Operational Level-of-Service Index Model for Rail Rapid Transit

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In planning a new transit system or considering alternatives to improve services of an existing transit system, it is essential to consider both the system capacity and the levels of service. However, the concept of transit level of service, unlike that of highways, is not well established. Although the level of service is directly related to capacity, their relationship is poorly understood. A level-of-service index model is described that attempts to establish levels of service for rail rapid transit on the basis of vehicle load factors and headways. The model clearly demonstrates the relationship between level of service and system capacity. It may be used as the basis for developing practical tools for assisting transit agencies to plan a new system or for rail rapid transit operators to better manage train operation, including, for instance, selection of optimal operating schemes and assurance of service quality. The proposed model also makes it possible to compare the levels of service offered by different rail rapid transit systems on a common basis, and it may be used to develop a standard service guideline, which may be adopted by local transit agencies with modifications to reflect local conditions.

As urban congestion in U.S. cities continues to worsen and the need for air pollution reductions becomes more urgent, guideway transit systems are likely to play a larger role in public transit. Guideway transit ridership has been steadily increasing in the past several years (*1*). At the same time, transit funding has become more uncertain, limiting the ability of transit agencies to increase system capacity or expand or improve services. Service quality is, however, important for the success of public transit systems since they must compete with automobiles, which offer excellent flexibility, comfort, and convenience. To maintain the trend of increasing demand for guideway transit and to invest wisely for transit service improvements, one of the important questions that needs to be answered is how resources should be managed to provide the best possible service for a system with a given capacity.

A system's capacity is affected by many factors, including vehicle capacity, vehicle load factor (defined as the ratio of the number of passengers on board to the number of seats), number of vehicles operated per train, headway, and so forth. Some of these variables, such as vehicle load factors and headway, directly affect passenger comfort and convenience and thus the level of service. A relationship therefore exists between the system capacity and the levels of service.

Levels of service are a set of qualitative and quantitative measures describing the conditions under which transit operates and those that are perceived by passengers. Presently, levels of service for transit are not defined. For highways the emphasis has been on moving vehicles, so levels of service are defined on the basis of vehicle densities. However, transit is concerned with moving not vehicles but mainly people. Transit levels of service may include such considerations as the coverage of major residential areas and activity centers, comfort, speed, and service reliability. For instance, convenient schedules, comfortable vehicles, and frequent, fast, and reliable service contribute to the level of service. Many of the factors describing transit levels of service are determined by the technical capability of the transit equipment, whereas others depend on the operating policies of the transit agency, which specify service frequencies and allowable passenger loading.

Just as it is for highway design and operations, level of service is an important concept for transit because it is useful in transit service planning and may be used partly as a measure of service quality. For instance, questions such as how many passengers can be transported per unit of time at a specific level of service, how many transit vehicles are needed to provide a specific level of service and rate of passenger flow, and how many passengers can be transported with a given vehicle fleet at the designed level of service are often asked. These questions can be answered more easily if the relationship between rapid transit capacity and level of service is understood and clearly defined, which, unfortunately, is not the case.

There is much operational experience, and many analyses of rail transit capacity have been conducted. For instance, the Board of Supervising Engineers for Chicago Traction analyzed street railway capacity in 1912 and passenger dwell times by door width in 1916 (*2*). Lang and Soberman derived rapid transit track capacity formulas in 1964 (*3*). More recent studies by Homberger (*4*), Pushkarev et al. (*5*), Vuchic et al. (*6*), and Vuchic (*7*) addressed rail transit capacity theory and practices further. A Transit Cooperative Research Program project on rapid transit capacity is also being conducted (*8*). In contrast, there have been limited studies on transit levels of service. The concept of level of service has been rarely used in rail transit operations, or, if used, it has been used rather arbitrarily and its scope has been limited. Whereas the *Highway Capacity Manual* (*9*) addressed transit capacity and levels of service, it mainly emphasized bus transit, and the information related to rail transit is minimal.

This paper presents results from a study of the relationship between level of service and transit capacity for rail rapid transit. In particular, a level-of-service index model is described that is used to study the relationship between capacity and level of service. The purpose is to define levels of service more systematically for rail rapid transit to provide a basis for the development of practical tools that will allow transit agencies to carry out better service planning and operations, making rail rapid transit systems more cost-effective. In the remainder of this paper, the concept of transit level of service is discussed, and a level-of-service index model for rail rapid transit is described. Its use in understanding level of service, its relationship to system capacity, and its applications are discussed. Finally, conclusions are drawn and suggestions for future research are provided.

Transit Levels of Service

Meyer and Miller (*10*) give the following definition of level of service:

> Level-of-service is a qualitative measure of the effects of a number of factors (e.g., speed, travel time, traffic interruptions, safety, comfort, operating costs, volume-to-capacity ratios) on the performance of a facility. These qualitative measures have been grouped into different levels to represent different facility or service conditions.

Various factors affecting transit level of service from a passenger's viewpoint have been identified (*8,9,11–15*), which cover several different aspects of service quality. The following are some of the factors:

- Coverage of major residential areas and activity centers;
- Transportation capacity;
- Directness of service;
- System accessibility (walking distance, feeder buses or a background network of bus lines, ample parking facilities, simple transferring, and handicap accessibility);
- Service period (days of service and service span);
- Service frequency (headway);
- Convenient schedules;
- Journey speed;
- Comfort (acceleration and jerk of the vehicle, the number and arrangement of seats, space for standing passengers);
- Cleanliness;
- Service reliability (i.e., on-time performance);
- Total amount of service (for example, as measured by vehicle miles);
- Total travel time;
- In-vehicle time;
- Out-of-vehicle time;
- Walk time;
- Wait time;
- Transfer time;
- Number of transfers;
- Availability of information (schedule, facilities, amenities);
- Character of the information (e.g., clear and adequate signage);
- Safety and security of passengers, both actual and perceived; and
- Fares.

TABLE 1 Levels of Service and Loading Criteria for Bus and Rail Transit

Peak-Hour LOS		50-seat, 340-sq ft Bus (HCM 1985) Approximate Passengers/Seat	50-seat, 340-sq ft Bus (HCM 1985) Approximate Square Meters[a] per Passenger	Urban Rail (HCM 1985) Approximate Passengers/Seat	Urban Rail (HCM 1985) Approximate Square Meters per Passenger
A		0.00 to 0.50	1.22 or more	0.00 to 0.65	1.43 or more
B		0.51 to 0.75	1.21 to 0.79	0.66 to 1.00	1.41 to 0.93
C		0.76 to 1.00	0.78 to 0.60	1.01 to 1.50	0.92 to 0.62
D		1.01 to 1.25	0.59 to 0.48	1.51 to 2.00	0.61 to 0.47
E	E-1	1.26 to 1.50	0.47 to 0.40	2.01 to 2.50	0.46 to 0.37
	E-2[b]			2.51 to 3.00	0.36 to 0.31
F[c]		1.51 to 1.60	<0.40	3.01 to 3.80	0.30 to 0.24

[a] 1 square meter = 10.75 square feet
[b] maximum schedule load for urban rail
[c] crush load

Some of these variables may be measured, whereas others are difficult to analyze or quantify. In addition, it is extremely difficult, if not impossible, to combine all these variables to arrive at a single level of service indicator. For rapid transit systems that have fixed guideways, route coverage cannot be easily changed once construction is completed. Service quality is mostly dependent on the practices of the transit operators. These practices may be examined, in part, by looking at the service standards adopted by the transit operators. According to Zhao et al. (*15*), these service standards vary greatly in their comprehensiveness. However, service span, policy headway, and vehicle load factors are commonly included in service standards.

Of all the level-of-service factors, vehicle loading or load factor may be the one most often used in service standards. The value of the load factor varies from agency to agency and depends on the number of seats, the floor area available to the passengers, anticipated average trip lengths, acceptable comfort level in terms of space per passenger, available operating funds, travel demand, and even political considerations. For instance, the largest number of seats and smallest number of standees should occur on the longer suburban bus routes or on commuter rail routes where a higher level of comfort is essential. Table 1 compares the levels of service defined on the basis of vehicle loading for bus transit and for urban rail transit (*9*). Level of Service A (LOS A) indicates the best level of facility performance, whereas LOS F indicates the worst.

Table 1 indicates that the recommended load factor for a standard bus with a normal scheduled load is between 1.26 and 1.50 passengers per seat with an average of 4.3 to 5.1 ft^2/passenger. Suggested load factors for urban rail transit vehicles are higher than those for bus transit. LOS D allows up to two passengers per seat and a minimum per passenger space of 5.0 ft^2. It is consistent with the use of 5.4 ft^2/passenger, suggested by Pushkarev et al. (*5*) as a realistic passenger capacity for rapid transit lines. (The suggested loading criteria for rail transit are not specifically for rail rapid transit.)

Level-of-Service Index Model for Rail Rapid Transit

Whereas load factors mainly affect the comfort of passengers, they do not reflect overall service quality because other important variables are not considered. Other variables that may be controlled by rail rapid transit operators and have a direct bearing on system capacity are headway, travel speed, acceleration and jerk rates, the number and arrangement of seats, and service reliability. For rail rapid transit, the maximum vehicle speed operated is commonly about 80.5 km/hr (50 mph), whereas the actual journey speed is influenced by dwell times, station spacing, and track geometry, the latter two of which cannot be modified without major reconstruction. The acceleration and jerk rates are also rather standard. It appears that headway is the other most important controllable variable with a direct bearing on both level of service and system capacity. From a capacity perspective, headway refers to the number of trains (vehicles) operated per hour, which is one of the two variables that determine the system passenger capacity. From a passenger perspective, headway is related to the out-of-vehicle waiting time. The shorter the headway, the higher the level of service. On the basis of these considerations and for simplicity, we presently combine load factor and headway to derive an index of the level of service for rail rapid transit.

Construction of the Model

Many possible function forms may be used to construct the model. Our choice of a circle function has been mainly influenced by consideration of the relative importance of load factor and headway. According to a survey conducted among rail rapid transit professionals, these two variables were ranked as equally important (*15*). Because of the lack of evidence indicating otherwise, it has been decided that the function chosen will reflect equal contributions from both variables to the level-of-service index. This requirement is satisfied by the circular function because of its symmetry.

To use a circle equation requires that the two variables, headway and load factor, have the same value domain. This is not the case, since the value of load factor may range from 0.0 to 3.0, whereas that of headway may range from 3.0 to 30 min under normal operating conditions for most rail rapid transit systems. To satisfy the requirement that the two variables have the same value domain, headway domain must be mapped into the same range as the load factor domain. A linear mapping, however, does not reflect the fact that passengers are more sensitive to the same headway change in shorter headways than in longer ones. For instance, passengers are more sensitive to a headway change from 5 to 10 min than from 30 to 35 min. Therefore, a logarithmic scale of headway is used in the model to reflect the greater sensitivity of the level-of-service index to headway changes in shorter headways. The level-of-service index model has the following form:

$$I_{LOS} = \text{sqrt}\{L^2 + [\ln(\alpha + \beta H)]^2\} = \text{sqrt}(L^2 + H_e^2) \quad (1)$$

where

- I_{LOS} = level-of-service index,
- L = load factor,
- H = headway (min),
- H_e = $\ln(\alpha + \beta H)$ is the equivalent logarithmic headway (min), and
- α, β = parameters used to map the domain of headway into that of load factor.

The model may be considered as an extension of the level of service definition based solely on load factor as suggested in the *Highway Capacity Manual* (*9*) by adding a modifying term that accounts for the contribution from the headway.

The two parameters α and β allow H_e to be adjusted so that appropriate headway values may be chosen to correspond to different levels of service. The values of α and β may be selected such that (*a*) H_e has the same value range as L and (*b*) H^A, the headway that corresponds to the highest level of service (LOS A), will give the limiting H_e^A for LOS A using Equation 1, whereas H^F, the headway corresponding to the lowest level of service (LOS F), will give the limiting H_e^F for LOS F. For example, if load factor L is 0.5 at LOS A and 3.0 at LOS F, assuming $H_e^A = 0.5$ for LOS A and $H_e^F = 3.0$ for LOS F, one has

$$\ln(\alpha + \beta * H^A) = 0.5$$
$$\ln(\alpha + \beta * H^F) = 3.0$$

or

$$\beta = (e^{3.0} - e^{0.5})/(H^F - H^A) \quad (2)$$
$$\alpha = e^{0.5} - \beta H^A \quad (3)$$

Using Equations 2 and 3, if $H^A = 2.0$ min and $H^F = 30.0$ min are chosen, we have

$$\alpha = 0.3318 \quad (4)$$
$$\beta = 0.6585 \quad (5)$$

Rail Rapid Transit Levels of Service Based on the Model

On the basis of the definition of levels of service given in the 1985 *Highway Capacity Manual* and using I_{LOS}

TABLE 2 Suggested Rail Rapid Transit Levels of Service

Rail Transit Level-of-Service	Index Values
A	0.00 - 0.50
B	0.51 - 1.00
C	1.01 - 1.50
D	1.51 - 2.00
E	2.01 - 3.00
F[a]	3.01 or more

[a] crush load

TABLE 3 Theoretical and Operated Minimum Headways of Rapid Rail Systems

City	System	Operated Minimum Headway (Minutes)	Theoretical Minimum Headway (Minutes)
San Francisco	BART	3:00	2:30
Vancouver	BCRTC	1:35	1:30
Chicago	CTA	2:45	N/A
Cleveland	GCRTA	6:00	2:00
Los Angeles	LACMTA	6:00	3:00
Atlanta	MARTA	8:00	1:30
Boston	MBTA	3:30	3:00
Miami	MDTA	6:00	3:00
Baltimore	MTA	6:00	1:30
New York	NYCTA	2:00	2:00
Philadelphia	PATCO	2:00	1:30
NY - NJ	PATH	3:00	1:30
Philadelphia	SEPTA	3:00	3:00
New York	SIRTOA	2:00	2:00
Toronto	TTC	2:27	2:00
Washington DC	WMATA	2:00	1:30
Average		3:40	2:06

defined in Equation 1 in place of load factor, a definition of levels of service that considers both load factor and headway is suggested in Table 2. There are three minor modifications. One is that we have changed the value of the load factor for LOS A from 0.65 to 0.50 for convenience. The second is that the upper limit of the load factor for LOS F is ignored since LOS F should not be used for service planning, and the lower limit is adequate to reflect the operating condition. The last modification is that for simplicity we did not subdivide LOS E into LOS E-1 and LOS E-2.

To apply the model, the headway values corresponding to LOS A and LOS F must take into account current operating conditions and future operating plans. To provide an understanding of current practices, Table 3 gives the theoretical and operated minimum headways for rail rapid transit systems in North America. Ten of the systems have theoretical minimum headways less than or equal to 2 min. The average theoretical minimum headway of the 15 systems is 2 min 6 sec, whereas the minimum operated headway is often 3 to 3.5 min. The trend of future train control based on moving block technology is likely to make the current theoretical headway practical in rail operations. On the basis of these data, a 2-min headway, or H^A = 2 min, is recommended for LOS A. Considering the widely used service standard on off-peak headway, which is between 20 and 30 min and falls into the range of LOS E, a 30-min headway or H^F = 30 min is suggested for LOS F. The values for α and β for H^A = 2 min and H^F = 30 min were obtained in Equations 4 and 5, which give the level-of-service index model as follows:

$$I_{LOS} = \text{sqrt}\{L^2 + [\ln(0.3318 + 0.6585H)]^2\} \qquad (6)$$

To illustrate the contribution of the headway to I_{LOS}, the level-of-service index, Table 4 gives the level-of-service indexes for different headways when load fac-

TABLE 4 Headway Influence on Level-of-Service Index (L = 1.0)

Headway (minutes)	2	5	10	15	20
Levels of service index	1.12	1.47	1.91	2.22	2.45
Levels of service	C	C	D	E	E

tor is held constant at 1. 0. It is observed that the headway has strong influence on level-of-service indexes and that a long headway effectively lowers the level of service.

Figure 1 shows the level-of-service index model. The arcs are level-of-service index contour lines representing the various levels of service. Each point in the chart refers to a particular operating condition or a level of service determined by the load factor and the headway. In other words, given a load factor and headway, the corresponding level of service may be easily determined. In Figure 1, the operating conditions during peak hours and the corresponding LOS ranges are illustrated for the systems operated by the Metropolitan Atlanta Rapid Transit Authority, the Metro-Dade Transit Agency, and the Greater Cleveland Regional Transit Authority on the basis of data obtained from their respective service standards, planning guidelines, or service policy (*16–18*). The off-peak operating conditions and the corresponding level of service ranges are shown in Figure 2. It may be seen that, according to this model, the peak-hour services for all three systems are planned on the basis of LOS D and E, and the off-peak-hour services are based on levels of service between D and E, which is reasonable and expected.

Calibrated Load Factors for Different Vehicle Configurations

Whereas load factors give a reasonable measure of passenger comfort and are taken into account in the proposed model, they do not always represent the same comfort level for passengers because of differences in rail rapid transit vehicle configurations. Because the number

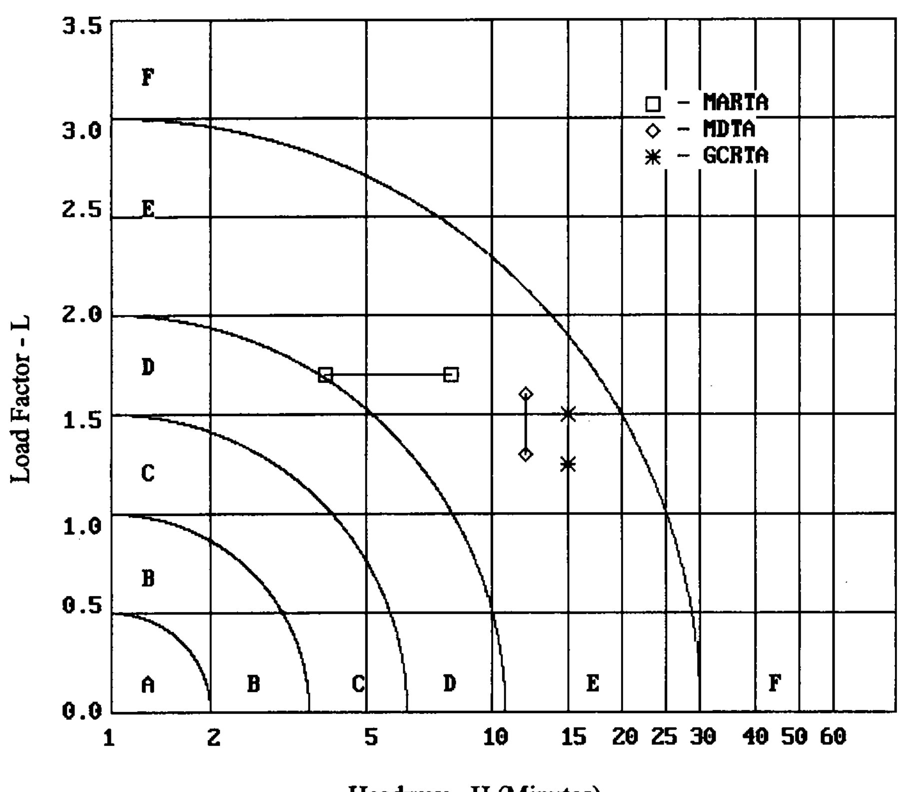

FIGURE 1 Peak-hour level-of-service ranges for three transit agencies.

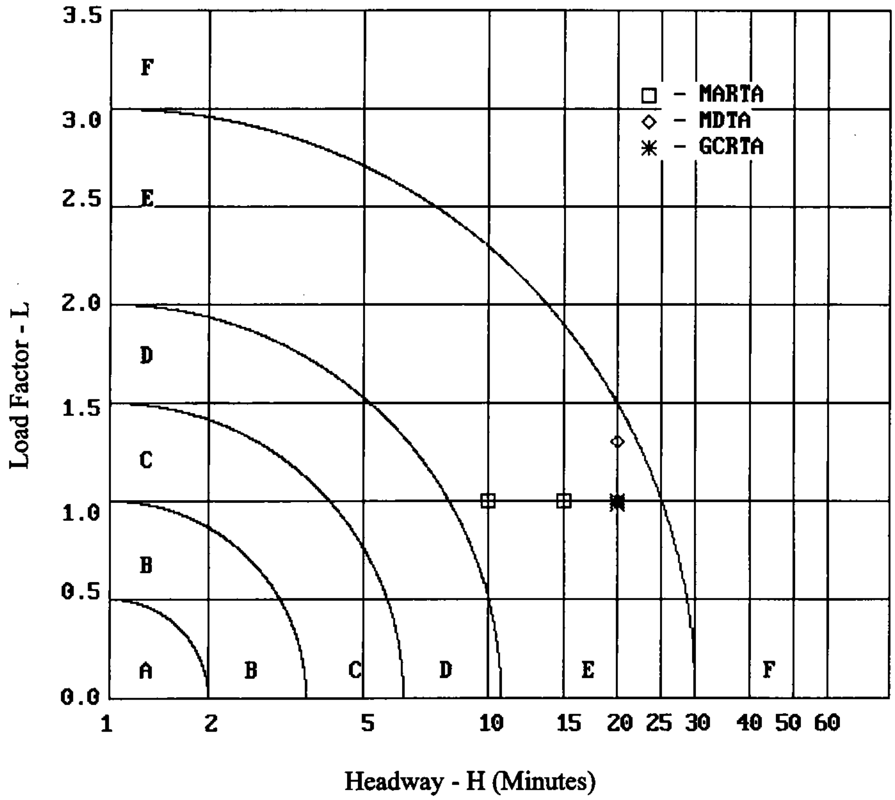

FIGURE 2 Off-peak level-of-service ranges for three transit agencies.

of seats often changes from one vehicle to another, the same load factor may have different meanings for different vehicles in terms of space per standing passenger. Inconsistent load factors for different vehicles is not a problem for the proposed model if the numbers of seats for all the vehicles are the same or similar. However, when differences in vehicle configurations cannot be ignored, using the same model for service planning within a transit property or for performance comparisons among transit properties will be misleading. It is necessary to use a refined or calibrated load factor to make the level-of-service index independent of the vehicle configuration.

For illustration, Table 5 gives load factors and the approximate space per standing passenger in square meters. The correlation is established by estimating space per standing passenger on the basis of the vehicles' dimensions, number of seats, and scheduled and crush capacities (*19*) and the typical space requirements for seated and standing passengers for urban rail transit as recommended in the 1985 *Highway Capacity Manual* (Table 12-7). Note that space per standing passenger is meaningful only when the load factor is greater than 1.0.

To use the proposed model, the desired space per standing passenger under the operational condition being considered needs to be determined first. The corresponding load factor may then be determined from Table 5 or a similar table. If the value of the space per standing passenger falls within a range in Table 5, the load factor may be calculated by using linear interpolation. The level of service may easily be determined with a known head-

TABLE 5 Space per Standee and Corresponding Load Factors

Approximate Square Meters[a] Per Standing Passenger	Load Factor
-	0.00 to 0.50
-	0.51 to 1.00
0.93 or more	1.01 to 1.50
0.47 to 0.93	1.51 to 2.00
0.27 to 0.47	2.01 to 2.50
0.22 to 0.27	2.51 to 3.00
< 0.22	3.01 or more

[a] 1 square meter = 10.75 square feet

way and space per standing passenger. When the load factor is greater than 1.0, and especially when it is greater than 1.5, it is recommended that space per standing passenger be used instead of load factor to calculate the level-of-service index.

Figures 3 and 4 show the planned peak levels of service for the New York City Transit Authority using the uncalibrated and calibrated load factors, respectively. In Figure 3, significant inconsistencies in the level of service for the three types of car are apparent. Figure 4, with space per standing passenger given along the vertical axis on the right side of the graph and calibrated load factors applied, shows consistent levels of service for all three types of car.

Relationship Between Level of Service and Capacity

Service planning and design need to consider not only the level of service but also transit capacity, since the desired level of service must be realized under the constraints of system capacity. The passenger capacity in the peak direction during peak hours may be estimated using the 1985 *Highway Capacity Manual* Formulas 12-5a and 12-6:

$$\text{Passengers/hour} = (\text{trains/hour}) \times (\text{cars/train}) \times (\text{seats/car}) \times (\text{passengers/seat}) \quad (7)$$

Let T_c be the number of cars per train (or train consist) and C_s be the number of seats per vehicle. Since trains/hour = 60/headway, Equation 7 may be rewritten as

$$\text{Passengers/hour} = 60/H \times T_c \times C_s \times L \quad (8)$$

where H and L are headway and load factor, respectively.

For the fleet of a given rail rapid transit system, the train consist and vehicle seating capacity are known, and the system capacity is therefore determined uniquely by the headway and load factor. This means that each point in the chart for the level-of-service index model also corresponds to a certain passenger capacity. As a result, a relationship between system capacity and level of service may be established, which is demonstrated by contour lines originating from the L axis in Figure 5.

As an example, consider the Metrorail system in Miami. Given that the vehicle seating capacity $C_s = 76$ and that, during peak hours, the headway is between 6 and 12 min, the load factor is between 1.3 and 1.6 (*17*), and the train consist $T_c = 6$, Figure 5 shows that the system offers a passenger capacity of between 2,964 and 7,296 ppdph.

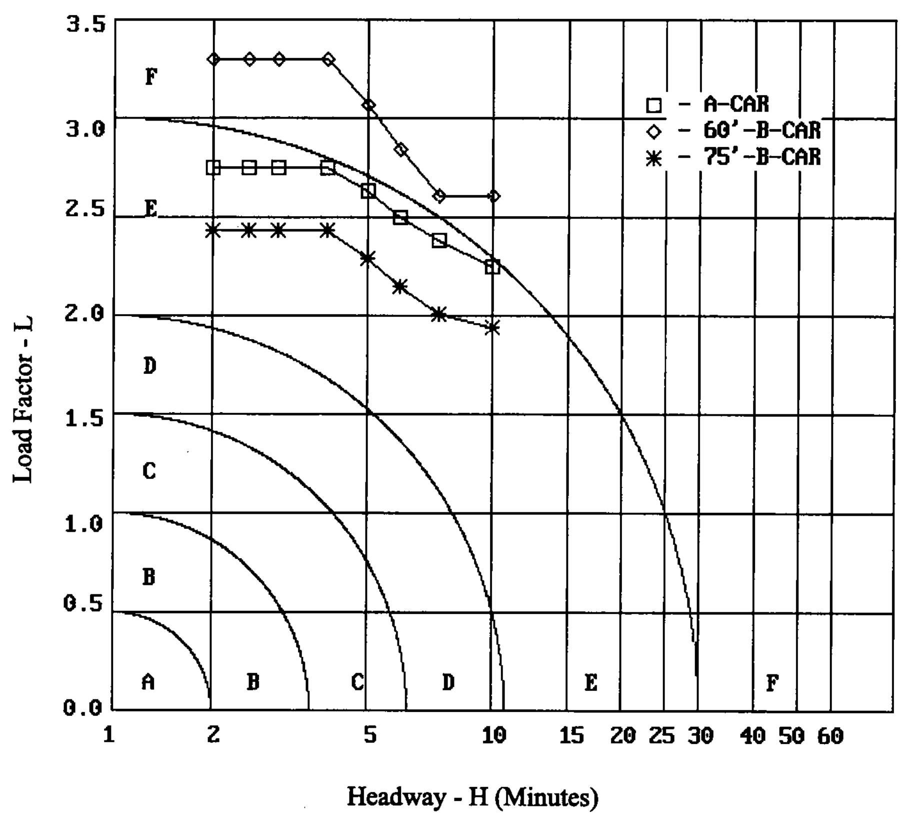

FIGURE 3 Planned peak-hour levels of service for NYCTA based on uncalibrated load factor.

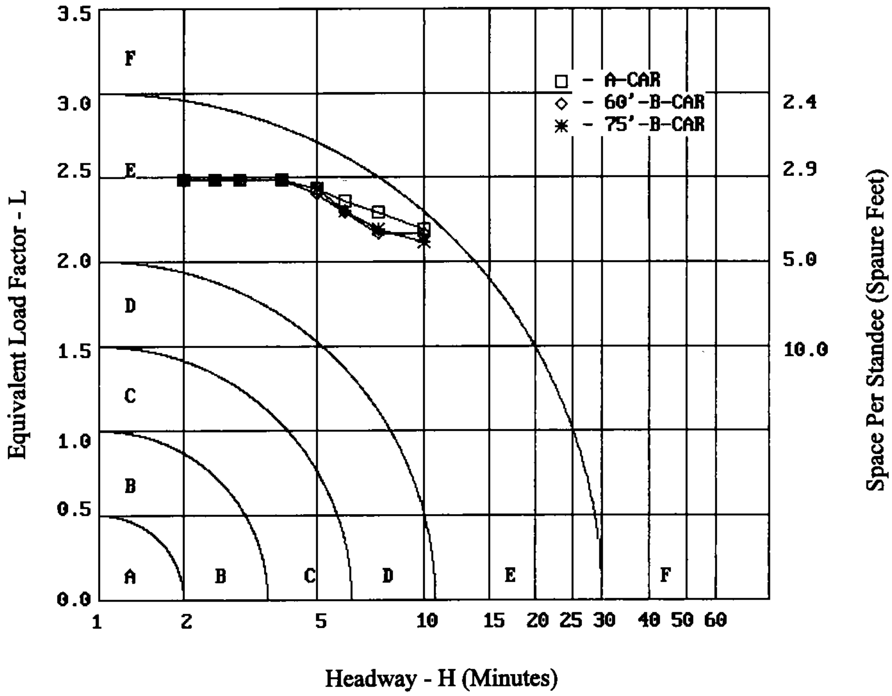

FIGURE 4 Planned peak-hour levels of service for NYCTA based on space per standee.

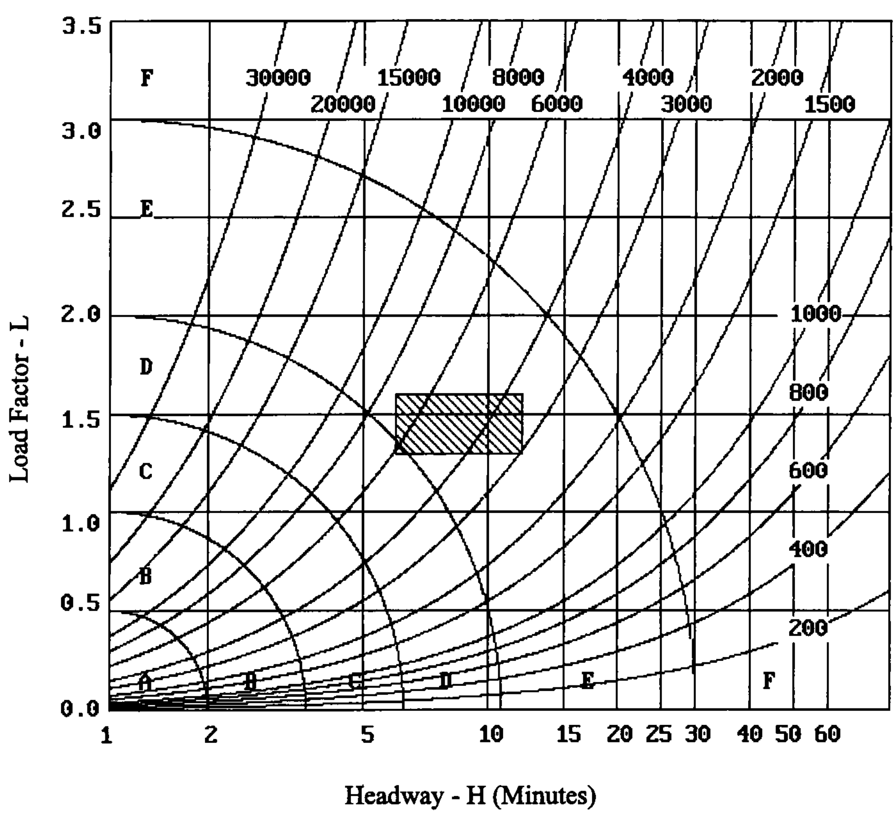

FIGURE 5 Relationship between level of service and system capacity.

Whereas line capacity is expressed in terms of an hourly passenger flow rate, in reality the passenger volume is not evenly distributed over time. For instance, there is normally a short period during peak hours that may last about 20 min during which the passenger volume will be much higher than the average during peak hours. Therefore, when planning for transit services for that period, the line capacity should be computed on the basis of the actual short-term passenger volume and the length of the period. In other words, if the average passenger volume in 1 hr during the peak period is 10,000, but during a 20-min period the volume is 3,800, the line capacity used for planning the service for the 20-min period should be 11,400. For this reason, many transit operators divide peak hours into periods of 0.5 hr or even less and design the services for each of them on the basis of demand.

Figure 5 may be conveniently used to plan the service on the basis of demand and to provide the basis for determining an operating schedule. Given the train consist, vehicle seating capacity, and the demand, the latter being predicted or observed, a passenger capacity contour line may be found from the chart that meets the given demand. By choosing a reasonable value range for the load factor on the basis of the service standards, the needed headways may be easily found from the chart. There will exist many combinations of load factors and headways that will meet the demand. The decision concerning the actual load factor and headway to be used may be made by considering the levels of service that they offer and the associated operating costs.

CONCLUSIONS

In this paper a level-of-service index model based on two important operational variables, load factor and headway, was described, and levels of service for rail rapid transit using the level-of-service index were suggested. The model is simple, has clear meanings in terms of system operations, and may be used to relate system capacity to level of service via the two variables. Testing the model with service data from several transit agencies has produced reasonable results. The model is useful because it allows an understanding of the concept of level of service and its relationship to rail rapid transit capacity. It may be further improved for use as the basis for developing practical tools to assist planners in determining the required facilities for a new system or an expansion or in designing optimal operating schemes while maintaining the desired level of service. From a performance perspective, the proposed model may be used to measure, in part, service quality and allow the levels of service offered by various rail rapid transit systems to be compared on a common basis.

This research is an initial attempt to understand rail rapid transit level of service and its relationship to capacity. Many issues remain unaddressed. Because of the many facets of service quality and level of service, more research is needed to further study the possible definitions of levels of service and practical measurements for ensuring service quality. More variables must be considered. To understand service quality from a customer perspective, a survey of transit users should be carried out. This is being accomplished through the Transit Cooperative Research Program. Levels of service may also be studied from a facility point of view (i.e., track capacity and its unitization for a given type of track environment, similar to highway levels of service being defined on the basis of vehicle densities). Another possible extension of the model is to incorporate a cost-benefit analysis that illustrates the cost implications and effect of a proposed service change on the level of service.

Aside from technical issues concerning system capacity and level of service, political decisions and inadequate funding also affect the ability of transit operators to increase or even maintain the system capacity or to improve services. For instance, Metropolitan Atlanta Regional Transit Authority has reported overcrowding on trains during the peak hours, but no services will be added because of budgetary constraints. Metro-Dade Transit Agency has also recently reduced the active fleet size in response to a shortage of operating funds. Because operating funds will likely continue to decline, transit services may be seriously affected both in quantity and in quality, making better service planning and design more important. On the other hand, the ability to measure level of service and the associated cost using tools such as the proposed method will allow transit agencies to influence the political decisions regarding transit service more effectively.

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