

abstract

BUS LINE REGULATION

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In the operation of a high volume bus line, bunching causes an effective loss of capacity, a loss which can be stated in terms of the standard deviation of the loads.

Based on the observed influence that the presence of checkers has on line performance, an experiment was conducted where checkers were asked to help regulate the flow of buses to maintain even loadings, in addition to the normal task of collecting data. Lightly loaded buses held briefly at a control point allowed additional passengers to board. The effect was measured downstream, where another checker noted loads and times at the peak point of the line.

Checkers reviewed their own numbers and notes and attempted to improve their strategies. The smoothing of the flow created enough additional capacity during the course of the experiment to justify the cost of the regulating checker. Further gains could be made by using the data, obtained in the process of regulation, to fine-tune the schedules. Regulation could be improved if the checker/ regulators could be assigned continuously to a control point.

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Provision of peak capacity on a bus line is costly, so every effort must be made to minimize the number of buses required to provide an adequate level of service. Even if the average flow of buses is well matched to the flow of passengers, there are frequently many empty seats at the peak point of the line. These empty seats represent the waste of bus bunching. If the flow of buses could be better controlled, more of the standees could have seats.

For demand-scheduled bus lines, transit operators have traditionally been concerned about the average loadings at the peak point, and have provided the requisite flow of buses to keep this average below a specified limit. Less attention was given to the random variations between loads on successive buses. On heavy RTD lines the standard deviations of loads range between 15 and 25 persons. Certain factors affect the loading variance, such as traffic inconsistencies, multiple services on a common route segment, loading pattern variations, route configuration, and average headway.

By reducing the variability in the loads, capacity is effectively added, without increasing the number of buses. From the rider's perspective, capacity means having a seat on the next-arriving bus - not having a space to stand, or having to wait for the following bus. In this paper the waste of effective capacity caused by load variability is quantified and the possibilities of real-time control and schedule control are explored. An experiment in line regulation is described and some preliminary results are given.

PROBLEM DEFINITION

Turnquist (1) and others have treated the topic of line regulation in terms of headway variations. In this paper the focus is directly on loadings, because for the bus lines that are the subject of this analysis (i.e. having headways less than 10 minutes) the overloads and unutilized capacity are of paramount concern, and aggregate passenger delay is secondary. (Although it is possible that when the loading issue is properly dealt with, the aggregate delay will be nearly minimized.)

Nomenclature

The loading pattern on a line can be defined by

$$x_{ijk} = y_{ij} + e_{ijk} \quad (1)$$

where x_{ijk} is the load at point i , on trip j , on day k ,
 y_{ij} is the load anticipated by the optimal schedule for the average day, at point i ,
on trip j , and
 e_{ijk} is a residual or error term.

The optimal schedule is the schedule which minimizes the overall cost of the operation while meeting various constraints or standards for passenger service, over the period for which the schedule is in effect. The schedule addresses persistent patterns of passenger travel, over the length of the line and throughout the day. Such a global objective will result in a degree of planned variation between expected loads on successive trips at any specific point.

The error term e_{ijk} is a result of a non-optimal schedule, as well as daily fluctuations in passenger volumes, traffic variations and other influences. The focus of this paper is on controlling the daily operation to compensate for these influences, and thereby keep e_{ijk} as small as possible.

Potential for Control

Several papers bear on the worth of making a special effort to control headways of a bus line. Shanteau (2) determined the relative influences of passenger arrival and headway variations on load variations, and found that the major factor (under certain conditions) is the headway variation itself. The conclusion was that much of the loading variation could be reduced if headways could be better controlled.

In another paper, Turnquist (3) traded off passenger time gained from regularized headways against passenger time lost from holding, to estimate domains where the benefit of a holding strategy is likely to be positive. In the situations most likely to justify headway control, an increase in effective seating capacity appears to be a more direct and measurable benefit than net aggregate time savings. An increase in effective capacity is the equivalent of the cost of running additional buses.

The rationale for the increased seating capacity is that a stream of buses coming at irregular intervals will have standees on some buses and empty seats on others. The extent that both occur together (albeit on alternate buses) determines the wasted capacity. This implies that the waste is either the number of standees or the number of empty seats, whichever is least. If the average load is greater than the number of seats, c , then the waste is the number of empty seats. If the average load is less than the number of seats, then the waste is the number of standees.

Assuming a distribution of loads that is approximately normal, the wasted capacity on the average bus for the case $x < c$ is given by

$$w = \int_c^{\infty} (x - c) f_x(x) dx \quad (2)$$

where $f_n(x)$ is the normal density function:

$$f_n(x) = \frac{1}{\sqrt{2\mathbf{p}} \mathbf{s}_x} \exp\left(-\frac{1}{2} z^2\right)$$

$$\text{where } z = \frac{x - \bar{x}}{\mathbf{s}_x} .$$

Through an integration and some rearranging of terms, (2) can be expressed as the standard deviation of load times a "capacity factor" :

$$\begin{aligned} w &= \int_c^{\infty} (z\mathbf{s}_x + \bar{x}) f_n(x) dx - c \int_c^{\infty} f_n(x) dx \\ &= \frac{\mathbf{s}_x}{\sqrt{2\mathbf{p}}} \int_{z_c}^{\infty} z \exp\left(-\frac{1}{2} z^2\right) dz - (c - \bar{x}) \int_c^{\infty} f_n(x) dx \end{aligned}$$

where

$$z_c = \frac{c - \bar{x}}{\mathbf{s}_x} .$$

$$\begin{aligned}
w &= \frac{\mathbf{s}_x}{\sqrt{2\mathbf{p}}} \exp\left(-\frac{1}{2}z_c^2\right) - (c - \bar{x}) \int_c^{\infty} f_n(x) dx \\
&= \mathbf{s}_x \left[\frac{1}{\sqrt{2\mathbf{p}}} \exp\left(-\frac{1}{2}z_c^2\right) - z_c \int_{z_c}^{\infty} f_n(z) dz \right] \\
&= \mathbf{s}_x g(z_c)
\end{aligned} \tag{3}$$

The capacity factor $g(z_c)$ is graphed as the right half of Figure 1. The left half is obtained from the case of $x > c$, average load greater than seating capacity:

$$w = \int_0^c (c - x) f_x(x) dx$$

which for high volume lines is approximately:

$$w = \int_{-\infty}^c (c - x) f_x(x) dx \tag{4}$$

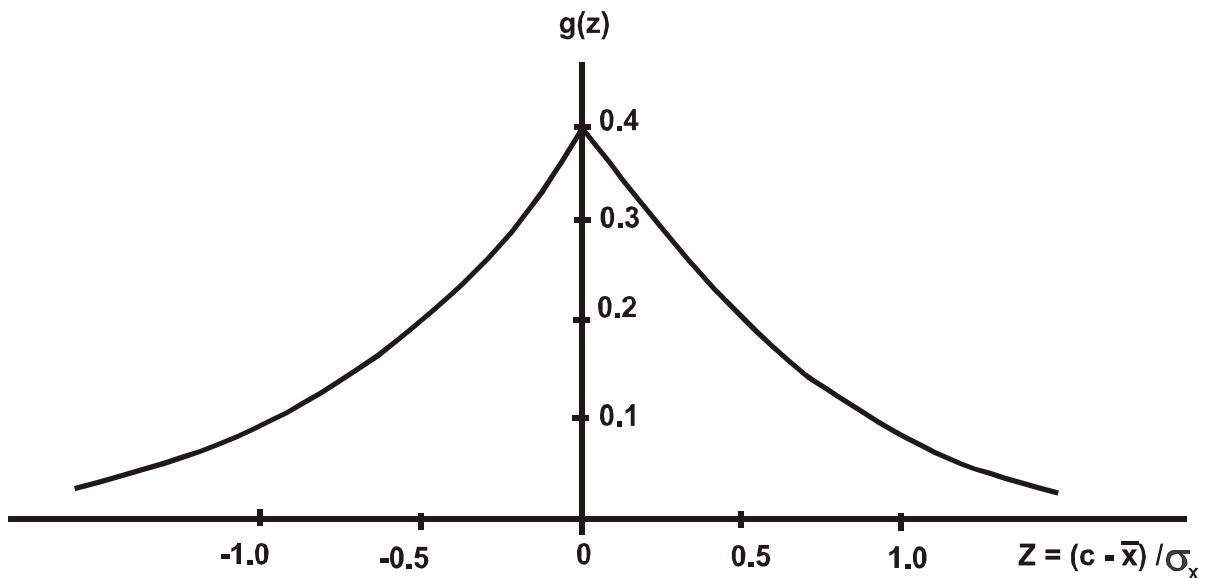


Figure 1 Relative capacity gain, for differences between number of seats and average load.

Having determined the capacity to be gained through elimination or reduction of loading irregularity, the remaining issue is: will the cost of regulation be less than the cost of the implied capacity it could substitute for? This paper describes an initial investigation into the amount of reduction in the standard deviation of the load that can be achieved by a line regulator.

REGULATION PROCESS DEVELOPMENT

On heavy lines, a variation of a minute or two in the headways can make a large difference in the loadings, and the loading itself can then significantly influence the running time. Individual drivers often attempt to minimize their own loads at the expense of others. The extreme sensitivity of loadings to slight variations in headways give drivers the opportunity to use various close-following tactics, analogous to the tactics of bicycle racers.

It has long been known that the mere presence of checkers causes line operations to improve, even though checkers have no disciplinary authority over drivers. The promise of capacity improvement from head way control, and the observed influence of checkers on driver behavior, suggested a test of the extent to which a checker could effect a reduction in the loading variations at the peak point.

Concept of the Checker/Regulator

The normal role of the checker is that of passive data collector, with any influence on drivers unintended. It was hypothesized that a greater degree of regulation could be achieved through active involvement but without disciplinary authority. The checker would continue to record data, but might ask drivers to wait briefly at the stop, or persuade patrons to wait for a less-crowded bus. Although holding of drivers would be the most frequently employed means of smoothing out the loads, holding of passengers could help out those drivers who would otherwise get swamped with passengers and thereby become progressively delayed in moving along the route.

The recorded data would be used by the regulator to assess his own performance, and could serve as a relatively continuous set of data to be used by schedulers for fine-tuning. Such time series data is seldom available from normal checking programs.

Adaptive Development of the Regulation Process

For the procedures to be developed, the only prior expertise was the checkers' basic understanding of street operations, based on years of observations and earlier experience as drivers. Without much pre planning, a pilot project was started. The first checkers to participate were simply instructed in the objectives of the experiment and asked to learn by trying. The collected data was used repeatedly as the basis for discussion of possible tactical improvements.

A loading-based strategy would be used, in contrast to the headway-based holding strategy discussed by Turnquist (1). Although holding would be involved, and early buses would be the most likely to be held, the primary criterion would be the load itself.

A control point would be chosen for maximum leverage. It should be a stop upstream of the peak point, with high boarding volumes. By having a continual flow of patrons walking to the stop, the loads on the buses can be adjusted effectively with short holds.

In the beginning, checkers were stationed only at the control point. As soon as the collected data gave evidence of an improvement, an additional checker was stationed at the peak point to obtain data on actual results of the regulation process.

The checker recorded the data on a precoded form. Precoded for each trip past the control point is a bus run number, destination terminal, time due at the control stop, and the nominal or expected load for each trip leaving the stop. The checker recorded the bus arrival and departure times, passenger load upon arrival and departure, and the bus identification number. Any desired notes were added, especially the length of time held, if at all.

Choice of Site

Line 16 appeared to have a marked need for control, as well as having an obvious control point and a well-defined peak point, so it was chosen for the experiment. The line traverses the CBD and runs west 9 miles, mostly along West Third Street. Because of a very sharp fall-off of passenger volumes as the distance from the CBD increases (Figure 2), there are shortline terminals at 3.7 miles (Rampart Street) and 5.6 miles (Wilton Place).

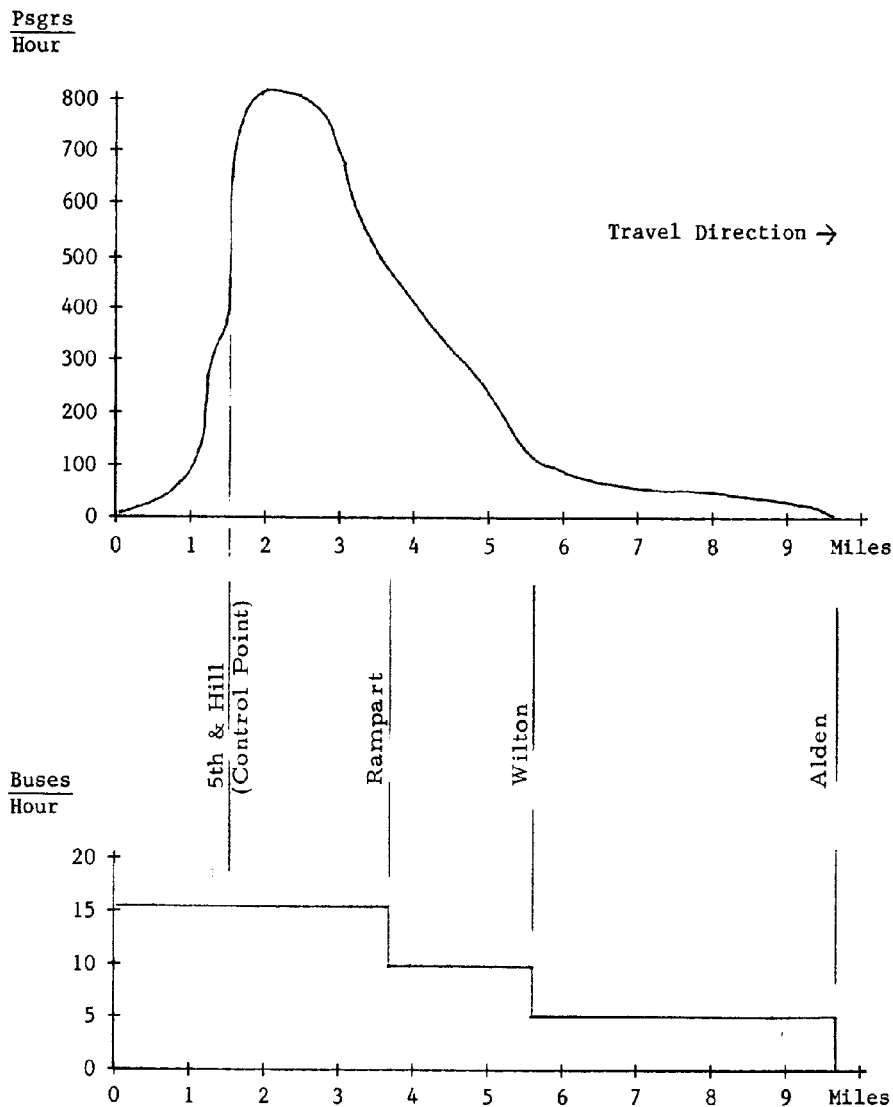


Figure 2 *Passenger and bus volumes on 16 Line during 1.5 hours of evening peak, outbound from CBD.*

There had been problems in the evening peak period, where buses destined for the far terminal frequently overloaded and passed up stops before getting through the CBD. This worked a hardship on patrons who wanted to go beyond the second shortline, yet their numbers did not justify additional trips to the far terminal. The overall volumes of passengers at the peak point did not appear to justify more buses on the line.

DISCUSSION OF THE RESULTS

Checkers were assigned to regulate the line during the hours of 1500 to 1800, outbound only, from February through mid-May, 1982. After mid-March, an additional checker monitored the peak point most of the time. After the regulation trial was concluded in mid-May, six days of monitoring at the peak point provided data for non-regulation comparisons. Figure 3 shows, for a typical day, the loads leaving the control point (x_{cj}), the loads arriving at the peak point (x_{ej}), and the corresponding deviations from schedule on arrival at the control point (T_{cj}).

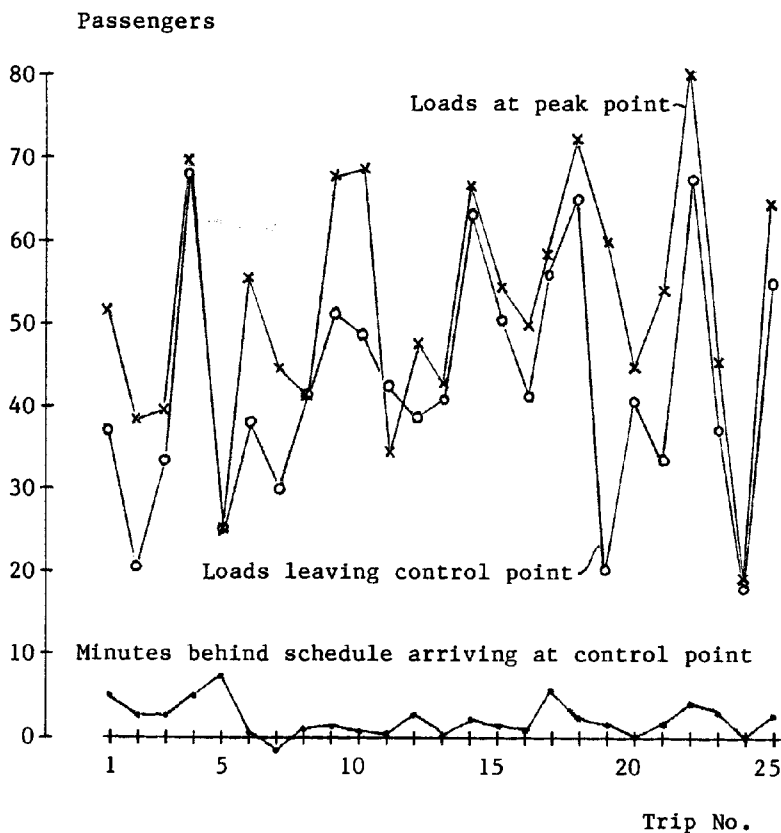


Figure 3 Load and schedule deviations for 16 Line outbound trips, from 1600 to 1730, April 12, 1982

The peak loadings occur during the period from 1600 to 1700. To be able to treat the data as a stationary process, the computations of means and standard deviations are limited to the 25 trips that occur during that period. Figure 4 shows the computed means and standard deviations,

$$\bar{X}_{ck}, \bar{X}_{pk}, s_{xck}, \text{ and } s_{xpk}.$$

Although the ultimate objective was to minimize s_{xc} , it was recognized that the real task of the checker was to minimize s_{ec} , the standard deviation of the error at the control point, by regulating bus departures from the control point. Based partly on the averages of the first two weeks, a judgmental version of y_{cj} was supplied to the checkers as a list of target values, and was later used to compute $e_{cj} = x_{cj} - y_{cj}$ and thus obtain an approximation of s_{ec} . This refinement proved to make little difference at this early stage of development in the regulation process however, and was abandoned.

After a few days, it became clear that there were persistent variations in loads in spite of appropriate actions by the regulating checker. These variations could be attributed to a non-

optimum schedule. Since it was not possible at that time to correct the schedule, the nominal target loads were revised to reflect the persistent variations, and thus limit the control effort required of the checkers.

Passengers

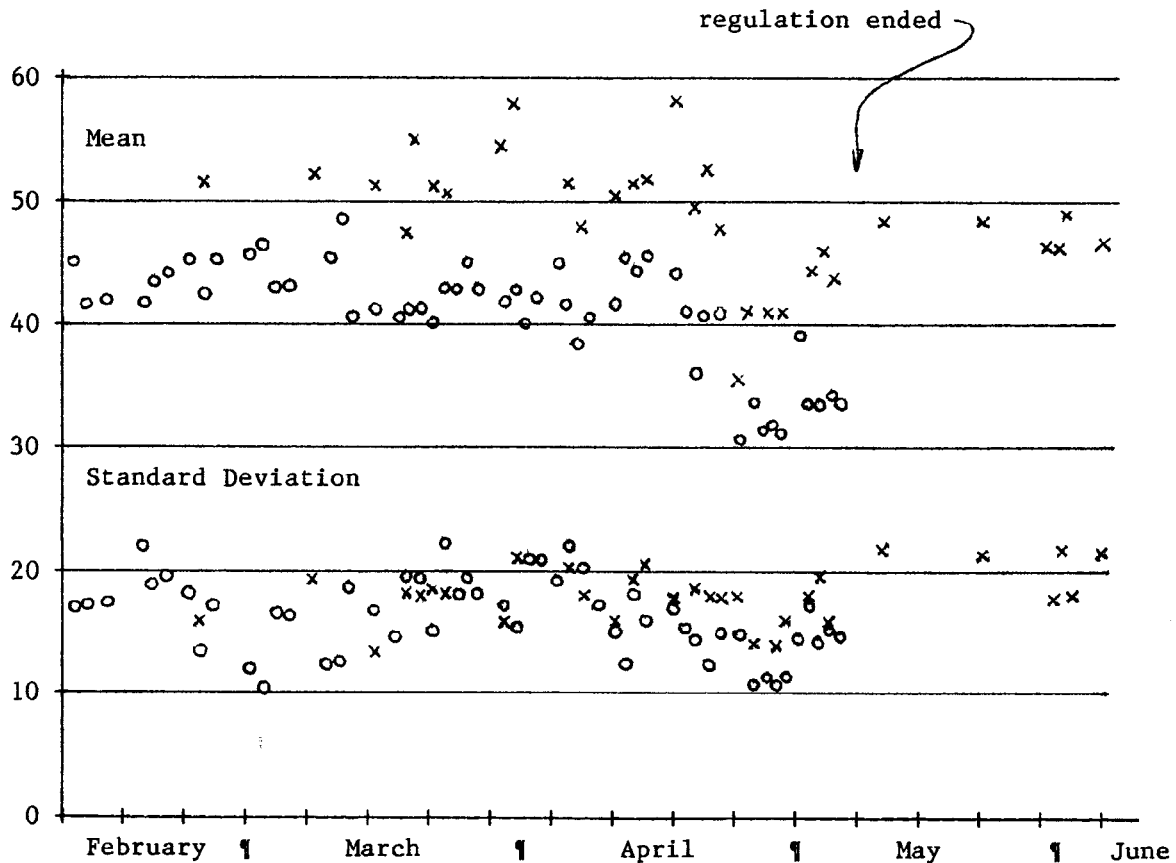


Figure 4 Load means and standard deviations, at control point and at peak point.

In the first stage of experimentation, a checker was selected for a special assignment to last for a couple of weeks. Since no one knew exactly what would work, the strategy was to let the checker try to see what techniques would be most effective. He made rapid progress and significantly reduced the deviations at the control point.

Next, the assignment procedure returned to the normal day-by-day seniority choice arrangement of the checkers, with "training" sessions preceding the work so that each new participant would have an idea of what had been done before and what was expected. During this phase, the regulation was less effective. Although the decline could have been due to differences in capabilities of the participants, it was hypothesized that better results could be expected if a single checker remained at the control point on a more continuous basis, since there should be a learning curve for the regulator as well as benefits from establishment of a day-to-day relationship with the individual drivers (i.e., they know that he knows what happened on prior days).

To test this hypothesis, a modification of the usual day-by-day seniority mechanism for choice of

assignments was devised, in which a checker would be "locked in" for periods of three to five days in a row. This seemed to have a positive effect, but the data was inconclusive.

The lowest standard deviations were obtained during two periods, one in early March, the other in late April. In the first period there was no regular checking established at the peak point, so there is no conclusive proof that the variation in loads diminished at that location. In the second period the mean loadings were off 27% due to raids on hispanic workplaces by the INS. While this may not entirely explain the low standard deviations that were obtained, there must have been some degree of influence.

Variations in bus arrival times and loadings have numerous causes. One class of causes is differences between drivers. They differ in their personal tendencies and in their status as regular or extraboard drivers. The driver on a regular assignment can get a good understanding of patterns of riding and traffic for the specific assignment, and can then react either to minimize deviations in loads and schedules, or to minimize loads. Extraboard drivers rotate assignments, so that they have little specific prior experience with each day's assignment.

An attempt was made to compare the variability in loads of the regular vs. extraboard drivers. As a class the latter appeared to have greater variations in loads, but the within-class load variations of the regular drivers was quite large, so the between-class difference could not be said to be statistically significant.

CONCLUSIONS

The nature of this experiment, i.e., "learn by trying," has led to some insights into the causes of loading variations, but the data is not ordered neatly enough to draw strong inferences. Nevertheless, a small reduction in loading variability was achieved. Over the course of the experiment, regulation was able to reduce the standard deviation of load at the peak point by 3.3 passengers. This translates to a saving of capacity of 0.8 seats per bus, or 0.42 buses on this line. At \$60 per peak hour bus, the implied saving is \$25 per hour, almost twice the cost of putting the checker on duty as a regulator.

A valuable byproduct of the regulation process is continuous data on line performance. The data hints at other causes of loading variations which have yet to be fully explored and/or corrected (untuned schedules for example). It seems quite possible that a gain of as much as \$100 per hour is attainable.

Some inferences can be drawn regarding AVM (automated vehicle monitoring). There were frequent indications that problems elsewhere on the line were causing excess variation at the control point, but investigations made after-the-fact were inconclusive. Simultaneous observations made over the entire line could answer some of these questions, and could be instrumental in correcting them (even in real time). The cost of duplicating that feature of AVM with checkers would be prohibitively expensive.

Another implication bears on the allocation of dispatcher manpower in the use of AVM. The checker/ regulators were kept very busy. Although part of their time is spent recording data and some of it answering queries of patrons, most of it is used in on-the-spot analysis and in communicating with the drivers. If a dispatcher in a control room is to accomplish the same or better results, with a lot more data at her disposal, she must be able to spend full time on just one line during critical periods.

SUGGESTIONS FOR FURTHER INVESTIGATION

At some point, a more sophisticated statistical analysis of loading based control will be warranted. At present however, the state of knowledge of the processes seems so primitive that greater progress is likely to come from the trial and error tests of tactics, monitored with fairly

simple data collection and analysis. Realization of what could not be controlled by a regulator acting at a control point suggests other potential areas of investigation likely to lead to further reductions in loading variability:

- o The data from the regulation process can be used to fine-tune the schedules. Significant loading variation appears to be caused by persistent arrivals at times which are only a minute or two earlier or later than desirable.
- o The learning curve has an effect on the process. What is the minimum number of days of continuous duty for the checker/regulator to reach peak effectiveness?
- o What is the effect of the driver's learning curve in getting used to the peculiarities of the specific run?
- o What is the impact on loading variability of having a significant proportion of "newcomers" on the line?
- o What is the extent of purposeful actions to increase loading variations (i.e., running light) and how could it be decreased, say through motivational techniques?
- o What is the relation between load variation and savings of travel time by passengers? How do headway-based strategies compare with loading-based strategies?

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