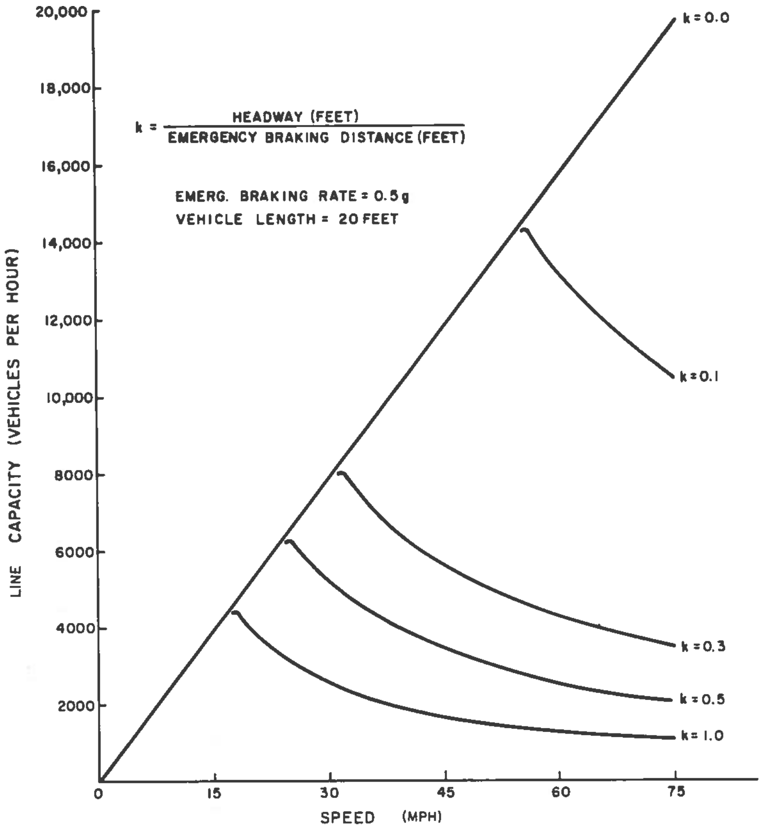

Figure 3-29. Speed vs. Capacity for DMSs

unknowns and could approach or exceed the construction costs mentioned above. Extensive cost studies of DMSs for realistic situations are needed.

Environmental Considerations for DMSs. The environmental effects of DMSs vary considerably, depending on the type of system selected. Rail pallets or autos on fixed guideways could be installed on existing railroad rights-of-way, detracting little from the area's aesthetics. The electronic highway would be similar to a conventional expressway in appearance and configuration. If a form of high-speed corridor service is needed, rail pallets or autos on fixed guideways would compare favorably from an aesthetic viewpoint with other types of service.

In regard to local air pollution, the least harmful propulsion system would be the electric motor. Diesel or other internal combustion engines would be more injurious to air quality.

Noise from a DMS should be equal to or less than that of today's highways, rapid transit systems and railroads. For rail systems, the need for heavy and noisy propulsion equipment would be eliminated because each small unit would have its own engine and the noise would be widely distributed.

Conclusions about DMSs. The advantages of DMSs include:

1. DMSs combine freedom-from-driving and potentially higher speeds with the comfort, convenience, flexibility and origin-to-destination service of the private automobile.

2. Private automobiles and captive transit vehicles could be intermingled to service Central Business District areas.

3. The operation of the vehicles under electric power on the guideway would reduce air pollution at the site.

4. The dual mode guideway would have higher capacity and would require less right-of-way width than a corresponding freeway because of positive vehicle control.

5. The safety of the traveler would be enhanced by guideway operation since vehicles are separated and lane change maneuvers would be automatically controlled.

The disadvantages of the DMSs include:

1. The vehicle checkout procedure for dual mode vehicles entering the guideway is a difficult problem.

2. A vehicle failure could shut down all or a major portion of the system.

3. The DMS is not suited for Central Business District operation. Dual mode buses or captive transit vehicles would have to be utilized for centers of high activity.

4. DMSs require an exclusive guideway.

In conclusion, automotive DMSs appear to be ideally suited for evolutionary development from today's automobile to the automatically controlled vehicle of the future. However, rail pallet systems would be the easiest to implement because of their relative simplicities.

Practically no data exists on system and equipment reliability. With DMSs, the command and control system is perhaps the most critical missing element. It is most complex for the electronic highway application, where control is not physically exerted by the guideway itself.

For DMSs to handle more than 5000 vehicles per hour at 50 mph, k-factors around 0.3 must be attained. It is uncertain at this time whether these k-factors can be reached in a practical operating system.

With the exception of the electronic highway, DMSs would be less harmful to the local environment than the forms of transportation currently employed. In-depth study is needed to determine the detailed impact.

DMSs using private automobiles would be best suited for intercity travel and, secondly, for intra-urban travel. They are not, however, well suited for service in the Central Business Districts where most of the urban problems focus, but a system incorporating publicly owned, dual mode transit vehicles would be appropriate for the latter service.

It is unlikely that a private corporation will undertake complete system development without a commitment to build at some location. It is also doubtful that a municipality or urban area transportation agency could afford the development cost of a system without assurances concerning the operating reliability and efficiency of the system. Therefore, the Federal Government would have to support work in dual mode development to remove some of the risks inherent in such innovative systems.

3.6 DIAL-A-RIDE SYSTEMS

Introduction. The Dial-A-Ride System exemplifies demand-responsive systems. Demand-responsive transportation systems are those in which vehicle routes are not prescheduled but are derived in response to trip requests. The vehicles could operate on existing highways and roads or in conjunction with automated guideways.

Dial-A-Ride has been developed to the point where many facets of the concept have been demonstrated (Refs 3-66, 3-67, 3-68 and 3-69). In the typical system, trip requests are made by means of a telephone call to a central dispatcher, stating the desired origin and destination. The most eligible vehicle would be then assigned to pick up the passenger. The optimization of vehicle assignments is essential in maintaining an efficient and economical system.

An illustration of the type of vehicle that could be used in a Dial-A-Ride system is shown in Figure 3-30. This particular vehicle was built by the Ford Motor Company and used by MIT in their Computer Automated Routing System Project (Ref 3-70).

Figure 3-30. Dial-A-Ride Vehicle (Photo: Courtesy of MIT)

Dial-A-Ride could operate with trip densities as low as 20 demands per square mile per hour. Assuming conservative ridership figures, this implies densities as low as 3000 people per square mile. In contrast, conventional transit usually requires at least 8000 people per square mile along its corridor of operation (Ref 3-71).

The people most attracted by Dial-A-Ride consist of those unable to command the use of a motor vehicle, and those who wish a low-cost (lower than taxi) alternative to auto trips. The first category includes the young, old, poor, disabled and those whose autos are temporarily unavailable. The second category includes commuters to the local line-haul station, service agencies, etc.

Dial-A-Ride Operating Strategy. The basic concept of Dial-A-Ride is that passengers will be picked up from where they are and will be delivered to their destinations within specified time intervals. Vehicles are not on a fixed schedule or predetermined route. However, predetermined trips can be scheduled into the system. Vehicle scheduling is dynamically performed as each trip request is received. Such a system can operate in many modes: (1) many origins to many destinations (many-to-many);

(2) many origins to few destinations (many-to-few); and (3) few origins to many destinations (few-to-many). Vehicle capacity could be as high as 20 passengers or as low as four. A range of 10 to 20 seems to be typical (Ref 3-71).

Communication between the customer, decision maker/dispatcher and bus driver can take several forms. Figure 3-31 shows the data flow or communication network for a manually controlled and voice communication system. The human decision-maker is the dispatcher who must assign passengers to vehicles and decide tour routes. Figure 3-32 shows the same voice communication network with a computer replacing manual control. This represents the present state of development. Figure 3-33 shows a computer control and digital communication system. In this configuration, the human operator and dispatcher are eliminated, resulting in a high degree of automation.

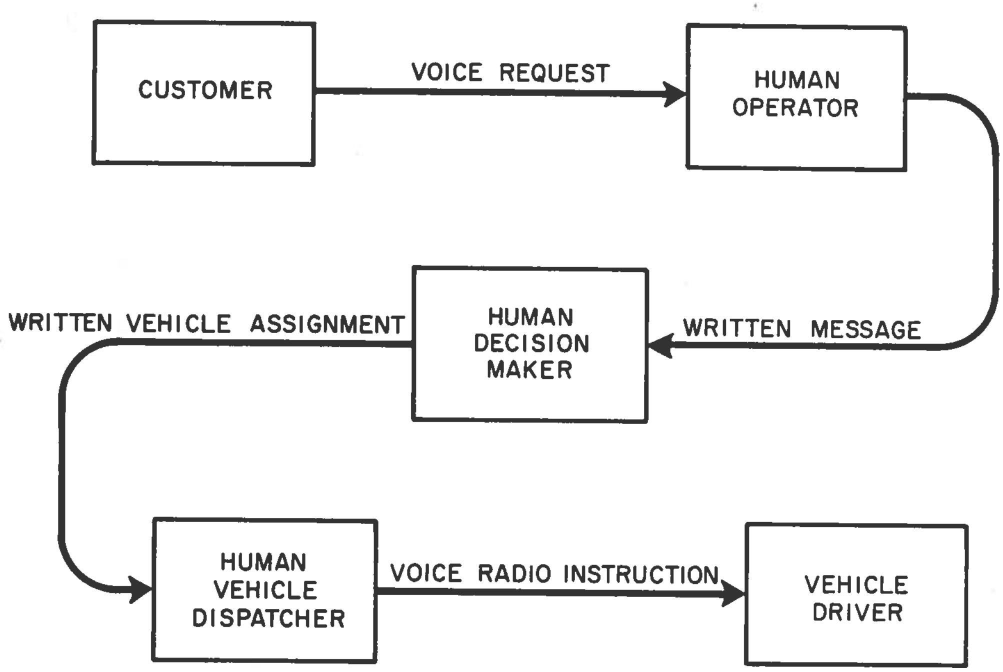

Figure 3-31. Manual Control/Voice Communication

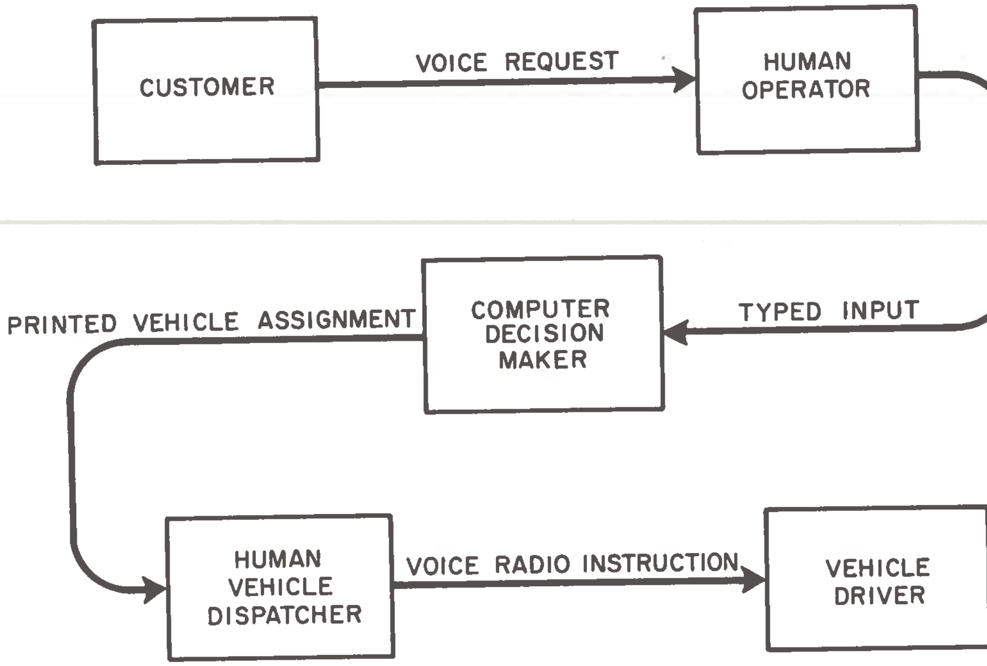

Figure 3-32. Computer Control/Voice Communication

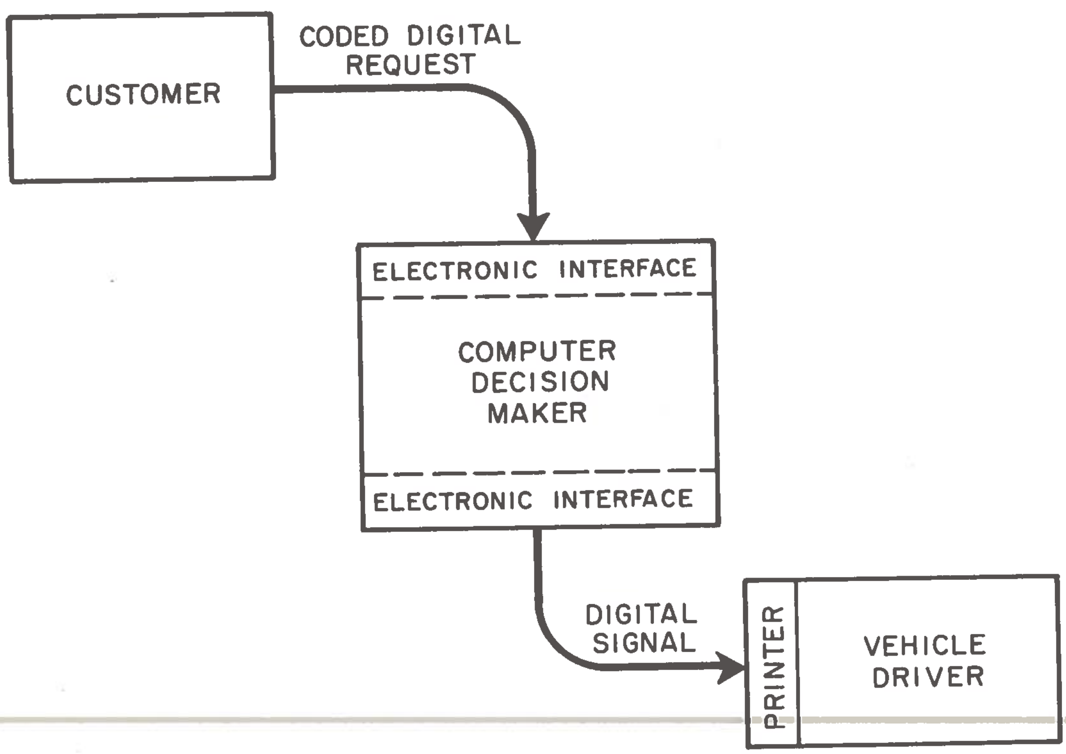

Figure 3-33. Computer Control/Digital Communication

Investigation of traditional voice radio dispatch techniques has indicated that, in a Dial-A-Ride system, a human dispatcher using voice radio could handle approximately 100 trip requests per hour, or about 5 to 10 vehicles (Ref 3-72). This message traffic completely utilizes one voice radio channel. The requirement for a separate dispatcher and radio channel for each 10 vehicles indicates that voice radio is not feasible for large systems because the number of dispatchers would become an economic burden. Also favoring digital communication is the fact that large quantities of radio channels are not likely to be available in the congested frequency bands used for police and taxi communications. A digital system operating on a single channel pair (two frequencies) could direct 180 vehicles and simultaneously poll the vehicle fleet at a rate of 40 vehicles per second for driver inputs or responses (Ref 3-72). Since all message traffic would be digital, the scheduling computer and the communications system would be directly connected, and only a supervisory or emergency voice dispatching capability need be retained.

Dial-A-Ride Costs. It has been estimated that the cost of a Dial-A-Ride system would be about equal to the cost of conventional bus operation, plus the additional cost for vehicle scheduling and communication operations. This latter cost will depend largely on the available technology and the efficiency of the operation. Two separate systems have been costed. Assuming that a typical 2 to 3-mile taxi trip costs twice as much as an unsubsidized bus fare ($1.10 to $1.90 compared to 50¢ and 75¢), Dial-A-Ride would fall somewhere in between, with an expected cost of 85¢. About 15 percent of the cost is for computer operation and communication equipment (Refs 3-71, 3-72). Individual vehicle costs could range from $5,000 to $20,000, depending upon design and features. Computer hardware rentals could range from $25,000 to $35,000 per month with purchase prices up to $1.5 million.

Some Test Data. One Dial-A-Ride system in operation at present serves the Pickering Station of the Go-Transit commuter railroad and the Bay Ridges Community near Toronto, Canada (Ref 3-67). This is a manually controlled system operating with a maximum of four vehicles. The feeder service to the railroad has been in service since July 1970 and is now carrying approximately 500 people per day. This service complements existing public transportation by providing feeder service to line-haul facilities in an area that cannot justify conventional public transportation. As of February 1971, a many-to-many service was initiated during off peak hours. This service presently carries 50 to 60 people per day. Fare is 25¢ per ride for adults and 15¢ for children.

The purest Dial-A-Ride system presently operating is in the new community of Columbia, Maryland. This is also a manually controlled system. It operates with a maximum of three vehicles during most of the day. Service is provided on demand between all points within the boundaries of Columbia. A fare of 25¢ per ride is charged. The cost is estimated to be 90¢ per ride. The difference is subsidized by the Columbia Association. Columbia's "Call-A-Ride" service is now carrying over 3100 persons per month. In the fall of 1970, 1500 persons per month were carried by the old fixed schedule service. Since this is the most advanced Dial-A-Ride system in operation, it could prove a most useful source of information on fare, service and patronage relationships.

Ford Motor Company and General Motors are examples of industrial companies that have done developmental work on demand-activated systems (Refs 3-73, 3-74). MIT and Stanford University represent academic organizations that have contributed to the development of demand activated systems (Refs 3-70, 3-71, 3-72, 3-75, 3-76, 3-77 and 3-78).

General Motors considered the economics of Dial-A-Ride based on a consumer survey of a hypothetical system and concluded that, for the particular set of circumstances, economical feasibility would be marginal (Ref 3-79). On the other hand, an MIT report conceived of circumstances in which a system would be profitable (Ref 3-80). However, operating experience from Go-Transit and Columbia, Maryland will provide information far more useful than hypothetical studies. Careful analysis of this recent data should be essential in evaluating the potential of Dial-A-Ride.

Environmental Considerations. The impact of Dial-A-Ride systems on the environment should be minimal. There will be few, if any, permanent facilities constructed. Since the small buses will operate on existing roads, no new roadbeds or guideways will be needed. Because the buses will be operating singly over variable routes, there should be no concentrations of air or noise pollution.

Critical Technologies for Dial-A-Ride. Computer algorithms have been developed that can be used to schedule and dispatch large numbers of vehicles. However, because no manual computer backup procedures or redundant computer configurations with approriate software have yet been developed, there are many system reliability questions still unresolved (Ref 3-76).

Configurations planned at present would require medium size computers, costing hundreds of thousands of dollars. An economical system utilizing small computers has yet to be developed for those situations where large computers cannot be economically justified.

There have been several computer programs developed to analyze certain aspects of Dial-A-Ride such as a simulation program to evaluate assignment algorithms. However, no model has been developed to optimize vehicle fleet size or study economic trade-off, both essential in determining specific system configurations. This would be a very useful tool for planning purposes.

For large systems, vehicle voice communication may be a problem because of the high cost of the required labor (dispachers) and the scarcity of radio channels. The solution here rests with the development of digital communications. A number of proposed digital communication systems have been investigated. Most of these do not provide the message rate needed for Dial-A-Ride or the necessary vehicle response. Automatic vehicle monitoring systems have also been investigated. It has been found that, although the digital transmission techniques employed are similar to those desired, the systems have been designed for a different purpose (vehicle location) and contain expensive extra features. Also, none of those investigated could be used without extensive modifications of the signal formats, essentially creating a new system which would probably be less flexible and economical than a system designed from the start.

Conclusions about Dial-A-Ride Systems. The Dial-A-Ride concept is operational in Toronto, Canada, Columbia, Maryland, and a few other localities. However, these examples are rather primitive. Even though the concept has been demonstrated, its economic feasibility is unknown. Indications are that the fare charged for Dial-A-Ride service will have to be higher than that for a standard bus but should be lower than that for a taxi.

Dial-A-Ride conceptually offers the most personal service of any bus system. Therefore, it should be very attractive to potential users. Its success will depend on whether a high quality of service can be maintained at a price the customer feels is reasonable.

The Dial-A-Ride system is extremely flexible. It does not require a large amount of investment in permanent equipment such as rails or guideways. By the very nature of its responsiveness, it is adaptable to shifting travel patterns that occur in regional transportation. Such a system does not compete with conventional transit such as railroads, airplanes, or buses but supplements them. Dial-A-Ride will serve areas that cannot justify conventional public transportation. In the range of 3000 to

8000 people per square mile, the range in which growing urban areas and small cities fall, Dial-A-Ride should have a significant impact. Dial-A-Ride can cover the spectrum of motor-driven vehicles from taxis to fixed route buses by offering different priorities of service at various times as the frequencies and modes of trip demands fluctuate and economic conditions warrant.

Additional research, development and demonstration of Dial-A-Ride systems is needed with emphasis on system modeling, small system computer configurations, manual scheduling and dispatching and digital communications to remove some of the more critical technological risks and to test market sensitivities.

3.7 PUBLIC AUTOMOBILE SYSTEMS

Introduction. The Concept of Public Automobile Systems (PAS) embodies small vehicles located throughout the area to be served at closely spaced stands. The passenger walks to the stand, acquires the automobile and drives to his destination. If the trip's purpose will require only a short transaction time, the driver will usually park the automobile and use the same vehicle for his next trip. If the purpose of the trip requires a long transaction time, the driver would turn in the vehicle at the nearest public automobile stand and pick up another vehicle when ready for his next trip. The vehicle would be powered by electric batteries or by some other low-power, low-pollution propulsion system. Vehicles with four-passenger capacity are most commonly discussed but two-passenger vehicles might also be used (Figure 3-34).

One possible application for PAS would be to provide service to suburban areas. In order for PAS to be sufficiently attractive, vehicle stands must be located within easy walking distance of every household in the service area. This would typically be one or two blocks. Each stand should be stocked with a sufficient number of vehicles so that one is always available when a trip is to be made (Figure 3-35). The stands must be able to recharge batteries if electric propulsion is utilized. A means of automated inventory checking would be needed since stands would be unmanned.

Many PAS trips would occur during morning and evening peak hours, creating high peak demand. The critical element of this

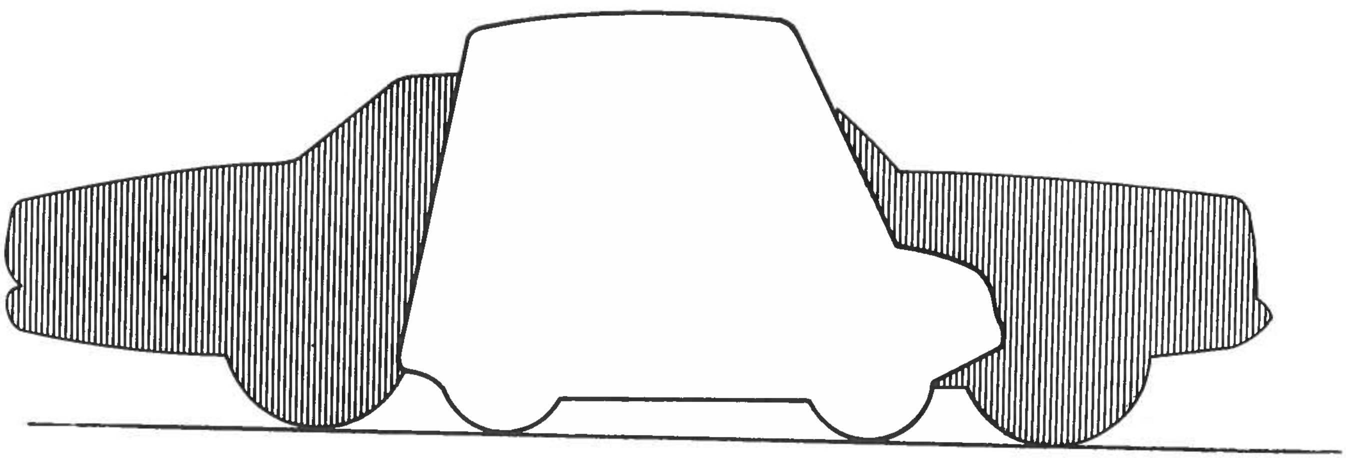

Figure 3-34. Comparison of a PAS Vehicle and a Standard Sedan (Source: Ref 3-40)

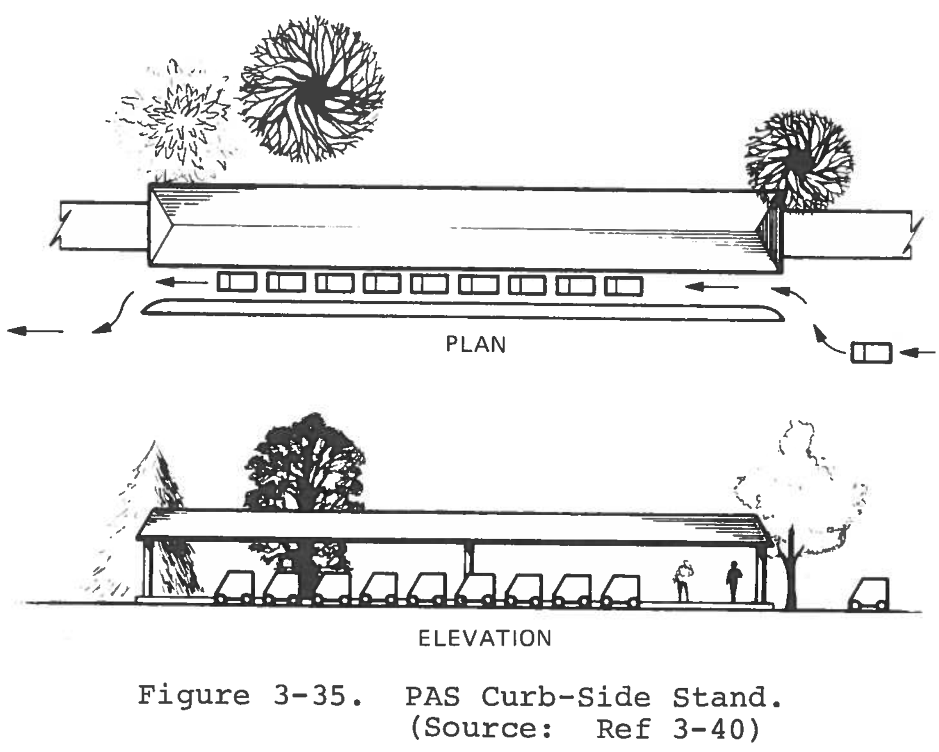

Figure 3-35. PAS Curb-Side Stand. (Source: Ref 3-40)

system concept would be to generate sufficient off-peak demand such that the vehicles are used many times during the day. The redistribution of unused cars from points of high work-trip concentrations to other parts of the service area for midday utilization would have to be studied carefully to minimize system costs. The reverse procedure would be necessary for the evening peak period. Redistribution of cars would be accomplished by towing vehicles in train-like fashion.

In suburban areas where PAS stands would be unmanned, vandalism of unoccupied cars could be a problem. A means of preventing unauthorized usage must also be devised although this does not appear to be especially difficult.

The PAS concept has potential for servicing fairly large MACs, such as Central Business Districts. In MACs, PAS stands would resemble parking lots and attendants would probably be desirable (Figure 3-36). Attendants would also discourage vandalism and reduce the possibility of unauthorized usage. Since the service area would be limited to a few square miles of intense activity, high utilization of the PAS fleet would be expected.

Since PAS would be used for travel within, rather than to and from, MACs, peak period demand would not occur during the

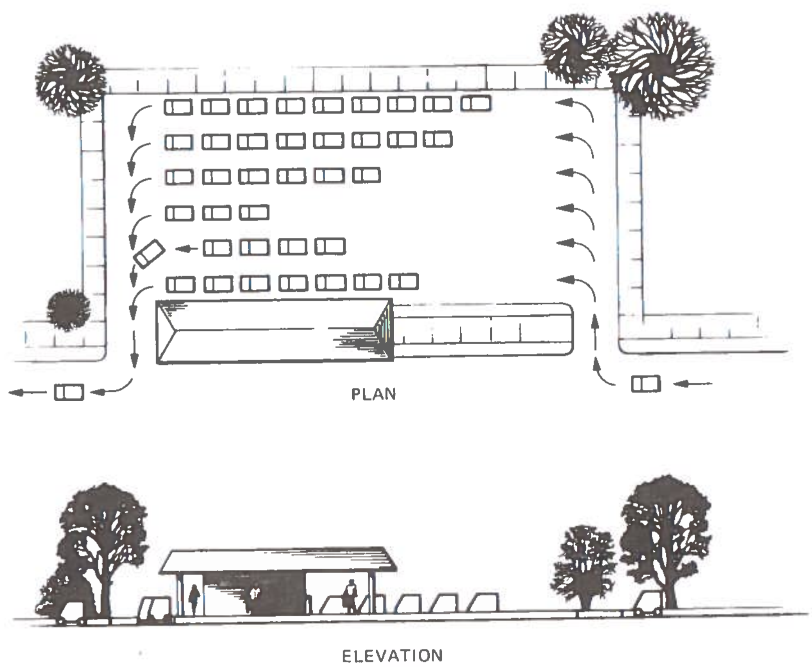

Figure 3-36. PAS Parking Lot.
(Source: Ref 3-40)

normal commuting hours. Demand would, therefore, be more uniformly distributed throughout the day. The system would operate most efficiently in Central Business Districts where mid-day activities (shopping, business, etc.) and evening activities (dining, theatre, movies, etc.) are substantial, or in airports where aircraft arrivals and departures are well distributed.

Advantages and Disadvantages of PAS. The advantages of PAS are that it has the potential of providing far better service than conventional transit, is more economical than taxi service, and might eliminate the need for additional family cars. The disadvantages are that clientele would be limited to those able to drive, vehicle recharging would be necessary (if battery powered), vandalism control would be difficult, and walking to and from PAS stands would be required. Managerial problems, which are by no means insignificant, include redistribution of empty cars, ensuring a dependable supply of cars, vehicle performance reliability, control of unauthorized usage and billing.

Test Data. A limited experiment of the public automobile concept will be tried in Montpellier, France (Ref 3-81). The scheme will put 150 passenger cars at the disposal of users for self-driving within the city limits. Coins costing 5 francs will enable the driver to cover approximately 8 kilometers (about 20¢ per mile). This fare is considerably cheaper than current taxi fares but is much more expensive than standard public transit fares.

Conclusions. PAS technically appears to have potential for use in urban areas. The number of vehicles required and the redistribution problem seem to favor its use in MACs rather than in large residential suburbs. The economic feasibility of PAS must still be proven.

It does not appear that additional research is necessary for the development of this concept. Work currently being done on low-pollution engines might well be used to increase the range beyond that of today's battery-powered automobiles.

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4. INTERURBAN PASSENGER SYSTEMS

4.1 INTRODUCTION

High-speed ground systems can provide transportation on short haul intercity trips (50-400 miles) that is competitive in total time with air transportation. Although speeds for ground systems are now limited to around 150 mph, speeds of 300 mph or more may become commonplace.

Ground systems are able to make frequent stops economically, thus allowing good coverage of the area between two major cities. Ground systems are also able to operate directly into large metropolitan centers, easing access problems for the system. They must operate on fixed, exclusive guideways which reduces their route flexibility. Furthermore, the guideways represent a very large capital investment. Operation of the vehicles themselves is relatively unaffected by weather conditions, but an exposed guideway may require much maintenance to keep it open during severe weather (e.g., a snow-storm). Ground systems supported by solid contact with the guideway (steel-wheel-on-rail systems) could require appreciably less power for operation than levitated (e.g. air-cushion-supported) ground systems, since they need not expend energy to support themselves.

The more likely high-speed ground transportation systems include rail, tracked air-cushion, and magnetically suspended vehicles. Magnetic-suspension technology is not sufficiently advanced to support detailed discussion in this report; however, some comments appear in Section 6.3. The tube-vehicle systems, discussed in Section 3.3, may also have some utility in interurban transportation.

Safety, Reliability and Public Acceptance. It is clear from the Metroliner experience that it is easy for designers and users of new equipment to overlook or underrate the importance of the overall maintenance problem. Penn Central was thoroughly conversant with the problems of maintaining the heavy and simple electric locomotives they had been using for thirty years but were unprepared for the new electronic systems. Maintainability must be stressed in all new systems from the very inception of design. A carefully thought out combination of equipment accessibility, failure identification, built-in test facilities, and fault-location systems can minimize lost time from the equipment point of view. This design approach must be coupled with carefully planned personnel selection for maintenance facilities and diagnostic equipment. Given these and good operational procedures, lost time due to equipment failure can be kept to a minimum.

Closely related to maintainability is reliability for, if equipment fails infrequently, few repairs must be made. The main goal, of course, is safety for the passengers, crew, and the public. From a design standpoint, a system or device is said to be fail-safe when its failure modes can all be identified with a high degree of confidence and when it can be demonstrated that each failure mode does not result in a hazardous condition.

For a system employing a guideway, reliability is a prime requisite. Since most guideways do not permit one vehicle to overtake and pass another one the breakdown of a vehicle or its control can paralyze a major segment of the system. Since failures will occur even with reliable designs, provisions must be made to remove stalled vehicles with a minimum of delay.

It is difficult to define the term 'safety' quantitatively, especially since it is desirable in principle to strive for absolute safety, a condition that unfortunately is incompatible with any productive action at all. In general, however, a common carrier subject to regulation by a governmental agency would be expected to offer a greater level of safety than is provided by a facility that is open to use by privately owned and maintained vehicles. The public would never accept a common-carrier system on which the exposure to hazard is comparable to that on the highways. The importance of reliability, safety, and maintainability must therefore constantly be called to the attention of all organizations planning actual transportation systems, written into the specific actions of all new equipment and subsystems, and not be allowed to drop from view for a while as has so often happened in the past.

The matching of the system and its equipment to the public must be carefully studied and planned for all proposed systems. The ground system and the software system must be joined by a desire to attract passengers to use the vehicle system. Lack of this desire translated into action provides the absurd situations that have hampered public acceptance of the Turbotrain and Metroliner and have effectively hurt the reputation and operation of the Long Island Railroad.

4.2 HIGH-SPEED RAIL SYSTEMS

Introduction. High-speed ground transportation by steel-wheel-on-rail vehicles is a major contender for intercity passenger travel in the short-haul range (50 to 400 miles) for the following reasons.

An extensive network of track linking every major city in the country exists. Thus, the high cost of installing new guideway systems is largely obviated. Some improvement or relocation of track may be desirable or necessary for high speed service, but this is far cheaper than a whole new system.

Rail vehicles can also attain high speeds. Current new equipment in this country, Europe, and Japan is capable of operating at speeds in the 120 - 160 mph region on ideal track, although actual track conditions normally restrict speeds to considerably less than maximum, especially here and in Europe. New European vehicles under development will be capable of over 150 mph and, because of a powered body-banking mechanism they will be able to maintain velocities through curves up to 50% higher than now achievable. Advances forseeable in vehicle construction, propulsion, and suspension systems may make possible vehicles operating continuously and comfortably near the upper feasible speed limits for rail systems (somewhere between 200 and 300 mph) without incurring prohibitive expenses for track alignment and maintenance. In particular, powered body-banking mechanisms and active suspension systems will effectively isolate the vehicle from track irregularities and imperfections and allow safe and comfortable cruising at far higher speeds than are now attainable. Thus, until the need arises for ground transportation systems with speeds above 300 mph, high-speed rail systems appear very attractive.

Over the past few years the Metroliner, Turbotrain, Long Island Railroad, BART, and New Haven commuter train have come onto the railroad scene, paving the way for future systems developments. Only enough detail has been given here to demonstrate existing possibilities and show how these are likely to develop in the years to come. The references cited in this chapter contain much more detail, especially the very comprehensive "High Speed Rail Systems" report of TRW Systems (Ref 4-1).

Preceding the efforts in the United States, several foreign countries had done extensive work in the same field. Japan started development of the 125-mph Tokaido line in 1959 and began service in October, 1964 (Ref 4-2). It utilized a new right of way, and tracks designed for exclusive use. Other nations have not taken such a frontal approach to trackage. Europe, for example, has concentrated on developing vehicle suspensions that would permit high speed operation on existing or only slightly improved roadbeds (Ref 4-3).

Prior to the establishment of the U.S. Department of Transportation (but after the passage of the High Speed Ground Transportation Act of 1965), the Department of Commerce convened a panel on High Speed Ground Transportation, which issued a report entitled "Research and Development of High Speed Ground Transportation" in March, 1967 (Ref 4-4). The panel was assigned the task to "survey, in a broad sense, the technical possibilities of novel modes and ideas for high speed ground transport systems and devices."

More specifically oriented toward rail transportation is the Northeast Corridor Transportation Project (NECTP), which has been supported by the Department of Commerce and the Department of Transportation for a number of years. Louis T. Klauder and Associates prepared studies in 1964 on improvements in railroad passenger service between New York and Washington and the recommendations in their report have been haltingly realized in the Metroliner and Turbotrain demonstrations (Refs 4-5, 4-6, and 4-7). Public acceptance of these has been good, despite many hardware, reliability, and maintenance problems (Refs 4-8 and 4-9).

Existing and Planned High-Speed Rail Systems. Improving rail transportation requires much more than technological advances. Advances in roadbeds, electrification, stations, controls and signaling are needed but changes in union regulations, maintenance personnel skills, maintenance facilities, and entrenched ways of doing business may be even more important. Efforts in this country to increase passenger rail speed and comfort have moved at a slow pace, due to a lack of commitment.

To prove to the public, Congress, and the railroads that such a commitment should be made, the Office of High Speed Ground Transportation has sponsored two demonstration programs to test public reaction to faster, better trains: the Metroliner and the Turbotrain.

The Metroliner. Seven round trips a day using six-car trains between Washington and New York with a 3-hour running schedule have shown convincingly that a modern train with a reasonably fast schedule can get and hold public favor (Refs 4-9 and 4-10). The trains themselves are not particularly innovative. They are complex and use much electronic equipment with solid-state components in their power conditioning and control elements. Propulsion and braking are conventional, scaled up from past experience to give a specified 160-mph capability. The cars are designed to ride on the existing Penn Central roadbeds between Washington and New York (75% or more of this is now welded track). Several new stations have also been installed. The ride is still greatly dependent on the quality of the track, for no effort at incorporating active suspensions of any sort was made. The ride, schedule and reliability are good enough so that the public accepts it as something which should be encouraged. However, it can only be regarded as a first step toward a future system.

The Turbotrain. Rail connection between Boston and New York is electrified only between New Haven and New York. As a result, the electrically powered Metroliner cannot be used on the entire New York-Boston journey. To service this region DOT leased from the United Aircraft Corporation two three-car gas turbine powered "Turbotrains" to inaugurate token high speed service

(Refs 4-11, 4-12, and 4-13). Technically the Turbotrain is quite advanced, utilizing aircraft technology in both car design and propulsion: several direct-coupled, free-turbine engines and passive pendulum type of suspension reducing passenger discomfort on curves. However, because of track limitations, the Turbotrain schedule is only a little less than the normal 4 hours and 30 minutes. In addition, poor ticket selling and station arrangements inhibit many people from using this train. No serious attempt has been made by the railroad to promote its use. In this experimental program, however, the vital importance to a transportation system of the interface elements of parking, station access, ease of ticketing, and relationships to other systems has been demonstrated.

The Turbotrain is also used in Canada on a high-speed run between Montreal and Toronto utilizing seven-car trains. Its impact on the public has been much greater in Canada than in the United States.

Foreign Systems: The oldest high-speed train system in full operation in the world is the Japanese Tokaido Line (Refs 4-1 and 4-2 and Figure 4-1). The system has become an international reference point for projecting performance requirements for new or improved rail systems.

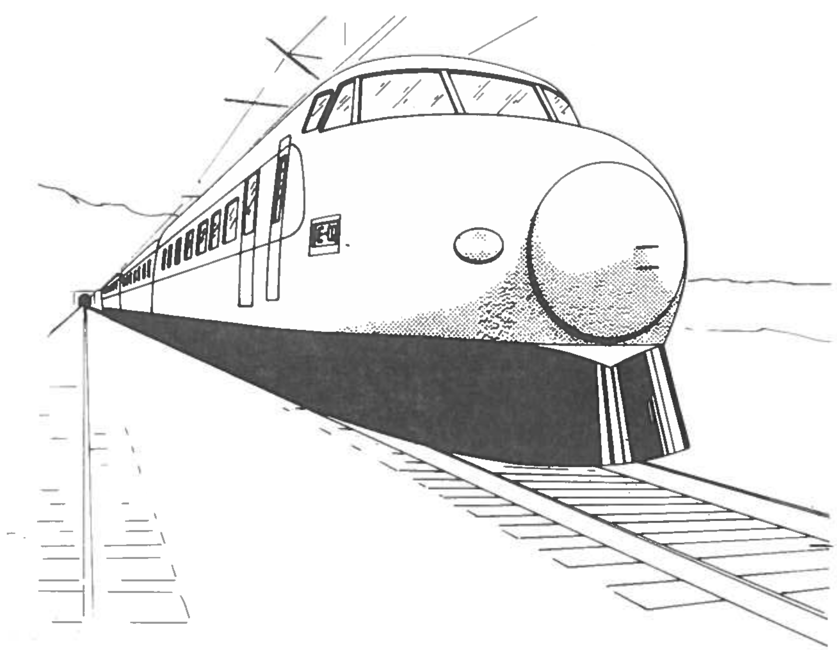

Figure 4-1. Japan's 125 mph Tokaido Express

One of the most interesting new approaches to cost effective high-speed interurban train systems is the Advanced Passenger Train being developed by the British Railways (Refs 4-1 and 4-3). This system can be adapted to gas turbine or electric propulsion. The emphasis on the developmental work is on vehicle-track dynamics; active suspensions will be used to enable a 50% increase in speed over present trains on the same roadbed. Initial design speed is 155 mph. Two four-car experimental trains are under construction for operation late in 1971. Two prototype trains are expected to be in revenue service in 1974 (Refs 4-1 and 4-3).

The French National Railways have been developing gas-turbine powered trains similar to the U.S. Turbotrain. 150-mph capability has been demonstrated, and two experimental trains for this speed range have been ordered. Ten trains for revenue service between Paris and Cherbourg have been planned for operation at a maximum speed of 110 mph over existing tracks in 1971. It is hoped that by 1975 similar trains for 150 mph service will have evolved (Ref 4-14).

German work has the same goal as that of the British Advanced Passenger Train - namely, design of improved train suspensions that will permit higher speeds on existing tracks. Electro-pneumatic servos designed to tilt the car body inward on curves have shown that safe and comfortable speeds on present tracks can be appreciably increased over those attainable with conventionally suspended trains (Ref 4-15).

<u>Some Basic System Relationships</u>. The time required for a trip is affected by the following four factors: average cruise velocity,acceleration/deceleration rates, station spacing, and station dwell time. The individual effects of these variables on the time required for a 200 mile trip are shown in Figures 4-1 and 4-3 for base conditions of: average cruise velocity = 160 mph, acceleration/deceleration=0.1 g, station spacing = 40 miles and station dwell time = 90 seconds. These performance values are indicative of what might be expected of a future, advanced high speed rail system. Numerical values are shown on Figure 4-2, while percentages (or sensitivities about base conditions) are given in Figure 4-3. For comparison purposes, the times required for a 200 mile trip on typical present equipment and on present "advanced" equipment (e.g., the Metroliner on existing track) are also indicated.

From the plots, it is evident that two factors of real significance are station spacing and average cruise velocity. Station spacings of less than 40 miles seriously degrade performance, while above this value they have little effect. The benefits of increasing average cruise velocity decrease somewhat

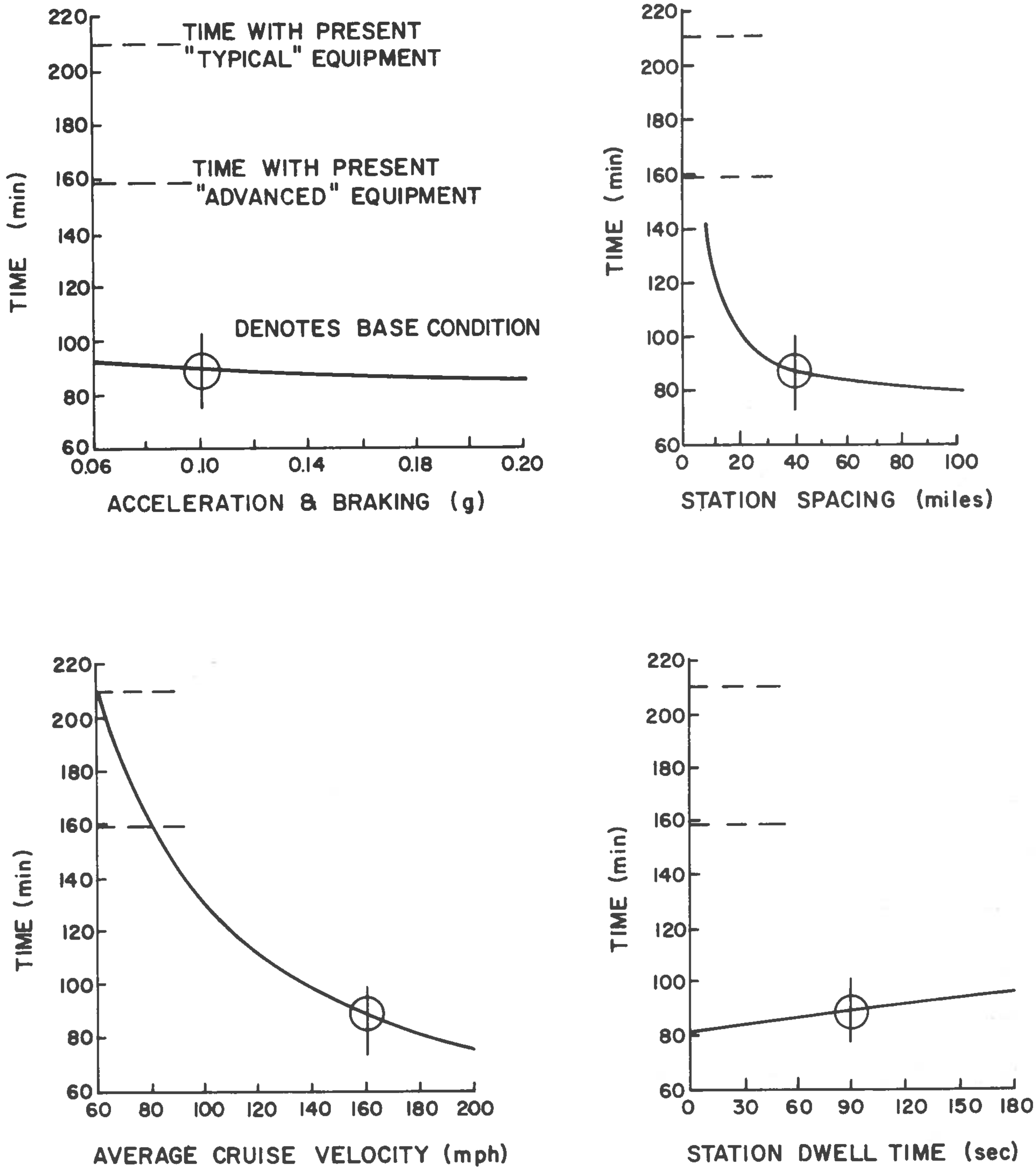

Figure 4-2. Effect of Various Parameters on Time Required for 200 Mile Trip. (Base conditions: acceleration and braking = 0.1g, station spacing = 40 miles, average cruise velocity = 160 mph and station dwell time = 90 sec.)

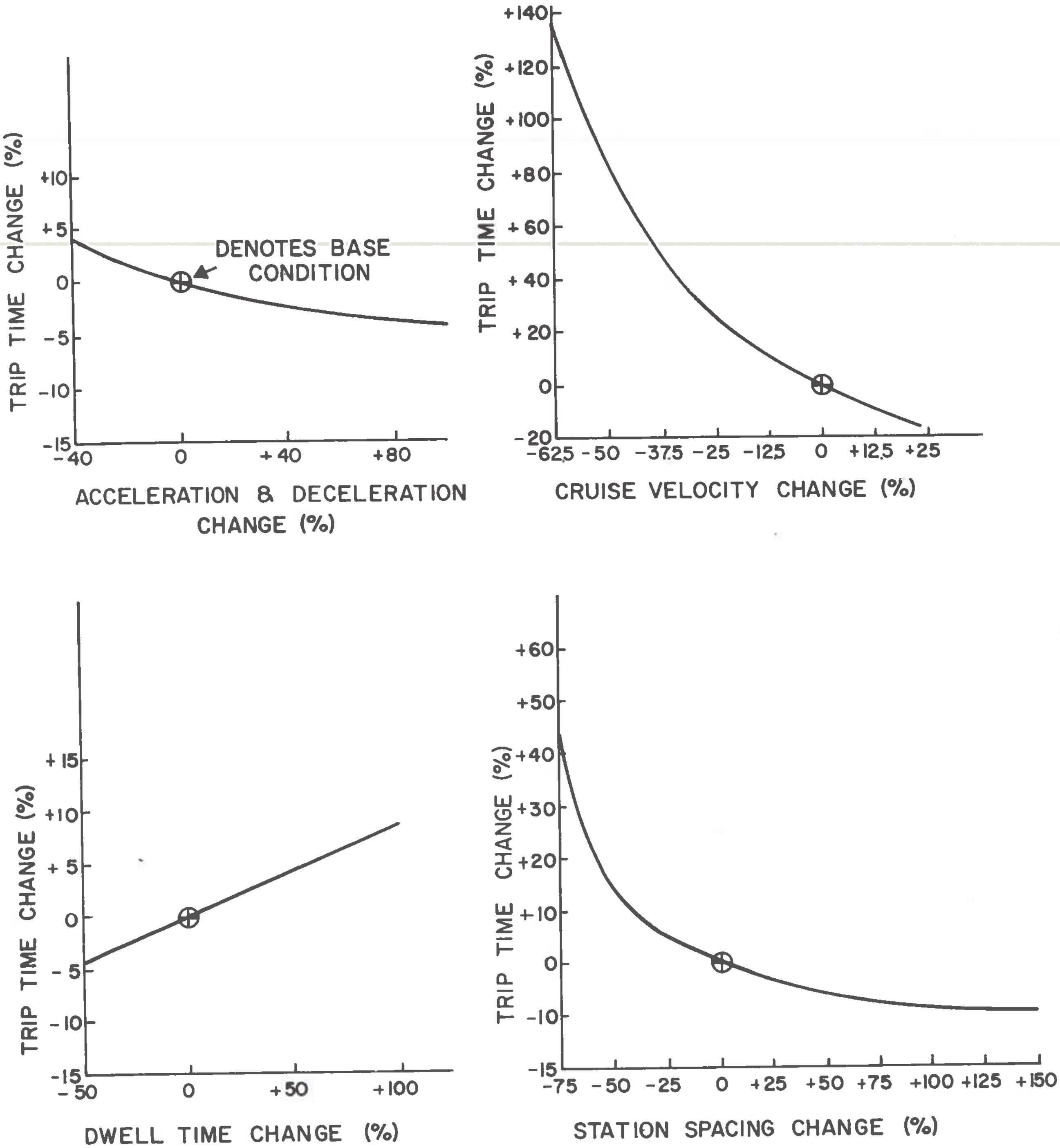

Figure 4-3. Percentage Effects on Travel Time of Acceleration and Deceleration, Average Cruise Velocity, Station Dwell Time and Station Spacing. (Base conditions: acceleration and deceleration = 0.1g, average cruise velocity = 160 mph, station dwell time = 90 seconds and station spacing = 40 miles.)

in absolute terms as the velocity increases, but they are still significant at the highest value examined. Therefore, in order to reduce trip time, a high average cruise velocity is desirable. Also desirable are reasonably high rates of acceleration and deceleration, since these enable the train to rapidly slow down for low-speed sections of track and quickly regain cruise velocity, thus minimizing the penalty for low speed sections. This effect is not reflected in Figures 4-2 and 4-3, since there the acceleration and deceleration rates are concerned only with the station stops.

Areas of Likely Future Progress. Much of the following discussion parallels that in Section 3.3 and is presented here for completeness of this section.

Present road beds can limit speeds in two ways: (1) curves often necessitate reduced speeds to lessen centrifugal force on passengers: and (2) imperfections and irregularities in the track can cause uncomfortable vibrations at higher speeds. The approaches to alleviating these limitations are either to eliminate their causes or to design vehicles that can cope with them.

Eliminating the causes of the problems may be costly and time consuming, depending on the degree to which it is done. A curve is put in a track to avoid some problem. If the curve is now removed, the problem can no longer be avoided. Straightening out sharp curves often necessitates acquiring additional property, which can be very expensive in highly developed areas, and may involve extensive excavation and construction if the terrain is unfavorable. Much of the track in this country is now being converted to smoother, welded rail which helps reduce vehicle vibration. Maintaining precision rail alignment now requires a great deal of effort. The track must be checked and adjusted frequently. New designs for roadbed construction and rail mounting are being pursued around the world, with the goal of achieving a far more stable roadbed and a much more precisely aligned track (with easier and more accurate adjustment) than is now possible. Typically, these approaches make use of concrete construction in the bed to provide a solid rail foundation. They can be expected to significantly ease the task of maintaining a very accurate track system, but they may suffer from a high initial cost. However, if the resulting long term maintenance costs are appreciably lower, they may be economically attractive.

Designing vehicles that can cope with the track problems involves powered body banking and active suspension systems, which will be discussed further below. These developments, though expensive in themselves, should cost far less than upgrading the roadbed and track. In all likelihood, a combination of both approaches will be used: track and roadbed upgraded to some extent and use made of advanced suspension systems.

Where new roadbed is installed, it may be possible to provide gentle, high-speed curves. But if sharper curves must be included, or if presently existing track with sharp curves is to be utilized, then the vehicles must be able to go through curves at significantly greater than normal speeds, or have a very high cruise speed for straight stretches (accompanied by high acceleration ability), or both. To pass through turns at higher than normal speeds without causing passenger discomfort (generally the limiting factor), a suspension system capable of aligning the vehicle to the proper bank angle is necessary. This may be accomplished by a passive pendulous suspension, as has been used on the Spanish Talgo trains (Ref 4-16) for several decades and is currently being tried in this country in the Turbotrain. This system is somewhat limited in overspeed through curves by the fact that its operation can reduce the overturning resistance of a vehicle through the curve, and also because rather large lateral displacements of the vehicle's center of gravity are necessary for higher speeds, thus limiting the allowable width of the vehicles to maintain adequate clearance.

For greater speeds and more control of the vehicle's motion, an active suspension system may be necessary (Refs 4-1, 4-2, and 4-3). This would forcibly bank the vehicle into an orientation that would eliminate the lateral acceleration on a passenger while passing through a curve. An active suspension can also increase a vehicle's resistance to overturning by moving its center of gravity into the curve. Another advantage of active suspension systems is that they can provide a significantly smoother ride over straight track than can a conventional, passive system. Vehicle swaying and pitching due to track imperfections and irregularities can be diminished considerably by an active suspension (Ref 4-17). Active suspension systems are being studied and developed in this country and in Europe. Although probably expensive and involving rather sophisticated equipment, this type of suspension would allow far more comfortable and far faster trips than are now possible at far less expense than would be required for extensive track and roadbed reconstruction.

For high-speed service, vehicles should be as lightweight as possible. The present use of long cars tends to concentrate a large amount of weight at a few points of the tracks, where the wheels make contact, making necessary massive and expensive track supports. The situation is more severe with aerial track structures. Lighter weight (and shorter) cars reduce the stress and consequent wear on rails and wheels, reduce the effort necessary for an active suspension system, and reduce the necessary strength and associated massiveness of aerial guideways. Lighter weight vehicles also reduce the power necessary for acceleration and the energy that must be dissipated during braking. For high speed service, a low center of gravity is also desirable. This helps increase stability against overturning or swaying due to track imperfections, curves, and cross winds. Low centers of gravity are achieved by reducing the overall height of the vehicle (important in increasing stability of cross winds), by concentrating as much weight as is practical near the bottom of vehicle, and by reducing the distance between ground and vehicle bottom. The independently-wheeled Talgo Train has a floor only about one and one half feet above the ground, as compared with around four feet in conventional rail vehicles.

The research defined by the Panel on High Speed Ground Transportation, described above and set forth in Ref 4-7, has been underway in the United States during the past four years. Some real progress has been made. Japan, England, France, and West Germany have also been advancing the state-of-the-art of high-speed rail transportation. Metroliner experience makes it clear that the public will use a rail system that provides travel times shorter than private automobiles and comparable, on an origin-to-destination basis, with existing airplane travel. The technology to construct and operate high-speed rail links between urban centers to meet public needs either already exists or is rapidly coming into being. The unanswerable question is when and how this technology will be applied in the United States.

Few plans exist for improving rail system performance to a significantly higher level than now exists in this country (e.g., Turbotrain and Metroliner) and Japan or now under development in Europe (e.g. England and France). An exception is England, where a 250-mph train is in the concept stage. The desirability of continued development of high-speed rail systems comes from several factors. It represents an orderly and continued evolution of an existing system, and thus its chances for successful development and implementation are greater than for a new system representing a radical departure from what already exists. If future advanced rail systems could use the present track gauge, the expense of installing a complete new guideway would be largely avoided, as opposed to the case for some new system. A higher speed system is more cost-effective than is a lower speed system, provided costs do not escalate too rapidly with speed. It appears that rail systems will be able to achieve speeds in the neighborhood of 200 mph or more. This makes them quite attractive in terms of time for distances up to 400 miles. Higher speeds and innovative ground systems will probably emerge eventually (viz., tracked air cushion vehicles), but they will be more difficult and expensive to achieve. In the interim, until very high-speed new ground systems are ready and needed, a high performance rail system appears to be a logical choice.

4.3 TRACKED AIR CUSHION VEHICLES

Introduction. The Tracked Air Cushion Vehicle can potentially provide passenger service on a short haul, intercity transit system. The basic principle involved is the use of an air cushion to suspend the vehicle above a guideway. This essentially eliminates all friction between the vehicle and the guideway surface, offering more propulsion efficiency. One other important benefit from this type of suspension is its relatively high ride quality (or passenger comfort) without unusual or severe guideway smoothness requirements.

Previous applications of the air cushion suspension have ranged from air-bearing laboratory equipment to the large air cushioned hovercraft used in marine transportation. In the ground transportation application, a track or guideway is used for the needed lateral constraint and route guidance; consequently the term Tracked Air Cushion Vehicles or "TACV" is used.

At the high speed end of the TACV operating spectrum (nominally 300 mph) one finds the intercity system application. Here, the TACV characteristics of low friction and superior ride quality enable much higher average and peak speeds than can currently be realized by rail systems. Extensive study of the application of a TACV to the Northeast Corridor has been conducted under the auspices of the Federal Railroad Administration (Ref 4-18). These studies have led to an FRA developmental research program to build and test a 300-mph TACV. Further discussion of this program appears later. Since wheel-supplied traction is not used for TACV, new forms of propulsion have been considered. Among these are turboprop and turbojet engines, but most favored currently is a linear induction motor (LIM) using the vehicles as one component (stator or rotor) and an element of the guideway as the other component. This type of propulsion requires a source of ac voltage which can either be supplied from a wayside line through a dynamic pickup system or be generated on board. For ecological reasons, the first case is preferred because it minimizes local pollution. In some instances, it may be more economical and beneficial to use onboard power generation, but the decision would depend on the system under consideration, the availability of wayside power, and other relevant system parameters.

TACV System Considerations. Fluid-support of vehicles operating close to the surface of travelways offers the attractive potential of fast, smooth rides with an accompanying economy in propulsive power. Another potentially significant advantage of the air cushion vehicle over its wheeled counterpart is its ability to operate on a cheap guideway. The guideway is generally the most expensive part of a ground transportation system, and the air cushion promises to reduce these costs by relaxing the guideway technical requirements.* First, the air cushion spreads the load and the guideway need not be designed to take the concentrated stress of wheels. Second, the inherent ride-smoothing ability of the cushion reduces the surface-evenness requirements. These and other benefits of air cushions, such as lowered maintenance requirements for vehicles and guideways, would accrue to both high and low speed transport. For the present, technical development is primarily concentrated on TACVs for high-speed transport of passengers. Disadvantages of air cushion support include the power required to maintain the air cushion and the noise caused by it. Also, switching of air-cushion vehicles from one track to another is awkward, so that a given vehicle may well be limited to a point-to-point-shuttle service on a single route. Thus, its applicability to network operations appears severely limited.

At this time, the air cushion is the most technically feasible means for supporting tracked vehicles between 300 and 500 mph. This range encompasses speeds above those at which traction wheels become impractical and below those at which aerodynamic resistance requires a prohibitive amount of power. Estimates of the limiting speed for steel traction-wheels (on steel rails) range from 200 to 300 mph. At the high end of this speed range, the power needed to overcome aerodynamic drag has increased, roughly, as the cube of air speed. This means that a 500-mph air-cushion vehicle will use 8 times the power of a 250-mph vehicle. Even though speed can be bought with power, other factors such as the ratio of payload to the weight of propulsion machinery become unfavorable.

One of the major concerns in air cushion development has been the efficient use of compressor power. Although a large cushion-ground separation is desirable, a large gap requires a high volume of air from the compressor. Many schemes have been suggested for limiting leakage while still providing adequate ground clearance.

Guideway Technology. The driving motivation behind the development of new guideway technology is cost. Tunnelling is still a very high cost procedure and, because land acquisition can be expensive, the elevated guideway is generally considered the most economical.

*These savings are only conjectured here and they may prove to be significant only for high-speed vehicles. Of course, if the speed is very high, the cost comparison is moot because the traction wheeled vehicle is no longer technically feasible.

In addition to structural problems, the major engineering concerns associated with TACV guideways include:

1. Methods for switching vehicles off the guideway. (For a high-speed high-traffic-density line, this is a very significant problem.)

2. Methods for mounting and alignment-maintenance of the traction rail (if a linear electric-motor is used for propulsion).

3. Methods for providing wayside power at high voltage and high current levels.

Propulsion Technology. A TACV propulsion system must provide non-traction thrust. Aircraft propulsion systems would appear to be the most applicable; however, they are generally ruled out for reasons of noise and air pollution. The linear induction motor (LIM) is, at present, the most likely TACV thruster, and it is under extensive engineering development.

The LIM concept presents the TACV designer with the choice of placing the secondary element in the guideway or on the vehicle. With the LIM secondary (which is merely a conductor) on the vehicle, the primary windings are placed in the guideway. This arrangement has the advantage of not requiring propulsion energy on the vehicle but has the major disadvantage of very high cost for the long primary required. Unless the aggregate length of the vehicles on the line is an appreciable fraction of the line's length, a short primary on the vehicle appears to be the most technically feasible and economic arrangement.

The source of electric power for the LIM primary on high-speed TACVs presents a very difficult engineering problem. A typical 300-mph TACV requires a thrust of 10,000 lb and uses 6 megawatts of power (Ref 4-19). Ideally, this power would be generated on board the vehicle; however, the only practical (at present) prime movers at this power level are fossil-fuel engines and their use is questionable because of noise and/or pollution problems. At present, the most feasible concept is to provide the energy from wayside power-rails through brush or non-contact collectors on the vehicle. The problems of collecting wayside power at high speed as well as schemes for LIM thrust and speed control are discussed later in this report (Section 6.2).

TACV Research and Development. Extensive research and development programs have been underway on TACV for some years. In Europe, a French program conducted by the Societé de Aerotrain started in 1965. A propeller-driven vehicle on an inverted-T guideway was first developed followed by a jet-propelled vehicle operated on the same track. Two operational vehicles were then developed. One was an 80-passenger vehicle propelled by a shrouded turboprop engine at speeds up to 186 mph. The second was a 40-passenger vehicle powered by a linear induction motor (LIM) and capable of 110 mph. Testing of these two vehicles began late in 1969.

In England, Tracked Hovercraft, Ltd. was formed in 1967 to consolidate previous air-cushion work into an overall test and demonstration program. A full-scale test vehicle and several miles of track are in the first phase of this program, which began testing in 1971. The British TACV is a LIM-propelled 300 - 350 mph vehicle for experimental purposes only. Future plans call for an additional five miles of test track. Also, additional research is being continued on air cushions and suspension, propulsion and aerodynamics.

In the U.S., TACV and its technology have been studied under the auspices of the Federal Railroad Administration Office of High Speed Ground Transport (OHSGT). MIT was placed under contract in 1965 to study high-speed ground transportation and since then has continued with analytical and experimental work on vehicle dynamics and air suspension systems. NASA has worked with OHSGT using NASA test facilities for TACV aerodynamic and dynamic tests as well as air-cushion research. Extensive system engineering studies have been conducted by TRW since 1967.

A LIM test vehicle has been obtained by the Federal Railroad Administration (FRA) from the Garrett Corporation to be operated at a test track at the DOT Test Facility near Pueblo, Colorado. This car, running on conventional rails and capable of speeds over 200 mph, was delivered to Pueblo in May 1971.

This general research, development and demonstration effort has led to the conclusion that the TACV is feasible and practical for speeds in the 150-mph regime. To extend this speed range, the OHSGT is developing a 300-mph research vehicle designated TACRV (Tracked Air Cushion Research Vehicle). A design contract for the vehicle was awarded to Grumman Aerospace in 1970 and a contract to manufacture the vehicle is to be awarded in 1971. A LIM for TACRV propulsion is being designed and produced by the Garrett Corporation under separate contract. The test guideway will be a five by eight mile oval track to be installed at Pueblo, Colorado. An initial section of eight miles is scheduled to be completed in 1972, and vehicular tests will be initiated at that time.

The basic purpose of this program is the extension of TACV technology with emphasis on: (1) dynamic interaction of the vehicle and guideway (including analytical models of same);

(2) ride quality and attendant suspension system requirements (including cost relationships); (3) air-cushion systems; (4) aerodynamics; (5) high-speed power collection; and (6) LIM performance.

The FRA is also continuing a cooperative effort with the European TACV programs including a provision to use Tracked Hovercraft, Ltd., as a consultant. Previously, Aeroglide of France was funded to conduct a preliminary design study for a tracked air-cushion research vehicle (part of the design studies that led to the 300-mph TACRV program). This study was completed in 1969 (Ref 4-20).

Costs of TACV Systems. There exists no really authoritative source for TACV system costs, such as those derived from an operational system. Some information has been developed by the Federal government as part of the Northeast Corridor study. The costs given here are therefore to be taken only as illustrative and possibly rather optimistic.

In Table 4-1, the relative costs of the major elements of the Northeast Corridor TACV are given as a percent of the total system cost (Ref 4-18). Also indicated is the overall project cost estimate. The average vehicle cost (based on 100 units) was estimated at $1.81 million. Guideway costs predominate. If land acquisition costs are negligible (using freeway right-of-way), the guideway costs can exceed 70% of the total system costs.

TABLE 4-1. NORTHEAST CORRIDOR TACV COSTS

Total TACV Investment Cost by Cost Element at a Typical Demand Level*

Cost Element	% of Total Cost
Research and Development	6
Land Acquisition	14
Guideway Construction	55
Guideway Electrification	8
Command, Control, Communications	5
Terminals	5
Yards and Shops	2
Vehicles (including spare parts)	5
Total	100
Total cost	$3,339,000

*Since these estimates are several years old, cost escalations since then should be taken into account. Also these numbers were derived from contractors' own estimates and should be so considered in any application.

4.4 MAGNETICALLY SUSPENDED VEHICLES

Magnetically suspended vehicles appear to be an attractive choice for speeds above those possible with rail systems. The idea of magnetic suspension however, is still in the conceptual stage. Magnetically supported vehicles will probably share the air cushion's switching difficulty, but they may be even less sensitive to guideway irregularities than air-cushion vehicles. Some proposed configurations have a levitation power requirement considerably less than that of air-cushion systems. The lift and propulsion elements of the vehicle could conceivably be combined into a single unit, simplifying vehicle design. A magnetically suspended vehicle would also be quieter.

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5. URBAN/INTERURBAN FREIGHT SYSTEMS

5.1 INTRODUCTION

The movement of goods in the United States is handled by five major modes of transportation: highway, rail, water, pipeline, and air. Table 5-1 summarizes the traffic using these modes in 1969.

It is interesting to note the average revenue per ton mile: pipelines are by far the cheapest at 0.25¢ per ton-mile, with air the most expensive at 30¢ per ton-mile. Water and rail are in the range of 1 to 1.4¢ per ton-mile. Highways are intermediate at about 14¢ per ton-mile. In terms of average distance traveled air averages 1000 miles per trip, trucks 125-350 miles, pipelines 370 miles, rail 500 miles and water 300-1400 miles.

These statistics indicate advantages of the various modes. Trucks provide the convenience of door-to-door pickup and delivery service and can charge higher revenues per ton mile; whereas rail, water and pipeline are in approximately the same price range for quantity shipments on a point to point basis. Air provides service for high value-added products where time and distance are important factors. In return for the specialized service they are paid a premium price.

5.2 RAIL

Overall Equipment Design. Present rail equipment suffers from high centers of gravity (resulting in sensitivity to tipping), from poor tractive forces at high speeds, and from low resistance to derailing at high speeds. Very heavy locomotives are required to obtain the traction necessary for pulling long, heavy freight trains. As a result, the track is subjected to severe loads from the forces applied through the locomotive wheels. New specialty cars, such as ore cars, are carrying loads of 125 tons and more placing tremendous loads on wheels and rails.

An attempt to alleviate these problems can be seen in the Santa Fe Railroad's experimental coaxial freight train (Figures 5-1, 5-2) (Ref 5-1, 5-2). This will consist of a long, continuous flexible sill running the length of the train, with wheels every four feet. Each wheel is separately powered, independently suspended, and measures sixteen inches in diameter. The floor height will be about half that of a conventional railcar. With each wheel powered, traction is distributed much more evenly. Because of the greater number of wheels to support the weight, much less track wear is expected. Individual,

TABLE 5-1. FREIGHT TRANSPORTATION 1969 (ESTIMATED)*

Mode	Revenues		Ton-Miles		Average Haul Length (miles)	Average Number Tons (Billions)	Average Revenue Per Ton-Mile
	$Billion	Share	Billions	Share			
Highway	55.0	73.0%	404	19.1%	355 by class 1. (125 by other)	2.4	14.0¢
Rail	10.6	14.1%	780	36.7%	500 by system 270 by carrier	3.0	1.4¢
Water	5.3	7.1%	525	24.7%	1400 by deepsea, 300 by river	0.9	1.0¢
Pipeline	1.1	1.5%	411	19.4%	370	0.7	0.25¢
Air	1.1	1.5%	3	.1%	1000	0.003	30.0¢
Other	2.1	2.8%	-	-	-	-	-
Totals	75.2	100%	2,123	100%			
Averages					300	7.0	3.7¢

*(Source: Ref 5-9)

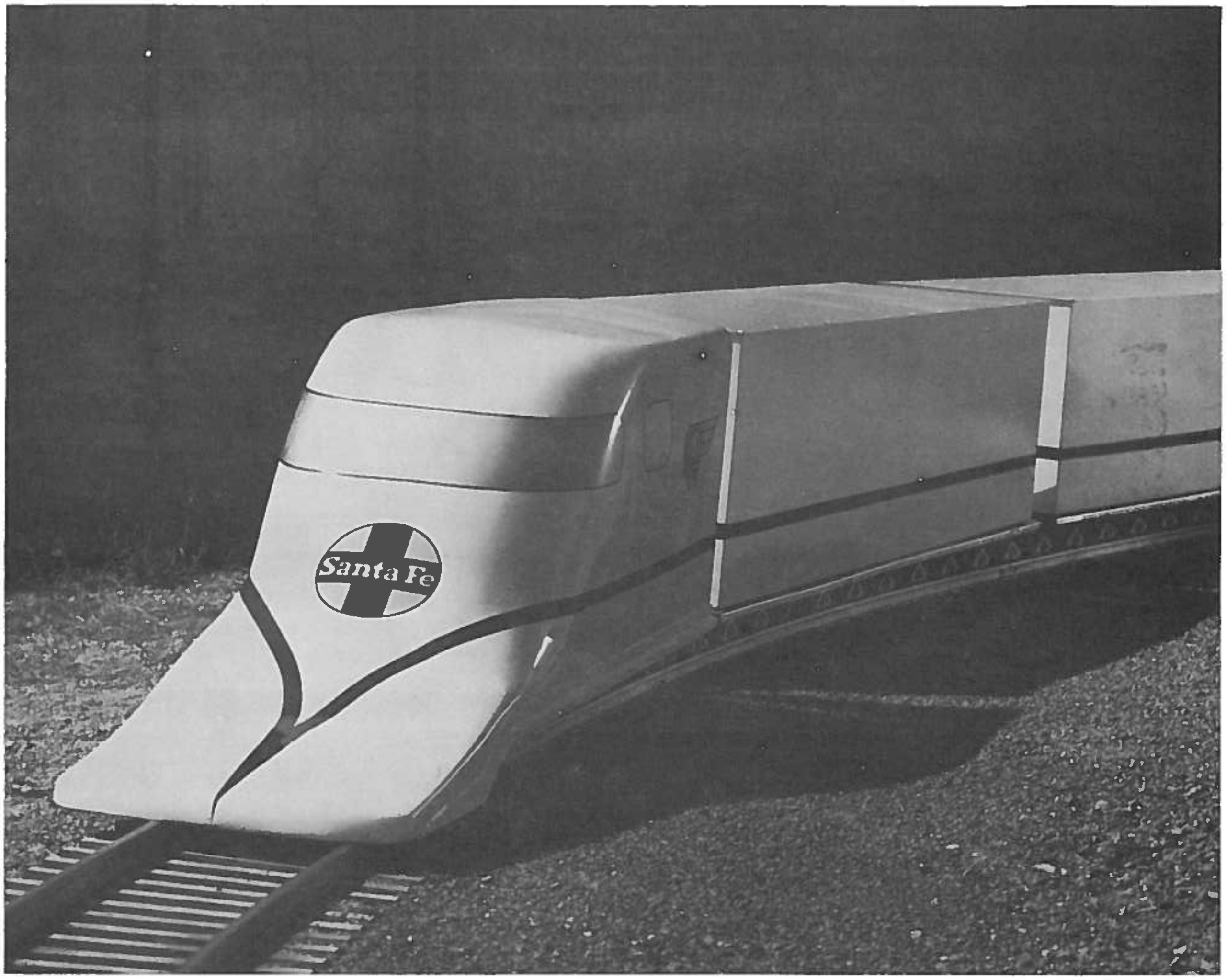

Figure 5-1. Model of Santa Fe Railway's Coaxial Train

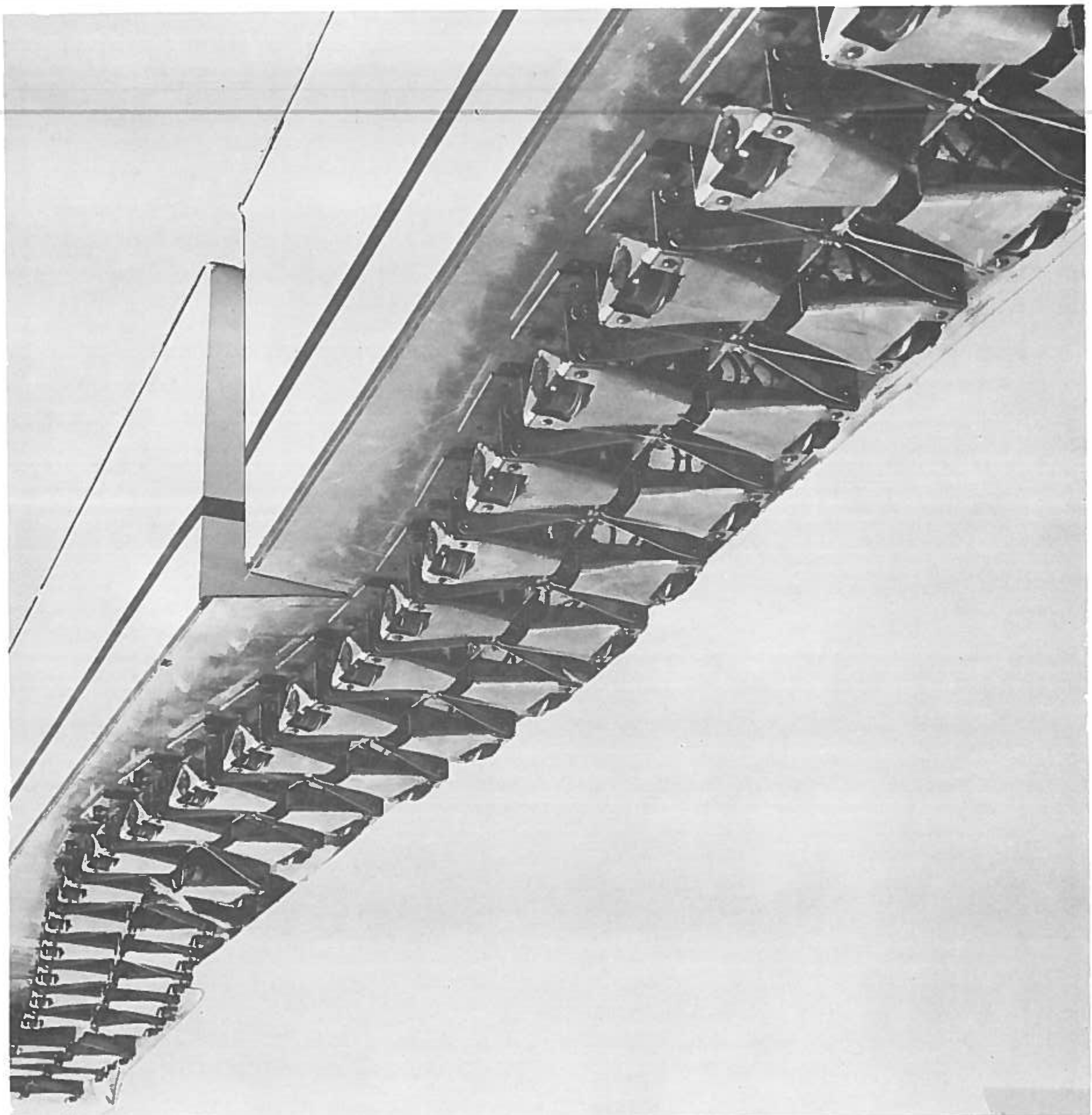

Figure 5-2. Underframe of Santa Fe Coaxial Train

independent wheel suspension provides smoother rides on poor quality track. The absence of axles should significantly reduce hunting and flange wear on curves. The Santa Fe concept probably represents the most advanced and imaginative rail work in this country and ranks with the more advanced of the world.

Railroad Electrification. Electrification is attracting strong interest in this country and is being extensively implemented in Europe (Ref 5-3). Electrification is advantageous under conditions of intensive traffic and high speeds. At low speeds, where adhesion is the limiting factor, diesel-electric and electric locomotives possessing the same weights, horsepowers, and numbers of axles will have nearly identical performance characteristics. At speeds much above 15 mph, though, diesel performance is limited by the power capability of the engine, whereas the electric locomotive can draw on the "unlimited" capacity of the generating station. This allows the electrics to pull heavier loads at higher speeds.

In railroad operations that are horsepower - oriented, electrification allows vehicle savings because fewer locomotives are required to haul a given train tonnage. In terms of operational effectiveness, electric locomotives of a given horsepower are roughly equivalent to diesels of 20% greater horsepower. Electric locomotives require no fueling, little service at terminals, and fewer and shorter major overhauls than diesels. Thus, locomotives are utilized more effectively. Electric locomotive maintenance costs are only 30 - 50% those of comparable diesels. Further, the life of an electric locomotive is about 30 years, compared with about 15 for a diesel. Finally, an electric locomotive costs less than a diesel and can be used in long tunnels and underground operations.

There are three primary drawbacks to electrification: (1) installation of the power distribution and conditioning system is quite expensive - typically $40,000 to $80,000 per track mile over and above the basic cost of the track; (2) operating flexibility is reduced, since the electric locomotive is restricted to operating on electrified track; and (3) when a line is electrified, existing communication and signalling facilities may have to be modified to reduce susceptibility to interference from the electric operations. An evaluation of electrification for a particular railroad having about 1,000 track miles, top speeds of 80 mph and moving 30 million tons per year showed the potential of considerable savings. Whereas 105 3300-hp diesels are presently required, only 57 6000-hp electrics would be needed. Locomotive investment would be about $5 million less with electrics. Over a 30 year period the investment required for electrification would be recovered 84 times over. This illustrates the advantages attainable on a railroad that is suited for electrification.

Automatic Car Identification (ACI), now being implemented, should offer substantial benefits to rail operations. Among its uses are: (1) determining proration of joint facility expense on lines, (2) recording demurrage placement and release movements; (3) automatic recording of car weights (by coupling with inmotion scales); (4) exchanging of waybill information prior to receipt of a car; (5) checking inbound trains inline; and (6) aiding the prepation of outbound consists. Cars are marked by color-coded reflective elements and identification is performed by optical sensors along the roadbed.

A major source of congestion and delay in rail-freight operations is the classification yard. The Chicago Terminal District yards represents one of the worst cases. An average of 25,000 cars in 1,000 trains enter and leave the yards each day. Average through-put time for a car is four days. Automation of facilities such as this, combined with automatic car identification, should significantly reduce the time lost in yards. The Santa Fe Railroad recently automated its Kansas City Argentine yard, which has a daily traffic of 6,000 cars. The automation process included installing computer systems for automatically routing and electronically weighing the cars and controlling their coupling speeds. Extensive use was made of displays and telecommunications. Through-put time was cut as much as 50%.

The more extensive use of "run-through" trains, which need not be broken down for classification of individual cars, extensively reduces transit times since the cars are not involved in lengthy yard operations. Pre-blocking of cars also reduces the overall transit times by reducing the time spent in classification yards, because each switching operation can handle a string of cars rather than an individual car.

Operational Philosophy. A variety of opinion exists about the nature of rail-haul operations in the future. Some feeling, expecially in this country, is that individual carload routing should end and that the railroads should specialize in moving large unit trains between a limited number of dispatching points (Ref 5-4). Fine-scale collection and distribution to and from these points would be carried out by trucks on roads. Piggyback and container loads, together with bulk items, such as ores, coal, grain, and automobiles, would make up the service. This would constitute highly multi-modal operation. Direct rail transportation from shipper to receiver would only occur for sufficiently large shipments. The promoters of this concept suggest creation and utilization of a basic, national rail network (consolidated from existing lines) designed to connect cities with populations of 500,000 or more. This would in itself link approximately half the nation's population. In addition, the resulting network would connect many intermediate, smaller communities (allowing close rail service to a sizable majority of the population) and would encourage the development of new communities along it. The active route mileage would be reduced from the present 206,000 to about 50,000 by the consolidation. Considerable savings should result in maintenance of right-of-way and structures, although the resulting heavier traffic on the lines may well result in higher maintenance standards and costs per mile of track. The envisioned route network is very similar to that of Amtrak.

The other end of the spectrum, increasing in popularity in Europe, reaffirms the importance of an extensive, fine-covering network of rail transportation, with pickups and deliveries of small loads (1 or 2 carloads, etc.) from local sidings at factories, warehouses, etc. (Ref 5-5, 5-6). Germany, for example, is rapidly constructing large numbers of new sidings; and British Railways expects 98% of its freight traffic to originate in private sidings by 1975. This approach views rail transportation as a complete, self-sufficient mode of transport.

Both approaches have opposing merits and faults. The track consolidation approach uses rail and truck transport in their most effective forms: heavy line haul by rail and collection and distribution by trucks. The extensive rail network approach uses rail as a means of reducing highway congestion from trucks in industrialized urban areas. Which of these alternatives (or the level of compromise between them) that is to the best interests of this country will not be clear until a national transportation policy emerges.

5.3 HIGHWAYS

Highways accounted for about 73% of freight revenues and 19% of the U.S. domestic ton-miles in 1967 (Ref 5-7). About 40% of this was under ICC regulations, the other 60% unregulated. Trends in highway vehicles have been in the direction of larger payloads per man-hour of driver time. Pressures from the trucking industry have caused changes in state laws permitting higher gross vehicle weights, larger axle loads, and longer tractor trailer combinations over the Interstate Highways. Some 33 states now allow double trailers.

Even though regulation changes allow larger over-the-road vehicles, motor carriers need technological improvements to further extend payload capabilities of their vehicles and reduce their operating costs. One possible way of reducing operating costs is through the introduction of the gas turbine. For about 15 years, interest in gas turbines has been high because maintenance costs are expected to be lower (due to its simplicity).

In high-speed continuous operations, fuel economy is high. Work begun by General Motors and Ford should result in the development of engines that achieve these benefits; hopefully this will be occurring this decade. GM has recently announced the availability of a new, four-speed automatic transmission for use in large turbine-powered trucks and buses. This transmission promises the same handling ease for these large vehicles as that now enjoyed by automobile operators. (Ref 5-8)

Specialized trucks have been introduced to capitalize on the ubiquitous nature of trucks in providing door-to-door service. One difficulty in providing such specialized service is that the contracted costs are high because the one-way rate must be set to cover the round trip if back haul is not available. Relaxation of length restrictions on multiple trailer combinations tends to reduce the cost of back hauling empties since mixed loads can be carried and a better balance obtained.

Trucking is the most labor-intensive mode of freight transportation. About half of the cost of line-haul operations is attributable to driver wages and benefits. Motor carriers look to technological improvements which will provide cost economies and increases in labor productivity. (Ref 5-9)

In urban areas, trucking is the dominant factor in handling goods movement on a door to door basis. All modes of freight transportation converge here and trucks must handle the terminal portion of the haul for all modes. They must compete with the automobile for the use of urban streets and highways and generally contribute to congestion, noise generation and air pollution. Planning for trucking in urban areas is inadequate or totally non-existent. Trucks are simply assumed to be equivalent to two or three passenger cars. (Ref 5-10) The assumptions used in making these equivalent calculations is insufficient for realistic design. Basic research is needed in freight flow patterns, service requirements for distribution centers, and alternatives for sharing available streets and curb space with passenger vehicles.

Another area requiring further research is noise, not only that generated by engines but also, and perhaps even more significant, that generated by tires. Air pollution suppression work on new or improved engines continues in gas turbines, steam and other external combustion engines. Further work in this area is needed.

In the area of safety, research is needed to improve control of multiple trailer combinations under various weather and road conditions. Attention should be given to technological developments to reduce the real and imagined hazards to passenger vehicles due to multi-trailer combinations. Failsafe redundant braking systems, lower center of gravity designs, elimination of jack-knifing potential, elimination of water spray from wet pavements, and absolute speed control would contribute to public confidence in essential freight movement by highway trucking.

5.4 PIPELINES

Introduction. The national investment in pipelines is roughly $15 billion and is growing at the rate of about $1 billion annually. (Ref 5-11) This investment is predominantly in petroleum pipelines but is diversifying. Liquid and gaseous cargos now include ammonia and other chemicals, fertilizer, natural gas, and helium. Slurry cargos include coal, limestone, sulphur, and woodpulp. In Canada, dry-bulk pipeline are being developed for transporting grains, ore, and other solids.

Pipelines provide an efficient and economical mode of transportation where relatively high demand exists for a particular type of commodity. However, since it is not economical to distribute pipeline cargo over a wide area, pipelines are almost exclusively used for interurban rather than urban movements.

Pipeline Performance Considerations. The performance of pipeline systems in relation to competitive modes of moving particular commodities can be compared on the basis of:

1. Capacity (volume/weight)
2. Cost (initial/operational)
3. Cargo considerations:
    a. Flexibility of cargos
    b. Ease of loading, discharging, and distribution
4. Safety
5. Environmental pollution
6. Reliability and accessibility
7. Power requirements
8. Degree of automation
9. Utilization of container back-hauls.

The capacity of a pipeline system is usually not a critical parameter. If demand is high enough to justify the cost of installing a pipeline, the design capacity can normally be made substantially larger than the anticipated demand. A cost of $150,000 per mile is typical for underground installation of a 36-in. diameter petroleum pipeline, however the cost would be much higher in difficult terrain. An efficient, large-diameter pipeline can move oil for 0.2 cent per ton-mile. The cheapest railroad rate is about twice this. Pipelines are usually at a disadvantage with respect to trucks and railroad cars when either cargo flexibility or the distribution of cargo over a wide area is desired.

With very few exceptions, pipelines do not pollute the environment. Thermal pollution is one exception; this can occur when the temperature of the cargo is substantially higher than the ambient temperature, as in the case of the proposed 48-in. Alyeska (formerly Trans-Alaska) Pipeline. Pipeline rupture constitutes another environmental hazard.

The power requirements of pipelines compare favorably with other transportation modes; however, there is concern about the industry's heavy dependence on electric power. There are not enough spare diesel or gas-turbine engines to take over in the event of an electrical power failure. The only significant safety hazard due to pipelines would occur if excessive pressure were permitted or through earthquake induced foundation movements. Newly adopted DOT regulations insure that hazardous liquids are transported at safe pressures.

Pipeline systems today are highly mechanized and automated. They are usually equipped with motorized valves, and can be operated by remote control. The continuous stream flowing through a line may consist of successive batches of different liquid products with negligible mixing between one batch and the next. The trend is toward computer operation, with the program directing the sizes of shipments and their routing. Approximately two-thirds of the pipelines are currently controlled by computers.

Pipeline Technologies. Although the technology of ambient-temperature, liquid pipelines is mature, the technology of slurry pipelines is not. About 100 slurry pipelines ranging in length up to 100 miles are now in operation in North America. These lines carry such commodities as anthracite sludge, phosphate rock, copper concentrates, borax, limestone, clay, sand, and gravel. In 1957, the first major coal-and-water slurry line was built in Ohio. The line was 108 miles long and 10 inches in diameter; it transported more than a million tons of coal per year. However, the operation of this line was discontinued in 1963 when a railroad offered more attractive rates for distribution of coal over a wide area. The closure of this line dramatized the fact that pipelines have a restricted cargo-distribution capability. A $35-million, 18-inch, 273-mile, coal-slurry line is now operational between northern Arizona and Nevada. The line is scheduled to deliver 117 million tons of coal over a 35 year period.

Compared to trucks and railroads the only significant disadvantages of pipelines are cargo inflexibility and fixed-point delivery. Secondary disadvantages are the difficulty of hiring qualified personnel, vulnerability to power failure, and the hazard of a remote rupture. Slurry and dry bulk systems are candidates for such cargos as coal, ore, and urban waste. In these cases the dry bulk systems offer the advantages of requiring lower power to suspend and move the payload, less need for pre-shipment preparation and no need for drying the cargo at destination. On the other hand the dry-bulk systems will probably have a higher capital cost than the slurry systems.

The movement of dry-bulk cargos by pipeline is a concept which should satisfy many of the requirements of the interurban freight market. The system consists of sealed capsules containing the dry bulk cargo moved through the pipelines by a fluid propellant. Areas requiring further research include selecting the best propellant, determining the best size and shape of the capsules, and how to dislodge jammed capsules. The movement of slurries through pipelines is another area in which further development will depend on new concepts and technologies. The important problems are the elimination of blockage, suppression of abrasion, and cargo separation.

One of the technical problems being addressed is that of reducing the cost of transporting natural gas. A recent study indicates that the transportation of natural gas in the liquid state, with the use of refrigeration, would be economical if the pipe were jacketed with vacuum insulation (Ref 5-12). Insulated pipe is already employed on a small scale in a 7-mile pipeline that carries molten sulphur ashore from where it is mined in the Gulf of Mexico, off Grande Isle, Louisiana.

When compared on a basis of performance, cost, and environmental benefits, pipelines are often superior to railroads and trucks. Exceptions exist where the cargo volume is too low to support new capital investment or where the required cargo distribution pattern extends over a wide area. The unique advantages of pipelines include their silence and underground location, their high capacities, their low unit shipping cost, and their adaptability for automation. Pipeline systems are also much less sensitive to increases in cargo volume than are railroads or trucks. Further, the installation cost of a pipeline is almost always lower than the corresponding cost for a railroad or truck guideway.

Only in the area of dry-bulk commodity movement does there exist a major deficiency in pipeline technology. Nearly all the work in this area is being done in Canada by the Alberta Research Council. This organization has invested $0.8 million over 10 years to develop capsule (dry-bulk) pipelines. Seventeen different firms are sponsoring this work and have approved a five year,

$4.75-million program to develop commercial methods of moving capsules through pipelines. A successful field test in a 20-inch diameter oil pipeline was made in 1965. A cylindrical capsule, 16-inch in diameter, 50-inch long, and weighing 500 pounds was transported 109 miles at 2 mph. Despite this test however, the concept is still in the preliminary stage. The terrain, climate, and natural resources in Canada are conducive to the development of dry-bulk pipelines. The need in the United States is less acute in view of its more extensive existing transportation network. Utilization of dry-bulk pipelines in the United States will probably be contingent on successful experience in Canada.

5.5 MARINE

Introduction. Marine systems can be characterized by the type of cargo and the route to be traveled. Figure 5-3 establishes some very general categories - each one having characteristic system requirements. As represented by this framework, the system technologies are not totally unique and, as shown in the figure, a particular type of vehicle may appear in more than one of the categories.

Waterborne passenger traffic has been decreasing steadily. Except for recreational cruises, airline competition has essentially eliminated passenger ship traffic. There has also been increasing airline competition for the transport of high-value-added goods. Table 5-2 shows a comparison of traffic growth from 1965 and 1969. Relative to ship cargo, aircraft carried only 0.075% of the total tonnage but 11.3% of the dollar value in 1965. In 1969, air cargo increased to 0.15% of the tonnage and 20.2% of the dollar value. Despite this doubling of competition in high-value-goods movements, ships continue to carry an increasing tonnage of low-value but essential dry-bulk and liquid-bulk commodities.

TABLE 5-2 - VOLUME AND VALUE OF U.S. IMPORTS AND EXPORTS BY CARRIER*

	Ships	Aircraft
1965	427 million tons $31.9 billion	0.33 million tons $3.6 billion
1969	488 million tons $41.1 billion	0.74 million tons $8.3 billion

*Abstracted from Table 886 (Ref 5-13)

Type of Waterway \ Payload Types	Passengers	General Cargo	Dry Bulk Cargo	Liquid Bulk Cargo
Ocean (International routes to and from the U.S.)	Liners, cruise ships	Cargo liners, tramp ships, lash ships	Colliers, grain ships, tramp ships, lash ships	Oil tankers, lash ships
Coastal (Domestic routes including those to and from Alaska, Hawaii and Puerto Rico)	Ferry-boats	Cargo liners,	Colliers, barges	Oil tankers, liquid natural gas (LNG) tankers
Inland Waterways (Rivers and canals)			Barges	Barges
Great Lakes (Domestic and Canadian routes)			Ore boats, ore barges, colliers	

Figure 5-3. Categories of Marine Transport Systems

At the present time most of the U.S. import-export tonnage is carried by foreign-flag ships. This has been accompanied by a decline in the number and quality of U.S. flag ships. In 1947, U.S. flag ships carried 57% of the nation's import-export tonnage. By 1969, this tonnage had decreased to 4.8%. From 1955 to 1969 the aggregate deadweight tonnage of the U.S. merchant fleet declined from 35 million tons to 25.1 million tons, while in the same period, the world-fleet tonnage more than doubled.

To gain a stronger position, the U.S. Maritime Administration has set a goal for 1980 of 15% of the U.S. import-export tonnage to be carried in U.S. flag ships. In working toward this goal, it is important to recognize waterborne transportation as an essential element in the overall system of goods movement.

Regaining a stronger competitive position for U.S. shipping will require the introduction of new technology to increase productivity at lower costs. Containerization is a prime example of the increases in transportation-system efficiency, that can be achieved by an overall systems approach to development.

Performance Requirements. Ship productivity, the number of tons of cargo delivered by a ship in a year, is a significant measure of efficiency for a marine transportation system. Ship productivity is a function of many factors including the following:

1. Ship speed

2. Ship payload

3. Load-unload rate

4. Distance between ports

Figure 5-4 illustrates the relationships between ship productivity and these factors. The product of ship speed and ship-payload yields the convenient parameter, SPP. In general the larger SPP, the larger the ship productivity. For conventional hull shapes there is an empirical relationship that gives the required size of a ship's power plant in terms of displacement and speed (for relatively low top speeds).

$$\text{Required power} = (\text{Constant})\ (\text{Speed})^3\ (\text{Displacement})$$

Because the costs of ship acquisition and operation are directly related to the required power, Figure 5-4 shows that it is more economical to increase the displacement (rather than speed) in order to increase the SPP. This, in part, explains the present trend toward larger displacements, especially in oil tankers. Figure 5-4 shows, however, that for a large SPP to pay off in terms of ship utilization, a high load-unload rate is needed. Super tankers do pay off because their centrigual pumps can move the liquid bulk cargo at rate well over 10,000 tons/hour.

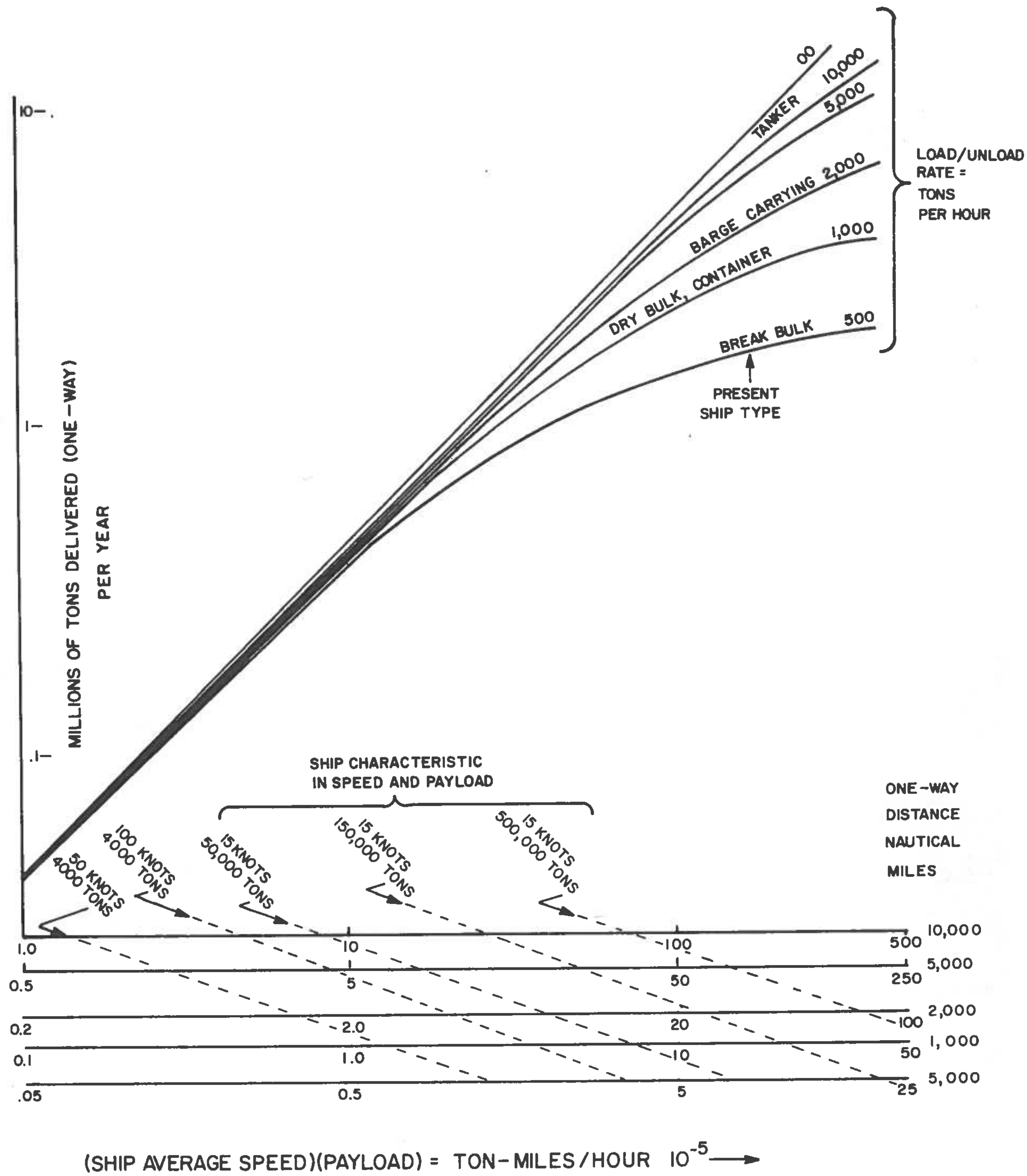

Figure 5-4. Ship Productivity

Under the present trend toward larger ships, payoff from technological development has been concentrated in ship construction and improved cargo-handling. The limited availability of cargo at a port at a given time along with the limitations of waterway and harbor depths will establish an upper limit of ship displacement. At the present time, tankers up to 1,000,000 dead weight tons are contemplated but this may represent a practical maximum. The largest dry cargo ship in the world, S.S. Doctor Lykes will enter service early in 1972 (Figure 5-5). It is 875 foot long and features a stern elevator with 2000 ton capacity that can take cargo aboard and unload without docking at congested inner ports. The ship can carry 38 fully loaded barges or 1800 containers totally 24,500 long tons.

Vehicle Design and Construction. Although Figure 5-4 shows the significance of the speed-payload product, it does not reflect the importance of quick-delivery capability. It is thought that the marine speed gap between 30 and 200 knots could be filled by high-speed surface vessels such as hydrofoils and surface-effect ships (Ref 5-14).

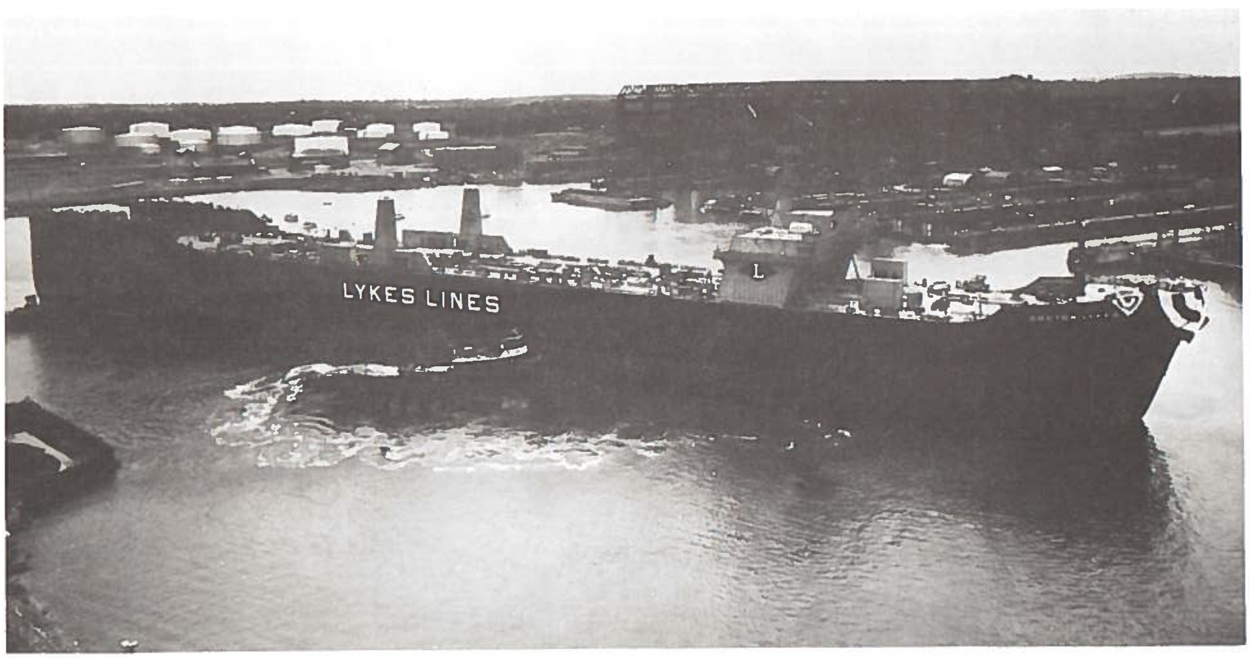

Figure 5-5. S.S. Doctor Lykes, World's Largest Dry Cargo Ship, (Photo: Courtesy of General Dynamics, Quincy Shipbuilding Division, Quincy, Massachusetts).

Hydrofoil craft have been the subject of considerable engineering study and test. In general, the studies show an economic feasibility at the present time for craft having speeds of 40 knots and 1500 - 3500-ton displacements (Ref 5-15). Future development of hydrofoil technology is heavily dependent upon the development of low weight-to-horsepower power plants. For example, with the development of lightweight nuclear power plants, a 100-knot, 3000-ton hydrofoil (payload = 20-30% of displacement) may be possible in the next 15 to 35 years. Whether hydrofoils can economically fill the marine speed gap is not yet known. Aside from the quick-delivery advantage, a high-speed, low-payload vessel is most applicable (in comparison to the productivity of slower but higher payload ships) to short routes. In addition, considering the competition from air carriers, the market for the hydrofoil is most likely to develop in coastal trade for medium-value, medium-priority cargo.

Surface-effect ships (SES) (e.g. hovercraft and hydrofoils) are candidates for the marine speed gap. An important advantage of these vessels is that no structural component increases in weight fraction with increased displacement as do the foil and strut weights of hydrofoils (Ref 5-15). Recent studies show that the various SES designs are economically attractive at displacements of 1000 tons or more and in ranges of 1000 miles or less. Depending upon demand, it is possible that 4000-ton, 100-knot, captured air-bubble craft will be developed in the next 15 years.

Along with the objectives of stability, large stowage space, and sea-worthiness, the hull designer is concerned with low drag and wave-making resistance. This is a particular concern with conventional displacement-hull ships. For example, wave-making resistance is such that a 40-knot conventional liner requires as much as a 40% increase in power for each additional knot of speed (Ref 5-15). Among proposed hull designs for reducing wave-making resistance is the catamaran. In this case, two slender hulls may have increased drag but a more-than-compensating reduction in wave-making resistance. In general, the catamaran offers speed and power advantages over equivalent conventional hulls. However, the chief use of catamarans would appear to lie in applications requiring large deck areas rather than those requiring the stowage of large quantities of bulk cargo. Other proposed hull designs involve the use of submerged buoyant members connected to an above-water hull by surface-piercing members. By adjusting the area of the connecting hull members and the underwater buoyant members, the design can trade off drag and wave-making resistance (for a particular speed range and cargo capacity).

Completely submerged hulls have frequently been suggested for bulk transport. Submarines begin to have less resistance to overcome than the equivalent (in payload) surface ship as the speed increases to the 25 - 35-knot range (Ref 5-7). The other major advantage of the submarine is the isolation from surface weather and ice. Except for under-ice operation, the added problems of life support, navigation, and special propulsion seem to prevent the submarine from being an economic competitor for surface ships.

The ship-building industry in the United States is the largest in the world. However, production is concentrated on special-purpose Navy ships. U.S. commercial shipbuilding lags behind that of other countries. For many years the construction of commercial ships has been supported by a U.S. government subsidy under which the U.S. builder was paid the difference between his costs and the cost of building the ship in a foreign yard. This subsidy has amounted to about 50%, but the Merchant Marine Act of 1970 is predicated on the reduction of this level to 35% by 1975.

To operate under this reduced subsidy and at the same time improve production rates, U.S. shipbuilders must not only undertake such cost-saving methods as serial production, but they must also inject a considerable amount of modern technology into ship-building (Ref 5-13). Much of the technology needed centers around shipyard organization including the use of aircraft and automobile in-line production processes. Conventional shipbuilding is characterized by a job-shop approach in handling materials and scheduling various production tasks. Important among the developing techniques are:

1. New methods for automated welding
2. Automated painting
3. Automated burning
4. Use of the computer in design and production control.

Since the days of sailing vessels, the trend in marine power plants has been towards providing power at lower specific weight. At the present time, steam-turbines and diesel-engine drives have specific weights in the order of 15 - 35 lb/hp. The present marine gas turbine has a weight to power ratio of 1 - 2 lb/hp (Ref 5-16). Because of their low weights, gas turbines seem to be the only feasible power source for high-speed hydrofoils and surface-effect ships. Despite their weight advantage, gas turbines use relatively expensive fuels and have thermal efficiencies of about 23% compared to 25% for steam and 35% for diesel. Gas turbines can be competitive with the other power sources if the gain in speed-payload product results in a compensating increase in ship productivity.

A potentially important technological development in marine propulsion is the nuclear reactor. In electric power generating plants, nuclear power has become more or less competitive with conventional plants; however, the special shielding and containment, the elaborate control devices, and the need for highly skilled operators make its application to marine use relatively expensive. Except for submarine cargo transports, nuclear power is not competitive (except at very high horsepower) with other marine power plants. Yet, with the continual development of nuclear power for electric generating plants as well as naval ships, it is predicted that low-cost, light-weight nuclear plants will be widely used on commercial ships over the next 35 to 75 years (Ref 5-15). Other disadvantages in the present use of marine nuclear power plants involve labor problems, lack of shore facilities, and safety considerations. The increasing use of nuclear propulsion by the Navy should serve to alleviate these operating problems.

Cargo Handling Methods. Although shipboard automation increases operational efficiency, the major reason for automation has been to avoid the increasing cost of labor. This is especially evident in the automatic control of propulsion machinery. In this case, the number of men required for watch duty can be reduced while maintaining safe operation.

In the near future, capital expenditures for on-line computers will likely be justified. This will make possible the use of on-line process control of ship operations. Among functions that could be accomplished are:

1. Control of propulsion units for optimum performance
2. Navigational computations and steering control
3. Cargo placement (trim computation)
4. Strain computations on the hull
5. Ship administration and data logging.

Automation will increase with economic justification, even extending to completely automated, unmanned slaveships.

One of the most significant improvements in ship productivity (as well as in the whole goods-moving industry) has been the introduction of new ways of packaging and handling cargo. For general cargo, standardized containers appropriate to all carriers from an inland point of origin to an overseas destination have been introduced. Examples of the new methods include on-board, high-speed conveyors for dry commodities and high-speed centrifugal pumps for liquid cargos. The new methods of cargo-handling required new ship designs of which the following are representative.

1. Container ships
2. Roll-on - roll-off ships
3. Barge-carrying ships
4. Lighter-carrying ships

Navigation and Operations Technology. New navigation technology has more often than not been developed for military purposes. However, many of these new techniques are now available for commercial operations. Representative of this technology are:

1. The development of the Omega system for world-wide position determination
2. Inertial navigation for submarines and for very precise course-keeping
3. Satellite navigation for world-wide precise-position fixing
4. New high-speed survey and charting methods for producing more accurate hydrographic charts which are updated at more frequent intervals
5. Improved methods for weather and sea-state prediction so that a ship at sea can take an optimum route

With the increase in ship speed and size there is an increasing problem of ship collision especially in congested port approaches. Contributing to this problem is the size and relatively low thrust of the super-tankers. Although radar is used effectively for navigation in congested areas there is a developing need for automatic means of controlling ship traffic in the approaches to busy ports. The increased size of ships has also made many port facilities obsolete. To deal with this problem, the following solutions are being proposed:

1. Offshore stations (connected by pipelines or auxiliary vehicles to shore facilities) for loading and unloading liquid-bulk cargos

2. The development of a few well-located ports specialized for large tankers, container ships, or another of the new methods of cargo handling

Bulk cargo traffic on the inland waterways has been increasing. To facilitate the movement of these goods there have been proposed:

1. Methods for increasing the shipping season on the Great Lakes

2. The development of new canals

3. Improvement of existing waterways to permit increased traffic of larger ships

Along with the increase in goods transport, has come the difficult problems of water and beach pollution. New methods for preventing, detecting, and cleanup of oil spills lead the developing technology in this vital area.

With the long time between ship design and completion, as well as other factors, such as legal restrictions on using foreign-built vessels in U.S. domestic trade, innovations in U.S. marine transport are relatively slow. The prediction of a recent survey of oceanborne shipping technology is that all oceanborne shipping will continue to move on conventional monohull displacement ships, at least until the end of this century. Speeds will go up only gradually as refinements to existing propulsion technology and hull design enable modest improvements in efficiency. Emphasis will be on improvement in productivity based on reduced port time and treatment of the ship as a part of an integrated transportation system (Ref 5-15).

5.6 INTERMODAL CARGO HANDLING: CONTAINERIZATION

There is a strong trend in both national and international trade toward automation and containerization for expediting the movement of cargo between various modes of transportation (see Figure 5-6). Automation means the introduction of mechanized equipment to perform or eliminate many of the manual tasks now needed in conventional cargo handling. Containerization means the introduction of large standard-sized, van-like bodies which can carry many smaller, various-sized pieces of freight. These can be loaded, unloaded, and transferred conveniently between trucks, trains, ships, and planes via highly mechanized procedures. Over the past decade, these new techniques have facilitated the concept of intermodal movement of goods into the transportation field in a very real way. It has been stimulated by the desire of transportation companies to reduce labor costs and difficulties and to reduce the time required for loading and unloading vehicles, leading to quicker turn-around and higher utilization of line-haul vehicles.

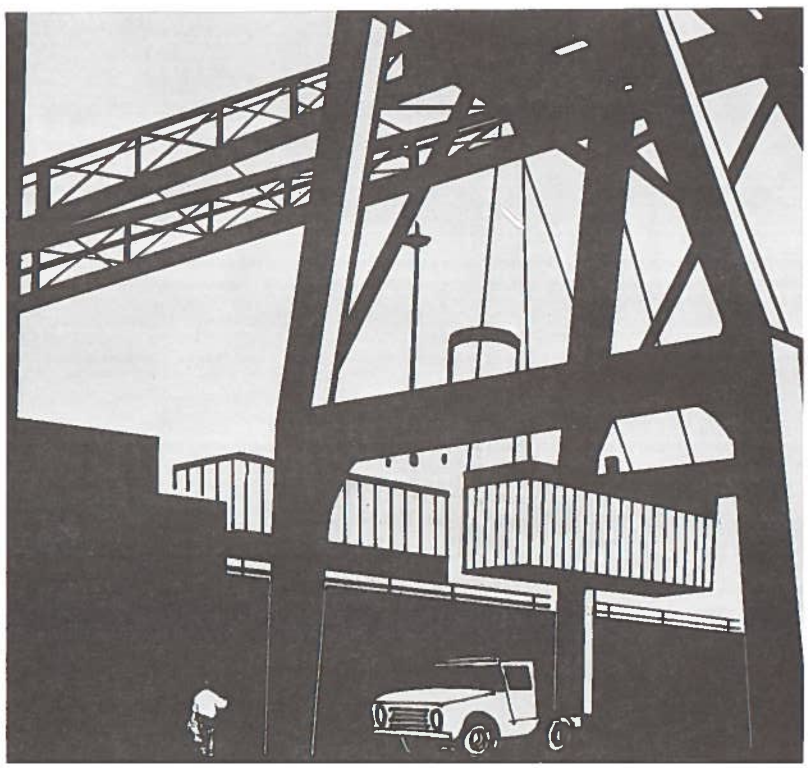

Figure 5-6. Container Movement Between Ship and Truck.

Containerization allows the coordinated movement of freight over two or more connecting modes and reduces freight losses through pilferage and damage which is characteristic of conventional loose freight operations (see Figure 5-7). The specially designed containers also provide better environmental protection from weather and shock in transit. They can be carried in the open aboard ships, trains, or trucks. They also provide convenient storage in open marshalling yards eliminating the need for a warehouse.

Freight containers of the modular, standardized, and weather-proof type first appeared in quantity in 1957, when the Pan Atlantic Steamship Company, the forerunner of Sea Land Service, Inc., modified several bulk-cargo ships for rapid loading and unloading. Container cells were installed to facilitate handling and greatly reduced ship turn-around time (Ref 5-18). Ship-mounted, gantry-type cranes were also introduced to transfer containers from ship to shore, as shown in Figure 5-8 (Ref 5-19). In 1959, Matson Navigation Company, serving Hawaii from the west coast, inaugurated major container operations with 8 x 8.5 x 24 foot containers weighing up to 22 tons.

Grace Lines soon followed with its own introduction of container operations. To reduce capital costs, operating-and-maintenance costs, and handling systems, it soon became apparent that industry-wide standization of containers was needed. Between 1961 and 1965 standards for external dimensions, strength, maximum gross weights, and interfacing fittings were worked out. Typical units are now 8 x 8 or 8 x 8.5 feet in cross section; and 10, 20, 24, 30, 35, or 40 feet long. Construction is varied, usually aluminum, fiberglass over plywood, or steel. For special purposes some collapsible, rubber-topped containers are used (Ref 5-18). Tare weight vs. payload of multimodal containers is of concern to airlines and motor carriers because of gross weight limitations and revenue potential. Rail vehicles and ships are less sensitive to weight considerations but will also benefit from light weight containers.

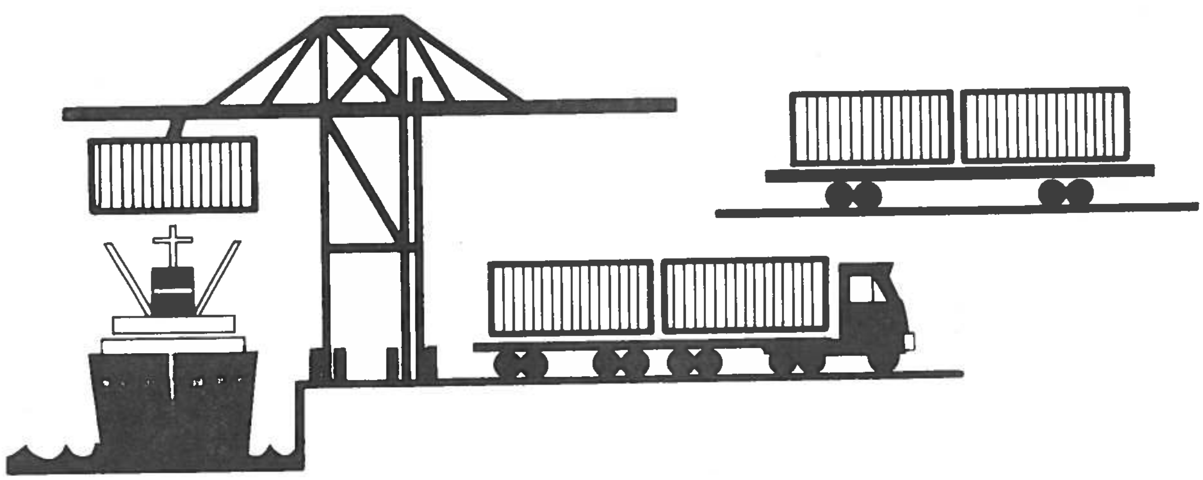

Figure 5-7. Intermodal Transfer of Freight in Closed Containers.

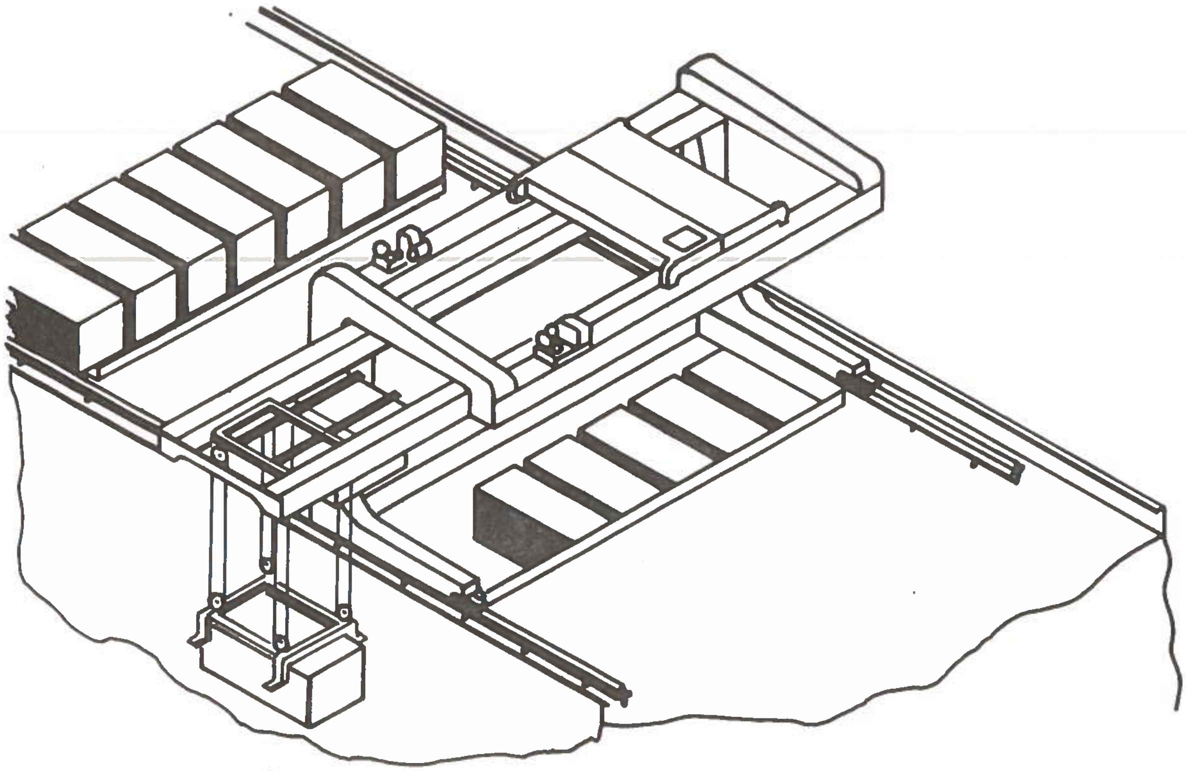

Figure 5-8. Deck Gantry for Container Handling.
(Source: Ref 5-19)

Container usage has been increasing rapidly over the past decade, growing from 18,000 units in 1960 to 54,000 units in 1965 and 145,000 units in 1967. Current estimates put the 1977 figure at around 640,000 equivalent 8 x 8 x 20 foot containers, as shown in Figure 5-9 (Ref 5-20). Currently, ship/truck interchange dominates the container picture, with ship/rail and rail/truck involvements much less. The introduction of new technology, wide-body jet airplanes (with carrying capacities of over 100 tons), and the increasing awareness of the total cost of distribution should increase the interchange of standardized containers among air, rail, motor and marine carriers in this decade.

The introduction of container operations requires substantial capital investments, but they are followed by a sharp reduction in labor costs. New containers, handling equipment, trailer chassis, bogies, flat cars, ships, and computers must be purchased to facilitate container operations. The cost of a typical dry cargo container, 8 x 8 x 20 feet, runs from about $2,000 to $18,000 (if refrigerated). Overhead cranes may cost anywhere from $30,000 to $1 million or more, depending on the capacity and flexibility of the installation. New container ships cost about $37 million (including containers), compared to about $14 million for break-bulk cargo ships. Typical berths cost about $3.5 million vs. about $2.5 million for conventional operations (Ref 5-20). However, the increased utilization of ships and berths and the reduced labor costs can more than offset the increased capital investment. The Canadian Transport Commission, for example, has estimated the capital-to-labor-ratio improvement at 11 to 1 (Ref 5-21). They assume a typical productivity figure to be 0.75 tons per manhour for ship-to-rail and ship-to-truck operations using conventional terminals and equipment; and 8.33 tons per manhour for the same service using 10-ton containers and special container-handling equipment.

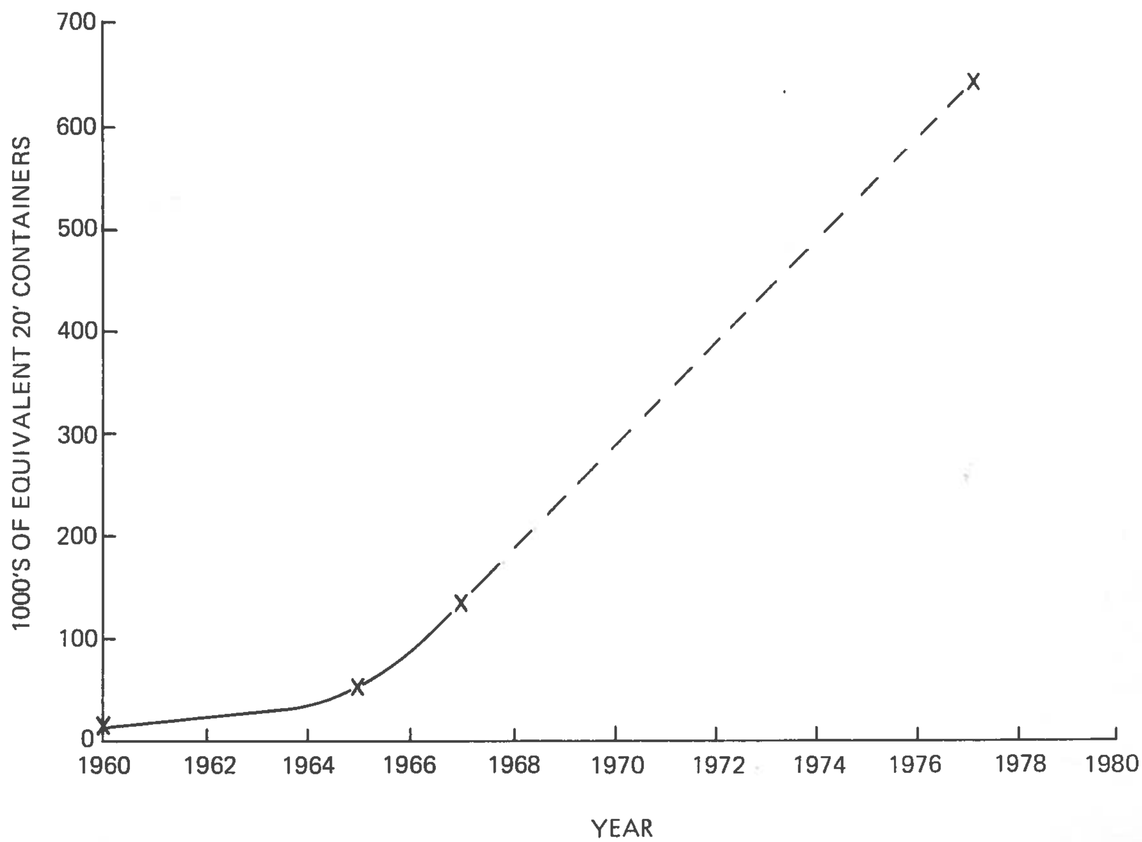

Figure 5-9. Estimated Growth in Container Demand

In the United States and Puerto Rico, there are 21 ports with a total of 73 berths and 63 container cranes currently in operation. Plans exist for adding about another 50 berths and 40 cranes (Ref 5-20). New York is the most active container port with 25 berths and 16 cranes (Figure 5-10). In Boston, the largest container crane will go into operation in 1971 in a public container terminal (Figure 5-11). It is 230 feet tall and can handle loads up to 70 tons. It is built with a maximum of flexibility and can move along the berth some 800 feet and perpendicular to it some 270 feet. It is of Japanese design and manufacture and costs about $1.25 million.

Where land use is a factor, the taller cranes allow better utilization of available land by stacking containers to heights of two or more levels. Computer usage is expected to improve operations further, particularly in the accounting and record-keeping operations associated with container flow. Better identification procedures to protect against errors in shipping containers will also benefit operations.

Figure 5-10. Typical Berth in Elizabeth, N.J., (Port Authority of New York).

Figure 5-11. Largest Container Crane in The U.S. (Massachusetts Port Authority, Boston, Massachusetts)

Not all goods are candidates for container shipment because of the size-and-weight limitations imposed by containers or because conventional single modal methods may be better, as it is with oil in pipelines. It is estimated, however, that 25% of all freight may eventually go by container, the greatest portion being general freight consisting of high-value-added products. So far, marine shippers are pushing the introduction of containers because they stand to benefit most. It is felt that the use of high-speed, mechanized, container operations is a strong force in making the United States merchant fleet competitive with lower-cost, foreign fleets in the movement of general and bulk cargo. The United States, being an innovator in containerization, currently enjoys the lead in this field and could capitalize on it. With continued development, containerization could revolutionize freight handling in the United States (Ref 5-17).

The intermodal standard container is the crux around which independent single mode carriers can develop to provide coordinated multi-mode door-to-door freight movements. Research is needed in materials and design of containers to meet the various operating requirements of each mode. The primary need is for several different designs capable of interfacing long haul vehicles and collection/distribution vehicles, e.g. rail and truck; ship, truck and rail, airplane and truck.

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6. TECHNOLOGIES

6.1 LOW POLLUTION VEHICLE TECHNOLOGY

Introduction. There is a great need for vehicles with 95 percent less pollutant emissions than in 1968 (Ref. 6-1). In 1967, Congress passed the Air Quality Act. The Department of Health, Education and Welfare (HEW) was given the responsibility of developing and setting standards for the control of motor vehicle emissions, with the Department of Transportation (DOT) responsible for enforcement. In December of 1970 President Nixon signed the 1970 Amendment to the Clean Air Act (Ref. 6-2). This amendment set the emission limits (Table 6-1).

TABLE 6-1. FEDERAL POLLUTION STANDARDS FOR AUTOMOBILE EMISSIONS (1970 AMENDMENT TO THE CLEAN AIR ACT)

Standard	Carbon Monoxide	Hydrocarbons	Oxides of Nitrogen
Typical automobile gas-piston engine with no controls	28 gm/mile	2 gm/mile	4 gm/mile
1975 Standards	4.7	0.25	0.4

The 1970 amendment has important implications for automobile manufacturers. Various modifications to the gas-piston engine might have made it possible for them to meet the requirements of the 1968 Air Quality Act. However, in order to reduce emissions to the levels required by the 1970 Amendment, it may be necessary to abandon the gas-piston engine. Continued use of these engines is made even more uncertain by the results of recent work at the National Center for Air Pollution Control. These results show that in view of the expected increase in the number of automobiles, it will be necessary to develop a pollution-free automobile by the year 2000 (Ref. 6-1). Even if the gas-piston could be made to meet the 1975 Standards, it is unlikely that it could ever be made pollution-free. In fact, at present, the position of the gas-piston engine is so tenuous that there is good reason for the Federal Government to conduct a program to develop an acceptable alternative. This recommendation was made by the Ad Hoc Panel on Unconventional Vehicle Propulsion in March, 1970 (Ref 6-3).

Development of an acceptable alternative to the gas-piston engine is urgent. Bringing conventional automobile powerplants to production is a long process, usually requiring five years. Significant production of an alternative powerplant would take about ten years; even then it might not have the performance capabilities of contemporary engines.

To achieve the low emission levels required by the 1970 Amendment and to eventually arrive at a pollution-free vehicle, five basic avenues of advancement are open: (1) development of an effective emission suppressor for the gas-piston engine; (2) development of a gas-turbine engine with an effective emission suppressor; (3) development of a battery-powered automobile; (4) development of a steam or vapor-powered automobile; and (5) combining these technologies in a hybrid vehicle.

Gas-Piston Engines. The development of a pollution-free gas-piston engine may not be technologically feasible. Further, it may not even be possible to meet the existing 1975 Standards. The basic technical problem is that since emissions of nitrogen oxides increase as the temperature of combustion increases, the higher temperatures that accompany most of the methods used to curb hydrocarbon and carbon monoxide emissions also increase pollution from nitrogen oxides. For example, a control device that would completely eliminate hydrocarbons would increase rather than decrease the emission of nitrogen oxides. In Los Angeles, an attempt to suppress hydrocarbon emissions led to an increase in the concentration of nitrogen oxides (Ref. 6-4).

In view of the serious reservations about the future of the gas-piston engine in both industry and government, there is little expectation that it can be made pollution-free or even meet the 1975 Standards (Refs 6-3, 6-5, 6-6, and 6-7).

Battery-Powered Vehicles. Battery-powered vehicles, deriving their power from stationary generating stations, are an alternative to the gas-piston-engine. However, before a decision can be made to develop this technology, it is first necessary to consider carefully the problem of the resulting air pollution. The increased combustion of fossil fuels required to recharge the batteries of electric automobiles might result in an unacceptably high level of air pollution. On the other hand, transferring the burden of air-pollution control from moving sources to stationary, possibly remote, sources offers several advantages. Debate over the issue is just beginning (Refs 6-8 and 6-9). The matter must be given careful and objective study by independent investigators. The highly controversial problem of radiation and thermal pollution is equally important. Recharging motor vehicle batteries by nuclear power (to avoid raising the level of air pollution) might result in unacceptable radiation and thermal pollution. Even if nuclear generating stations could be utilized without undesirable effects, only a few generating stations will be available during the next 10 to 15 years. Nuclear energy's share of the electricity-generating market is expected to reach 20 to 25 percent by 1980, and 50 percent by 2000 (Ref 6-8).

Another question affecting the decision to invest in battery technology is how the general public will accept low-performance automobiles. There are prospects that patterns of transportation, particularly in the cities, may change in the future toward smaller and less-powerful vehicles. If so, two types of batteries would be strong candidates for further development: air-metal and nickel-zinc. High cost precludes nickel-cadmium and silver-zinc batteries. In the case of nickel-zinc, it would be necessary to replace the zinc electrodes each time the battery was recharged; however, the zinc could be recycled for further use. There has been some concern about the down time associated with recharging batteries in an electric vehicle. This could be avoided by leasing batteries from service stations. Discharged batteries could be replaced in five minutes or less.

Limited range still remains the major disadvantage of battery powered vehicles. Batteries with greater specific energy densities (watt hours per pound) are needed. High specific power (watts per pound) is also required to provide vehicles with the ability to accelerate quickly and to drive up grades at reasonable speeds. The combination of these two requirements is difficult to meet.

Figure 6-1 shows battery characteristics in terms of specific power and specific energy. This chart simplifies the real situation in that it neglects other important parameters such as state of charge, ambient temperature, age of battery, and previous history. Broadly speaking, though, the two parameters chosen are adequate to describe battery performance for automotive power applications. Figure 6-1 also indicates that for a 2,000-pound vehicle, the range and speed can be obtained from specified values of specific power and specific energy.

For an electric vehicle to achieve performance broadly comparable to that of today's gas-piston engine-powered cars, a low-cost, high-temperature alkali-metal battery must be developed (Ref 6-4). In Figure 6-1, sodium-sulfur and lithium-chloride represent the alkali-metal batteries. Sodium-sulfur has a substantial advantage over lithium-chloride because its operating temperature is only 300°C rather than 600°C. Bringing the technology of high temperature alkali-metal batteries to maturity will be a massive task. Formidable problems in materials research and safety are involved. Public acceptance of high-temperature alkali-metal batteries is also a major question; the presence of a 900-pound battery containing alkali metals and elements such as chlorine and sulphur at temperatures as high as 600°C is obviously not a particularly desirable feature

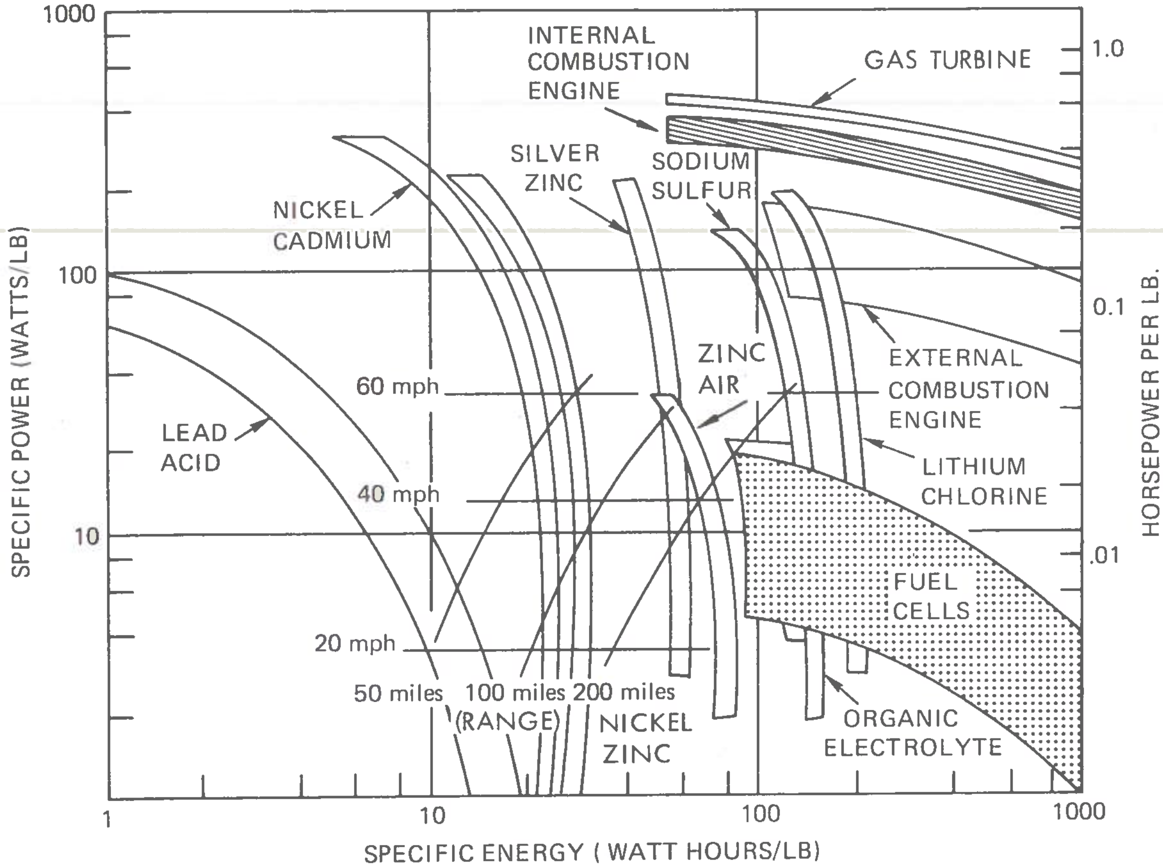

Figure 6-1. Vehicle and Motive Power Source Requirements

for the family car. Effective, low-cost insulating materials are clearly essential. The design must make the battery as crash-proof as possible. Groups presently developing batteries in this class are optimistic that this can be done.

Assuming that the performance of a conventional vehicle must be matched, metal-air batteries appear to be power-limited. They are likely to be more costly on both a weight and performance basis than high-temperature systems, although neither technology is advanced enough to generate firm cost estimates. Metal-air batteries, however, appear to have reasonable prospects for commercial and lower performance vehicles, particularly if advances are made in the utilization of lighter structural materials. In general, metal-air batteries have a major advantage in operating at close to ambient temperatures. Further development of metal-air batteries is therefore justified.

Alkali-metal batteries using organic electrolytes also have the advantage of operation at ambient temperatures and have high energy densities but low physical densities. The major problems limiting their potential use involve recharging at practical current densities and the achievement of adequate cycle life. It is conceivable that mechanical artifices might be introduced into these systems to overcome the electrochemical problems, but as yet such approaches have not been investigated. In view of these observations, this class of batteries do not merit major effort. However, it will undoubtedly see further development in view of its potential applications in other areas.

<u>Fuel Cells.</u> Prospects for the fuel cell as a vehicle power source are not favorable, partly because of its low power density, but mainly because of its inherently greater complexity and high cost relative to batteries (Ref 6-4). There seems to be no justification for a fuel cell development program oriented exclusively toward civilian highway vehicles, although fuel cells may well find vehicle applications in the military or in specialized industrial fields.

Fuel cells avoid the battery's recharging requirements, but the shortage of necessary catalytic platinum metal makes their widespread use impossible. Results of research to obtain a noncritical replacement for the platinum catalyst have been unsuccessful.

In 1967, federal spending on research and development on electrochemical power sources, exclusive of the major fuel cell hardware programs for space vehicles, was estimated to be in the vicinity of $10 million annually. However, only a small proportion of this was directly relevant to the needs of civilian electric vehicles. Expenditure by private industry on power source development relating to electric vehicles was estimated at 5 to $7 million annually in 1967 (Ref 6-4).

<u>Rankine-Cycle Systems.</u> Rankine-cycle power systems offer a most promising alternative to the gas-piston engine. Both steam and organic working fluids are under consideration. Reduction of component production costs is the only significant difficulty facing Rankine-cycle engines. This difficulty does not result from inherent inefficiencies, but rather from the relative immaturity of the technology. However, substantial progress has already been made.

In 1970, the Ford Motor Company investigated the added production costs which would result from replacing a conventional gas-piston engine and its automatic transmission system with a Rankine-cycle system available at that time (Ref 6-10). A 302-in.^{3}, V-8, 200-hp, gas-piston engine and its automatic transmission system were compared to a 105 hp, Rankine-cycle system (these systems have nearly the same performance capabilities). It was estimated that the Rankine-cycle system would add 40 to 80 percent to the production costs presently attributed to a conventional vehicle's engine and automatic transmission system. The engine and transmission usually account for about 30 percent of the total automobile production costs. The Rankine-cycle system would consequently have added from 12 to 25 percent to the total vehicle cost. More recent designs are expected to reduce these potential increases.

A reciprocating Rankine-cycle engine delivering 100 hp at the shaft is a practical automobile power plant. Since the reciprocating Rankine-cycle engine can deliver high torque at low speed, its characteristics are well matched to those required for vehicle propulsion. Only a simple transmission system is required, and the maximum power rating of the engine can be reduced substantially compared to the power rating required for a conventional gasoline engine, which develops high torque only at high speeds. Prototype 100 hp, Rankine-cycle engines have been built using both steam and organic working fluids. Now the question is: Which working fluid will yield the lowest emissions and have the lowest production costs? An organic fluid permits a lower operating temperature and also reduces the emission of nitrogen oxides. Although long startup time has, in the past, been one of the major drawbacks in the use of the steam engine, modern boiler technology has substantially reduced this problem.

Rankine-cycle engines use an external burner that operates under constant controlled conditions at atmospheric pressure and, hence, produces very low concentrations of oxides of nitrogen in comparison with gasoline, diesel, or gas-turbine engines. There are no requirements for the use of lead, and the fuel burns with excess air so that very low levels of carbon monoxide and unburned hydrocarbons are emitted. Table 6-2 presents typical emissions from a steam-engine automobile as compared with the 1975 Standards for a 4,000-pound vehicle.

TABLE 6-2. TYPICAL STEAM-AUTOMOBILE EMISSIONS AND THE 1975 STANDARDS (4,000 LB VEHICLE)

Standard	Hydrocarbons	Monoxide	Oxides of Nitrogen
1975 Standards	20 ppm	0.2% (by weight)	100 ppm
Steam Automobile	20 "	0.05% "	40 "

With the exception of electric cars which transfer the air pollution-control problem to stationary generating stations, only Rankine-cycle cars have demonstrated the capability of meeting the 1975 Standards. Further, they do not have to undergo a long development cycle to achieve satisfactory performance.

Hybrid Power Plants. A hybrid powerplant consists of one component providing steady power for continuous, long-range driving and a second providing peak power for acceleration and hill climbing. The most promising candidates for the first category are small gas-turbines and small Rankine-cycle engines. Usually, batteries are proposed for delivering peak power. An air-zinc or a nickel-zinc battery could deliver more than adequate power to meet peak demands, but only for short intervals. The engine recharges the battery during periods of off-peak power requirements. Existing low-cost, lead-acid batteries can meet the power-density requirements of a hybrid city bus, making this vehicle an attractive possibility. Hybrids can control emissions because the engine portion of the combination can be made to operate under conditions of constant temperature and pressure. The Ad Hoc Panel on Unconventional Vehicle Propulsion concluded in 1970 that hybrids have not received sufficient innovative development (Ref 6-3).

The necessary duplication of functional capabilities tend to give hybrid vehicles a higher basic cost than vehicles having only one power source. The major uncertainty in the cost of hybrid electric vehicles is the control system. High-amperage control systems are presently expensive, but the price of the major component (silicon controlled rectifiers) should fall with increasing volume.

As a result of the 1975 Standards and the long-term need for pollution-free vehicles, hybrid automobiles face a particularly uncertain future. Production of hybrid automobiles meeting the 1975 Standards probably would not be feasible until the latter part of the decade. On the other hand, hybrids employing internal combustion do not offer substantial promise of reducing automobile pollution to the even lower levels that will be required by the year 2000. Hybridization may be employed, however, during a transition period between the utilization of the gas-piston engine and a pollution-free engine. One of the larger power sources used in any hybrid automobile produced in large numbers should be expected to mature into a pollution-free sole power source.

Gas Turbines. The gas turbine has potential as a low-emission automobile engine if costs and size can be reduced (Refs 6-3, 6-11, and 6-12). There is extensive experience in gas turbines for heavy vehicles but little for passenger car engines. Work on gas-turbine engines was initiated years before emission controls were required because they offered other potential advantages such as lighter weight, smaller size, reduced vibration and reduced maintenance. Gas turbines emit low levels of carbon monoxide and unburned hydrocarbons. The reduction of emissions to 1975 Standards, however, has not been demonstrated by gas turbines. In spite of their potential advantages, the applicability of gas turbines to passenger cars is doubtful. Gas turbines are more expensive than gas-piston engines, primarily because of expensive materials and complex fabrication techniques required for the high temperature components (Ref 6-3). Fuel economy would also be low in initial models. Metal fatigue caused by temperature cycling during stop-and-go driving might give serious difficulty.

Conventional gas and diesel engines repeatedly ignite their fuels with a spark. The resulting combustion occurs in a small fraction of a second while under conditions of rapidly varying temperature and pressure. This uneven burning results in incomplete oxidation of the fuel. The incomplete combustion leads, in turn, to the emission of pollutants. By contrast, gas turbine engines burn their fuel continuously at uniform conditions of temperature and pressure. As a result, their objectionable emissions are much less. Diesel, conventional gasoline and gas-turbine engines are all internal-combustion engines. To distinguish between their emission characteristics, the first two are sometimes referred to as spark engines. Approximate comparative emission data are shown in Table 6-3.

TABLE 6-3. COMPARATIVE EMISSION DATA FOR INTERNAL COMBUSTION ENGINES *

Engine Type	Hydrocarbons	Carbon Monoxide	Oxides of Nitrogen
Gas-piston engines	900 ppm	3.5% (by weight)	1500 ppm
Diesel engines	150-500 "	0.2% "	2000-3000 "
Gas-turbine engines	40-50 "	0.3 "	200-350 "

*(Ref 6-6)

The first large scale use of turbine trucks will be in long-haul operations where weight and reliability savings are of the utmost importance. Later, they will be used in other areas of the urban and interurban goods movement market. As of 1970, four major manufacturers have invested about $10 million in research and development, and about $50 million in manufacturing facilities are either committed or under consideration (Ref 6-13). The best time estimate for substantial turbine-truck production is five years. Serious work on turbine trucks dates back 15 years; now several prototypes are undergoing long term field tests hauling revenue freight. Work actually began long before the tightening of emission controls because of the gas turbine's potential advantages of reductions in weight, size, vibration and maintenance.

Compared to diesel trucks, turbine trucks have several advantages. Scheduled engine maintenance will be reduced by at least 45 percent; reliability gains are expected to be higher. This will result from the fact that gas-turbine engines have fewer moving parts than diesel engines. The emissions and noise levels of turbines will be substantially lower. Turbine trucks are also more powerful per unit weight. This will result in a typical added cargo capacity of 1,000 pounds in early models and over 2,000 pounds in later models. In spite of the fact that this is only about 1 to 2 percent of the total cargo weight, this improvement can spell the difference between profit and loss.

Turbine trucks have several disadvantages. Their initial costs will probably be about 10% higher than diesel trucks, and their fuel consumption is higher under stop-and-go driving conditions. The ability of the turbine to operate at maximum efficiency is related to its operating temperature and pressure. The higher the temperature and pressure, the higher its efficiency. Temperature is critical. As the temperature rises above 1,750°F, structual integrity begins to fall off very rapidly, and the life of the turbine decreases. Thus, there is a compromise between performance, life and fuel economy.

It is anticipated that the gas turbine's higher fuel costs will be offset by maintenance and reliability savings. The weight savings are, therefore, a measure of the direct operational savings to be derived by switching from diesel trucks to turbine trucks.

Automobiles and buses are candidates for gas-turbine engines; but before they can be used in these vehicles, further development is needed, primarily because contemporary gas-turbine engines are now too large for automobiles. In addition, they are not presently suited to the stop-and-go driving patterns of buses. Gas-turbine trucks are certain to be used rather widely. This experience will permit a realistic evaluation of the desirability of developing gas-turbine engines for automobiles and buses.

Stirling-cycle engines, using helium or hydrogen as the working fluid, are competing for the same truck market as gas-turbine engines. Substantial work on Stirling-cycle engines is being done in the United States. Compared to gas-turbine and diesel engines, Stirling engines have more favorable torque-speed characteristics and better fuel economy under partial engine loads. Present disadvantages are comparatively high cost and weight.

6.2 PROPULSION, POWER AND BRAKING TECHNOLOGIES

Wheel-Driven Systems. The maximum propulsive force applied before a wheel spins or "breaks loose" depends upon the adhesion or frictional force between wheel and guideway. The adhesion increases with vehicle weight, but the force needed to accelerate the vehicle increases in the same proportion. Unfortunately, the adhesive force decreases as the vehicle speed increases and, therefore, limits the maximum speed. The exact speed at which this occurs is not known because of insufficient theoretical and empirical data. The maximum speed is estimated to be between

250 and 300 mph for rail systems. A good, accurately aligned guideway is necessary at high speeds. The rails for the Japanese high-speed Tokaido Line are maintained on a daily basis. Auxiliary propulsion such as fan jets or propellers could make up for inadequate wheel-rail friction, but these systems are inherently noisy and contribute to air pollution.

Electric Traction Motors. Electric traction motors are used in high-speed rail vehicles such as the Metroliner (Refs 6-14 and 6-15). The dc series-wound motors used have very high starting torques, which is important for rapidly accelerating the vehicle to its cruise speed. Speed is varied by voltage control. This type of motor lends itself to dynamic or regenerative braking. The typical weight-to-power ratio range is 7 to 11 lb/hp. Hope exists for reducing this to 5 lb/hp. The alternating-current, squirrel-cage induction motor is another candidate for propulsion. It is expected that 2.5 lb/hp is attainable in this case. The induction motor needs a sophisticated power conditioner to deliver the required starting and running torque with the smallest possible motor. Dynamic or regenerative braking requires additional complications in the power conditioner when compared to the dc series motor. The motor itself, however, is capable of maximum torque over its entire speed range. It is also smallest in size and weight and possesses good braking characteristics when used with the proper power conditioner.

At high cruise speeds where aerodynamic drag is significant, the propulsion power needed increases as the cube of the speed. The specific motor weight then becomes very important. The weight of a typical 5000-hp motor for a 300-mph vehicle would be 35,000 lb at 7 lb/hp, compared to the Metroliner motors which collectively weigh nearly 9000 pounds (160 mph). There is a case, then, for considering other approaches to electric propulsion over the conventional rotary motor.

Linear Motors. The linear motor appears to have a significant weight advantage over the rotary motor. The two types having the greatest promise are the synchronous motor and the induction motor (Ref 6-16). The induction motor is the more fully developed of the two, and present designs yield specific weights near 2 lb/hp. In the linear motor, thrust is developed against a reaction rail, which forms half of the motor and is analogous to the rotor in a conventional induction motor. The reaction rail is stationary on the guideway and is not part of the vehicle. The thrust against the reaction rail is produced by electromagnetic effects and is not limited by mechanical characteristics such as in a wheel-traction vehicle.

The linear motor also develops a magnetic attraction between the primary (located in the vehicle) and the reaction rail that is several times the thrust. Consequently, the most popular linear motor configuration is one with the primary straddling the reaction rail and creating an air gap on each side. The magnetic attraction forces on the rail cancel if the rail is perfectly centered between the primary pole faces. Consequently, guidance and alignment of the motor primary with respect to the reaction rail is a major consideration (Refs 6-17 and 6-18). If the vehicle has wheels and is guided by rails like a conventional railroad vehicle, motor alignment is straightforward. If the vehicle is suspended by an air cushion or magnetic levitation, guidance may be more difficult. There are no flanged wheels to resist lateral thrust such as may be caused by a cross wind. Proper operation of the motor requires an air gap between primary and reaction rail. To maintain this air gap and thereby guide the vehicle, air jets operating against the reaction rail appear promising.

The linear motor, like the rotary ac traction motor, needs a sophisticated power conditioner for maximum performance. A frequency converter is needed to supply power from zero frequency up to as high as 300 Hz at high power levels. Present power-conditioning schemes with this capability physically outweigh the linear motor itself and do not yet have adequate reliability.

The linear synchronous motor is far behind the induction motor in the development cycle. The synchronous motor may ease the demands on the power conditioning apparatus when compared with the linear induction motor, but this area needs further exploration.

The systems discussed so far would take electrical power from a wayside line. These electrified systems would have low noise and would introduce no significant air pollution in the proximity of the vehicle. The electrical generating station may or may not use air polluting equipment, so an electrified system may not be totally pollution free.

Gas Turbines. Gas-turbine engines can be used to power high-speed vehicles. Their exhaust has a low concentration of pollutants when compared to other hydrocarbon-burning engines. In spite of this, gas turbine engines may not be acceptable in urban areas because of smog and noise contribution, but they might be used in rural areas where the high cost of electrification may not be justified (Ref 6-14). They would not be useful in underground operations.

Gas turbines are very lightweight, with weight-to-power ratios typically around 0.5 lb/hp. Their poor fuel economy is currently a drawback; this problem is even more pronounced at partial throttle. Improvement of fuel economy might come about by increases in operating temperature and pressures or through the use of regenerative configurations. Regenerative engines, though more complicated and expensive, show potential of reducing fuel consumption by as much as 40 percent at partial-throttle conditions (Refs. 6-14 and 6-19).

Electrical Power Systems. The electrical power requirement for a high-speed (300 mph) ground vehicle is on the order of six megawatts per vehicle (Ref 6-20). This power is roughly divided into five megawatts for the propusion system and the rest for other subsystems on the vehicle. The power is distributed to the power-collection rails at substations that are spaced at intervals along the vehicle guideway. The spacing is determined by the allowable voltage drop along the power collection rail. The voltage drop is roughly proportional to the distribution frequency and can be very significant. The Metroliner, for example, uses 11 kv at 25 Hz for primary power. At 60 Hz, the voltage required is 22 kv because of the increased voltage drop on the wayside line.

Direct current is the most economically distributed power from the standpoint of power-collection-rail efficiency (Ref 6-14). The voltage drop on the rail is minimal. The DC must be obtained by rectification of the 60-Hz, AC power line, which is the only type of power available nationwide. An AC-to-DC converter is needed at each substation to supply the DC. A disadvantage of using DC is that the switchgear needed to clear faults will be large compared to switchgear needed for AC systems of the same power level. The power-conditioning equipment aboard the vehicle can clear a fault in the propulsion system in many cases if the distributed power is AC (Ref 6-15). If DC is used, fault protection must be provided by additional switchgear.

Alternating current at the generator frequency is distributed by simply stepping down the main-line voltage (typically 35 to 115 kv) with passive transformers. No frequency conversion or rectification equipment is needed. The power is more effectively distributed as three-phase rather than single-phase power. It therefore requires three power-collection rails along the guideway rather than the two needed for DC. The substations must be spaced at closer intervals because of the increased voltage drop.

The voltage picked for distribution reflects compromises between power losses (which vary inversely with voltage level), insulation and safety problems (which increase with voltage level), and motor requirements that dictate the design voltage level inside the vehicle. Motor-insulation requirements make voltages in the 4 to 8-kv range practical, with higher voltages causing flashover and breakdown problems. Currents are already in the 1000-ampere range when 4 kv is used. Lower voltages raise current to undesirable values.

The power-conditioning equipment converts the distributed power at the collection rails into the voltage or frequency levels (or both) needed by the motor for all the starting, stopping and cruise conditions. The power-conditioning unit provides speed control for the vehicle by varying the voltage or frequency (or both) to the motor. Assuming the motors are linear induction, the requirement on the power conditioner is to change 4 to 8-kv, 60-Hz power into power from zero frequency to over 200 Hz at zero to full voltage (4 to 8 kv) (Ref 6-20). The linear motor can supply contant thrust from start to full speed under these conditions. At the present time, power conditioners with adequate capability are beyond the state of the art. There are no semiconductors that can withstand the voltage or power levels needed. Consequently, the approach has been to cascade semiconductors, usually silicon controlled rectifiers, in series and parallel strings to meet the requirements. Power conditioners that can meet variable-voltage/variable-frequency requirements are heavier than the motor and still not well developed. Development of the linear induction motor and the vehicle are well ahead of the power conditioner. Therefore, the first high-speed vehicles are expected to use an unsophisticated type of power conditioner. These units will provide primary voltage control without variable frequency. Motor supply frequency will be 60 Hz, the same as the input line. Voltage control will be accomplished by putting variable or tap-switched reactors in the line to reduce the voltage available to the motor. Silicon-controlled rectifiers may also be used to chop the input line voltage and vary it from small values to full line voltage for the motor. Since the thrust output of the motor is proportional to the square of the applied voltage, a large change in the thrust can be accomplished with only a moderate voltage change.

Braking Technology. The braking of high-speed rail vehicles is difficult for two reasons. First, at high speeds much energy must be dissipated. Second, the effectiveness of brakes that slow or stop the wheels is limited by the adhesion of the wheels to the rails, and the adhesion available decreases with speed.

Tread-shoe brakes of the conventional railroad type require the dissipation of braking heat through the wheels and brake shoes. This tends to overheat and distort the wheels at large braking loads such as those encountered by the Metroliner and the New Tokaido Line.

Disc brakes have a greater heat-dissipation capacity than tread brakes and are being used on modern high-speed train bogies, such as the Budd Company's Pioneer III and the bogies of the New Tokaido Line. These brakes are only normally used at low speeds, but they are designed to meet the complete emergency-stopping requirements of the trains. Tread brakes could not be readily designed for that severe condition.

Hydrodynamic brakes provide another means of wheel braking. Counter-rotating vanes or some other mechanism, connected to the wheels, churn a liquid such as water mixed with antifreeze, thus dissipating the vehicle's energy. The liquid, heated by the churning action, is cooled in a radiator. This type of brake is currently used on many diesel locomotives (Ref 6-21). It absorbs large amounts of energy without requiring a large quantity of metal as a heat sink. Hydrodynamic brakes are planned for the British Advanced Passenger Train (Ref 6-22). They are light in weight (0.3-0.5 lb/hp), rugged, and inexpensive (about $2/hp). They are generally fast in response and work well with an anti-slip control system.

With electric motor drive (linear or rotary), the motor can function as a generator in braking to regenerate the vehicle's kinetic energy as electrical power and return it to the power system. This scheme (called regenerative braking) requires a fairly complicated power-conditioning system. The Zurich three-car (suburban) trains use regenerative braking almost to a stop, returning the power to the supply line (Ref 6-23).

Non-regenerative dynamic braking, with either DC or single-phase AC motors is relatively simple to implement compared to regenerative braking. This is because the generated voltage does not have to be greater than line voltage. Rather than being fed back into the supply line, the generated power is dissipated into a resistor bank. This method is used by most DC electric railroads and rapid-transit systems; the Metroliner, for example, uses resistors mounted under the car floor to brake from top speed down to 70 mph, giving about 0.06 g deceleration (Ref 6-24). The German electric Class E-40 locomotive can brake almost to a standstill electrically (Ref 6-25). The New Tokaido Line cars also use dynamic braking, with an automatically controlled rheostat, down to 30 mph (Ref 6-26).

Eddy-current braking by means of a stator-coil arrangement, similar to that of a linear motor offers a non-tractive means of braking at high speeds. It essentially acts as a linear motor with reversed thrust. The system has been tested on the Japanese New San Yo (Ref 6-27) and will be used on a new Russian high speed passenger train (Ref 6-28).

Aerodynamic braking dissipates the kinetic energy of the train directly to the atmosphere, without the need of intermediate cooling. At high vehicle speed, this can provide a very effective means of deceleration since it is not dependent on wheel traction. Aerodynamic braking can be increased by use of controllable spoilers or flaps.

Magnetic shoes attracted to the rails electromagnetically do not depend on car weight to produce frictional forces. In fact they can aid the wheel brakes by adding additional vertical forces to the car weight. This method is used in the Frankfurt, Germany, subway, where normal acceleration is 0.175 g and emergency braking is 0.365 g. Magnetic shoes are heavy, but large forces and friction coefficients considerably larger than available through rail-wheel adhesion are obtained.

Power Collection Technology. The large amount of power that must be collected at high speeds by advanced vehicles requires extensions in the present state of the art. Mechanical wear, thermal effects, dynamic action, and electrical arcing are potential areas of difficulty.

The overhead catenaries used in most high-speed trains throughout the world are flexible, leading to problems at high speeds. The collecting pantograph deflects the wire at the point of contact, and, as the train speed approaches the propagation speed of the transverse wave in the catenary wire, the deflection amplitude becomes large. Matsudaira suggests that a value of 20 percent below the critical speed be taken as limiting for safe service (Ref 6-14). The Metroliner can operate satisfactorily at 160 mph on the Penn Central test track, but severe arcing occurs. Westinghouse and General Electric Company studies conclude that pantograph-catenary systems are not feasible at speeds appreciably above 200 mph.

Rigid-rail power-distribution systems avoid the dynamic problems of the catenary. Conventional third-rail systems operate at about 600 volts DC. The Bay Area Rapid Transit System has a 1000-volt-DC third rail. Voltages up to 4000 volts DC are being considered by General Electric, while Westinghouse is considering 9000 volts DC. General Electric states that although no data appear to be available for sliding or rolling contact collection near 300 mph, there appears to be no reason to take a pessimistic attitude toward the feasibility of a high-speed sliding contact system. Arc suppression, regulation of contact loading, and possibly contact cooling are areas that need investigation. Multiple contacts with different dynamic resonances and servo-driven contacts are considered, with the latter a leading contender. Figure 6-2 shows a power collection device for speeds of 300 mph (designed by the Garrett Corporation). Rolling contacts would have little wear, but where contact area is small, large heavy wheels would be required, and the collection must be made twice: once from roller to rail and once from roller to car.

Westinghouse is looking at solid contact shoes, multiple contact shoes, wire-bristle contact in single or double suspension, wire-bristle pinch contact, and spring-leaf contact "deck of cards". Two contact rails for single-phase AC are used rather than a return through the rails because of the possibility of damage to the rails and wheels at the high-current levels and interference with track control circuits. Spacing is about 12 inches at 7500 volts, with insulators holding the rails about 8 inches from the vertical supporting wall at the side of the guideway.

Attempts to circumvent the problem of wear by using non-contact current collection devices have not yet proven very successful. General Electric identifies four general methods of contactless power transfer: (1) controlled electric arc; (2) magnetic induction coupling; (3) capacitive coupling; and (4) electromagnetic waveguide coupling. Of the four methods listed, it is felt that the controlled electric arc is probably best. Problems with the arcs extinguishing at high speeds, material wear, and radio noise are its principal problems. The inductive, capacitive, and electromagnetic waveguide concepts are not feasible because higher frequency excursions will have to be compensated by the brush-holder spring and dashpot. Based on experience with brushes for rotating machinery, the brush material should wear per unit length much less than the distributor rail does, and since the rail is much longer than the brush, its wear will also be reasonable.

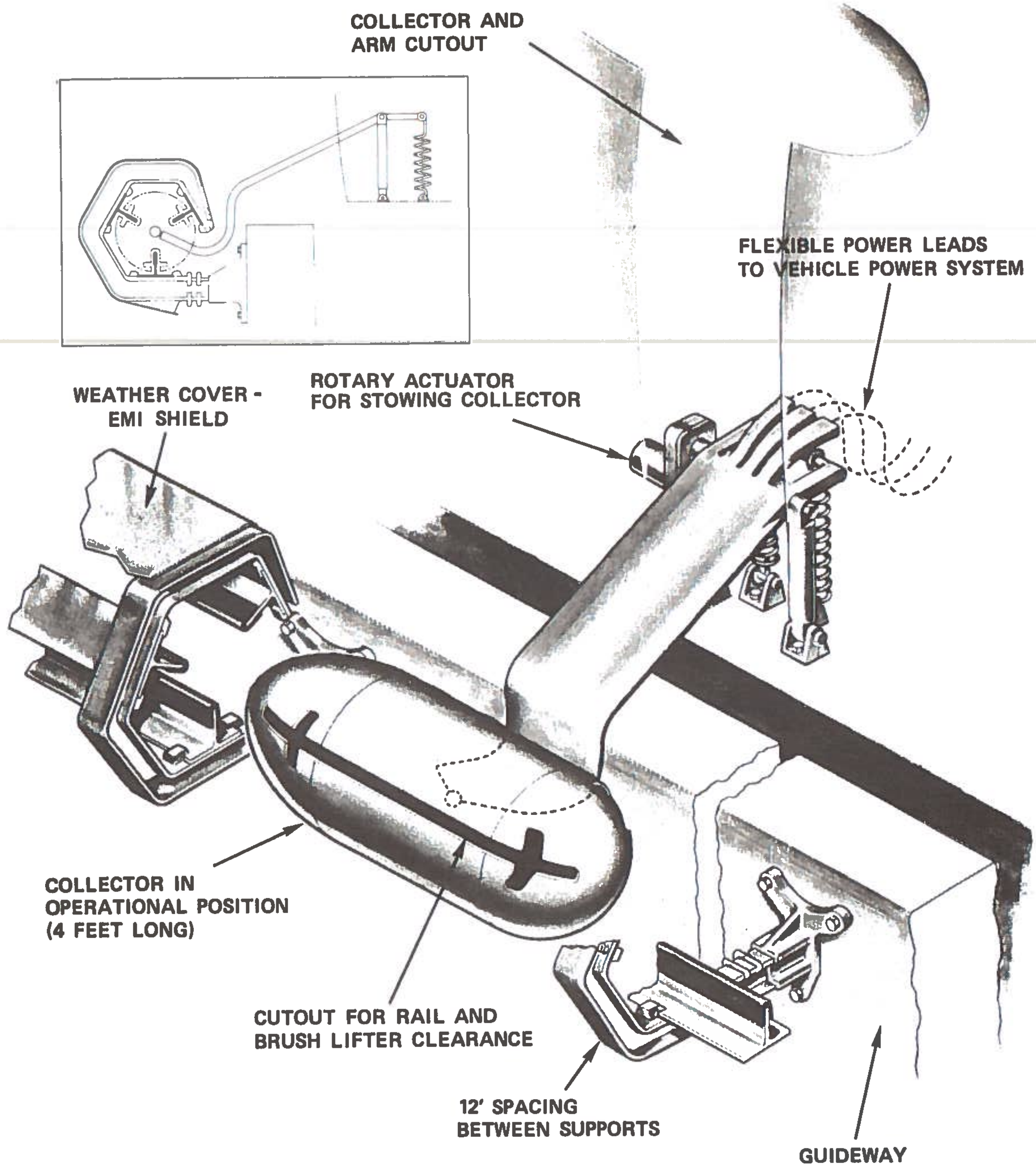

Figure 6-2. Wayside Power Collector for 300-mph Vehicles (Illustration: Courtesy of the Garrett Corporation)

6.3 SUSPENSION AND SUPPORT TECHNOLOGY

Introduction. Support systems, as used in this discussion, refer to the means of transmitting the weight of the vehicle to the ground. They usually involve wheels, air cushions, or magnetic fields. Suspension systems, on the other hand, refer to the means of isolating the vehicle from vibrations due to the support system and to the means of maintaining vehicle orientation (e.g., resisting sway due to cross winds and turns, etc.). They can be either passive (consisting of springs and shock absorbers)or active (employing servomechanisms).

Suspension Systems. Passive suspension systems, using springs and shock absorbers, are found on nearly all vehicles. They provide guideway irregularity isolation for certain limited ranges of excitation frequencies and can provide limited body banking through curves (Figure 6-3). The development of active

PASSIVE | **ACTIVE**

PASSIVE

ADVANTAGES:

1. EXISTING TECHNOLOGY
2. CHEAP
3. REQUIRES NO POWER

DISADVANTAGES:

1. EFFECTIVE OVER LIMITED RANGE OF EXCITATION FREQUENCIES.
2. DOES NOT PROVIDE POSITIVE CONTROL OF VEHICLE BODY ORIENTATION.

ACTIVE

ADVANTAGES:

1. EFFECTIVE OVER WIDE RANGE OF EXCITATION FREQUENCIES.
2. PROVIDES POSITIVE CONTROL OF VEHICLE BODY ORIENTATION.

DISADVANTAGES:

1. EXPENSIVE
2. REQUIRES POWER
3. REQUIRES SOPHISTICATED CONTROL SYSTEM.

Figure 6-3. Comparison of Suspension Systems suspension systems offers greatly improved comfort and speed in ground vehicles for a nominal cost. Using acceleration or displacement-controlled servomechanisms they can provide better isolation of the vehicle from guideway irregularities and better control of the vehicle orientation on curves than present passive systems.

The ability of passive suspensions to satisfactorily isolate the vehicle from shocks and vibrations due to guideway irregularities is limited to a finite range of excitation frequencies, which is governed by the selection of the spring and damping constants of the system. For a very narrow range of frequencies, the system performs fairly well, but in practice a quite-wide range of frequencies will be encountered. The system performance must then be compromised in order to provide some effectiveness. A common problem, even for very narrow frequency ranges, is that the desired degree of vibration isolation requires a prohibitively large amount of vehicle movement.

A passive system provides limited body banking on curves through a pendulum arrangement, as on the United Aircraft Turbotrain. Here, the centrifugal force caused by a curve tilts the vehicle body into an angle that reduces or eliminates the turning sensation experienced by passengers. This enables the vehicle to pass through curves at somewhat higher speeds without unduly stressing the passengers. The limit to this type of orientation control arises because it requires sizable lateral displacements of the vehicle center of gravity, which moves outward in the curve. Thus, vehicle dimensions are restricted to maintain adequate clearance, and the vehicle's resistance to overturning is reduced.

Studies of active suspension systems show that for some frequency ranges, particularly those where a passive system is most deficient, an active system can reduce vehicle vibration levels by nearly an order of magnitude below what would occur with a passive system (Refs 6-29 and 6-30). Since the intensity of vibration increases with increasing speed, much higher speeds can be attained comfortably on a given section of track with active suspensions. The degree of necessary guideway smoothness and alignment is also reduced, resulting in significant reductions in construction and maintenance costs for guideways.

In addition, while passing through curves, an active suspension system can forcibly bank the vehicle into an angle that reduces or entirely eliminates the centrifugal force experienced by the passengers, and is not subject to the bank limitation of the passive, pendulum suspension caused by the lateral motion of its center of gravity. With an active banking system, the proper combination of body and suspension design can insure that, even though highly banked, no part of the vehicle will extend outside the allowable body envelope. Thus, clearance need not be a problem. And if desired, an active banking system can be used to increase vehicle stability against overturning on a curve by moving its center of gravity into the center of the curve during the banking process. Thus an active banking system is capable of higher speeds through curves than a pendulous passive system, and is capable of far higher speeds on curves than a vehicle with a conventional passive suspension containing no banking provision. Active banking systems are currently being developed for railway vehicles in England, France and Germany. (Refs 6-22, 6-31, 6-32 and 6-33).

An active suspension can be used on virtually any type of ground-based vehicle to improve its ride qualities and average speed capability. In addition to the foreign railway applications mentioned above, serious consideration is being given to their use on railway vehicles in this country and on TACV systems (Figure 6-4). Because of the necessary response times and the

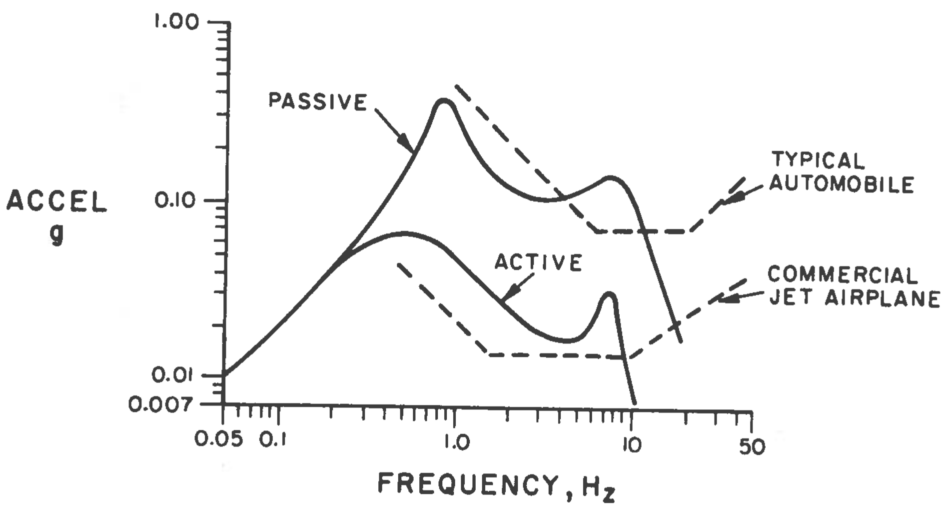

Figure 6-4. Comparison of Calculated Ride Quality for the TACRV With Active and Passive Suspension Systems for Various Vibration Frequencies (Ref 6-30)

magnitudes of the forces that must be applied, hydraulically powered systems will probably be used for high-speed, heavy vehicles.

Support Systems. Contact between the vehicle and its guideway can be by pneumatic wheels, steel-flanged wheels (railroad system), air cushion, or magnetic field. Figure 6-5 illustrates the various types schematically.

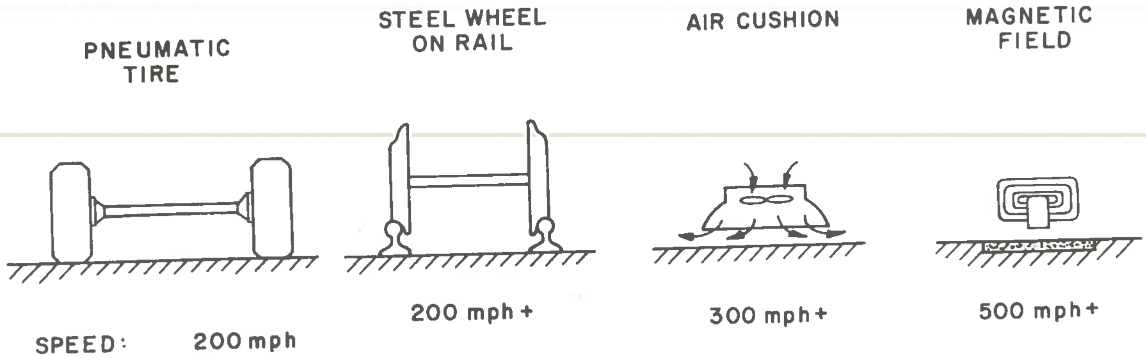

Figure 6-5. Types of Support Systems

Pneumatic Tires. Pneumatic tire support is widely used and is being considered for transportation at speeds of 125 mph. Even though tire wear is more serious at higher speeds most tire companies see no serious obstacle to developing tires with speed capabilities of at least 200 mph. Factors contributing to this wear are the amount and rate of flexure a tire experiences. Both of these cause heat buildup within the tire which weakens it. At higher speeds, a larger diameter tire may be chosen, since it will rotate slower and thus have a lower flexure rate than one of smaller diameter. Since the amount of flexure is a function of the weight, reducing the amount of flexure implies constructing lighter vehicles or using more tires to support it. New construction techniques and materials can be expected to increase resistance to heat buildup and consequent tire weakening. Tire lifetime at very high speeds may be a limiting problem.

Tread noise could be a problem at high speeds, but indications are that proper tread design and materials can alleviate this situation significantly. To a degree, pneumatic tires can absorb irregularities in the guideway by virture of their flexibility, thus acting as part of the suspension system. On one hand this may reduce the necessary accuracy of guideway alignment and its associated cost, but on the other hand this will contribute to tire wear. Pneumatic tires have a high coefficient of rolling friction compared to steel wheels. This means that more traction is available for accelerating and braking. However, it also means that more propulsive energy is required to overcome this friction while cruising.

Steel Wheels. Steel flanged wheels can operate at several hundred miles per hour; they require considerably less propulsive effort to overcome rolling friction while cruising than pneumatic tires. Their lower rolling friction, however, means there is less traction available for accelerating and braking. And since rolling friction decreases with increasing speed, this poses a severe problem at higher speeds. Extrapolation of data indicates that somewhere between 200 and 300 mph the decreasing propulsive force delivered by wheel traction and the increasing air resistance will balance each other. Consequently, the achievement of higher speeds will require a nontractive type of propulsion. It may be possible to increase traction at high speeds by means of a suspension system that maintains a very even contact between wheels and rails or by cleaning impurities from the rail surfaces with a plasma torch (Refs 6-34 and 6-35).

Steel flanged wheels also produce considerable noise due to wheel resonance and wheel-rail abrasion (Ref 6-36). The wheel tends to act as a drumhead and becomes a very effective loudspeaker for transmitting noise. Solutions to this problem include interrupting vibration paths through the wheel, absorbing vibrations before they are amplified by the wheel, and reducing the forces causing the vibrations. Separate wheel-and-rim arrangements, with an elastomeric material separating the two, may help reduce wheel noise. Composite wheels, with elastomeric materials sandwiched in, interrupt the vibration paths and diminish the drumhead effect of the wheel.

Wheel noise can be reduced if some of its sources are eliminated. When wheels and track are worn and bumpy, they pound and grind at each other, causing a good deal of noise in addition to serious wear. Bolted track is another noise producer. Well-maintained wheels and welded track can reduce the noise level significantly.

Wheel-rail abrasion noise is the most severe on curves when the wheel flanges are in rubbing contact with the rails. This wears the wheels and rails and also causes the familiar screeching and howling sounds. A possible solution to this problem is flangeless turning, a scheme the British are developing (Ref 6-31). In this, the conicity of the wheels is used to provide the force required to turn the vehicle through a curve when it is moving at speed. This should cause much less noise and wear than if the flanges provided the turning force as on conventional wheels. This scheme requires a rather sophisticated design of the suspension system and wheel profile. The method works only at higher speeds. At low speeds, the conicity does not provide sufficient force for the turning, and the flanges do the job instead, as on conventional wheels. Another approach to the problem is that used in the Turbotrain. Its articulated vehicle and wheel suspension arrangement actually steers the wheel through a curve, causing it to constantly remain tangent to the track (Ref 6-37). In this way very little flange-rail contact occurs. Two wheels on an axle are forced to rotate at the same speed causing wheel slippage on curves, with accompanying noise and wear. Putting differential gears on the axles or eliminating the axles altogether would result in reduced wear and noise.

The wheel noise problem is only partially understood. The details of wheel vibration and excitation and the amplification of noise needs to be studied further in order to prevent or muffle the sound as much as possible. Present approaches are largely intuitive and empirical but their success suggests that satisfying results could be obtained if more were known about the subject.

A further problem of steel wheels involves the profile of the surface (traditionally a smooth cone) that makes contact with the rail; this is subject to wear. This wear significantly changes the profile and, with this change, the riding qualities of the vehicle deteriorate because the suspension system is designed for the unworn profile. The standard remedy for this problem is to machine the wheels back to the original profile at frequent intervals. Ultimately, this limits the life of the wheel, since it is constantly being machined to smaller and smaller diameters. The British are trying a new approach to the problem based on the fact that, once a wheel achieves the "worn" profile, its profile then changes very little over a long period of time (Ref 6-31). They are also designing a suspension system for rail vehicles that is optimized for the characteristics of the worn profile, and the wheels are initially machined to this profile. This is expected to improve the overall riding qualities of the vehicles and reduce the maintenance necessary for the wheels.

Air Cushions. The use of an air cushion to suspend a vehicle above a guideway essentially eliminates all friction between the vehicle and the guideway surface, offering much more efficiency in propulsion. Another benefit from this type of suspension is a relatively high ride quality (or passenger comfort) without unusual or severe requirements on the smoothness of the guideway, compared to present day wheel-on-rail systems.

Previous applications of the air cushion suspension technology have ranged from air-bearing laboratory equipment to the large air-cushioned bovercraft used in marine transportation. In the ground transportation application, a track or guideway is used for the needed lateral constraint and route guidance; consequently, the term "tracked air cushion vehicle" is used here.

Nowhere has the air cushion had a more natural application than in the advanced marine technology of high-speed boats (surface-effect ships). Non contact with the water results in great propulsive efficiency; furthermore, the air cushion provides a smooth-riding boat with a capability for flexibility in route selection. Such a boat can "fly over" rough sea conditions.*

For land transportation, air cushions may allow lower guideway costs than wheeled vehicles for several reasons: first, the air cushion spreads the load, and the guideway need not be designed to take the concentrated stress of wheels; second, the inherent ride-smoothing ability of the cushion reduces the requirements on the guideway surface evenness. These and other benefits or air cushions, such as lowered maintenance requirements on vehicles and guideways, would accrue to both high and low speed transport.

Disadvantages of air cushion support include the power required to maintain the air cushion and the noise caused by it. For the present, technical development is primarily concentrated on TACVs for high-speed transport of passengers.

At this time, the air cushion is the most technically attractive means for levitating tracked vehicles that are to operate in a particular and important speed range. This range encompasses speeds above those where traction wheels become inefficient and below those where aerodynamic resistance demands a prohibitive amount of power. Nominally, this speed range lies between 250 and 500 mph. At the high end, the power needed to overcome aerodynamic drag increases roughly as the cube of air speed. This means that a 500-mph air cushion vehicle will use 8 times the power of a 250-mph vehicle. Also, at high speeds there exists the possibility of a flow interaction between the air cushion and the onrushing atmosphere that could affect the operation of the cushion and thus limit top speeds. Operating in an evaluated tunnel with the pressure reduced to 0.1 atmosphere reduces the drag by a factor of 10. Very high speeds, 500 mph and up, may then be maintained with practical propulsion power levels. However, the air cushion is then no longer applicable and levitation would have to be provided by magnetic fields. Because the technology of magnetic levitation is not adequately developed, the

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*As an example, for the past two years, 170-ton hovercraft (air-cushion boats) have provided regularly scheduled transport across the English Channel at speeds of 70 mph over calm seas and at lower speeds over waves up to 12 feet (Ref 6-39).

air cushion, although relatively noisy and limited to operation at atmospheric pressure, is now the more feasible means of supporting and guiding high-speed ground vehicles.

In a simple example of air cushion levitation, a vehicle is mounted on an inverted cup chamber that is open to the ground. Air under pressure is supplied to the cup and the vehicle rises. But as the lip of the cup separates from the ground, air leaks out and the lowered chamber pressure allows the vehicle to descend. With an adequate air flow, there is an equilibrium lip-ground separation and the vehicle is levitated. At this equilibrium, the vehicle weight is just balanced by a force that is determined by the area of the cup (air cushion) and the cushion air pressure.

The essential characteristic of a stable suspension is that the lift force increases as the vehicle descends from the equilibrium height, and it decreases as the vehicle rises from the equilibrium height. Figure 6-6 shows three concepts for stable air cushion support.

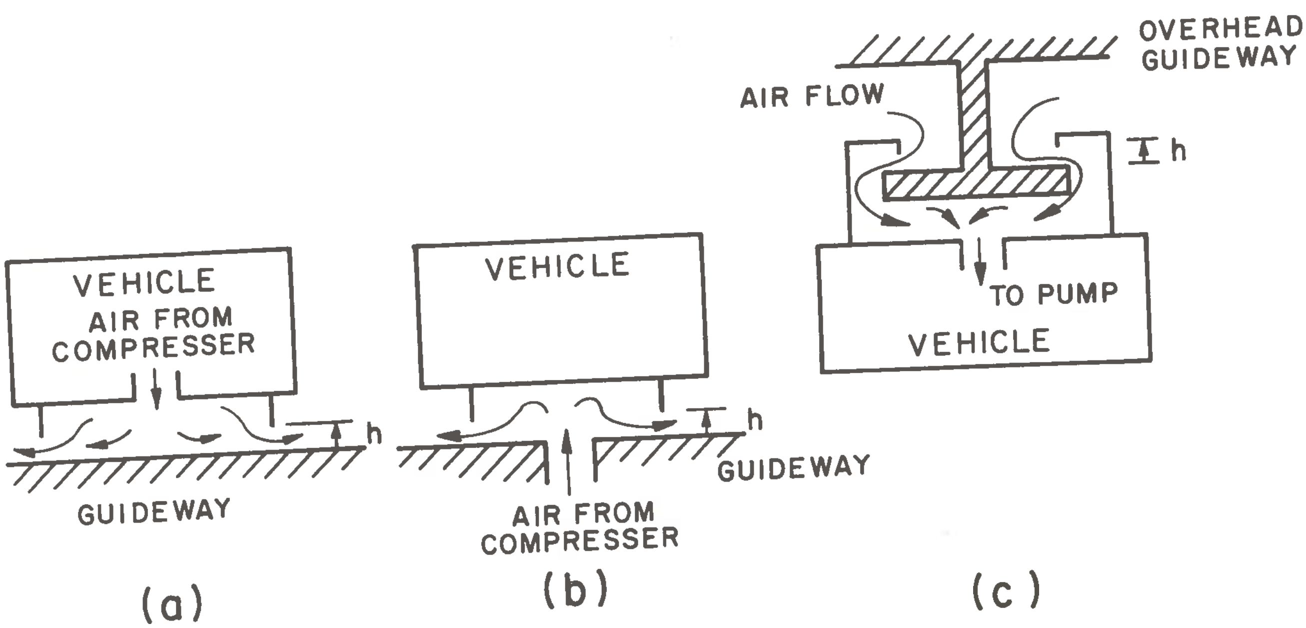

Figure 6-6. Stable Air Cushion Suspensions

In these configurations, the lift force increases as the leakage gap, h, closes and decreases as h opens. In Figure 6-6(a) and 6-6(b), the support force is provided by a higher-than-ambient pressure in a simple plenum. For Figure 6-6(a), the air pressure is supplied by an onboard compressor; for Figure 6-6(b), the compressed air supply is in the guideway. In concept, the compressed air in the guideway could be valved automatically to the plenum as the vehicle passed over evenly spaced outlets. In Figure 6-6(c), the support force is provided by maintaining a lower-than-ambient pressure (i.e., a partial vacuum) in the cushion. Historically, there have been many proposed air-cushion configurations (Ref 6-39). Generally, though, the scheme in Figure 6-6(a) has been applied to concepts for high-speed, relatively large TACVs, the other two configurations being more appropriate to low-speed, relatively small vehicles (Refs 6-40 and 6-41).

In another form of air cushion, lift is provided by an air foil or the ram-wing effect (Ref 6-39). In this case, lift is aerodynamic and is dependent upon the vehicle forward speed and, in a complex way, upon the ground clearance. Figure 6-7 illustrates the ram-wing concept. Without wheels or other auxiliary support, the ram wing is not applicable to a stop-and-go vehicle.

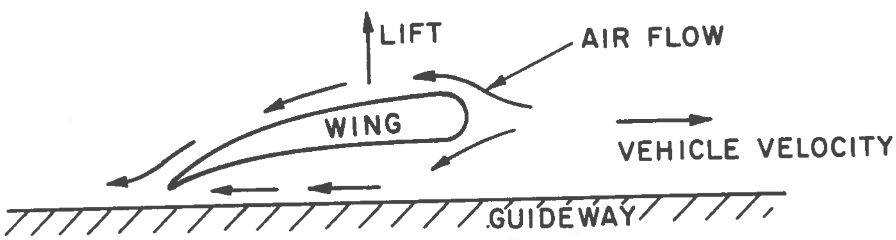

Figure 6-7. Ram Wing Concept

One of the major concerns in air cushion development is the efficient use of the air in the cushion. Although a large cushion-ground separation is desirable, a large gap requires a high volume of air from the compressor. There have been many suggested schemes for limiting leakage but at the same time providing adequate ground clearance. Two of the most developed schemes are:

1. Flexible skirts around the periphery of the cushion permit a small leakage gap and allows the vehicle to surmount obstacles without damage, even with a small air gap.

2. Peripheral jets feed air to the cushion, creating a "jet sheet" that tends to contain the pressurized air amd limit the leakage.

The current literature (e.g., Refs 6-39, 6-42, 6-43, 6-44, 6-45, and 6-46) contains many comparative studies of flexible-skirt and peripheral-jet cushions as well as other hybrid variatons.

In the design of a suspension system, the next major concern beyond levitation is ride quality. Ride quality is subjective to a great extent, but there are empirically-derived standards. To meet these standards, a suspension system is designed in conjunction with a specific guideway. As a fluid suspension, the air cushion permits many practical design options for motion damping and the incorporation of secondary suspension schemes. Among the fundamental objectives of the current TACV programs are the analysis and test of a wide range of suspension design variations (Refs 6-47 and 6-48).

Current TACV programs also are concerned with efficient means for providing compressed air for the cushions. Fan-jet engines are efficient for this purpose but present problems of air and noise pollution. The problem is also made difficult by the fact that rather significant amounts of power are needed to provide enough compressed air for practical levitation heights. For a 40,000 lb TACV, the area available for air cushions might be in the order of 400 ft^2 and as a result, a cushion pressure of 100 lbs/ft^2 is needed for levitation. For a hover height of 1 in., the area of the leakage-gap would be 16.6 ft^2, requiring about 500 hp or, equivalently, 370 kw.

The driving motivation behind the developments of new guideway technology is cost. Use of a TACV is attractive in this respect since it allows construction of lighter weight and less accurately aligned guideways than do wheeled vehicles, and hence its guideway should be less expensive.

Since the guideway has the dual purpose of supporting and guiding the vehicle, it must provide bearing surfaces at right angles. Three obvious geometries are shown in Figure 6-8. The

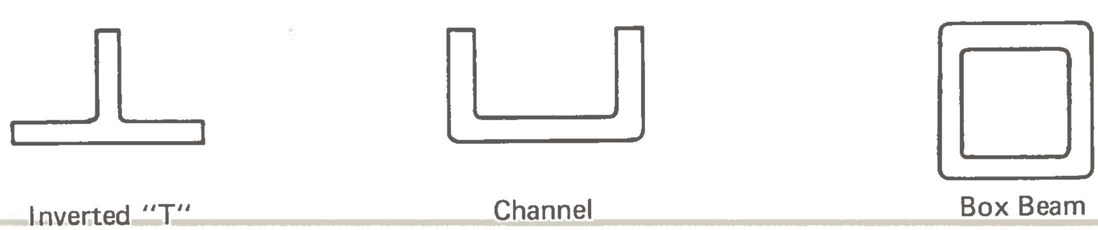

Figure 6-8. Air Cushion Guideway Concepts

inverted-T, the box-beam and the U-channel are being exploited in TACV programs in France, England and the United States, respectively. The relative merits of these geometries have been examined extensively in recent literature (Refs 6-42 and 6-45). The U-channel has the significant attribute of protecting the vehicle from cross winds, although at the cost of some increase in drag. It is also the most expensive to construct. Other guideway geometries are possible; for example, a V-shape would permit the combination of the support and guidance functions in the same air cushions. However, the trend in TACV technology has been to use separate cushions for support and guidance to avoid the problems of complex dynamical interactions.

In addition to structural problems, the major engineering concerns associated with TACV guideways include:

1. Methods for switching vehicles off the guideway (for a high-speed, high-traffic-density line, this is a very significant problem).

2. Methods for mounting and alignment-maintenance of the reaction rail (if a linear electric motor is used for propulsion).

3. Methods for providing wayside power at high voltage and current levels.

Magnetic Field Suspension. The support of ground-based by magnetic fields appears feasible for speeds in the range of 300 to 600 mph (Refs 6-49, 6-50, 6-51, 6-52, 6-53 and 6-54). It would avoid the dynamics and stability problems of wheels at these speeds and also the possible flow interaction problems that an air cushion suspension may encounter. Magnetic suspension will also be considerably quieter than an air cushion, and could be used in an evacuated tube system where the air cushion would be impractical. Also, magnetically suspended systems appear to be less sensitive to the guideway irregularities than wheels on range or air cushion systems. And since propulsion at these speeds will most likely be by linear electric motors, the use of magnetic suspension may make possible utilization of the same structure and equipment on the vehicle for both propulsion and suspension. This could result in a simplification of construction and consequent reduction in costs.

Magnetic suspension is the least understood and developed of the vehicle support schemes discussed. Studies of the subject are going on in this country, sponsored by the FRA, and in some foreign countries (e.g., Germany and Japan). Figure 6-9 shows a prototype German vehicle. Questions remain to be answered concerning the feasibility of the scheme in terms of power

Figure 6-9. Magnetically Supported Vehicle Developed by Messerschmitt-Boelkow-Blohm, West Germany. Photograph courtesy of "Aviation Week and Space Technololgy" Magazine.

requirements, stability of support, the shielding of passengers from the strong magnetic fields generated, necessary guideway regularity and guideway construction.

Some preliminary studies indicate that the magnetic lift force increases with velocity and approaches an asymptotic value, and that a magnetic drag force may be present that initially increases with velocity, reaches a maximum value and then approaches zero at still higher speeds. Thus, the technique of magnetic suspension would appear to be most useful at very high speeds. Initial estimates suggest that the power required for support is, at most, about the same as that required for an air cushion support system, and or perhaps as much as an order of magnitude less, depending on the configuration.

Magnetic support will probably require use of cryogenic equipment, since the necessary magnetic fields can best be achieved practically with superconducting magnets. To simplify operations, the cryogenic apparatus should only be on the vehicle, not on both vehicle and guideway as some schemes would require.

6.4 TUNNELING TECHNOLOGY

Introduction. The two basic considerations in tunneling technologies are: (1) the excavation technique; and (2) the method of sustaining the opening. About 75 percent of the tunnel costs result from these. Research and development efforts directed at the reduction of tunnel construction costs should, therefore, be concentrated on the problems associated with soil and rock disengagement and with tunnel supports and liners.

An increasing demand for underground excavation during the 1970s has been noted in answers to a recent questionnaire sent to 600 individuals in 17 countries by the Organization for Economic Cooperation and Development (OECD). The summary report (Ref 6-55) states that $54 billion will be spent on underground excavation by OECD member countries in the next decade, with $34 billion in the U. S. alone. It is estimated that 7,500 miles of hard rock tunnels will be excavated and 520 million cubic yards of soil and rock will be removed. It has also been estimated that upwards of 2,000 miles of transportation tunnels will be constructed in the U. S. by 1990, exceeding the total built to date. Under the best conditions tunneling costs run about $5 million per lane mile, reaching $30 million in less favorable conditions. These high costs impede the widespread use of tunnels. However, other considerations such as urban sprawl, congestion, aesthetics and new technologies are stimulating greater interest in the use of tunneling.

Some recent projects serve as good examples of this interest:

1. The skyscrapers common in every major city require the construction of many service facilities underground (subways, parking, highway extensions and utilities).

2. Some 20 cities are studying the feasibility of subways as part of new transit systems. San Francisco's Bay Area Rapid Transit (BART) System has 25 miles of its 75-mile network of double tracks built in twin tunnels.

3. More urban center designs include highways passing under cities rather than over or through cities as they have in previous years.

4. Future systems studies include consideration of tube vehicle systems such as the gravity-vacuum system for increased operating speeds and avoidance of environmental interference.

These trends provide positive inducements to reduce construction time and cost in tunneling.

Existing and Future Technology. Conventional tunneling methods, based on drilling and blasting techniques, have been improved over the years, but not enough to catch up with new tunneling demands. Improvements include the introduction of tunneling machines in softer rock, use of tungsten-carbide cutters to extend machine lifetime, and special car handling processes to cut the cost of muck disposal. A major portion of the cost of tunneling by boring is the replacement of worn cutters. The outside or gage cutters wear more rapidly than the other cutters and ways of reducing their wear are needed.

Geologic conditions, such as rock hardness, composition, heterogeneity and structure may have a significant effect on the efficiency of a given method of rock excavation. Other geologic conditions, such as faults, joints, foliation, weathered zones, hydrothermally altered zones and in-situ stresses in the rock mass, have extremely important effects on the maintenance of safe working conditions. Control of groundwater inflow and rock-support requirements often account for a large percentage of the total cost of making an underground excavation. They may also impose severe constraints on the types of excavation methods that are technically feasible in a given rock and may greatly affect the efficiency of those methods of excavation that are technically feasible.

In tunneling research programs, emphasis has been placed on those construction processes which promise the greatest cost savings. The following processes are included:

1. Rock fracture

2. Supports and liners

3. Materials handling

4. Soft ground construction systems.

A fifth concern, route selection, does not relate to construction processes per se but promises to reduce construction and operating costs, also.

Rock-Fracture Methods. The emphasis in rock-fracture research is on the disintegration of hard rock since this represents about 25 to 50 percent of the total cost of hard rock excavation. New rock-fracture methods being considered include chemical treatment, lasers, electron beams, high-velocity water jets, high-velocity pellets and flame jets (Refs 6-48 and 6-56). Other less promising methods being examined are microwave heating, ultrasonics and low-velocity water jets. Their lack of appeal is largely due to the very high energy required per unit volume of rock removed.

Field experiments using chemical agents (aluminum chloride) have been carried out by MIT in boring tunnels for the new Chicago sewer system. Initial results show a 12 percent increase in the rate of advance in limestone at low additional costs.

Lasers have high potential. United Aircraft is investigating the possibility of mounting a laser on a boring machine to weaken rock ahead of the cutter blades. It seems feasible to use the laser beam as the gage cutter, thus replacing the mechanical cutter blades most subject to wear.

Basically, three modes of heat use for rock destruction have been investigated. Heat can be used to weaken, spall, and melt or vaporize rock. Melting or vaporizing methods require tremendous quantities of energy and have not yet received serious consideration. Thermal spalling appears to offer promise for very hard rock where the rock demonstrates good spallibility. However, the development of systems to exploit the spalling method involves the application of new technology in machine design and methods for life support, and for crew protection and operation in hot and toxic environments. Using heat to weaken rock in conjunction with mechanical tunneling machines is the most promising technique. Research has shown that, with high rates of heat addition, hard rock can lose over 90 percent its original strength. A major problem expected with the use of heat weakening systems for hard-rock tunneling is the control of the ambient temperature in the tunnel. Excess heat in a tunnel is difficult to handle and expensive to eliminate.

Work on rock fracture, utilizing hypervelocity fluid jets, has met with encouraging results. The Russians have employed a water cannon successfully and in the U.S., Terraspace, Inc., is designing a water cannon capable of firing high-velocity, high-pressure pulses of water.

Supports and Liners. Tunnel supports and liners account for 30 to 50 percent of total tunnel costs. The University of Illinois has been conducting research into new cost saving materials such as rapidly setting cements and in unique structural shapes to better resist severe earth loadings (Ref 6-48).

Materials Handling. A study to identify future material handling requirements showed that concepts well along in the development cycle will be adequate (Ref 6-57). The group of systems chosen include simple mechanical approaches and basic pneumatic and hydraulic conveyances.

6.5 CONTROL SYSTEMS TECHNOLOGY

Current Status. Automatic ground transportation control systems currently operate traffic signal systems and automated rapid transit systems. Typical installations of computerized traffic signal systems are found in Toronto and New York (Refs 6-58 and 6-59), and automated rapid transit in Philadelphia and San Francisco (Refs 6-60 and 6-61).

The technologies associated with computer-controlled traffic signals have reached a high level of sophistication. On the other hand, computer control of public transit or automatic vehicle systems is in its very early stages of development. Current automatic rapid transit systems employ the fixed-block method of control. This is adequate for systems with large headways. However, many of the new systems, in order to provide adequate capacities, propose shorter headways than are possible with fixed-block control.

The complexity of automatic vehicle control varies from the simple rapid transit shuttle to the "electronic highway" interconnected area-wide network. In between there are other rapid transit configurations, personalized rapid transit (PRT) systems, and dual mode systems (DMS). It is estimated that the performance requirements of longitudinal movement control necessary for PRT and DMS may be two orders of magnitude more severe than for existing train control (Ref 6-62).

Automatic Train-Control Systems. Through the years, train control systems, although limited in scope, have been reasonably successful. This control has historically been accomplished through:

1. The use of a schedule and timetable

2. A dispatcher who can override the schedule and timetable

3. Equipment which senses the presence of a train and activates a signalling device.

The latter approach is associated with the fixed-block train separation system, which is used on virtually all rail systems currently in operation.

The fixed-block approach consists of track circuits of a predetermined length. When a block is occupied, a signal is flashed at the entrance to the preceding block. The block length must be sufficient to allow the train to stop without encroaching on the occupied block. Block length, therefore, determines the separation between trains.

Fixed-block signal systems have been designed with safety paramount at the expense of operating efficiency. As train speeds increase, block lengths must be increased. Thus, the capacity of a given line is related to the number of blocks into which the line is divided. Since the exact position of a train within a block is not identified under this system, it is assumed to be just inside the entrance to the block. In most instances, this additional factor of safety makes the separation between trains longer than it needs to be.

Recent developments in train control have resulted in the automation of fixed-block control systems. Cab signal equipment has been added to pick up the signals from the track circuits. A direct interface between the cab's signal equipment and the automated equipment has eliminated the manual operator. Station control has also been automated to regulate stopping and starting, door opening and closing, and dwell times. However, automating these control functions does not significantly improve the performance capability of a given line. Fixed-block control is still the limiting factor in train throughput. A major improvement in train operation could be realized if a moving-block train separation system were to be developed. Under the moving-block system, a block is the separation between vehicles or trains. This block is not physically laid out on the track but moves with the vehicles or trains and can be varied at any time. No moving-block system is yet operational.

Some Considerations of PRT Control Systems. The precise control of the velocity and separation of closely spaced vehicles on a guideway is likely to be one of the most difficult control problems in urban transportation. Some form of a moving block-control system appears to promise good operational efficiency.

Precise velocity and headway control become more critical as the separation between vehicles is reduced to a fraction of the safe stopping distance (k<1). For k<1, the control system should be designed so that, for the maximum controlled deceleration, all following vehicles are able to stop without collisions. For the "brick wall" stop (derailments, etc.), it will not be possible to prevent succeeding collisions, but the control system should limit the number of vehicles involved to an absolute minimum. This emergency stopping procedure might be an overriding control initiated when the emergency occurs. As smaller k factors are permitted (to increase capacity), the sensitivity of the control system to small position errors must be increased; however, the resultant higher accelerations and jerks will be felt by the passengers. The quality of the ride can be improved by limiting the acceleration and jerk rates, but only by compromising the safety of the passengers.

There has been considerable discussion concerning the feasibility of operating small vehicles in uncoupled trains in order to maximize the system capacity (Ref 6-63). The theory is that rear-end collisions would not be severe because of the low velocity differential between succeeding vehicles. However, this places additional complexity on the control system, and a period of low relative safety is faced as the vehicles converge. The operational strategies for such a scheme also become more complex.

Most PRT schemes allow the utilization of a mix of vehicle types (i.e. 4 to 6 passenger vehicles, 20 to 40 passenger vehicles, and cargo-carrying vehicles) operating on the same guideway. Precise control of these different size and different weight vehicles is not well understood.

Merging and demerging control is interrelated with headway and main-line speed control. A PRT vehicle entering the main line intercepts a gap in the vehicle flow. The merge-control system should have as high a reliability and accuracy as possible for reasons of safety and capacity. It is desirable to merge vehicles at main line speed. Nevertheless, for instances where a capacity problem exists at a junction, a reduction in the speed of the converging flows (reducing the separation between vehicles) will increase the throughput of the system. For synchronous slot* strategies, delays would occur principally in the stations while waiting for an empty slot on the main line. For other operating

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*A sequence of imaginary "slots" of equal length travel down the main line at uniform velocity. Each slot is reserved for one vehicle and is long enough for all speed change maneuvers while still maintaining the minimum separation required for safety.

strategies, delays may be encountered at any switch point. For these strategies, merging control can be accomplished in one of two ways:

1. Controlling only one of the converging lanes and allowing insertion of vehicles into proper gaps in the uncontrolled lane

2. Controlling both lanes.

When volumes on one branch are a small percentage of the total junction volume or where total approach volumes are a small fraction of junction capacity, the first method of control is acceptable. However, when the sum of the vehicular flows on the converging lines approach or exceed the junction capacity, the second method of control is superior (Ref 3-62). Even then, long queues or delays may develop. Demerging is a less complex situation. Control of this maneuver is limited to preventing vehicles from overtaking and bumping preceding vehicles (for a partial on-line acceleration strategy).

The function of automatic routing is the guiding of the vehicle along the quickest path from origin to destination. This procedure should take into account delays due to congestion, vehicle failures and partial system failure in calculating the minimum time path. The highest level of complexity is dynamic routing, in which the course of each vehicle may be varied on route as changes occur in the performance of the systems (Refs 6-64 and 6-65).

Safety control involves three functions: (1) vehicle performance monitoring; (2) guideway integrity and safety monitoring; and (3) vehicle control procedures. Vehicle performance monitoring permits the sensing of abnormalities in vehicle functions. Potential failures may be identified and corrected through such surveillance. This can be expanded to include a comprehensive checkout of each vehicle for operational readiness before dispatching it onto the system. Guideway integrity and safety is as important as vehicle safety. The desirability of detecting structural defects, discontinuities, buckling, shifting, and excessive vibration in the guideway before serious damage occurs to vehicles and passengers is obvious. The detection of potential hazards such as snow, water, ice, or foreign objects on the guideway, is also an important safety precaution. The safety aspect of vehicle control is the maintenance of a proper longitudinal spacing between vehicles. Emergency stopping procedures must be reliable for any automated transportation system to be acceptable. This is unquestionably the most critical element in system design.

Dual Mode System (DMS) Control. DMS, operating on a fixed guideway, are virtually identical to PRT systems and have the same control system difficulties. One additional level of complexity is introduced at the street-guideway interface. Each vehicle must be thoroughly screened for operational readiness every time it enters the guideway. This means that a complete diagnostic checkout system must be installed at each entry point. Since there are automobile diagnostic centers presently in existence, this does not appear to be as much a problem of technology as one of cost. A rapid and inexpensive diagnostic method must be developed for DMS to be practical.

The electronic highway DMS control is more complex than the fixed guideway system. The electronic highway must provide a means of lateral control since there is no physical guideway structure to provide restraint. This lateral control will most likely be provided by centering over inductive wires buried in the roadway. This does not appear to be a serious technological problem.

The control functions utilized in overall network operation are often combinations of central, local and on-board methods. There is no clear cut separation of the regulation functions of each of these types. For example, headway, speed and acceleration can be regulated by either an on-board or a local controller. Merging control can be exercised through local or central devices. Emergency braking procedures could be initiated by any one of the three but is more likely to be started by the local or on-board controller. The tasks of overall system monitoring of vehicle dispatching and vehicle routing are usually performed by central control. Nevertheless, it is possible that local control decisions may be allowed to override the central routing or dispatching decision for safety reasons. Furthermore, for redundancy and reliability, it is desirable that central and local control serve as back-up systems for each other. Therefore, it is not especially desirable to completely separate the various elements of total network control.

Conclusions. Present control systems are inadequate for future automatic, small-vehicled systems. Precise control of headway and speed will be the most critical problem in future systems, especially when headways less than the safe stopping distances are utilized. Some form of moving block or synchronous slot systems appear to be prime candidates for this type of control. The reliability of the control system is most important. Redundant systems have been proposed also for those systems which would operate with $k > 1$. The safety of these systems will have to be thoroughly proven before there will be public acceptance.

A program is needed with the goal of designing, building and testing a control system capable of failsafe operation, with vehicle separation reduced to a small fraction of the safe stopping distance ($k < 1$). Until such a control system is developed, PRT and DMS will reach only a fraction of their potential and will not offer significant improvements in urban travel.

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APPENDIX

PERSONALIZED RAPID TRANSIT ANALYSIS

In addition to this report, "Transportation Systems Technology: A Twenty-Year Outlook" a complementary technical report entitled "Personalized Rapid Transit Systems: A First Analysis", Number DOT-TSC-OST-71-11, has been prepared and is available.

The latter report expands the analysis of the Personalized Rapid Transit System concept and provides more detailed data and trade-off considerations. The following is an outline of its contents.

1. INTRODUCTION
   - 1.1 Logic of the PRT Concept
   - 1.2 The Placement Problem
   - 1.3 Claustrophobia in Underground Systems
   - 1.4 The Interchange Problem
   - 1.5 Line Capacity Problems
   - 1.6 Station Capacity Problems
   - 1.7 System Design Problems
   - 1.8 Component Technology Problems
   - 1.9 Modified PRT Concepts

2. PRT CAPACITIES
   - 2.1 Speed Change & Merging Strategies
   - 2.2 Strategy and Capacity
   - 2.3 Effects of Acceleration Limits and Station Spacing
   - 2.4 Safety Considerations for Small Headway Operation
   - 2.5 Concluding Comments on Line Capacities
   - 2.6 Station Capacities

3. CAPACITY REQUIREMENTS OF URBAN GRIDS
   - 3.1 Uniform, Capacity-Limited Grids: Capacity Equations
   - 3.2 Urban Demand Characteristics
   - 3.3 PRT Grids in Uniform Urban Areas
   - 3.4 PRT Grids in Areas with Centers
   - 3.5 Examples of PRT Capacity Calculations
   - 3.6 Conclusions

4. SURVEY OF MANUFACTURERS' CONCEPTS
   - 4.1 Underfoot/Pneumatic Tire Systems
   - 4.2 Overhead/Pneumatic Tire Systems
   - 4.3 Underfoot/Air Cushion Systems
   - 4.4 Overhead/Air Cushion Systems
   - 4.5 Underfoot/Steel Wheel on Rail System

5. COSTS

6. APPENDIX A

7. REFERENCES