Abridgment

Temporal and Spatial Dimensions of Running Time in Transit Systems

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Transit running time is examined during various times of the day, in different directions of travel, and at different points along the route by using empirical data from Cincinnati, Ohio. Simple models relating running time to temporal and spatial dimensions are also reported that could serve as practical transit sketch planning tools. Several conclusions are drawn from the empirical analyses. It was found that transit running times are highest and most variable during the afternoon peak period. Daytime and evening off-peak service also have reliability problems. Finally, regardless of the time period, it is apparent that variation in running time increases with distance from route origin so that service deteriorates as the vehicle proceeds downstream. The implications of these results are that the afternoon peak should be examined more thoroughly in terms of causes of unreliable service and techniques that can be used to improve service predictability. Further research into fluctuations in daytime off-peak travel and the reasons for low predictability of evening off-peak service is also suggested.

It is generally agreed that precise knowledge of transit vehicle running time is an important operational problem that affects both travelers and operators. Operators rely on run times for both setting schedules and allocating vehicles to routes. Travelers are affected in terms of the reliability of service, which stems directly from the predictability of vehicle run times. It is known that buses do not operate in a consistent manner on a route, yet there have been few attempts to examine the extent to which temporal and spatial factors contribute to this effect.

This paper reports on the results of a comparative analysis of transit running time during various times of the day, in different directions of travel, and at different points along the route by using empirical data from Cincinnati, Ohio. Simple models relating running time to temporal and spatial dimensions are also reported. These models could serve as useful tools in transit sketch planning.

ANALYSIS METHODOLOGY

The data used in this study were collected in 1978 by General Motors by using automated vehicle monitoring (AVM) equipment on the Queen City Metro (Cincinnati) bus system (1). The data consist of observations on two bus routes (routes 43 and 45) that travel over city streets and extend radially from the central business district (CBD) along the same corridor. Peak-period service intervals are 12 min; service intervals drop off to 15-20 min during the off-peak. With the exception of the CBD and suburban termini, there are no holding points on the route. These routes have characteristics that are common to transit routes in many metropolitan areas.

The routes were segmented into a series of one-way links (10 on route 43, 8 on route 45), demarcated by the location of AVM equipment. The time at which each bus passed an AVM location was recorded. Information was collected over the entire day. Ten days of data were available from route 43 and 12 days from route 45.

Because of the availability of detailed transit service data across time and space, the following temporal and spatial issues of transit operation were examined through cross-cutting analyses:

1. Do average running time and reliability (running-time variation) vary during different times of day?
2. To what extent does outbound differ from inbound travel?
3. Does reliability deteriorate as vehicles progress farther along the route?

The analysis focused on defining spatial and temporal segments, computing running-time measures for each segment, and conducting comparisons of measures across segments. The spatial segments were defined as the distances between adjacent AVM sites.

Four temporal segments, corresponding to different operating periods during the day, were defined:

Segment	Time
Morning peak	6:00 to 9:00 a.m.
Daytime off-peak	9:00 a.m. to 3:00 p.m.
Afternoon peak	3:00 to 6:00 p.m.
Evening off-peak	6:00 p.m. to 6:00 a.m.

Three running-time measures were used in the analysis: (a) mean running time, (b) running-time variation, and (c) cumulative running-time variation. These measures were selected because they represent important features of running time and reliability on transit routes. Mean running time provides the operator with information on how to plan the schedule. Running-time variation represents the variation in running time originating on a particular link during the time period in question. Both the standard deviation and the coefficient of variation of running time were examined. They are useful for determining slack time in the schedule and for comparing reliability among links.

The third measure, cumulative running-time variation, was defined to measure the variation in bus running time from the route origin to each location on the route. This measure describes the degree to which the variation in running time on each link propagates as the vehicle travels farther along the route. Cumulative variation in running time is also related to passenger wait times at transit stops. As this variation increases, passenger waiting time also increases.

The data were not disaggregated by run or by day because of the orientation toward temporal and spatial issues and an interest in maintaining the operator's perspective.

Regression models that relate average running time across time periods were also developed, as were models of the relation between average running time and running-time variation. The intent of this effort was to provide planners with simple models that could be used to provide rough estimates of running-time characteristics for other systems.

MEAN RUNNING TIME

By comparing running times on the same link for different time periods, temporal effects were examined. The longest average running times occurred during the afternoon peak for practically every link on both routes. One would expect this result since the afternoon peak is more spread and more people (work and nonwork) are traveling during this period than during any other.

The shortest mean running times occurred during the evening off-peak, a result supported by all but one link on the two routes. This makes sense since traffic and passenger demand are generally at their lightest in the evening. In fact, evening off-peak mean running time was typically 20-25 percent lower than afternoon peak mean running time, as evidenced by the following regression equation:

$$\mu_{eop} = 21.3 + 0.775\mu_{ap} \qquad R^2 = 0.90, N = 18 \tag{1}$$

where

μ_{eop} = mean running time for evening off-peak (s),
μ_{ap} = mean running time for afternoon peak (s), and
N = number of observations, where each link/time-period pair forms a single observation.

Morning peak mean running times were roughly 10 percent lower than those for the afternoon peak:

$$\mu_{ap} = 4.2 + 1.078\mu_{mp} \qquad R^2 = 0.92, N = 18 \tag{2}$$

where μ_{mp} is the mean running time for the morning peak, in seconds. This may be due to a shorter and less severe peak in the morning. Thus, fewer buses experience the peaking effect in the morning, and the effect itself may be smaller in magnitude than for the afternoon commute.

Mean running times during the daytime off-peak were sometimes higher and sometimes lower than for the morning peak. This may be caused by the occurrence of several minipeaks (due to lunch, school, part-time workers, etc.) during the midday period, which can at times lead to travel conditions that are quite similar to those during the morning or afternoon peak period. The only relation that could be established was that average running times during the daytime off-peak were typically 1 min slower than during the afternoon peak:

$$\mu_{ap} = 65.7 + 0.992\mu_{dop} \qquad R^2 = 0.94, N = 18 \tag{3}$$

where μ_{dop} is the mean running time for the daytime off-peak, in seconds.

Little attention was given to comparing different links in the same time period and direction on a given route. Since the characteristics of each link on a route vary significantly, analyses of this kind would not produce any meaningful results.

Directional analysis of the same segment of the route was, however, of interest, particularly a comparison of inbound travel during the morning peak and outbound travel during the afternoon peak. The results showed that, in general, afternoon peak outbound mean running times exceeded morning peak inbound mean running times.

RUNNING-TIME VARIATION

Standard Deviation

The standard deviation of the results for link running time was generally less conclusive than in the analysis of mean running time. The standard deviation of running time was greater in the afternoon peak than in the morning peak, and in most cases afternoon peak outbound running times were more variable than the morning peak inbound. However, neither of these findings was particularly surprising, since higher variation in running time is usually correlated with higher mean running times and the causes of higher mean running time (general traffic, passenger boarding and alighting, etc.) are likely to cause higher variation as well. This was substantiated by the following regression equation, which relates the standard deviation to the mean running time:

$$\sigma_t = 26.6 + 0.135\,85\mu_t \qquad R^2 = 0.37, N = 72 \tag{4}$$

where σ_t is the standard deviation of running time, in seconds, and μ_t is the mean running time, in seconds. Based on a scattergram of the mean and standard deviation of running time, it was felt that a nonlinear specification might improve the statistical validity of the model. The result below shows little improvement over the linear specification:

$$\sigma_t = 0.651\mu_t^{0.795} \qquad R^2 = 0.39, N = 72 \tag{5}$$

Coefficient of Variation

Sometimes a better measure of running-time variation is the coefficient of variation, which is defined as the standard deviation divided by the mean. This can be a more meaningful measure because it "normalizes" the variation by the mean running time and allows for a more equitable comparison of transit running time across links and time periods (2). For all observations on both routes, the range of the coefficient of variation was between 0.10 and 0.32. The coefficient of variation was lowest during the morning peak, particularly on route 43, and was larger during both off-peaks than during the morning peak (for all links). This is due to higher variation in relation to mean running time during the off-peak and suggests that in some respects reliability problems may be more acute during the off-peaks than during the morning peak. Of course, the number of vehicles and travelers affected during the off-peak is relatively small. Nothing conclusive could be reported about the afternoon peak period.

For these data, the coefficient of variation had larger values at smaller mean running times. This is borne out by rewriting Equation 4 as follows:

$$\mathrm{cof}_t = \sigma_t/\mu_t = 26.6/\mu_t + 0.135\,85 \tag{6}$$

where cof_t is the coefficient of variation of running time. Since mean running times are lowest during the off-peak (particularly in the evening), this relation is consistent with the finding reported above.

Histograms of running time were also developed for each link and time period to examine the most appropriate distributional form for transit running time. Although no form-fitting analysis was conducted, the percentage of running times lower and higher than 1.96 standard deviations from the mean (95 percent confidence interval for normal distributions) was computed to examine extreme value qualities. The basic conclusion was that link running times generally do not have a consistent distributional form.

CUMULATIVE RUNNING-TIME DEVIATION

The most important result was that cumulative running-time deviation increased as vehicles proceeded farther along the route. This relation held true for both inbound and outbound travel, on both routes. This finding implies that service deteriorates as vehicles move farther away from the route origin and is consistent with results of a similar study conducted in Minneapolis by Loo (3). Thus, operators will have more difficulty pinpointing expected vehicle arrival times at the destination terminal as route length increases. Travelers boarding farther downstream will also have longer and more uncertain wait times than those boarding closer to the route origin, if no reliability control strategies are in effect.

The cumulative running-time deviation was lowest during the morning peak for outbound travel and during the afternoon peak for inbound travel. This result is intuitive, since the flows are traditionally light in those directions for those time periods, which minimizes the likelihood of unexpected delays. It is also interesting to note that the cumulative running-time deviation for outbound travel during the afternoon peak was considerably higher than the same measure for inbound travel during the morning peak, which implies that transit operations are typically less stable during the afternoon. Finally, the cumulative running-time deviation was unexpectedly large during the evening off-peak. This may be due to differences in driver behavior, since they have greater flexibility in the evening.

DISCUSSION OF RESULTS

The models reported in this study can be used by planners to develop crude estimates of transit level of service during different time periods. If data are available on morning or afternoon peak travel only, approximations of service levels during other time periods can be derived. The relation between average running time and running-time variation can be used to assess slack time and vehicle requirements for maintaining a feasible schedule. It is assumed that these models would only be used in preliminary stages of planning and that more detailed planning activities (e.g., speed runs) would be conducted before any schedule modifications were made.

A limited test of the transferability of these models was conducted by using data from route 5 in Minneapolis (evening off-peak data were not available). Predictions of running-time measures on route 5 were made by using the Cincinnati models and were then compared with those observed in Minneapolis. Prediction error (PE) was defined as follows:

$$PE = (\text{predicted} - \text{observed})/\text{observed} \qquad (7)$$

For the temporal models presented in Equations 2 and 3, the average prediction errors were 2 and -9 percent, respectively, which indicates reasonably accurate representation of observed average running times. For the models reported in Equations 4 and 5, the average prediction errors were -6 and -14 percent, respectively. These models tended to underestimate standard deviation of running time, particularly in the nonlinear specification. The lower accuracy of the standard deviation models can be attributed in part to the low R^2 of the original estimates.

SUMMARY AND DIRECTIONS FOR FURTHER RESEARCH

Several findings can be reported from the empirical analyses discussed in this paper. Average transit in-vehicle running times were highest during the afternoon peak, roughly 10 percent higher than during the morning peak and 25 percent higher than during the evening off-peak. Average running times in the outbound direction during the afternoon peak were higher than those in the inbound direction during the morning peak.

In general, higher variation was correlated with higher mean running time on links. The standard deviation of running time was greater in the afternoon peak than in the morning peak, particularly when afternoon peak outbound travel was compared with morning peak inbound travel. The coefficient of variation was found to be lowest during the morning peak and highest during the off-peaks.

The predictability of vehicle arrival time and passenger waiting times definitely deteriorated as the vehicles moved farther away from the route origin. This problem was more acute for outbound travel during the afternoon peak than for inbound travel during the morning peak.

Based on these findings, it appears that provision of transit service during the afternoon peak is transit's most serious time-related problem. During the afternoon, average running time and the variation in link and route running times were considerably higher; efforts are being made to determine the causes of this problem (4). It is important to note, however, that the implications of longer and less reliable afternoon peak travel may be more acceptable to users than similar conditions in the morning because the perceived penalties for late or uncertain arrival are generally less severe on the work-to-home than on the home-to-work trip.

It is also apparent that operators have more difficulty predicting vehicle arrivals, and passengers are offered a lower level of service as buses move farther away from the route origin. This confirms the need to study effective ways of controlling reliability in transit systems (5,6).

Evening off-peak travel conditions appear to be highly variable in relation to average running time. Further research should be conducted to ascertain the causes of this problem and the impact it has on ridership during the evening period.

Finally, additional study of the daytime off-peak period is warranted. No definitive pattern emerged in the study of conditions during the daytime off-peak, although there were some similarities with running times during peak periods. Segmentation of this period into smaller time periods may provide some insight into this issue.

It is extremely important to note that all of these implications are derived from the study of a couple of routes in a single transit system. Links were typically 2-3 miles in length, and average link running times were in the 6- to 15-min range. Validation of whether the established relations hold true for routes with similar qualities in other systems and for routes with different characteristics has been explored only on a limited basis and remains a necessary direction for further research.

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Multistage Approach for Estimating Transit Costs

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The need to improve estimates of the costs of operating specific routes and services is greater than ever given the current financial problems of the transit industry. Managers are increasingly relying on performance audits to evaluate the cost-effectiveness of different operations. A multistage technique for allocating systemwide transit cost estimates to more disaggregate levels and accounting for the unique features of an operation is presented. Cost centers and pay-hour adjustments are used in distilling the cost estimates of specific services for two California transit properties. Significant differences are found between the cost estimates generated by "aggregate" unit cost equations computed from systemwide data and those generated by the techniques presented. Finally, suggestions are made as to how unit cost estimates might be used in an ongoing transit planning effort.

Growing interest in line-by-line analyses of transit performance and the estimation of how much it costs to expand services has created the need for more refined methods of allocating systemwide transit costs. Attributing system costs to a specific route, time period, distance increment, or even individual passenger trip requires highly precise, disaggregate data as well as a strong theoretical foundation.

The ideal cost allocation process would causally attribute each and every operating and capital expense to the specific route directly responsible for its encumbrance. Daily cost estimates that reflect the individual characteristics of each route could then be divided further into time-of-day components. By prorating the resultant peak and off-peak cost estimates among the users of each route (on the basis of, say, passenger miles traveled), a reasonable approximation of incremental cost incurred in serving each patron could be derived. Several factors, however, impair the use of such an approach. For example, few expense items can be linked directly to a specific bus route much less to a particular time of day. Most transit cost records are kept at either a systemwide or divisional level, which precludes precise measurement. Moreover, detailed records of such important cost factors as drivers' wages, equipment, and general overhead expenses are not always maintained on a time-of-day basis. Even when such information is available, one is faced with the arduous task of "attributing" the effects of such factors as part-time work prohibitions and spread-time penalties to the costs of serving both peak- and base-period users. Just as important, however, is the fact that peak/off-peak cost allocation theory remains partial and fragmented. Although a growing body of literature has evolved over recent years that offers insights into the transit cost allocation problem, no widely applicable or universally accepted approaches have yet emerged.

This paper presents a multistage process for allocating transit costs to more disaggregate levels by using expense records from two California transit operators. Each stage seeks to refine original cost estimates to better reflect the expense characteristics of any bus operation under study. First, a systemwide unit cost allocation formula is presented for each transit property, and this is followed by a "cost-centers" refinement of the equation. The cost-centers model is then used to estimate the daily cost of operating specific routes. The daily cost for each route is further divided between the peak and base periods by using attribution procedures that account for the effects of labor prohibitions and peak demands on total costs. The paper concludes with suggestions on how detailed unit cost estimates might be used by transit planners.

UNIT COST ALLOCATION MODELS

Cost allocation models estimate operating expenses by associating them with certain output factors. The most commonly used technique is the unit cost method (1,2). Under this approach, expense items are segregated into subcategories such as labor, maintenance, and fuel. The subcategories are then stratified among several variables, such as vehicle hours or vehicle miles of service, which are considered causally linked to the encumbrance of expenses in each subcategory. A multivariable equation can then be derived by calculating a unit coefficient for each factor (e.g., by dividing the total cost of all subcategories by vehicle hours).

Under the unit cost method, subcategories of operating expenses have traditionally been linked with one of four factors: (a) vehicle miles, (b) vehicle hours, (c) revenue passengers, or (d) peak buses (3). Typically, the following associations are made. The costs of fuel, tires, maintenance, and repairs are related to vehicle miles. Driver