LIGHT RAIL TRANSIT SYSTEM
EVALUATION

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Evaluation of a light rail transit system involves many considerations that are specific to sites or systems and cannot be treated in a general study. However, it is possible to establish a value for reductions in running time relative to reductions in direct operating cost, savings in passenger time, and increases in net system revenue. These values, which depend on passenger volume, can be related to capital cost improvements. These include eliminating on-street running, eliminating grade crossings, instituting high-platform loading, and varying fare-collection systems. Brief commands are included on other factors of system evaluation including reliability, safety, and provision for future growth. The paper concludes that, although certain intensive improvements are likely to be justifiable, these must depend on a more detailed system-specific evaluation. In general it suggests that the planning and design of light rail transit should keep the system as simple as possible and, on the surface, avoid automatic application of rapid transit or railroad standards—and costs.

Light rail transit encompasses a wide range of electrically propelled, steel-wheel vehicles. Many costs, both capital and operating, are site specific or system specific. This makes a general economic evaluation of LRT systems difficult and, in some respects, dangerous because applying general conclusions out of context is too easy.

This report will concentrate on the economic trade-offs between capital and operating costs with specific respect to the 2 predominant advantages of LRT: its low infrastructure costs when existing rights-of-way are used and the increased labor productivity possible with higher speeds, larger vehicles, and multiple-unit operation.

LRT involves a system with a basic infrastructure cost of 1 to 2 million dollars/mile (0.6 to 1.2 million dollars/km), excluding land and vehicles but including most basic stations and spacing signals. Vehicles and their storage and maintenance facilities will add 400,000 dollars/mile (249,000 dollars/km) for every 1,000 passengers per peak-hour direction (phd) at a typical schedule speed of 20 mph (32.2 km/h). (Vehicle cost is inversely proportional to speed and can be factored accordingly.) Major increases to the infrastructure cost will occur if grade separations, elevated or below-grade operation, elaborate stations, sophisticated signaling, or remote power supervision is required. In part, an economic justification for these extra infrastructure costs can be related to reductions in operating costs.

Operating costs used in this evaluation are in Canadian dollars and are derived from 1975 estimates by the Toronto Transit Commission (TTC) for new 4-axle light rail vehicles operated under union requirements with a basic hourly operator rate of $6.50. These operating costs can then be adjusted for 6-axle and multiple-unit operation as outlined in Table 1. For the multiple-unit operation we assume that the union will tolerate 1 person per train and either off-vehicle or self-service fare collection. Either fare collection procedure may incur additional costs. Although the factoring of costs by 2 or 3 for multiple-unit operation is not strictly correct because of the fixed and variable components of these costs, it is adequate for this exercise. The
TTC estimates are for a fleet of 200 new cars and high standards for track maintenance and overhead. The costs were derived for average schedule speeds and have been adjusted to a 20-mph (32.2-km/h) average. Adjustments for other average speeds can be made accordingly. Maintenance of track and overhead are approximately independent of speed in this range. Power and fuel; vehicle maintenance, cleaning, and service; and transportation and fringe benefits are inversely proportional to average schedule speed at the respective approximate ratios of 25, 50 and 100 percent.

TIME VERSUS COST

There is little question that the major trade-off in an economic evaluation of light rail transit is that between travel time and capital cost. In a planning study that examines an inventory of possible rights-of-way in potential corridors of demand there are 2 considerations:

1. Deviations from the low-cost right-of-way to better serve the corridor, particularly potential major patronage generators; and
2. Improvements in the low-cost right-of-way to decrease travel times.

The deviations mentioned in item 1 could involve massive increases in basic infrastructure cost to provide a new at-grade, elevated, or below-grade alignment. These are wholly site specific and are outside the realm of this paper. The improvements mentioned in item 2, whether they be grade separations, route relocations, or high-platform stations to reduce loading time, involve the same time-cost relationship.

The dollar value of reducing travel time has 3 major components and is, of course, volume dependent. The 3 components are direct operating cost, value of passenger’s time, and time elasticity.

Direct Operating Cost

The most tangible savings are lowered direct operating costs resulting from reduced running time. The data given in Table 1 indicate the following direct operating cost (DOC) savings per train minute saved:

1. \( 20.3 + \frac{86}{V} \) cents/min/single 6-axle car,
2. \( 20.3 + \frac{172}{V} \) cents/min/2-car train, and
3. \( 20.3 + \frac{258}{V} \) cents/min/3-car train.

\( V \) is the average system schedule speed in mph (km/h). The values are for instances with 1 operator per train. If each vehicle must have an operator, the single-car factor can be multiplied accordingly.

The number of vehicles required to carry 1,000 passengers/phd/mile (1.6 km) of line at V mph (km/h) with a speed margin and layover allowance of 10 percent is 14.67/V, based on an average peak-hour occupancy for a 6-axle vehicle of 150 passengers. Peak-hour service with buildup and build down involves this number of vehicles per mile (kilometer) of line operating 6 h per day for 300 days per year. It is reasonable to assume that off-peak service for 14 h a day plus weekends will double this annual "peak" figure to produce

1. 52,800 annual vehicle h/V per 1,000 passengers/phd/mile (1.6 km) of line and
2. 52,800 annual vehicle miles (84,995 annual vehicle km) per 1,000 passengers/phd/mile (1.6 km) of line.

The assumption is based on a typical Canadian urban load distribution. Operations with high peaking or no attempt to provide full transit service for 18 to 20 h/day and 365 days/year will involve lower savings. Again, this is a system-specific evaluation.
Note that, although there will be the average 150 passengers per vehicle in the peak hour, the load factor over the peak period and off-peak period will be substantially lower. The annual cost savings for each 1-min reduction in running time can then be expressed in 1975 dollars as 528 (20.3 + 86/V) per 1,000 passengers/phd/year/min reduction in travel time. This expression can be applied to a range of light rail operations.

1. A line with passenger demand of 2,000 passengers/phd at a schedule speed of 20 mph (32.2 km/h) would save 25,000 dollars/year/min reduction in travel time.
2. A line with passenger demand of 5,000 passengers/phd at a schedule speed of 20 mph (32.2 km/h) is likely to involve multiple-unit operation in the peak period. If an operator is required on each vehicle, the savings per minute is 65,000 dollars/year/min reduction in travel time. With maximum labor efficiency, the savings would be 50,400 dollars/year/min reduction in travel time for a 2-car, multiple-unit operation.
3. A line with passenger demand of 8,000 passengers/phd and headways of just more than 1 min would produce savings of 104,000 dollars/year/min reduction in travel time for a single-car operation. However, at this headway, 3-car, multiple-unit trains are appropriate and would show a savings of 87,000 dollars/year/min reduction in travel time.
4. A line with a demand of 12,000 passengers/phd would have a savings of 156,000 dollars/year/min reduction in travel time with 1 operator per car or 131,000 dollars/year/min reduction in travel time with 1 operator per train.

The results of these 4 hypothetical systems are given in Table 2. The annual reductions in DOC have been capitalized at 10 percent. This exercise can be repeated for any patronage level and easily can be tailored to the specifics of any projected system. Therefore, more than the mere generalizations and assumptions in this paper can be used.

Value of Passenger Time

It is possible to assign a value to passenger time savings in a cost-benefit analysis. Cost-benefit analysis is a much abused field, and some practitioners can prove that almost anything is economical if they are given enough leeway with the intangible factors. However, cost-benefit analysis does have some value, particularly in comparing reasonably similar alternatives when the input factors are clearly defined.

The value assigned to time savings is often taken as half the average hourly income of the community being studied. For the purpose of this exercise, 4 dollars/h will be used. The average includes not only the salaries of hourly income earners but also those of professionals. (The value used for Shaker Heights, Ohio, would be greater than that used for Newark, New Jersey.) A peak-hour volume of 1,000 passengers/phd corresponds to some 6,000 daily riders in the United States and some 8,000 in Canada (the difference is due to the significant difference in off-peak transit use). In this paper, we shall be working with the Canadian pattern of riding.

A reduction of 1 min in running time will save 40,000 passenger h/year per 1,000 passengers/phd, which is a value of 160,000 dollars. This amount is independent of average schedule speed or multiple-unit operation. The resultant savings are given in Table 3 for the 4 hypothetical systems.

Time Elasticity

The final factor in this evaluation is the effect of time on ridership and the generation of any extra revenue. Time elasticity is a difficult but important subject. Time elasticity applies to overall transit travel time and cannot be used on a per-mile (per-kilometer) basis as the other factors can. This makes it a system-specific evaluation, but, if we take a 10-mile-long (16.1-km-long) line with an average speed of 20 mph
(32.2 km/h) and an average ride length of 7 miles (11.3 kilometers) and assume that the access-egress time averages 15 min, then we can conclude that an elasticity of +0.35 will give a passenger a gain of about 1 percent/min reduction in running time.

It can be expected that a passenger increase in the peak hour would involve extra transportation cost, but increases in the shoulder of the peak or at off-peak times will only slightly increase the load factors and thus will produce extra revenue with no DOC increase. If we assume that half the passenger increase is in this category and that revenue approximates 6 cents/passenger mile (3.7 cents/passenger km) less approximately 20 percent to reflect senior citizens’ fares, then we can conclude that the corresponding annual savings is as that given in Table 4.

The dollar amounts given in Table 4 are minor compared to the DOC decrease or the value of passengers’ time. However, passenger generation has other important benefits that cannot be quantified here. These include reduction in road traffic, lowered congestion, fewer road accidents, and less pollution. These factors are more important in the overall comparison of light rail, the transit status quo, and other modes of potential transit improvement than they are in a cost-benefit evaluation of light rail capital improvements.

The capitalized savings given in Tables 2, 3, and 4 could be summed, but it is undesirable to consider together tangible and less tangible benefits. One of the sad features of cost-benefit analysis is the confusion of assumption with truth.

**CAPITAL IMPROVEMENTS**

Let us now relate the savings that result from reduced running time with possible capital improvements.

**On-Street Operation**

Where no suitable alignments are available, street operation is possible. In mixed traffic, speeds of 10 to 15 mph (16.1 to 24.1 km/h) are typical for transit outside the city center. This is 6 to 4 min/mile (3.7 to 2.5 min/km) compared with the 3 to 2 min/mile (1.9 to 1.2 min/km) that light rail is capable of on private right-of-way, which represents a potential running time savings of 1 to 4 min/mile (0.6 to 2.5 min/km). The options to be examined would be preferential lane marking and traffic signaling at minor cost; elevated operation at some 10 to 15 million dollars/mile (6.2 to 9.3 million dollars/km); or below-grade operation at 15 to 20 million dollars/mile (9.3 to 12.4 million dollars/km), excluding stations. A new private surface right-of-way requires a minimum of 3 acres of land/mile (0.75 km²/km), which will vary greatly in cost; it could involve acquisition of thirty 60,000 dollar residences for a total cost of 2 million dollars. Examination of Tables 2, 3, and 4 will show that the 2 lower cost alternatives have a positive cost-benefit ratio but that the high-cost alignment options will balance approximately only if the less tangible cost savings associated with passenger time savings are taken into account.

**Grade Crossings**

Ideally, there should be no delay where grade crossings can be fully protected and light rail transit can be given absolute priority. There may be opposition to the potential traffic delays, and it is important to note that, unlike conventional railroad crossings where protection circuits have to guard against slow trains in addition to fast trains with potentially long cycle times, light rail transit has fast, uniform service that will minimize crossing time. For example, 5,000 passengers/phd can be served by 3-car, 6-axle trains on 5-min headways that require two 20- to 30-s occupancies per headway period; this would hold road traffic for less than 10 percent of the time. No speed restrictions on light rail transit should be necessary or tolerated at grade crossings.
Table 1. Estimated operating costs for new light rail vehicles.

<table>
<thead>
<tr>
<th>Item</th>
<th>Single-Unit Vehicle (cents/mile)</th>
<th>Multiple-Unit Vehicle (cents/mile)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maintenance of track, overhead, trolley,</td>
<td>4-axle</td>
<td>2 × 6-axle</td>
</tr>
<tr>
<td>traction, power distribution, and buildings</td>
<td>6-axle</td>
<td>3 × 6-axle</td>
</tr>
<tr>
<td>and service</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vehicle maintenance, cleaning, and service</td>
<td>27</td>
<td>34</td>
</tr>
<tr>
<td>Power and fuel</td>
<td>15</td>
<td>40</td>
</tr>
<tr>
<td>Transportation</td>
<td>6</td>
<td>22</td>
</tr>
<tr>
<td>Fringe benefits</td>
<td>51</td>
<td>51</td>
</tr>
<tr>
<td>Total</td>
<td>111</td>
<td>125</td>
</tr>
</tbody>
</table>

Note: 1 cent/mile = 0.6 cent/km.

Table 2. Reduction in direct operating cost for a 1-min reduction in running time.

<table>
<thead>
<tr>
<th>Line Volume (passengers/phd)</th>
<th>Annual Savings in Direct Operating Cost (1975 Canadian dollars)</th>
<th>Capitalized Value (1975 Canadian dollars)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1 Operator/Car</td>
<td>1 Operator/Train</td>
</tr>
<tr>
<td>2,000</td>
<td>26,000</td>
<td>26,000</td>
</tr>
<tr>
<td>5,000</td>
<td>65,000</td>
<td>50,400</td>
</tr>
<tr>
<td>8,000</td>
<td>104,000</td>
<td>87,000</td>
</tr>
<tr>
<td>12,000</td>
<td>156,000</td>
<td>131,000</td>
</tr>
</tbody>
</table>

Table 3. Value of passenger time savings for a 1-min reduction in running time.

<table>
<thead>
<tr>
<th>Line Volume (passengers/phd)</th>
<th>Annual Savings for Passenger Time (1975 Canadian dollars)</th>
<th>Capitalized Value (1975 Canadian dollars)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2,000</td>
<td>220,000</td>
<td>3,200,000</td>
</tr>
<tr>
<td>5,000</td>
<td>800,000</td>
<td>8,000,000</td>
</tr>
<tr>
<td>8,000</td>
<td>1,260,000</td>
<td>12,600,000</td>
</tr>
<tr>
<td>12,000</td>
<td>1,920,000</td>
<td>19,200,000</td>
</tr>
</tbody>
</table>

Note: These figures are valid only at the “peak point” on the line. If the time savings is at the outer end of the line, fewer passengers will benefit and the results must be factored accordingly. Reduce the figures by 25 percent to apply it to a U.S. case with low, off-peak ridership.

Table 4. Net revenue increase for a 1-min reduction in running time.

<table>
<thead>
<tr>
<th>Line Volume (passengers/phd)</th>
<th>Annual Increase in Net Revenue (1975 Canadian dollars)</th>
<th>Capitalized Value (1975 Canadian dollars)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2,000</td>
<td>8,000</td>
<td>80,000</td>
</tr>
<tr>
<td>5,000</td>
<td>20,000</td>
<td>200,000</td>
</tr>
<tr>
<td>8,000</td>
<td>32,000</td>
<td>320,000</td>
</tr>
<tr>
<td>12,000</td>
<td>48,000</td>
<td>480,000</td>
</tr>
</tbody>
</table>
Where grade crossings are at or close to signalized road intersections, light rail transit passage will have to be phased with the control cycle. Preemption is possible, although there is some controversy over its value; for example, at close transit headways, it can be more effective to ensure that the transit headway will be a multiple of the traffic light cycle times along a route. Average holds at a traffic light with random arrival times average approximately 25 percent of the cycle time and are typically 15 to 20 s long. However, light rail vehicles (LRVs) must approach such a signal at a speed permitting a full stop; this restriction together with retardation and acceleration time can increase the average delay to 30 to 60 s. Grade separations using the low headroom of light rail transit and 6 percent ramp grades can be built under a 4-lane road (without major underground utilities) for as little as 500,000 dollars. Reference to the capitalized value of 1-min time savings shows that such a separation could be justified at relatively moderate passenger volumes.

Where grade crossings occur at stations, vehicle speed either entering or leaving will be quite low; therefore, any effect on running time will be minimal. Passenger-pedestrian grade crossings similarly are unlikely to have an effect on running time. This means that, in many cases, the cost and inconvenience of passenger underpasses or overpasses at stations are unnecessary, although traffic volume, approach speeds, and operator line of sight must be taken into consideration for safety purposes.

High-Platform Loading

Station dwell times can accumulate to an appreciable portion of total travel time. The time spent at stations can be reduced with high-platform loading, which in effect eliminates the steps into the vehicle. Certainly, all moderate-to-high-volume stations should be considered for high platforms. The cost increase need not be high. If all on-street stops are eliminated, a high-platform system will both minimize station dwell times and reduce vehicle capital and maintenance costs associated with the high-low loading mechanism.

An evaluation of high platforms actually is site specific, but let us consider, for example, a system with 2,000 passengers/phd, which is equivalent to 2,400,000 annual trips. A savings of 1 s/passenger (for loading and egress) would save around 40,000 dollars/year or a capitalized value of 400,000 dollars assuming 2 sets of double doors on single 6-axle cars. Time saving and its value at stations now take us into the question of fare collection and multiple door use.

Fare Collection

Fare collection is too large a subject to discuss in detail. Requirements for an efficient system are to minimize delays to vehicles and inconvenience to passengers. Where multiple-unit operation is suitable, it is desirable to avoid operators on other than lead cars. This introduces the difficult problem of union requirements; present staffing rules on North American properties have 1 person per car on light rail lines but not on rapid transit lines despite their somewhat nebulous difference. Off-vehicle collection, fully automatic or with station collectors, and passenger-operated doors can remove the need for more than 1 person/train, but can themselves introduce problems and high costs. European semiautomatic or self-service fare systems can be the best solution for multiple-unit light rail service. The self-service or semiautomatic fare collection common in Europe is quite distinct from the honor fare collection where no check is made on passengers' honesty. This system is used primarily in the Soviet Union. Honor systems would be totally unworkable in North America. Self-service systems can be used with an operator monitoring fare payment; in fact, exact cash fare is a type of self-service fare system. New systems may be able to introduce modifications to these methods. For example, in peak periods a few high-volume stations (usually in city center) can have off-vehicle collection; at other stations boarding passengers can use only the lead car where the operator is located. Off-vehicle pass and ticket
sales at a variety of outlets will minimize the inconvenience that results from exact-fare requirements. Pay-as-you-exit inbound and pay-as-you-enter outbound requirements are necessary with centrally staffed stations.

The potential for improved operator productivity on light rail systems with and without multiple-unit operation is substantial as shown by the data given in Table 1. Every attempt should be made to design the system and its fare collection and to negotiate with the unions to take full advantage of this potential.

OTHER FACTORS

Reliability

What are the chances for service disruption and how long will it last? Light rail without a wholly segregated right-of-way is difficult to analyze. At specific levels of maintenance, the interval (miles or kilometers) between in-service vehicle breakdowns can be predicted. Given the economic limitations on maintenance, vehicle breakdowns will occur, but disruptions can be minimized because LRVs can tow or push each other. Power supply, communications, and any signaling also will have failures. External incidents, such as trees taking down overhead wires, stalled automobiles on a street section, and building fires along the right-of-way, are likely to introduce the most problems.

These incidents may amount to two or three 2-h downtimes per year; on the average, operator strikes may lose 1 or 2 days of service per year. It is economic nonsense to provide central power supply supervision and power supply component redundancy in substations. These safeguards are only protecting against a 2-h outage every second year, and they can double or indeed triple the capital cost of the power supply system. All things are relative to the weakest link, and care should be taken not to overdesign specific items merely because of existing standard practice in rapid transit or railroading.

Safety

Light rail as an amalgam of surface transit and rapid transit should combine some safety facets of each. Collision damage should be less than what is normal for a bus system. Suicides will occur occasionally as they do on rail systems. Again, care should be taken not to overdesign to avoid every eventuality. Accidents and claims will be within the range of and probably less than normal transit experience. Recently, in my Vancouver light rail work I was arranging for a light rail median in a soon-to-be-rebuilt arterial road with a 35-mph (56.3-km/h) speed limit. The highway engineer was concerned that a road vehicle could veer from its lane and strike an LRV or that an LRV might strike a left-turning road vehicle where a turn lane trespassed on the track allowance. I had difficulty making the point that occasional incidents would be tolerable and that a 3-ft-high (0.9-m-high) concrete barrier or an elevated section would not be necessary. In the end I said to think of an LRV as a bus that has the advantage of running in a fixed, predetermined path. Light rail vehicles have the cross-section, axle-loading, and braking capabilities of a bus and are operated manually by an equally trained and capable operator. At times they should be regarded and treated just as a bus (but, I would hope, with higher traffic priority).

Light rail transit in subways will require the usual rapid transit safety elements. Greater power supply redundancy, ventilation control, and means to evacuate passengers in an emergency are appropriate only where long subway sections are planned. Short tunnels can have adequate safety without the expense and maintenance of such measures. How short is short will depend on the grade, natural ventilation, station location, and spacing.
Future Growth

How much allowance and cost should the initial design allow for future growth? The pre-metro concept of light rail transit can be advantageous, but it requires initial construction with large radii of curvature, lower grades, greater axle load, and slightly larger profile, all of which add to cost. Very few of the intermediate capacity corridors in North America that are candidates for light rail transit are likely to generate demands greater than 25,000 passengers/phd. If they do, good planning may indicate 2 intermediate capacity routes rather than 1 heavy route. Also there may be lower cost options that help to handle greater volumes such as staggered work hours.

Planning for upgrading to full rapid transit is important. But what is more important is to ensure that moderate growth within the scope of a light rail system can be accommodated. There must be adequate land adjacent to the maintenance and storage depot to hold a larger fleet of cars; station entrances must be able to accommodate higher passenger volumes; and platforms must be able to be raised or lengthened without crippling problems and costs.

CONCLUDING COMMENTS

It should be apparent that a general paper on system evaluation cannot answer the many planning and design questions in the application of light rail that are system specific and site specific. The basis for several economic trade-offs has been shown. There will be situations where it is cost effective to move to more massive infrastructure costs. However, the basic recommendation must be that light rail transit should be kept simple and on the surface. Light rail transit should be treated as its own genre, and automatic application of rapid transit or railroad standards and their ensuing costs should be avoided. Where appropriate, establishing union roles and fare collection systems specifically tailored to light rail operations should be considered.

Although a pragmatic systems evaluation is an important part of the planning process, planners should aim at a system that is less than 100 percent perfect because perfection is unnecessarily expensive. Light rail transit is a well-proved, flexible mode that tolerates compromise; therefore, compromise confidently. A single light rail line in operation is worth much more than a gross of planning studies in the files.