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Abstract

The need for providing high-performance transit services has been increasingly recognized in most cities in recent years. The most important elements for obtaining such services are separate rights-of-way for transit and guided technology.

The basic transit system features, such as transit unit size, service frequency, degree of automation and stopping patterns are described and their impacts on performance are analyzed. Rail rapid transit and light rail modes are found to retain clear superiority in high and medium capacity mode categories, respectively; various rubber-tired automatic guided systems are increasingly replacing steered (highway) modes in applications of lower medium capacity range where high performance is needed. Individual automated guided cabin systems (personal rapid tranit) do not represent a viable concept under any conditions.

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ANALYTICAL REVIEW OF GUIDED TRANSIT SYSTEMS

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The need for providing high-performance transit services has been increasingly recognized in most cities in recent years. The most important elements for obtaining such services are separate rights-of-way for transit and guided technology.

The basic transit system features, such as transit unit size, service frequency, degree of automation and stopping patterns are described and their impacts on performance are analyzed. Rail rapid transit and light rail modes are found to retain clear superiority in high and medium capacity mode categories, respectively; various rubber-tired automatic guided systems are increasingly replacing steered (highway) modes in applications of lower medium capacity range where high performance is needed. Individual automated guided cabin systems (personal rapid transit) do not represent a viable concept under any conditions.

1. RECENT DEVELOPMENTS OF GUIDED TRANSIT SYSTEMS

In 1950 there were 17 cities with rapid transit systems in the world; today there are 62, as Figure 1 shows. In addition to these "pure" rapid transit systems, a number of cities (e.g., Copenhagen, many Japanese, Dutch and Swiss cities) have introduced regional rail systems which are very similar to rapid transit by their physical and operational characteristics. Finally, some of the new light rail transit (LRT) systems do not differ much from rapid transit systems: Essen, Edmonton, Newcastle and Utrecht belong in this category.

This unprecedented pace of rapid transit construction shows that there is a great need for high-performance transit systems in large cities throughout the world. In some cities, particularly in developing countries, rapid transit is primarily needed to physically transport large volumes of passengers. In many developed countries it is primarily the high quality of rapid transit service that is required in order to provide service competitive with the private automobile. The automobile thus actually increased the need for rapid transit and accelerated its construction in recent decades.

The large scale and very high investment cost of rapid transit, however, limit the use of this mode to heavily travelled corridors and, mostly, large cities. Yet, there is an increasing need for greatly improved transit services also in medium-size cities and corridors which carry less than 10,000-20,000 passengers per hour, the range which usually justifies rapid transit construction.

Figure 2 shows a conceptual diagram of system performance vs. investment cost for the major presently used transit modes. The lowest area on this diagram represents modes operating on streets: buses, trolleybuses and streetcars. They require low investment, but offer low level of service, generally not competitive with the private automobile. Rapid transit or metro occupies the upper area on the diagram: it offers high performance, but requires high investment cost.

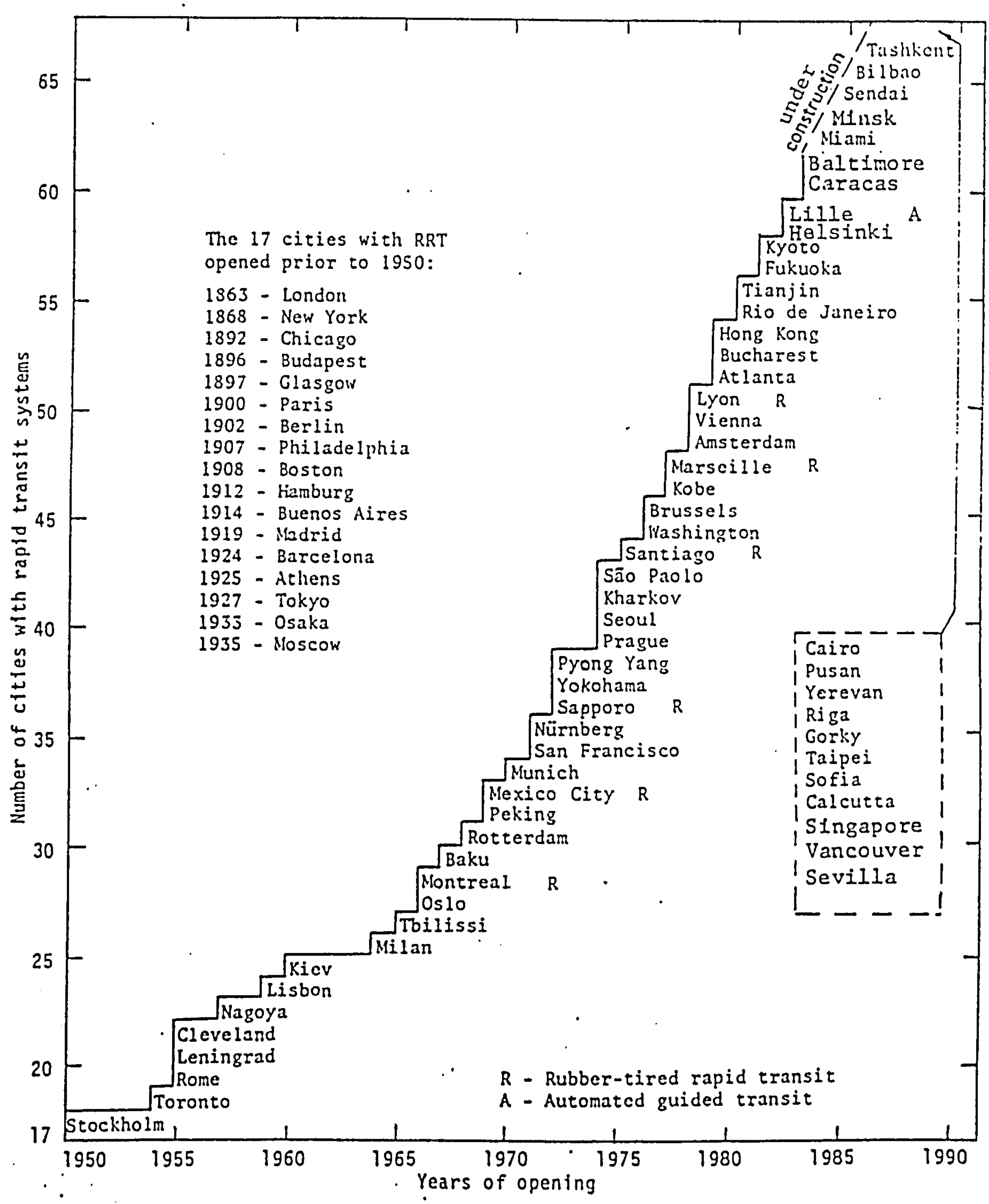

Figure 1. Rapid transit systems of the world: number and years of opening.

Between these two very different mode categories - street transit and rapid transit - there is a large area which has been neglected in many cities. Actually, most medium and large cities need to "fill this gap": they need much better transit services than buses on streets can offer, but they cannot afford the very high investment rapid transit requires.

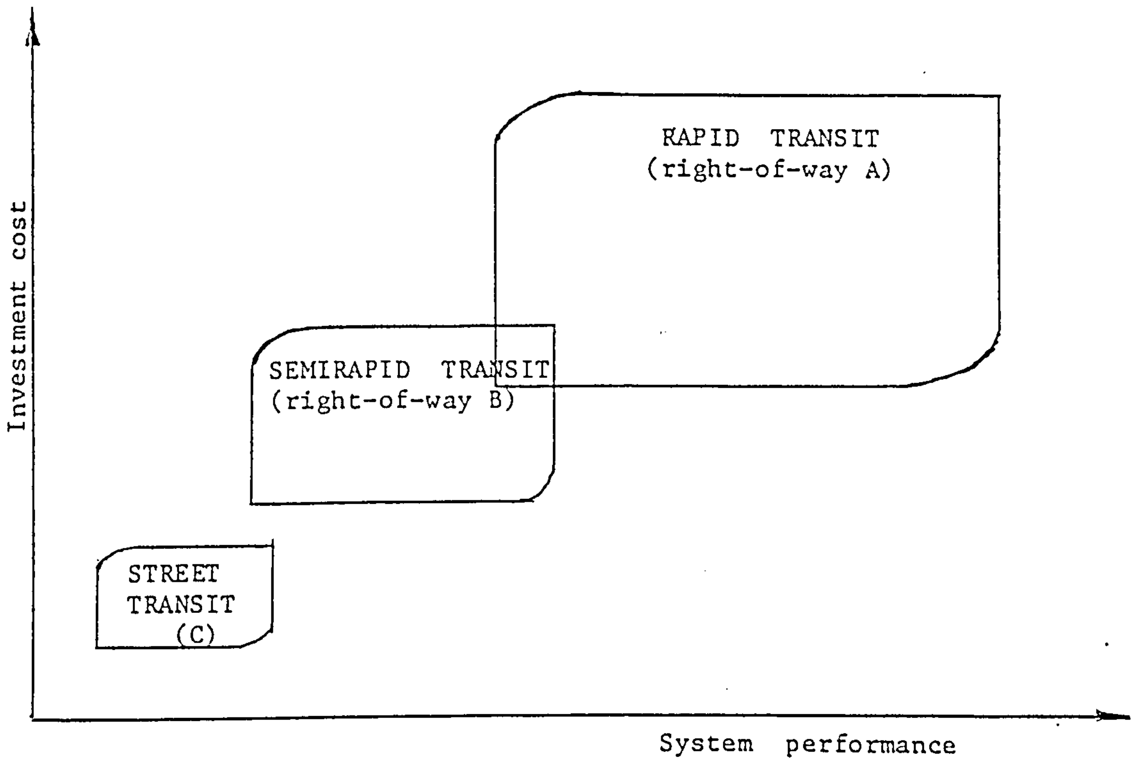

Figure 2. Transit system performance/investment cost relationship for different categories of transit modes (conceptual diagram)

Source: Vuchic [7]

There are generally two ways to "fill the gap" of the medium-performance medium-cost systems. One is to improve buses by provision of separate rights-of-way for portions of their lines. The other is to use guided systems which are smaller, more adaptable to different urban situations and require less investment than rapid transit: light rail is by far the most used mode in this category.

There have been many developments of transit systems that belong in this category during the last 20 years, but there have been few successes and many failures. A major problem has often been inadequate understanding of the requirements and conditions of transit system operations.

This paper analyzes guided transit systems, their physical and operational characteristics, and their place in urban transportation. An evaluation of major presently operated and proposed systems will be made on the basis of the analyses of their individual features.

2. REQUIREMENTS FOR HIGH-PERFORMANCE TRANSIT

The major elements which constitute high performance of transit systems are defined here. Various transit systems have different "combinations" of these characteristics; no system is the best in all of them. Comparison of various systems therefore involves analysis of trade-offs among different characteristics.

High Capacity is determined by the minimum throughput of the critical station. Since guided systems require a substantial investment cost, they are justified only where there is substantial travel demand. Therefore high capacity is always an element of high performance.

High speed is desirable for passengers, but its absolute value depends on trip length and purpose, speed of the competing modes (e.g., auto on streets or auto on freeways), etc.

High reliability is often the most important characteristic for passengers. Experience has shown that passengers will rather accept somewhat lower speed (longer travel time) with a highly reliable service, than very high speed they cannot count on with certainty.

High frequency of service makes passengers feel that it is always available and thus contributes to their attraction.

Comfort and convenience are important for passengers, but particularly for those who also have a private automobile as an alternative. Availability of seat, smooth vehicle movement, moderate temperature, cleanliness and vehicle aesthetics are components of this requirements.

Investment cost is usually the most important single factor in determining feasibility of a transit system. Lower investment cost is therefore the key factor in increasing the use of transit systems.

Operating cost also influences feasibility of introducing a system and it has a major influence on the type of service which can be offered once the system has been built. Low operating cost allows high service frequency. Labor cost is its major element.

Area coverage, influenced by investment cost and physical characteristics of a transit system (alignment geometry, cross section and station size), determines how many trips transit line or network can serve directly. When coverage is limited, like with rapid transit, other transit modes are used as feeders.

Safety and security must be satisfied to a very high degree in every transit system, but the requirement is even greater on high-performance, controlled systems.

Price (fare) strongly affects ridership, but it is not directly related to transit system technology and operating characteristics. It will therefore not be included in further analyses here.

3. CHARACTERISTICS OF GUIDED TRANSIT SYSTEMS

Physical and operational characteristics which mostly determine performance of transit modes can be classified into several major physical and operational features. They are presented here.

3.1 Right-of-Way Categories. Transit rights-of-way can be classified into the following categories:

- C - operation on streets in mixed traffic;
- B - partially separated rights-of-way, such as in curbed medians, but with some contacts with street traffic (most commonly, at-grade crossings);
- A - fully separated rights-of-way, no contacts with other traffic.

These right-of-way categories have a major impact on transit system technology: buses are best suited for rights-of-way C, while increasing separation makes guided systems more and more advantageous. On rights-of-way A guided modes represent the only logical solution.

The characteristics of rights-of-way and system technologies influenced by them create a strong correlation between right-of-way categories and transit system performance. Compared with street operations (C), partial separation (B) requires additional land and investment cost, but it provides a substantially higher system performance. In addition to independence from street congestion, systems operating on rights-of-way B - semirapid transit - can have 2-3 car trains with a length of up to 70 m and capacity of some 600 spaces (light rail transit).

Further and ultimate step in upgrading transit right-of-way is its full separation from all interferences (A). Investment cost for this separation, particularly in central cities, is extremely high, but such systems, designated as rapid transit modes, are superior to all other modes in their speed, capacity, reliability, safety and other performance components (see Figure 2). This results from the fact that fully controlled systems can have very long trains (up to 10 cars and over 2000 spaces), automatic signal control, or fully automatic operation. Actually, technology and design of rapid transit systems take advantage of the specialized operating conditions, such as multiple doors and absence of steps, on-board fare collection facilities and emergency brakes; wide bodies; high speed, capability to utilize high geometric alignment standards, etc.

Compared with rapid transit, semirapid transit is more diversified - adaptable to a greater variety of alignment and operating conditions. This requires some additional features and capabilities adaptable to lower geometric standards, higher dynamic performance, body design specialized for local conditions, etc., but it also gives this mode a broader range of applications. Since semirapid transit (light rail and buses) can operate on both rights-of-way, B and A (as well as on C), their network can be much more easily extended than is the case with rapid transit, a feature particularly useful for providing service in expanding suburban areas; they are also adaptable to operation in center city malls.

3.2 Guidance/Support Technology. For small passenger volumes rubber-tired vehicles steered by the driver represent the optimal technology: it allows movement on all streets and requires virtually no investments for infrastructure. While guided technology cannot be used for low passenger volumes due to its higher investment costs, when these costs can be justified by high volumes, the advantages of external guidance tend to prevail. In summary:

Guided compared with steered transit modes differ in the following:

+ Ability to have larger vehicles and operate them in trains, resulting in :
  - a. Much greater capacity; and
  - b. Much lower operating costs per unit of capacity;

+ Electric traction possible:
  - a. Superior dynamic performance;
  - b. Much lower negative environmental impacts;

+ Narrower right-of-way:
  - a. Lower investment cost, particularly in tunnels and on aerial structures;
  - b. Easier "fitting" into urban development, parks and other environmentally sensitive areas;

+ Greater riding comfort:
+ Higher safety (various types of signal control possible);
- Must have right-of-way A, with the significant exception of rail technology;

- Requires higher investment cost;
- More limited network;
- Lower operational (rerouting) flexibility.

Thus, all guided technologies except rail can operate only on fully separated rights-of-way (A).

Most guided modes utilize steel wheel on steel rails, but there are also guided technologies with rubber tires in use and magnetically suspended and air-levitated in development and testing.

Rubber-tired guided compared with steel wheel/steel rail technology is characterized by:

+ Greater ability to have smaller vehicles;
+ Lower noise in curves;
+ Better adhesion resulting in:

  a. Greater climbing ability;
  b. Ability to operate with shorter headways.

- Similar vehicle weight per unit of floor area;
- Inability to have crossings with street traffic - or between its own guideways;
- More complicated guideway/guiding wheels mechanism (12-24, instead of 8 wheels);
- More complicated switches (with the exception of systems with "on-vehicle" switching);
- More vulnerable to weather conditions;
- Greater rolling resistance, therefore higher energy consumption and heat production.

Consequently, rubber-tired guidance is used for small vehicles, rail for large vehicles and high-capacity systems, with a considerable range of overlap between the two.

3.3 Transit Units: Vehicles and Trains. For low passenger volumes small vehicles are most economical, since they can operate at shorter headways (intervals) for a given volume than large vehicles. As passenger volumes increase, it is desirable to shorten the headways so that passengers enjoy high frequency of service (shorter waiting times). However, this factor disappears at a certain point. While it is highly desirable to reduce headways from 10 to 5 min., it is much less important to reduce them from 5 to 2.5 min., and passengers will hardly notice further shortening of headways, under 2.5 min.

On the other hand, reliability of service decreases as the headways become shorter. Operation of lines with headways close to the minimum determined by safe distances between transit units is highly sensitive to any delays. Thus, there is a range of headways which is most desirable: it is approximately between 5 and 1.5 minutes, varying somewhat with technology and operating factors. Above that range passenger waiting becomes undesirable; below it, reliability of service suffers.

Capacity of a transit system can be increased, basically, by two changes: reduction of headways and use of larger transit units.

For an analysis of the relationship of headways and vehicle capacity it is useful to define the concept of transit unit (TU): that is a set of vehicles traveling physically together, i.e., a single vehicle or a train. Line capacity is the product of its maximum frequency and TU capacity; and the maximum frequency is the inverse value of its minimum operational headway. This relationship is shown on the diagram in Figure 3. For example, capacity offered by TUs with 50-space capacity operating at 1.5-min headways (frequency of 40 TU/h) is 2000 spaces/h.

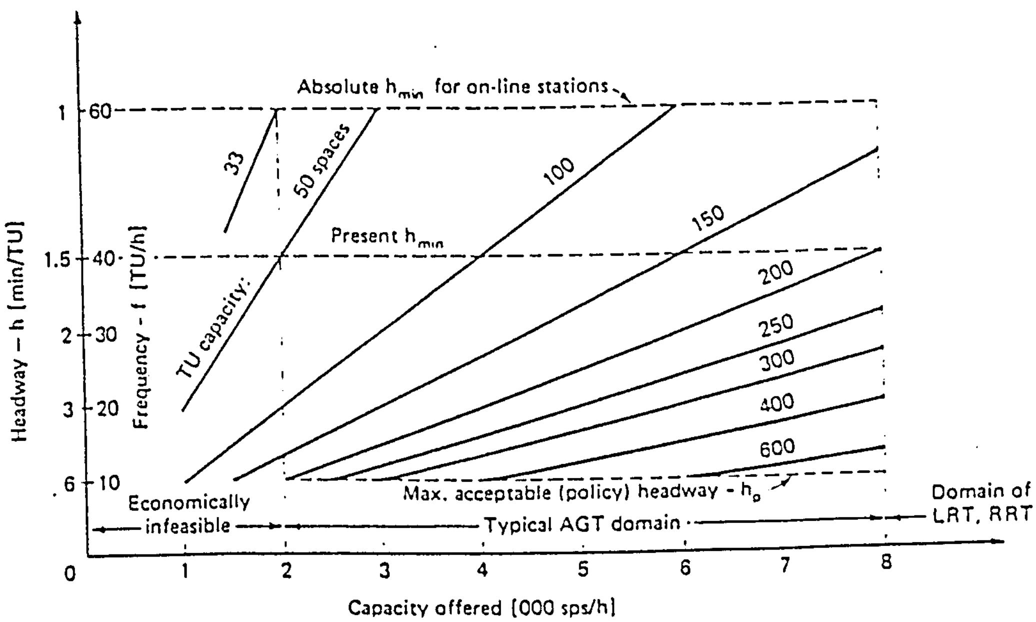

Figure 3 TU capacity of GRT modes as a function of frequency and offered line capacity

Source: Vuchic [7]

Capacity required for guided systems is by definition high (their infrastructure construction cannot be economically justified for low passenger volumes). While for rail modes the design volume is always at least in the range of 5,000-8,000 sps/h (for rapid transit going as high as 60,000 sps/h), it is conceivable that some systems may require lower investment and therefore be justified even for capacities down to 2000 sps/h. As the diagram in Figure 3 shows, for the presently shortest operated headways of 1.5 min the smallest TU capacity required to provide 2000 sps/h is 50 spaces; if with full automation and some other physical/technological changes headways of 1 min could be reached, the required TU capacity would be 33 spaces.

Further reduction of headways can only be achieved by off-line stations, which are possible, but extremely difficult to provide on urban transit systems because of large space requirements and costs. There is presently no regular transit system with all off-line stations.

The optimal size of a vehicle is determined by the TU capacity required for maximum line capacity, discussed above, and the capacity of a minimum TU needed for operation at times of low demand. For that minimum capacity required, it is better to have few large vehicles rather than many small vehicles. For example, to provide a transit unit with 250-space capacity, two vehicles with 125 spaces will be more comfortable for passengers, have shorter train length and involve lower investment and operating costs than a train with five 50-space vehicles.

Guided systems for transit applications usually operate with TUs which are greater than demand requires during off-peak hours. Their greater economy and efficiency for carrying large passenger volumes during peaks, as compared to smaller TUs, usually outweighs their somewhat higher operating costs during the off-peak periods.

It is interesting to examine the general relationship of TU capacity, maximum frequency of operation, and the resulting line capacity for different modes. The diagram in Figure 4 shows that when different modes - from passenger automobile over the minibus, bus, streetcar, light rail and rapid transit - are plotted on a TU capacity/max. frequency diagram, they form a hyperbolic area: as TU capacity increases, max. frequency decreases; yet, line capacity - product of these two - increases with TU. Capacities per one lane (track) for private automobile, bus, light rail and rapid transit have ratios of approximately 1:3:8:24 (from 2500 to 60,000 persons/hour).

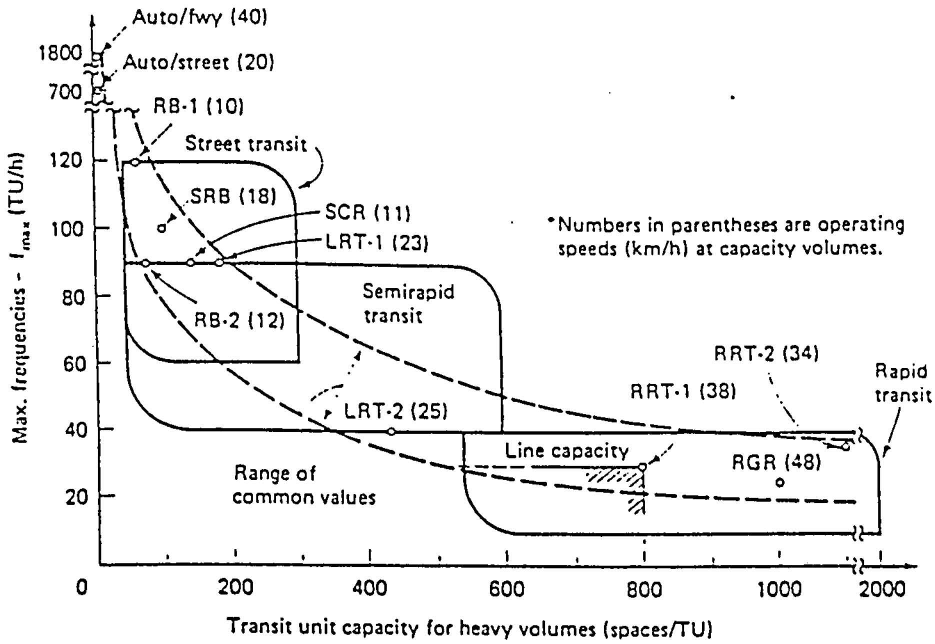

Figure 4. Vehicle capacities, maximum frequencies and line capacities of different modes

Source: Vuchic [7]

3.4 Driving Methods. Types of driving and control of transit vehicles vary from manual driving and visual control to fully automated driving and control. "Between" these two extremes is semi-automatic driving with various assisting automatic signal controls; most rapid transit systems belong in this category.

Generally, the higher performance a transit system has, the more is automatic control for it necessary and economically justified. However, with driving automation this correlation is not so simple. Systems with large TUs (such as rapid transit) usually need and can justify to have drivers, because of their high productivity (in space-km/man-hr). The smaller the TUs are, the more it is necessary to achieve full automation. The great electronic complexity and high investment of full automation are more than offset by the cost reduction through reduced labor requirements. Elimination of the driver not only reduces overall cost, but it permits higher frequency of operation in off-peak hours without additional costs.

Thus, while full automation is easier to physically achieve and economically justify on high-capacity guided systems, it is more needed--and it is often a sine qua non--of medium capacity guided modes if these are to provide high-frequency service.

Naturally, most components of automation, and particularly automatic driving, can be applied only on systems with rights-of-way A.

3.5 Stopping Patterns. There are three basic types of TU stopping patterns at stations:

i. On-demand, only when passengers request. This pattern can be applied at times or on line sections with very low demand, such as late evenings in suburban areas. In most cases, however, high passenger demand for guided systems and the requirement for exact, predictable schedules makes this type of operation unusable.

ii. Local operation, with all TUs stopping at all stations. This is by far the most common type; it is the slowest, but simplest to schedule, operate and explain to passengers.

iii. Accelerated operation, which involves scheduled "skipping" of some stations by some TUs. Skip-stop, zonal and express operations belong in this category. Accelerated operations can be used during the periods of high demand (to avoid long headways), particularly on lines with more than two guideways (tracks).

3.6 Network Connectivity. Service among different stations in a transit network can be offered in three different ways.

i. Independent lines forming a network, with passengers transferring at common stations; this is found on many rapid transit systems, such as in Paris (with very few exceptions-branches), Tokyo and Montreal.

ii. Overlapping of lines, where different lines converge from branches, run together, separate and join others, etc. This type of networks is typical for most streetcar and some rapid transit and regional rail networks (New York, London, regional rail in Hamburg and Philadelphia). Network operation is more complicated, but it can be better tailored to demand and it requires fewer transfers.

iii. Direct service among all branches, so that passengers would not have to transfer at all. TUs would travel among all branches of a network. This type of service, suggested for some proposed modes (e.g., personal rapid transit), is totally impractical since it would result either in very low frequency of service between any two branches or stations, or an extremely high frequency of operation in the network - similar to private automobile. Moreover, physical accommodation of large guideway interchanges would be in most cities impossible. No transit system has ever applied this type of operation.

4. TRANSIT MODES AND SPECIFIC SYSTEMS

By their performance characteristics, primarily capacities, the numerous existing and experimental guided transit systems can be grouped into three sub-categories of rapid transit (modes with rights-of-way A) and one of semirapid transit (B).

4.1 High Capacity Rapid Transit. Rail rapid transit, regional rail and rubber-tired rapid transit belong in this group of modes. The first two are technologically very similar their major distinctions are in their network characteristics (urban vs. regional) and in their ownership (transit agency vs. railways). The third mode, rubber-tired rapid transit, has basically the same components as rail rapid transit (right-of-way A, guidance, signal control, etc.), but different support/guidance technology.

For most applications the two rail modes have more advantages than disadvantages as compared to the rubber-tired mode (as explained above, in section 3.2). The latter, in use in seven cities (Paris, Lyon, Marseille, Montreal, Mexico, Santiago and Sapporo), has the following major shortcomings: limited vehicle size due to weight limit on rubber tires (therefore inferior for very heavily travelled lines), higher energy consumption, and vulnerability to ice and snow conditions.

In most respects high capacity rapid transit modes represent the highest possible level of transit system performance: the greatest capacity, reliability, speed, comfort and safety. Their only major shortcomings - high investment and large physical size - limit their applications to lines and networks with high volumes of passenger travel.

Alweg Monorail also belongs in this group of modes. It operates only on two regular transit lines (in Tokyo and Seattle), and it has had no new applications or developments in recent years. It is, however, frequently proposed for construction and continues to enjoy a popular image as a "system of the future".

4.2 Medium-Capacity Rapid Transit. There are a number of systems with many diverse technological features which belong in this group of modes. Although few of them are presently in operation as regular transit systems, most of them are recent and activities in their development are increasing. The major ones are the following.

Light Rail Rapid Transit is by far the oldest of these systems. Represented by the Norristown Line in Philadelphia and Line 8 in Gothenburg, this mode is actually light rail transit on right-of-way A only. Single cars or short trains are operated therefore at higher speeds than on regular light rail transit lines; signal control and high level platforms are often used.

Advanced Light Rail Transit, presently under construction in Vancouver, is also a light rail transit system on right-of-way A, but has several new features: fully automatic operation, linear induction motor propulsion and steerable trucks (bogies). The concept of full automation for a medium-capacity system is very appropriate. Steerable truck is also a promising innovation, while the merits of the linear induction motor must still be proven in practice.

Kobe New Transit (KNT) and a similar system in Osaka consist of six 2-axle rubber-tired car trains operated automatically. While the system is physically and operationally sound, the small vehicle size (8.00 x 2.39m) is questionable when they are always operated in 6-car trains: large cars coupled in 3- or 4-car trains might offer greater comfort and better economy.

Transit Expressway or Skybus consists of medium-size (9.30 x 2.60m) rubber-tired vehicles, guided by another set of rubber tires along a central "I" beam, which operate automatically as single units or trains of 2-3 (theoretically up to 10) vehicles.

In several competitive proposals for high-capacity rapid transit lines the Skybus was found inferior to rail transit; however, this system has been selected over many others for applications as short medium-capacity shuttles in airports.

Its first full transit-type application will be as center city "people mover" and feeder to rail rapid transit in Miami, presently under construction.

VAL System in Lille has made a significant step forward as the first fully automated transit system in full-scale operation. However, its basic physical and operational features are more oriented to short shuttle than to regular transit services: the narrow 2-axle vehicles cannot offer the capacity and comfort comparable to those of light rail vehicles.

Other systems which belong in this category have had more limited applications, or are presently still under development or testing. They include the Airtrans (Dallas - Fort Worth Airport), H-Bahn and M-Bahn (test lines in Germany), Dashaveyor and several others.

4.3 Low-Capacity Rapid Transit. The basic concept of these modes is that small cabins (up to 16-space capacity) would operate automatically over extensive guideway networks on on-call basis.

Morgantown system has been in operation for several years, serving a line between center city and university campus. While physically operational, this system would gain efficiency if its 16-space cabins would be replaced by considerably larger units.

Aramis proposes 10-space cabins which would be capable of operating with very short headways, necessitating all off-line stations. Again, it would be easy to show that larger vehicles operating at longer headways would offer superior performance.

Personal Rapid Transit concept consists of 3-5 space cabins operated automatically over an elaborate guideway network. This concept is fundamentally unsound since in low density areas where small cabins would be appropriate, construction of guideways would be unaffordable, while in high density areas guideways could not physically fit and large cabins would be optimal.

4.4 Semirapid Transit. By far the most common representative of this category is light rail transit, perfected considerably since the 1950s.

Light Rail Transit (LRT) is conventional rail transit operated mostly on rights-of-way B. Its single cars (usually articulated, 20-30m long) can also be operated in 2- or 3-car trains, visually or with signals on all types of rights-of-way (including C and A).

The main "compromise", or lower-type component than rapid transit which LRT has is the ability to operate on other than rights-of-way A. This limits the length of trains and slightly decreases their other performance characteristics. Yet, LRT is superior in many features to medium-capacity rapid transit systems which have much lower capacity 2-axle vehicles, often untested components or operational features. With its considerably lower investment requirements due to its ability to utilize right-of-way B (and, where necessary, C), LRT represents for many medium-capacity applications a "performance/cost package" superior to those of other guided modes.

O-Bahn, recently developed guided bus technology, represents an attempt to retain the simplicity of the motor bus while capturing the advantages of guidance and ability to utilize different types of right-of-way (usually C and A). The concept is severely limited, however, by the fact that the O-Bahn requires the high investment for both right-of-way A and guideway structure, while it fails to utilize the most important advantages of guidance: large vehicles (high comfort and economy), operation of trains (great increase in capacity, labor productivity and safety), and electric propulsion (better performance, superior in environmental impacts). Moreover, O-Bahn loses the ability of buses to bypass each other.

The O-Bahn concept can therefore compete with buses on busways only under special conditions (very limited right-of-way) and its performance is generally inferior to that of LRT.

5. CONCLUSIONS

The above analysis of guided transit systems features and specific modes, supported by the current developments in numerous cities around the world, leads to the following conclusions.

i. There is a growing need in cities to provide high performance transit systems for which guided modes are the most logical choices.

ii. Intensive construction of rapid transit systems (mostly rail) is likely to continue and include an increasing number of cities, as they grow in size and the problem of congestion continues to worsen.

iii. There is an increasing need to provide medium-capacity transit systems which require lower investment than rapid transit, but offer much higher performance than buses. Light rail transit is presently the leading mode for most of these applications.

iv. Fully automatic operation will result in lower operating costs of guided transit systems (regardless of guidance technology), but high investment cost remains a serious limiting factor.

v. There will be increasing applications of different medium-capacity rubber-tired guided modes, mostly for short, high frequency services in central cities, airports, etc., but also for some regular transit lines.

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