PHYSICAL, OPERATIONAL, AND PERFORMANCE CHARACTERISTICS OF THE LIGHT RAIL MODE

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An overview of the light rail mode is presented. General characteristics and application of the mode are described, emphasizing the versatility of its guideway, the railway track. Physical characteristics of the right-of-way and ranges of dimensions for right-of-way and vehicles are discussed. Stations are discussed briefly. Basic technical simplicity of the light rail mode is pointed out as a significant virtue. Operating characteristics (both maximum running speeds and typical average operating speeds) are indicated. Acceleration of typical vehicles is noted. Frequency of service is discussed, and ranges for various traffic control systems are given. Riding quality and visual impact are pointed out as being favorable. Capacity of light rail lines is given as a few thousand to 12,000 passengers/h. In special cases, a high of 18,000 passengers/h can be achieved by using multiple-unit trains of 3 or more cars. Choices a designer has to attain maximum capacity are stated. Capital costs of contemporary new light rail systems are given as ranges of costs for various configurations. It is concluded that light rail transit is a medium-cost mode providing a medium level of capacity at medium speeds that can find application in many corridors or areas in medium and larger sized urban areas. It is pointed out that light rail is an existing mode with proved capabilities that needs little or no new research and development.

Light rail transit is an urban electric railway having a largely segregated but not necessarily grade-separated right-of-way. Speeds, capacity, and overall performance are generally lower for light rail transit than they are for fully grade-separated rapid transit, yet LRT is substantially superior in capacity and performance to any form of transit operating on public streets or roadways in mixed traffic. Because it is not fully grade separated and because it is not designed to have as high an overall performance and capacity as rapid transit does, LRT generally costs much less to construct per route mile (route kilometer). This lower cost allows LRT to be economically justified in urban areas or in specific corridors where conventional rail rapid transit is not feasible either because of cost or demand considerations.

Light rail transit is a medium-cost mode that provides a medium-speed service for a medium volume of passengers. It therefore falls into that cost-service region between conventional rail rapid transit and motor bus, yet there is considerable overlap upward into the traditional cost-service domain of rail rapid transit and downward into the domain for which motor buses have been considered most appropriate.

During the past 2 decades, there have been a number of novel modes proposed to fill various medium-speed and capacity needs. It has been evident to planners and researchers, as well as to inventors and promoters, that medium-demand corridors exist in many medium and larger sized metropolitan areas consituting a significant market for these novel modes. However, any new technological innovation needs considerable research and development before it can be used in the marketplace. Highly publicized difficulties of the few operating prototypes of some new modes give cause for caution before such modes are adopted widely. Yet the need to service mediumdensity corridors is clear to many planners and political leaders.

Light rail transit is suitable to fill this role today. Light rail transit is an evolutionary development of the street railway and full-scale rapid transit and has some features of both. Its subsystems have been fully developed and proved, and there is no need for costly, time-consuming research and development.

Because it is the result of evolutionary development, some say that LRT is an obsolete concept. It must be pointed out to such critics that the 2 major modes of travel today, the automobile and the airplane, had their beginnings at about the same period (1890-1910) as did the electric railway (1, pp. 196-197, 280-299). Today's automobile and its related roads and today's aircraft and related ground support evolved over approximately 70 years of, at times, intermittent and, at other times, very active development and culminated in reliable and widely accepted equipment. It appears that evolution has produced more useful transportation devices for society than revolution has.

Let us therefore look more closely at the physical, operational, and performance characteristics of LRT to see how it can contribute to improving urban and suburban transit.

PHYSICAL CHARACTERISTICS OF LIGHT RAIL TRANSIT

The 2 basic characteristics of the light rail mode are its guidance system (steel wheel on steel rail) and its power source (externally generated electric power). Both have evolved from the predecessors of LRT—the street railway and rapid transit.

The railway track and its related flanged steel wheel provide the simplest, cheapest, most effective, and most thoroughly developed guideway known to engineering. It has been in use for more than 150 years (1, pp. 66-93) on railroads and for 90 years or more in urban railways, yet it is still far superior to any other form of guidance available for implementation today. The railway is the only guideway that is equally adaptable to tunnel, aerial structure, freeway median strips, medians of boulevards, grade on private rights-of-way, and paved streets in mixed traffic. No other guideway, available now or proposed, is this versatile. If the railway had not already been in common use, its invention would be heralded as a great breakthrough! Switches and crossings are fully engineered and can be ordered from a number of suppliers.

The use of externally generated power supplied to vehicles at 600 Vdc provides environmentally clean energy at the use point and permits operating in subways and other enclosed areas with no ventilation problems. It also allows very high installed horsepower (wattage) per vehicle if desired, which is far more difficult to provide in internal combustion engines. The use of direct current with a steel railway track allows a single current collector for the positive side and the use of the track for the negative side. This obviates the need for multiple collectors as required for some of the new modes. The problems of these are just beginning to be appreciated. Simplicity of its guideway and power collection system are the primary virtues of LRT. From these basic items, a complete system has been developed.

The right-of-way, including track, wayside power, communication, and signal systems, is the physical foundation for this fixed guideway system. Rails used are somewhat lighter than those generally used for main-line railroads or rail rapid transit. The rails are about 100 lb/yd (50 kg/m) or somewhat less for present day installations compared with 115 lb/yd (55 kg/m) to 135 lb/yd (60 kg/m) for main-line railroad. This weight differential can result in a significant difference in cost for a complete system.

Width required for a double-track light rail right-of-way, including adequate platforms, is approximately 40 ft (12.2 m). Between stations, 24 to 35 ft (7.5 to 10.5 m) often suffices.

Light rail transit is especially versatile for both vertical and horizontal curvature; the new Boeing light rail vehicle (LRV) is designed to take a curve with a 42-ft (12.8-m) inside radius (2); traditional street railway equipment, exemplified by the PCC car still in use in most U.S. light rail systems, could negotiate a 36-ft (11-m) radius (3). Such curves can be negotiated only at very low speeds [10 to 15 mph (16 to 24 km/h)]; therefore, their use generally is not recommended; however, such curves can be used where civil engineering needs make it necessary or expedient. The Boeing LRV can accept a vertical curvature radius of 310 ft (95 m) on a crest of a hill and 460 ft (140 m) in a sag (2). Nonarticulated cars can accept even more severe vertical curvature. While it is usually desirable to employ the largest possible radius to allow maximum operating speed, it is a strong advantage, especially in urban areas, to have highly versatile geometric characteristics when laying out a given line or system. It is therefore possible to install LRT in places where other guided modes cannot fit.

For types of right-of-way, LRT is the most versatile of any guided system. Its track may be on a private right-of-way, at grade, or grade separated. If it is below grade, surface streets pass over the light rail line. The track also may be on an aerial structure or in a median strip of a freeway; both provide grade separation. More commonly, the median of a boulevard or arterial road has been used with infrequent grade crossings with other streets. Often such crossings are protected with signal lights, railroad gates, or traffic signals with preemptive control to give LRVs priority. In congested city centers, subway sections have been used for short distances. In some places, particularly in western Europe, segregated paved track is used in the city center, sometimes on thoroughfares on which automobiles are excluded entirely (5). In streets that already have street railway track or have traffic flow light enough to permit it, light rail track can be installed in the street pavement and LRVs can be operated in mixed traffic. Each of these right-of-way variations can readily be employed within 1 given system, or if required, on 1 route. The same vehicle can be used throughout.

Grades of 4 to 6 percent are common in light rail practice and pose no particular difficulty other than a moderate reduction of speed on an upgrade and an increase of required braking distance on a downgrade. There are a number of examples of substantially steeper grades that, although their occurrence is infrequent, indicate clearly the alignment versatility of the light rail mode. For example, the portal on the San Francisco Municipal Railway system (Muni) has a grade of 8.9 percent. Muni has a grade of 8.6 percent leading to a curve of 42.5-ft (12.7-m) radius on the L line. The new Boeing LRV is designed to operate over this grade and curve combination (2).

Light rail stations can range from a stop sign painted on paved streets to simple trackside platforms on private rights-of-way. These platforms often have a small shelter, or controlled access stations such as those used on rail rapid transit subways or aerial structures could be provided. Where traffic is heavy and prepaid fare collection is desired, as it is on conventional rapid transit, light rail station design is nearly identical to that of conventional rapid transit. There is a strong tendency toward simple, inexpensive stations on nearly all existing light rail installations.

The size and weight of the LRV are usually less than that of rapid transit vehicles. The Boeing Vertol-UMTA standard LRV currently being built for Boston and San Francisco is 72 ft (22 m) long and 8.5 ft (2.55 m) wide; it rests on 3 trucks; the center unpowered truck is under an articulated joint (2). The distance between truck centers is about the same as it is on the existing single-unit PCC streetcars being used on the same routes. These measure 46 ft (14 m) long and 8.33 ft (2.5 m) wide; there is 22.75 ft (6.8 m) between truck centers (3). This results in a rather long overhang on the front and rear of the car, the effect of which is minimized by some tapering of the car ends. Height is typically about 10 ft (3 m) over the roof, plus 1 or 2 ft (0.3 to 0.6 m) more for whatever current collecting device is installed (trolley pole or pantograph). Some PCC cars were built to lengths of 50 ft (15 m) and widths of 9 ft (2.7 m). In Europe, cars are usually narrower and shorter than they are in North America. The spaciousness of LRVs permits a wide variety of interior arrangements. They can be equipped with spartan seating allowing extensive standing room for high-density, short-haul travel, or they can emphasize comfortable seating for long-haul suburban traffic.

Nearly all new transit equipment is air-conditioned. Light rail vehicles can be air-conditioned if desired. Because of the climate of San Francisco, the LRVs for that city are well ventilated, not air-conditioned. An important aspect of the air-conditioned LRV is that its performance is not impaired by the addition of air-conditioning equipment. Air conditioning is powered separately by externally supplied electrical energy and is in no way connected with the vehicle propulsion system. In diesel motor buses this is not the case. The bus engine generally powers the air-conditioning compressor and blowers. This degrades bus performance whenever the air-conditioning system is operating. In some situations, a driver can have the engine propel the bus or air-condition it but not both at the same time!

An important and often overlooked characteristic of LRVs and the entire light rail concept is the relative simplicity of this mode compared with contemporary rail rapid transit systems and particularly compared with fully automated new modes. The more equipment or subsystems there are in a complex system, the more there is to go wrong. A reliability engineer can calculate this readily. Most contemporary light rail installations demonstrate a high degree of technical reliability and operate a high percentage of their vehicle fleets during each rush hour. The percentage of vehicle down time is low, and maintenance needs are moderate.

TRAFFIC CONTROL FOR LIGHT RAIL SYSTEMS

The simplest traffic control for light rail systems is on-sight control, which means that the operator of a train or car merely operates the vehicle an estimated safe braking distance behind the preceding vehicle. This type of control will be retained on the street portions of both Boston and Muni routes, and is also commonly used on street or surface sections of European light rail lines.

A higher type of traffic control is provided by block signals that provide a visual indication to the train operator of the condition of the block ahead or speed at which to run or both. Block signals are commonly used on private rights-of-way (including elevated and subway sections) of many present light rail lines. These depend on the operator's observing and responding to visual indications on wayside signals. It is uncommon to employ rapid-transit-type trip stops on LRV, particularly those that may operate in street traffic on a portion of their route because an unwanted obstruction can too easily inadvertently trip a car and cause an emergency stop. (Shaker Heights, Ohio, Rapid Transit trains do use mechanical trip stops on the joint section of track shared with Cleveland Transit System trains. This use of trip stops by light rail transit is unique to the United States.)

Several European light rail lines using wayside signals have an intermittent inductive train stop that triggers an emergency brake application if a train attempts to pass a red signal (5). This type of stop enforcement is unaffected by encounters with other vehicles or debris in the street.

Cab signals may be readily adapted to the light rail mode; in fact, this is being done for the Market Street Subway portion of Muni. The cab-signal concept has been used for many years by certain railroads and has been applied to a number of rapid transit lines during the last decade. Normally a cab-signal system will indicate visually to the train operator the speed at which to operate. The system also will apply the brake to slow or stop the train if it is operated in excess of the indicated allowable speed. The cab-signal concept provides all-weather capability because the train operator does not need to see wayside signals. This allows full-speed operation in snow, rain, or fog.

The primary virtue of cab signals is that they improve performance. A train (or vehicle) need not proceed at restricted speed from, say, a yellow signal to the next signal if the signal should clear to green. With a cab signal, the operator immediately knows the condition of the block ahead and can accelerate or decelerate accordingly. In addition, where visibility is impaired, as in a subway section with curves, cab signals provide the operator with a continuous indication of the block or blocks ahead. Cab-signal systems therefore provide somewhat higher capacity and safety over wayside-signal systems.

It is natural in a cab-signal system to progress to fully automatic train operation. This would add the capability of automatic station stops in which deceleration to a stop and positioning at a platform would be programmed as has been done on several recently implemented rail rapid transit lines. No light rail system yet implemented or proposed has opted for a fully automatic train operation.

OPERATING CHARACTERISTICS

Light rail maximum speeds are in the range of 40 to 60 mph (65 to 95 km/h). The obsolescent but still used PCC streetcar has a maximum speed of 42 mph (66 km/h); the top speed of the new standard light rail vehicle (SLRV) is 55 mph (88 km/h). Certain suburban light rail equipment can attain speeds in excess of 70 mph (110 km/h), but this is unusual.

Overall schedule speeds for light rail lines on fully segregated rights-of-way generally fall in the 15 to 35-mph (24 to 56-km/h) range depending on station spacing and degree of segregation. If the track is in the street, schedule speeds will be much lower; they will range generally from 10 to 15 mph (16 to 24 km/h), and maximum speeds will be limited to whatever the allowable speed is for traffic in the street. In most places, the speed limit is 25 to 35 mph (40 to 56 km/h).

Acceleration of 3 mph/s (1.33 m/s^2) is a generally accepted industry standard based on what a typical standing passenger can tolerate. The PCC streetcar was designed and built to attain a rate of 4.75 mph/s (2.11 m/s^2) in the lower speed ranges; some operating properties reduced this somewhat, however. For instance, San Francisco's PCC cars are set for 4.25 mph/s (1.89 m/s^2).

Acceleration of the Boeing LRV has been found to be 2.6 mph/s (1.16 m/s^2), but it holds this rate to a higher speed. Therefore, its overall performance is expected to be quite attractive when station spacing allows the vehicle to attain its 55-mph (88-km/h) running speed.

Past accomplishments indicate that it is technically possible to attain whatever rate of acceleration is desired within the limitations of adhesion. The tolerance of standing passengers and the various costs related to installing the desired horsepower (wattage) (or torque) are the controlling factors.

Headways between vehicles on light rail lines vary widely. Minimum headways traditionally have been achieved on unsignaled routes at relatively low speeds operating with on-sight control under visual rules. Under such conditions, 1-min headways commonly have been attained; in some cases, 30-s headways were used for relatively short periods such as 15 to 30 min. Such frequent service requires effective dispatching to prevent irregularities in operation.

Minimum achievable headways depend on many factors. The major ones are vehicle speed, braking rates, degree of safety, system response time, train length, station dwell time (which is influenced by number, design, and arrangement of door openings, doors, and steps, and number of passengers boarding and alighting at stations), and the effect of random influences on the line. Random influence on the line is determined primarily by the degree to which the right-of-way is exclusive.

With wayside signals, speeds can be increased safely, but then this forces an increase in required braking distance. As a result, headways become longer, so that headways of about 60 s are about the best that are achieved on signaled lines having moderate speeds in the 30 to 40-mph (48 to 64-km/h) range. In certain special situations, closer headways are attained by using permissive signals that allow a vehicle to pass a red signal at restricted speed, which is typically 15 mph (24 km/h). Strictly speaking, a train that has passed such a red signal is operating under visual rules rather than signal protection.

Higher speeds, such as 60 to 70 mph (84 to 110 km/h), have been attained on a few suburban light rail lines. These systems typically use wayside signals sited to permit headways of 3 to 5 min because that is all that traffic requires. Fixed wayside signals (with mechanical or inductive trip to enforce a stop signal) generally allow headways of 2 min with speeds in the 45 to 60-mph (75 to 95-km/h) range.

At present, no light rail line in the United States or Canada is using a cab signal or automated mode of operation. However, Muni is installing cab signals in its Market Street subway, and these will offer several operating speeds with a maximum of 55 mph (88 km/h). Headways of 60 s are expected.

Equally important to capacity operation is that light rail systems can operate economical off-peak headways of 10, 12, 15, or even 20 min by using 1-person vehicles with fare collection on board. Although such headways are not difficult, that they have been popular with many riders, particularly when they repeat every hour, has been an important characteristic of existing light rail systems.

A few light rail routes have single track with passing sidings for opposing vehicles or trains to pass. In some cases, single track has been used simply for economy as it has on outlying suburban lines requiring infrequent (15- to 30-min) headways. In other cases a short, single-track section can provide an inexpensive means of coping with a physical or geographic constraint. Bridges and tunnels are typical places where single track has been employed successfully.

Riding quality of LRVs can be described as good to excellent. This depends greatly, however, on the maintenance of both vehicle and roadbed. Ride is superior to that of buses because the body of a rail vehicle is carried on 2 or more trucks that smooth out irregularities in the track (guideway). Noise levels of LRVs are low. Most cases are considerably less noisy than diesel engine buses. Most contemporary LRVs are equipped with resilient or rubber-cushioned wheels that lower or nearly eliminate wheel squeal on curves.

Visual aspects of LRVs are pleasing. Large picture windows provide the passenger with a clear view of the station or stop or scenery. The total effect of a light rail line is usually unobtrusive, although some object to the visual effect of overhead wire components.

The combination of a pleasant ride at attractive speeds is one reason many motorists willingly park their cars to ride an electric-rail-transit vehicle.

CAPACITY

A light rail route can be designed to economically handle up to 12,000 or 18,000 passengers/track/h. Higher numbers are attained by using multiple-unit trains. For instance, the 72-ft-long (21.6-m-long) Boeing LRV would have a rush-hour capacity of about 150 to 180 passengers, depending on seating arrangements and assumed space per standee. A 3-vehicle train thus would accommodate easily 450 passengers. At a 2-min headway, 30 such trains could pass a given point in 1 h. This results in an offered capacity of 13,500 passenger spaces/h. A 4-vehicle train would handle 18,000 passengers/h although, at this level of traffic, fully grade-separated rail rapid transit may be a better choice.

Several existing light rail systems carry 10,000 to 15,000 passengers/day on a given route. Such volumes require that only 2,000 to 4,000 passengers be carried during a rush hour, which is attained easily with 1- and 2-car trains on 3- to 5-min headways. Yet these passengers enjoy a speedy ride not attainable by transit vehicles in mixed traffic. This is what generates higher per capita LRT ridership in a given corridor.

A light rail system can be designed for modest traffic and can be upgraded from time to time as demand increases. It is not necessary to invest large amounts of money in an initial system at 1 time. Investment can be distributed over a long period of time and grow in increments as the need arises. Several options in vehicle and station characteristics give a designer numerous investment choices and combinations.

A system can be designed for moderate headways of, say, 5 min. As traffic increases, train length can be increased from 1 to 2 or even 3 or more vehicles. Concurrently, stations must be lengthened (which may require substantial investment) and substation capacity increased to provide power for longer trains. On the other hand, it is sometimes easier to decrease headways from, say, 5 min to 2 min with 1- or 2-vehicle trains before additional capital is invested in lengthening stations and increasing substation capacity. It also might be necessary to alter significantly a signal system when changing from a 5- to 2-min headway. This could be costly. Short trains on short headways and longer trains on longer headways have their place. Both may be needed.

COSTS

The basic attribute of light rail transit is that the costs of installing a light rail system are significantly less than they are for fully grade-separated rail rapid transit or for fully automated novel modes requiring full grade separation. Yet, light rail can provide a fast, frequent, attractive service that can attract a significant number of riders who would not (and do not) use conventional surface transit.

Light rail vehicles cost from 450,000 to 600,000 dollars for a 6-axle articulated vehicle (Boeing Vertol-UMTA SLRV being built for Boston and San Francisco). A single-unit, 2-truck car that is 50 ft (16 m) long and 8.5 ft (2.45 m) wide is expected to cost about 250,000 dollars in Canada (4). Although the unit price of a vehicle appears high, it should be borne in mind that its service life is about 30 years; its schedule speed will be in the region of 20 to 25 mph (32 to 40 km/h); and its capacity ranges from 75 passengers (for a single car seating 50 to 60) to more than 200 for the articulated LRV. This is 2 to 3 times the life of a bus, 2 to 3 times the average operating speed of a bus, and from one 1.5 to 3 times the passenger capacity of a bus.

Construction of a double-track light rail route should cost from 4 to 8 million dollars/route mile (2.5 to 5 million dollars/route km). This includes track, power distribution facilities, signals, and communications. It does not include land. Aerial structure costs 10 to 20 million dollars/mile (6 to 13 million dollars/km). Subways cost 30 to 50 million dollars/mile (18 to 30 million dollars/km). A yard and maintenance shop might cost 3 to 5 million dollars for a car fleet of 50 to 100 vehicles.

A light rail line needing 50 to 100 cars and 10 to 15 miles (16 to 24 km) in length that is constructed on surface might cost between 50 and 100 million dollars. If an abandoned or underused railroad line is available, costs might be significantly lower, possibly as low as half that amount, because new civil engineering work would be minimized.

CONCLUSIONS

Light rail transit is a medium-cost mode that will fit many corridors or urban areas requiring a medium-capacity and medium-speed mode. Light rail transit is versatile in where its guideway (railway track) can be installed. It can be completely grade separated; it can be segregated horizontally from other traffic; it can be within a mixed traffic stream. The conventional rail track is the only guideway that is so versatile.

Light rail vehicles are attractive to passengers and are environmentally clean because they are propelled electrically. Noise and visual effects levels are low.

The performance of LRT is superior to any surface mode and is nearly as good as that of some rail rapid transit or novel modes. Yet it can cost much less.

Light rail transit may be an attractive transit mode for some locations that have not been candidates for any form of rapid transit. It is a mode that exists now and can be implemented now with little research and development. It is a mode with proved capabilities.

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