11

Design for Maximum Cost Effectiveness

11.1 Introduction

In the previous chapters, specific topical areas of transit systems theory have been developed with a view to determining requirements, characteristics, and parameter choices that will increase cost effectiveness. The fundamental viewpoint taken of transit systems theory is not to take specific transit systems and transit concepts as they are known at the time of writing and explain how and why they work (although this is and must be an integral part of the process), but to consider the "transit system" as a multidimensional field of requirements, characteristics, and parameter choices all of which are subject to change, and to vary these factors until the cost effectiveness of the entire system is maximized. Such a process is very complex. It requires analysis by and interaction among many people of many disciplines over many years in a context in which many ideas are being tried in the laboratory, on test tracks, and in operation. Then it requires synthesis—the ultimate purpose of transit systems theory.

The previous chapters have laid groundwork felt by the author to be needed in synthesis of the design of a transit system of maximum cost effectiveness. Some areas which perhaps should have been covered are not covered in depth and, in some cases, not at all. Two examples are:

1. Computer simulations of operation of vehicles near and in stations, at interchanges, and in entire networks. Much of this kind of work has been done [1] and its existence has enabled the author to proceed with confidence in the development and explanation of the underlying algebraic theory in a form that can more easily be taught, and to offer the results of this chapter as realistic and practical possibilities.

2. Propulsion, braking and suspension. While many combinations of methods have been proposed and tested, and the choice of the best combination is important, the details are not felt to be needed in this book. The *requirements* for a propulsion and braking system are, however, of fundamental importance and are discussed in section 11.4. On the other hand, no similar reason has been found to consider suspension means and requirements on the same basis other than to note that the means proposed are wheels, air, and magnetic fields, and that some of them may be more suited to the optimum guideway configuration than others.

The synthesis of an optimum transit system is not a simple step-by-step process, it is a web of interconnected influences. But the exposition of it must by necessity proceed step-by-step with a certain clumsiness associated with referencing back and forth in the argument. There is a certain danger in conveying the impression that the process is easier than it is, and in that all of the drama is washed away, hopefully to be told in other kinds of books. Moreover, it must be recognized that a single optimum system might not result, but different optima for different purposes. With these caveats, we proceed first by reviewing in this introduction the reasons for concentrating on automated guideway transit systems, and then, section by section, by developing a series of arguments leading to a system optimized to the extent possible in a book of this length.

Manually Driven versus Automated Transit

A great deal of information is available on the characteristics of transit systems in which the vehicles are driven by professional drivers. Rapidly rising deficits and poor service levels inherent to these systems indicate that continued attempts to expand transit service in this way will become increasingly unjustifiable. On the other hand, systems of manually driven vehicles using one of the riders as a driver (commuter vans) have proven economically viable, at least in the special circumstance in which both the origins and destinations of the trips taken by one vanload of people are closely clustered in comparison with the trip length. Attempts to expand this kind of service too far, however, run into the difficulty of increased circuity of the route and the increased unattractiveness this brings to the trip. Moreover, where commuter vans are used to carry people from suburban residential areas to inner city work places, they may because of their higher service level attract patrons away from the fixed route, fixed schedule bus system, thus further increasing its deficit. A conflict therefore develops which limits the extent to which commuter vans can be used.

The hope of overcoming some of these problems has turned interest to the potential of automated systems. In addition to offering the prospect of increased cost effectiveness, automated systems appear to permit increases in safety and reliability and to offer the prospect of twenty-four hour, on-demand service just as is obtained with elevators and escalators.

Exclusive versus Nonexclusive Guideways

Automated systems may, in theory, operate either on exclusive guideways or on nonexclusive guideways, that is, in mixed traffic. While there are some advocates of the latter approach, the problems of object detection and of recovery from a lateral steering failure in time to avoid a collision are sufficiently fundamental that such an approach has not been seriously considered except at very low speeds. Thus the logical choice for automated transit is to use exclusive guideways, either underground, elevated, or at-grade. At-grade guideways, while low in direct cost, suffer from the disadvantages that communities are divided by the lines, safety is a problem at crossings, and snow and ice are difficult to remove. Because of the low cost of at-grade systems, however, there are circumstances in which they are used. These exclusive guideway systems are usually referred to as automated guideway transit (AGT) systems. Their advantages are that they permit increased time reliability and safety, decreased trip time, and much decreased land use for transportation. Indeed, the latter factor may be the most fundamental reason for interest in AGT systems.

11.2 Guideways

The guideway is the most expensive component of an AGT system, therefore the optimization of its parameters is primary in cost minimization of the system. If the guideway is underground, minimization of the cross-sectional area of the vehicles and hence of the tunnels minimizes cost per unit length. If the guideway is elevated, the results of chapter 10 lead to the conclusion that the cost per unit length of the guideway will be minimized if the weight, size, and weight per unit length of the vehicles are minimized, and if the guideway is a deep, narrow monobeam. These conclusions run counter to much of contemporary practice, which is based on the use of duo-rail vehicles. Such systems, however, evolved from street vehicles in which the width between wheels is the only means of achieveing lateral stability. The use of deep, narrow monobeams clearly requires a completely different suspension system which must be designed from scratch. Several such designs are currently in test or in operation [2].

Much progress will be possible in the field of AGT systems once it is understood that the goal should be as described above. Practical use of the smallest vehicles for a given required capacity depends on development of design concepts in which minimum headway can be accomplished safely and reliably without excessive cost. These are the topics of chapters 7 through 9, and will be discussed below. Development of the best lateral suspension system using the vertical dimension of the guideway for lateral stability requires consideration of various mechanical design possibilities and the requirement of switching. Use of the smallest vehicles is possible only if the stations are off the main line. This conclusion is clear from the results of chapter 4, which show the capacities obtainable with on-line versus off-line stations. On-line station systems are inherently large-vehicle, high cost systems if adequate capacity is to be achieved. As a parallel, the freeway obtains its capacity from the fact that a flow of low capacity vehicles on the main line is uninterrupted by stops.

The practical use of off-line stations with small vehicles requires the development of a rapid and highly reliable switching mechanism. To decrease the *required* reliability of the switch and to increase the time available to throw it and verify that it has been thrown, the switch should be on board the vehicle rather than in the track. Many designs of such switches have been developed [3]. The problem of switching rapidly with a transit system using deep, narrow monobeams plagued designers for many years, and led most of them to abandon the idea of a rapid switch that does not require movement of a guideway element. In the past decade, however, this problem has been solved in several ways: (1) by use of a bogey inside the guideway from which the vehicle is hung [4], (2) by use of a U-shaped guideway with bottom-supported vehicles which obtain lateral stability from wheels riding on the inside vertical surface of the U-beam [5], and (3) by use of box beams but with a specially designed switch section in which the joining beams are cut so that the wheels which straddle the box beam can pass through but in which the bending stresses are carried by vertical plates outside the path of the wheels and joined to the inner beams by means of shear plates used as the tracks for the wheels [6]. The third configuration produces the most complex switch-section structure, but permits use of an optimum box-beam cross section away from the switches. The other configurations sacrifice somewhat the cost and weight of the beam away from the switch section but thereby achieve a structurally simpler switch section. At the time of writing, no truly comparative analysis of these configurations, considering all aspects of the interfaces with the vehicles, has been completed. Therefore it is not yet known which is the better choice.

11.3 Vehicle Fleet Costs

Figure 5-1 shows the reported initial cost per unit capacity of twenty-nine different guideway transit vehicles in development or in operation in various countries. By capacity is meant the design capacity of a vehicle in persons, that is, the number of seats plus the nominal number of spaces available for standees in uncrowded conditions. Some of the smallest vehicles included in figure 5-1 allow no adult standees at all. The conclusion of figure 5-1 is that the cost of a guideway transit vehicle per unit capacity is independent of capacity. This conclusion is rough because all of the costs in figure 5-1 have not been normalized to the same date and there has been no standardization of cost-reporting procedures. It does, however, make sense because the larger vehicles are manufactured by job-shop practices on an individual basis and require large machinery to move major parts; whereas, the smaller vehicles can be manufactured with higher production procedures and can be moved much more easily.

The cost of a vehicle fleet is the cost per unit capacity of a vehicle multiplied by the vehicle capacity multiplied by the required number of vehicles. The product of the latter two terms is the capacity in persons required of the entire fleet of vehicles. If the vehicle cost per unit capacity is constant, then *the fleet cost is proportional to the total capacity of the fleet and independent of the size of the vehicles*. But the total capacity required of a fleet of vehicles is simply the peak demand in people per unit of time multiplied by the average trip time and divided by the average load factor of a vehicle (see equation (4.3.26)). If the peak demand is considered given, the conclusion is that *the fleet cost is proportional to the average trip time divided by the average load factor*. Thus, the fleet cost is minimized by minimizing the average trip time (so vehicles can be used more often) and by maximizing the load factor (so each vehicle is used as intensively as possible).

From equations (4.3.2, 4.3.9 and 4.3.10), the average trip time can be written in the form

$$\text{Average trip time} = (\text{average trip length})/V_L$$

$$+ (\text{station dwell time} + V_L/a_m + a_m/J)(\text{number of stops}) \qquad (11.3.1)$$

in which V_L is the line speed, a_m is the service acceleration, and J is the comfort level of jerk. The factor a_m/J is, from chapter 2, about one second in all types of systems and is determined from comfort considerations. Because V_L appears in the denominator of one term and the numerator of another, there is a finite value of V_L that minimizes trip time; however, in most urban applications, this value is too high to be practical, and, in any case, the work of chapter 10 and section 3.6 shows that the guideway cost is strongly influenced by line speed. Thus there is a value of line speed that minimizes the total system cost, but it must be determined by considering both fleet cost and guideway cost. Once this value is determined, equation (11.3.1) shows that three operational factors determine the trip time: (1) the station dwell time, (2) the number of stops, and (3) the service acceleration. The station dwell time is minimized if the service is on demand with minimum delay of vehicles; the number of stops can be reduced to a minimum of one by using off-line stations and nonstop service; and the service acceleration can be maximized by using seated-passenger vehicles. These requirements are all compatible with and indeed made possible by the use of the smallest size of vehicle, and hence are compatible with the requirements of guideway-cost minimization. Moreover, as shown in chapter 3, the length of off-line ramps is minimized if the service acceleration is maximized, thus further reducing cost; and, from equation (4.5.22) and figure 5-6, on-demand, nonstop service is the only practical alternative in an off-line station, network system of anything but the smallest size.

Minimization of the fleet cost was shown also to require maximization of the average vehicle load factor. To maximize the load factor with on-demand, nonstop service in which people ride only with travelling companions, the vehicle must be as small as practical. The average number of people traveling in automobiles varies from about 1.2 during the rush period to about 2.1 in off-peak periods. Thus, the number of seats per vehicle should be more than two but probably not more than four. From the analysis of section 7.5, the author would judge that a three-seat vehicle with side-by-side seating is optimum. The fraction of a day's trips in which more than three people ride together is quite small (about three percent according to one survey), and in these exceptional cases, more than one vehicle per party can be used. The load factor also depends on the amount of deadheading in the system. As indicated in section 4.3, the amount of deadheading depends on the nonuniformity of demand in all systems. A more important factor, however, is the off-peak service and its relationship to total operating cost. If off-line station on-demand service is used, vehicles move only when there is demand for service. On the other hand, with on-line stations, the vehicles must move continuously on a schedule whether or not demand exists, for if they cease to run or decrease schedule frequency due to low demand, the service will appear more unreliable and patronage will drop further. Thus, lower load factors in a twenty-four hour period can be anticipated in large, scheduled vehicles than in small, demand activated ones, and hence the operating costs will be relatively higher in the larger vehicle system.

All of the system optimization requirements thus far discussed are seen to mesh without incompatibilities. Furthermore, the service level required of a system optimized by the considerations thus far discussed is the best that can be offered and will therefore maximize patronage. Before a conclusion can be reached, however, the operating and maintainance costs of the vehicle fleet per unit capacity per year must be examined. Based on data obtained from unpublished sources, it is evident that these support costs per unit capacity will fall slowly as the vehicle size increases. Whether or not the smallest vehicles gives the lowest cost per trip then depends on the relative load factor. Further research in this area is needed. The possibility of use of the smallest vehicles depends on the achievement of a sufficiently small headway safely and reliably. These requirements are discussed in the following sections.

11.4 Propulsion and Braking

The design requirements to permit safe operation at minimum headway are the subject of chapter 7. See section 7.8 for a detailed summary of these requirements. Among them is the requirement that direct, linear propulsion and braking be used instead of rotary propulsion and braking through wheels. It is shown in chapter 7 that, for seated-passenger vehicles, this change will reduce the minimum headway from about two to three seconds with rotary motors to about one quarter second with linear motors, that is, by a factor of at least eight. With 0.25-second headway and three seats per vehicle, the throughput is 43,200 seats per hour or, with a rush-hour load factor of 50 percent, 21,600 persons per hour. With automobile traffic on freeways, the maximum throughput per lane is about 2000 persons per hour. Therefore, 21,600 persons per hour is equivalent to over ten freeway lanes of traffic, a throughput far in excess of most requirements.

Three types of linear propulsion have been considered: (1) mechanical, (2) air, and (3) electric propulsion. Mechanical propulsion is used on moving sidewalks and ski lifts, applications for which speeds below about five meters per second are adequate. At speeds of interest for more general urban applications (say 10 to 25 m/s), friction losses and wear are too great for mechanical systems to be practical. Air propulsion, used on two developmental systems in the United States, is inherently noisy, and the means required to quiet the noise once generated make these systems uncompetitive for most applications. Electromagnetic propulsion, on the other hand, is quiet and applicable at any reasonable speed. Electromagnetic propulsion, besides satisfying requirements for safety at short headways, has the following advantages:

1. The guideway need not be heated to remove thin layers of ice or water because magnetic fields are unaffected by them.
2. If the vehicles use wheels, the tires can be smooth and the track smooth, thus minimizing noise as a cost to the community.
3. No moving parts, no wear, and minimum maintenance.
4. Grades up to 15 percent can be negotiated without difficulty; indeed if there were no power limitation no grade would pose a problem.

Automated guideway systems have been developed using a variety of types of linear electric motors—linear induction motors (the most common), linear synchronous motors, and linear pulse dc motors. The later two types promise higher efficiency but are not as well developed as LIMs. More research and development is needed to determine which types of linear electric motors are the most cost effective, and to bring the designs into full commercial readiness. To minimize the weight of linear electric motors used on board vehicles, the heat transfer design of these motors must be improved as much as is practical. In-the-track motors can be lighter because they are pulsed and have some time to dissipate heat between passages of vehicles, but many more of them are needed. Hence, unless the throughput is very high, the cost trade-off will favor in-the-vehicle motors even though they increase the weight of the vehicles and create problems of power collection [7].

Disadvantage – close [illegible]

11.5 Standing versus Seated Passengers

Provisions for standees are made aboard trains, city buses, and streetcars; but not in taxis, limousines, and jitneys. Room for standees permits rush hour flows to be handled by "crush loading" each vehicle with standees and thereby increasing the capacity of a given fleet of vehicles. On the other hand, such service is not considered comfortable by most people and is avoided if alternatives are available. The alternative to increasing capacity by crush loading in special cases such as the termination of a sports event is to time these extra heavy demands in off-peak periods and to draw then from a pool of available vehicles, much as a fleet of taxis handle them now.

From the viewpoint of cost effectiveness, the considerations are as follows:

1. Figure 5-1 shows that, based on the design capacity of a fleet of vehicles, there is no economic advantage in automated systems in using larger vehicles that permit standees. Standing-passenger vehicles must be taller, wider, and generally longer than seated-passenger vehicles. As a result, as shown by figure 5-4, the larger vehicles, all of which permit standees, are much heavier per unit length than the smaller, seated-passenger vehicles. The consequence is, as shown by the work of chapter 10, that the guideway weight per unit length is greater in proportion to the increased vehicle weight per unit length. In addition, because of the larger profile of standing-passenger vehicles, the wind torques on the guideway are greater. Therefore, for systems in which torsion is critical (section 10.6), the guideway weight is further increased up to 40 percent if the vehicles are designed to accommodate standing passengers.

2. For standing-passenger vehicles, the safety considerations of chapter 7 cannot be applied—there is no way to protect standing passengers in a collision. Compared with seated-passenger vehicles in which passengers are protected as summarized in section 7.8, the required reliability of control and braking systems in standing-passenger vehicles must be increased in proportion to the increase in the probability of injury during a collision. In essence, with standing-passenger vehicles, the tacit assumption must be made that there will be no collisions. In the real world, regardless of the precautions taken, such an assumption is not realistic. If the same probability of injury as in a system with seated and protected passengers is insisted upon, the cost of the control and braking systems for standing-passenger vehicles must be greatly increased. These considerations, however, do not apply to seated-passenger vehicles in which there are long throw distances and no protection mechanisms—such vehicles must be treated in the above considerations as if they were standing-passenger vehicles.

3. It has already been mentioned in section 11.3 that the acceleration and deceleration ramps of off-line station systems must be longer if stand-

[illegible] [illegible]

ing passengers are to be permitted because the tolerable acceleration and deceleration is only half as much. The formula for the length of one of these ramps is given by equation (2.2.6). Since a_m/J must be chosen equal to one second in both standing- and seated-passenger systems, and this factor is small compared with V_L/a_m, it is seen that the length of these ramps must be almost doubled if standing passengers are to be permitted.

No precise estimate of the ratio of cost of a standing-passenger vehicle system to a seated-passenger vehicle system on a completely comparable basis has been made; however, we can roughly estimate the ratio of guideway costs from figure 5-4. Compare a forty passenger vehicle with a three passenger vehicle. In these cases, the data of figure 5-4 is for standing-and seated-passenger vehicles, respectively. A forty passenger vehicle should be able to be built with a mass of say 1100 kg/m, and a three passenger vehicle with a mass of 300 kg/m. The ratio is 3.67, and from section 10.10, this should also approximately be the ratio of cost per unit length of the guideway. For the fleet cost, it is necessary to compare the increased cost of more reliable control and braking systems required of standing-passenger vehicles with the increased cost of providing for passenger protection in seated-passenger vehicles (see Chapter 7). Not enough data is available to make such a comparison; however, the cost of protection devices is included in the cost of the smallest vehicles of figure 5-1. In any case, the increased guideway cost with standing passenger vehicles is so great that the trade-off favors the specification of seated and protected passengers in an optimum AGT system. The comfort of the service provided with such a choice and the increased patronage it is likely to bring is a further dividend of the seated-passenger system.

11.6 Reliability

The process of synthesis of the characteristics of a transit system of maximum cost effectiveness has up to this section dealt with the acquisition cost of the system and not with its total life cycle cost. This is proper because it is easier to consider life cycle cost if we have specific configurations in mind. On the other hand, a configuration that is optimum from the viewpoint of acquisition cost may have to be discarded because of excessive support costs for operation and maintenance. Thus, consideration of the total life cycle cost must be an integral part of the synthesis process.

Consideration of life cycle cost includes all of the costs needed to keep the system operating at a specified level of reliability throughout its lifetime. The theory of life cycle cost minimization is developed in chapters 8 and 9. There, by a Lagrangian minimization process, it is shown how to find the optimum balance between acquisition and support costs for each subsystem in a transit system so that the life cycle cost of the entire system is minimized subject to a given level of service availability. The result is an equation (equations (8.8.3, 8.8.4)) for the mean time between failure of each subsystem that provides the proper balance and minimizes system life cycle cost. We called this the required reliability and spoke of allocation of reliabilities among the subsystems in such a way that the life cycle cost of the system is minimized.

Carrying the theory through rigorously to find the proper allocation of reliabilities requires knowledge of the rate of change of life cycle cost of each subsystem with respect to its mean time to failure. However, these quantities enter as the square root, which weakens their influence, and by making plausible simplifying assumptions about them it is possible to gain a great deal of insight into the means for achieving needed reliability. Indeed, without such a theory of reliability it would not be possible to proceed with confidence with a system of the general characteristics derived in the preceding sections.

To achieve sufficient reliability in small-vehicle systems, the theory shows that it is necessary to incorporate in the system the following features:

1. Redundancy in critical on-board components
2. Failure monitoring
3. Rapid automated pushing of failed vehicles

The theory of redundancy (section 9.2) shows, by equation (9.2.21), that with failure monitoring and automated pushing, the required reliability of each redundant element lies in an easily achievable range. The theory also shows (section 9.10) that reliability is improved if a minimum of functions are provided in the central facility and if as many of the control functions as possible are placed on board the vehicles. Because of the availability of low cost microprocessors, it can be expected that a high degree of sophistication in on-baord controllers, including the above three functions, will not raise the cost of each vehicle by a significant amount. Estimates by new-system developers of on-board control costs have been in the range of ten percent of the cost of the vehicle. Thus, while a great deal of effort is needed to fully commercialize small-vehicle AGT systems, the theory of reliability fully supports their feasibility without inordinate cost.

11.7 Dual Mode versus Captive Vehicles

The preceding paragraphs have concentrated on the basic characteristics of vehicles and guideways required to maximize cost effectiveness. Now we consider a basic configurational characteristic and its implications for the system as a whole. Dual mode [8] in its pure form is a system of vehicles and guideways designed so that the vehicles can be driven manually on the streets, but possess the needed control equipment to enable them to be operated automatically on the guideway. Thus, the need for a transfer to ride the automated system is completely eliminated, articles can be stored in the vehicles, and it would appear that such a system is ideal. The alternative is a system of automated vehicles captive to guideways, but such a system may require a transfer from a street vehicle to board it, and possibly another transfer at the terminal station. If it were not for seven fundamental difficulties with the pure dual mode concept, the captive vehicle configuration would hardly seem worth considering. But let us consider these difficulties and then examine the possibility of a compromise solution.

1. The first difficulty of pure dual mode is due to the requirement that the guideway would have to be wide enough to accommodate ordinary street vehicles—at least small ones. From the theory of chapter 10, this indicates immediately that the guideway would be a minimum of 40 to 50 percent more expensive than a monobeam guideway optimally designed for captive vehicles (section 10.2). The wider guideways would have greater visual impact and, in the region of the double guideway needed at the off-line ramp points, might be particularly objectionable. Thus, for reasons of both cost and visual impact, a less extensive network of guideways would be obtainable if the system were dual mode instead of captive vehicle. Some analysts argue that a less extensive network would be satisfactory if the system were dual mode, but this view caters to the auto owners and neglects the poorer members of society.

Snow
Removal

2. Dual mode vehicles would be propelled by rotary motors and braked through wheels. As indicated in section 11.4, the reduced friction obtained in wet weather would increase the minimum no-collision headway to about two seconds and therefore would limit the flow to 1800 vehicles per hour, only a little more than the capacity of a single freeway lane. To obtain a desirable capacity of say 6000 people per hour with no single-failure collisions (see section 11.11) the average number of people per vehicle would have to be at least 3.3, thus implying group riding and not the individual-owner vehicle implied by pure dual mode. The larger, group-riding vehicle would be heavier per unit of length and would therefore increase the weight and cost per unit length of the guideway in proportion. To obtain an average load of 3.3 people per vehicle would require, because of variations in demand, approximately a ten-passenger vehicle [9]. From figure 5-4, such a vehicle can be expected to weigh about 50 percent more per unit length than the smallest captive vehicle. Thus the guideway weight and cost would increase by the same factor, and, together with the increased cost for a wider guideway, would increase the guideway cost by a factor of about $(1.5)^2 = 2.25$ over the cost of an optimum captive-vehicle guideway. Moreover, in northern climates where ice could accumulate on the guideway, the guideway would have to heated. It would not do to apply salt to the surface for fear of shorting out the power rails. Thus the operating cost of a

(non-optimum guideway cross section

dual mode system would exceed that of an optimized captive vehicle system.

3. Since dual mode vehicles would be driven on both ordinary streets and guideways, they would have to have provisions for both and would therefore inherently be more complex than either captive automated vehicles or ordinary automobiles, and would cost more than either. Pure dual mode vehicles would therefore be available only to the more affluent members of society. In early stages in which only small segments of the system were built, it could be used only for a small fraction of the trips one would make. Therefore the personal gain through reduced congestion and reduced trip time expected of the automated portion of the trip would as a whole be small, thus reducing further the incentive to purchase a dual mode vehicle. Use of the larger, group-riding vehicles, described in the previous paragraph, would reduce the attractiveness of a one-vehicle trip because of the circuity of the pick-up route needed to obtain a sufficiently high load factor to amortize the guideway.

4. At the entry points to the automated guideway, inspection stations must be placed to insure that the propulsion, braking, and control systems aboard each vehicle are functioning properly. A wheel-locking failure would be particularly severe with rotary drives because the automated pushing procedure would not work and an entire line would be blocked until the failed vehicle were removed. The inspection must be sufficiently comprehensive to check vehicles that have been off the line for a long period of time and to take into account that the control system may have been tampered with. Little is known about the time such an inspection precedure would take. But if it does take up to say a minute, the throughput of the station is severely restricted and the inconvenience of parking a street vehicle, walking through a captive vehicle station and boarding a ready and waiting vehicle may not be a greater deterrent to travel on the automated system. In a captive vehicle system, maintenance of the vehicles would be completely under the control of the system operator.

5. To accommodate all types of travelers, the dual mode stations would have to process both dual mode vehicles entering and leaving the system and captive vehicles at station platforms similar to those of a captive vehicle system. Thus a dual mode station is a captive vehicle station plus ramps going to and from the street, an inspection station, and an abort lane to remove disqualified vehicles. Such a station would take more land and would cost more than a captive vehicle station.

6. In downtown areas, congestion on the streets beyond control of the automated systems could cause the vehicles of a dual mode system programmed to exit at the congested location to back up onto the guideway. To prevent such a serious bottleneck, additional vehicles programmed to exit would have to be rerouted to another exit point and could, by their

presence, overload the guideway. Also, with the pure dual mode concept, each vehicle would have to be stored in the downtown area just as is the case with the present automobile system and little improvement in street congestion can be expected. For this reason, it has been suggested that a dual mode system operate in the downtown as a captive vehicle system, that is, with off-line stations only and no exit and entry ramps. But in such a case, a private dual mode vehicle would have to be shunted into an ordinary parking garage. Upon returning to the station at the end of the day, the dual mode vehicle owner would have to call his vehicle and wait perhaps five or ten minutes for its arrival. To avoid this problem, special multistory parking garages for dual mode vehicles could be built with exit and entry ramps right onto the guideway. Again this is an elitist approach and would add to the cost of the system. Furthermore, the volume of a dual mode parking garage would have to be several times larger than that for a captive vehicle system because of the requirement to retrieve a particular vehicle.

7. In a captive vehicle system, each vehicle could be used for up to six to ten trips during the rush period. Thus, when compared with a pure dual mode system, the captive vehicle system would require correspondingly fewer vehicles and would be much more conserving of scarce resources.

In the pure dual mode concept, it is seen that one problem is compounded upon another, and that the problems are fundamental and not likely to be solved by technological advances. Such a system is cost ineffective in comparison with an optimized captive vehicle system. To make dual mode work with adequate capacity, the vehicles must be larger than the optimum-sized captive vehicles—small buses essentially which operate in the mode of the commuter van. Thus the privacy aspect of dual mode is removed and with it its main advantage.

A compromise that would overcome difficulties 1 through 4 would be the use of pallets of optimum design to which small automobiles could be clamped. Very little engineering design has gone into this concept, however, and it does not solve difficulties 5 through 7.

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11.8 Guideway Configurations

The process of optimization has up to this point settled on a system of small, seated-passenger vehicles designed to protect the passengers in case of collisions, and propelled by linear electric motors. The vehicles ride captive on monobeam guideways and use off-line stations as entry and exit points. Switching to the off-line stations and to other guideways is performed by switches on board each vehicle. To obtain adequate reliability, all critical on-board systems are redundant and failure monitored, and each vehicle is capable of engaging and pushing a disabled vehicle ahead of or possibly behind it. To obtain sufficiently low support costs, design simplicity must be maintained, but this is compatable with the use of linear drives. The theory of minimization of life cycle costs is essential here. The vehicles could ride either above the guideway, below it, or both; and would be suspended on wheels or magnetic fields, but probably not on air cushions because of the wide guideway they seem to require. Once such a basic configuration is established, many other optimizing decisions will be determined in an engineering development program.

The above design choices lead to a package of technology suited to an almost infinite variety of guideway configurations. Moreover, because of full switching capability, the system can begin as a single loop and be expanded loop by loop or line by line as needed. The capacity of an optimized system is adequate for almost all line-haul applications (section 11.4); and, because of the switching capability, radial lines can lead into collection and distribution networks in centers of major activity. As mentioned in section 11.1, sufficient computer simulation has been performed on a wide variety of line and network configurations to provide confidence that in most applications the above-mentioned configurations are fully practical. Because of the use of off-line stations, the productivity of a line-haul segment (which is provided by closely spaced stations) can be high.

The design of optimized network configurations, that is, the placement of lines and stations, is a science in itself. It is an iterative process fundamentally involving the use of behavioral mode split modeling and has not been treated in detail in this book. Nonetheless, the author does not slight its importance and has observed many cases in which faulty system design has resulted from inadequate attention to the difficult problem of patronage analysis.

11.9 Control

The control of AGT systems has received more attention in the literature than almost any other of its aspects [1]. The analytical aspects of obtaining adequate response under all conditions are well understood; however, the best means for obtaining reliable intervehicle positional and rate data on board each vehicle is probably yet to be developed. To satisfy safety requirements developed with train systems, these data must be present even if a vehicle lies dead on the guideway. Heretofore, however, insufficient attention has been paid to the coupling of such specifications with the probability of and consequences of failure. An optimized AGT system cannot be treated as if the vehicles were trains, tacitly assuming from a long tradition that the consequences of failure were the same. With redundant on-board elements, failure monitoring, modest speeds, lightweight vehicles, and passenger protection devices, an optimized AGT system bears no resemblance to a train system and the specification of its safety should be based on performance standards, not on design standards from another era. The problem of safety standards is an institutional one, but it also depends on development of adequate data based on the results of research and development.

11.10 Energy Conservation

Thus far the energy efficiency of an optimized AGT system has not been discussed. Clearly, with dimming prospects for continued availability of cheap energy, energy considerations enter very strongly into life cycle cost calculations and must be a primary concern in every phase of design. Let us consider the optimum design from the viewpoint of energy conservation.

1. Nonstop trips at uniform speed give a velocity profile that minimizes energy use. Trips with many stops require that the kinetic energy of the vehicle be restored after each stop. Equation (2.6.6) gives the energy consumed in a nonstop trip at constant speed once line speed is attained. If the trip has many stops, and D_s is taken as the total trip length, then the first term must be multiplied by the number of stops. By use of regenerative braking, some of the kinetic energy of the vehicles can be recovered as the vehicle is stopped.

2. Equation (2.6.6) shows that the energy per trip is minimized if the vehicle mass is minimized, a key requirement of the optimized system.

3. Equation (2.6.6) also shows that the energy per trip is minimized if the frontal area of the vehicles is minimized. If the vehicles were trained, however, the air drag term enters only once for each train and therefore is less than if the vehicles operate singly. But training of vehicles ~~at stations~~ increases the station dwell time and therefore the number of vehicles that have to be moved, in proportion to the increased average trip time. Also, from the discussion of equation (4.5.22), trained vehicles would require passengers to stop at intermediate stations, thus increasing the kinetic energy term of equation (2.6.6). If the vehicles travel nonstop between stations, Figure 2-4 shows that the line speed is lowered for a given average speed. Both the air drag and kinetic energy terms in equation (2.6.6) are proportional to the line speed squared. With all of these considerations, it is not at all clear that trained systems with the same average speed as an individual vehicle system would have a lower energy per trip. The trade-off calculations need to be made in specific circumstances. Certainly, in individual vehicle systems, greater attention should be paid to streamlining the vehicles to reduce the drag coefficient C_D in the air drag term of equation (2.6.6).

4. The use of off-line stations and on-demand service means that vehi-

cles need circulate only when demand exists. As discussed in section 11.3 in connection with the vehicle load factor, with systems using scheduled service, the vehicles must circulate to maintain schedules regardless of demand. Thus, in periods of low demand, substantially more energy is consumed by the system than if the vehicles moved only when trips need to be made.

5. The use of linear electric motors eliminates the problem of reduced traction if there is water, snow, or ice on the guideway. With rotary motors operating through wheels, the guideway must be kept dry to keep the level of traction acceptably high. In some applications, guideway-heating energy has been as high as propulsion energy. Linear electric motors, however, vary a great deal in efficiency. Two-sided linear induction motors use substantially less energy than one-sided motors because the magnetic flux paths are much more tightly coupled. The strength of the effective magnetic field is inversely proportional to the air gap, therefore suspension designs that permit the smallest air gap are to be preferred. Linear syncronous and linear pulsed dc motors promise higher efficiency than linear induction motors, but are not as highly developed. In all of these motors, end effects reduce efficiency and must be reduced by careful design. The optimum design of an AGT system clearly requires a strong research and development program on these motors.

11.11 Capacity Requirements

In section 11.7, it was mentioned that a capacity of 6000 people per hour per direction was desirable. As mentioned in section 11.4, the maximum capacity of a single freeway lane is about 2000 people per hour. This figure is obtained from surveys of traffic on freeways and is discussed in most traffic engineering textbooks. Three-lane freeways, common in many metropolitan areas as major line-haul transportation corridors, therefore have a capacity of about 6000 people per hour. Figure 5-6 shows that with a network system, the average flow reached 4000 people per hour only with the highest densities considered, which are far higher than obtained in most cities except within the central core. Equation (4.5.19) shows, however, that the flow is proportional to the average trip length. Therefore in very large spread cities, such as Los Angeles, flows on freeways higher than 6000 people per hour are routinely obtained. A guideway system is not expected to attract all of the line-haul traffic, indeed if half the rush hour traffic were attracted, it would in most cities be considered a resounding success. With these considerations in mind, it is clear that the specification of 6000 people per hour maximum flow for a suburb to downtown dual mode system will cover a wide range of applications, but that to achieve such a capacity with vehicles with rotary drives will require group-riding vehicles. On the other hand, if the guideway system is optimized, the calculation of section 11.4 indicates that it is not capacity limited.

Notes

1. *Personal Rapid Transit II,* Audio Visual Library Services, University of Minnesota, Minneapolis, Minn., 1974; and *Personal Rapid Transit III,* Audio Visual Library Services, University of Minnesota, Minneapolis, Minn., 1976.

2. *Lea Transit Compendium,* Vol. 2, No. 3, p. 25, and Vol. 2, No. 4, pp. 9, 17, and 37, N.D. Lea Transportation Research Corporation, Huntsville, Ala., 1975.

3. The systems referenced in Note 2 are the best examples.

4. Such a design is used by the H-Bahn and Monocab Systems referenced in Note 2.

5. Such a design is used in the High-Capacity PRT System developed by the Aerospace Corporation. See *Personal Rapid Transit,* op. cit., pp. 325-382; *Lea Transit Compendium,* op cit., Vol. 2, No. 4, pp. 9-12.

6. Such a design is used in the Cabintaxi System referenced in Note 2. See also "Cabintaxi: Urban Transport of the Future," *Elevator World,* April 1977. The detailed theory is developed by Dr.-Ing. Klaus Becker, in "Über den Einfluss von Fahrgeschwindigkeit und Streckennetz auf Verkehrsmenge und Kostenstruktur einer neuartigen Kabinenbahn," genehmigte Dissertation, Berlin, 1974.

7. Private discussions with developers of three new German AGT Systems indicates, however, that power collection problems for urban-speed systems are considered solved in Germany.

8. *Dual-Mode Transportation,* Special Report 170, Transportation Research Board, Washington, D.C., 1976.

9. This assumes a load factor of one-third, judged by the author to be reasonable on the average for group service with reasonable waiting time and counting deadheading. If, say an eight-passenger vehicle had been assumed, the argument that the dual mode guideway is substantially more expensive than a captive vehicle guideway is not changed.

Appendix A
Derivation of the Amortization Factor

P = principal (original cost of equipment)
p = annual payment on principal and interest, assumed constant
A = p/P = amortization factor (see section 5.1)
r = annual interest rate
n = lifetime of equipment, or period over which loan is paid
I_i = interest payment at end of ith year
P_i = payment on principal at the end of ith year

$$p = I_i + P_i \tag{A.1}$$

$$P = \sum_{i=1}^{n} P_i \tag{A.2}$$

Interest paid at the end of the ith year is applied to the balance of principal owed during that year. Thus

$$I_i = r\left(P - \sum_{j=1}^{i-1} P_j\right) \tag{A.3}$$

By using equation (A.2), we have from equation (A.3)

$$I_{n+1} = 0 \tag{A.4}$$

If equation (A.3) is substituted into equation (A.1), the result may be written in the form

$$P_i = p - rP + r\sum_{j=1}^{i-1} P_j \tag{A.5}$$

Thus,

$$P_1 = p - rP$$

$$P_2 = (p - rP)(1 + r)$$

$$P_3 = (p - rP)(1 + r)^2$$

By induction, assume

$$P_i = (p - rP)(1 + r)^{i-1} \qquad \text{for } i = 1, 2, \ldots, k \tag{A.6}$$

Then, from equation (A.5),

$$P_{k+1} = (p - rP)\left[1 + r \sum_{j=1}^{k} (1 + r)^{j-1}\right]$$

$$= (p - rP)\left\{1 + r\left[\frac{(1 + r)^k - 1}{r}\right]\right\} = (p - rP)(1 + r)^k$$

Thus, P_{k+1} can be derived from equation (A.6) by substituting $k + 1$ for k. It is therefore proved that equation (A.6) holds for all k.

Now, substitute equation (A.6) into equation (A.1) and set $i = n + 1$. Using equation (A.4), the result is

$$p = (p - rP)(1 + r)^n$$

from which

$$\frac{p}{P} = A(r, n) = \frac{r(1 + r)^n}{(1 + r)^n - 1} \tag{A.7}$$

Let I be the total interest paid.
Then

$$\frac{P + I}{P} = \frac{np}{P} = nA \tag{A.8}$$

is the total payment for the equipment per unit of principal.

The present value of the total payment at year $i = 0$ is

$$PV = \sum_{i=1}^{n} \frac{p}{(1 + d)^i}$$

where d is the discount rate. Summing the series,

$$PV = \frac{p[(1 + d)^n - 1]}{d(1 + d)^n}$$

or, using equation (A.7),

$$\frac{PV}{P} = \frac{A(r, n)}{A(d, n)} \tag{A.9}$$

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