7.2.1 Control Point Holding Strategies

From previous research it appears that holding strategies may be the most promising for improving transit reliability. There are many variables involved in such strategies: number and location of control points, criteria for application, length of delay, stages of application, and the quantity of information required for these decisions. It has been found that the number of control points should be kept small; otherwise increased travel time resulting from holding buses will likely outweigh the reduced wait time benefits. Control points should be located where significant passenger turnover occurs so that total passenger delay is minimized. Where few passengers continue through such a point, splitting bus routes into two separate routes may be a better strategy. Distributing corrective action over a number of consecutive buses may result in more flexible policies and less inconvenience to passengers. Different policies may be optimal at various points along a route, where different passenger boarding patterns prevail. The effectiveness of control strategies will clearly depend on the quantity and quality of data available for decision-making.

The demonstration would entail selection of a fixed route bus system which is significantly affected by service unreliability. Two or three of the more unreliable routes would be examined, and location of control points selected. Buses would be equipped with radio telephone equipment and all drivers would maintain communication with a bus dispatch center. Each bus would report to the dispatcher when reaching a control point, relaying information on time of arrival, volume on the bus and the number of people waiting to board at the control point. The dispatcher, aware of the status of the buses prior to and succeeding the bus located at the control point, would make a decision of whether to hold the bus and the duration of time to hold the bus. The effects of this strategy would be measured in terms of benefits to the users and operators and the tradeoffs between benefits to people waiting for a vehicle and those delayed by a holding strategy.

Control point holding strategies are currently in effect in Dublin, Ireland and Toulouse, France. In both cases, the transit operating agencies have reported decreases in the mean and variance of passenger wait times. Neither agency has conducted an analysis of passenger in-vehicle times, partronage, and operator costs.

Depending upon the success of employing a holding strategy, the demonstration could be extended to include other control strategies which would involve radio-telephone communication and a dispatching process. This would include coordination of the following strategies:

1. Transferring passengers and turning particular buses.

2. Injecting standby buses.

3. Running buses out of service until reaching particular points on the route.

4. Altering bus routes on a temporary basis.

Considerable work has yet to be done on holding strategies. The simple holding strategy based on a two-point lateness model (Barnett, 2) might be refined. Strategies could then be tested with alternative models, different numbers of control points, and different sources of information.

It might be most efficient to coordinate such a study with the SCRTD-AVM demonstration in Los Angeles. When AVM equipment is installed, holding strategies will be applied and effects evaluated. A comprehensive reliability demonstration might include the testing of numerous strategies with various types of monitoring: manual, radio and automatic. However, in using the Los Angeles site, care must be taken to separate the effects of the AVM system from the effects of the control strategies, a potentially difficult task.

7.2.2 Priority Schemes

Priority schemes, particularly exclusive right-of-way for buses, have been significant elements in the Service and Methods Demonstration Program. These schemes have been predominantly directed at reducing mean transit travel times to encourage modal shifts to transit. Exclusive lanes or freeways have been successful in attracting riders by effecting such travel time reductions and by doing so in view of auto users. Kulash found the reliability effects of such strategies to be minor, based on simulation results, and concluded that such improvement schemes should be justified on the basis of reduction of mean travel time rather than variance. Since numerous demonstrations of exclusive lanes have already been undertaken, it is recommended that in future demonstrations of this nature, efforts be taken to insure that reliability effects are measured to assess the validity of Kulash's statement.

Signal preemption is another priority strategy which is generally directed at mean travel time. By preventing major delays at signals, the preemption strategy should reduce travel time unreliability as well. Signal preemption may also be used as a control device specifically oriented towards improving reliability. Preemption may be selectively used to speed up a bus behind schedule. The effects of these alternate uses of the signal preemption capability should be studied and measured in a demonstration. Moreover, buses can be given a form of priority by retiming traffic signals in a manner so as to facilitate bus movement. The low cost involved makes retiming of traffic signals particularly attractive.

The following demonstrations are suggested:

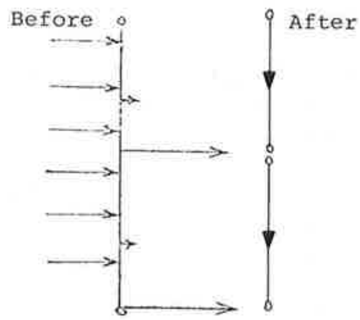
1. Signal pre-emption only (selective and general use)
2. Exclusive lanes only
3. Exclusive lanes with signal preemption (selective and general use)
4. Exclusive lanes with separate signal phases
5. Exclusive lanes with speed modification or other control strategies
6. Retiming traffic signals to facilitate bus movement.

7.2.3 Restructuring Routes

As discussed earlier in this report, service attribute variability increases along a route and that splitting long routes into shorter routes, or into express and local routes may be valuable strategies to improve reliability. If, in fact, reliability can be improved by redesigning routes at little or no additional cost, such strategies may be a first step in improving reliability. Expensive right of way, priority and automated control schemes should only be considered after low cost strategies, such as route restructuring, have been attempted.

While the aim of a route redesign demonstration would be to determine the effects of redesign on reliability, an important element to examine will be the effects of redesign on other aspects of service. For example, the inconvenience of transfers and the predominance of particular travel patterns must be considered in route redesigns. Where major turnover occurs, routes may be split into two entirely separate routes (see Case I in Figure 7.1). The Harvard-Dudley line of the MBTA in Boston, for example, has a significant turnover in the Auditorium area where Dudley-Back Bay transfer passengers alight and Back Bay-Harvard

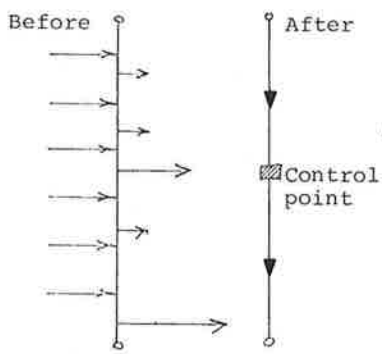
Case I - Split Route



Benefit: Improved Reliability of Arrival Time, Headway Regularity (Wait Time)

Disbenefit: Transfers required for all through trips

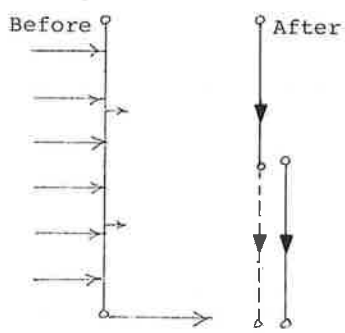
Case II - Holding Point



Benefit: Improved Reliability of Arrival Time, Headway Regularity (Wait Time)

Disbenefit: Through passengers are subjected to delays at the control point

Case III - Express/Local Service



Benefit: Improved Reliability of Arrival Time, Headway Regularity (Wait Time)

Disbenefit: Reduced frequency, Transfer required for intra-route trips

Note: Arrows to left and right of the line under the "Before" heading indicate the initial boarding and alighting distributions respectively. Each distribution is appropriate for the particular reliability improvement strategy suggested.

FIGURE 7.1 STRATEGIES FOR RESTRUCTURING ROUTES passengers board. Boarding counts would give an accurate assessment of the inconvenience caused by splitting the route at Auditorium versus the improved service which would result from shorter more reliable routes. Where turnover is less significant, holding strategies may be utilized to provide through service at some smaller inconvenience (delay) due to the possibility of layover (Case II). Finally where long routes experience constantly increasing loads with little major turnover, the use of express and local services may be the ideal strategy (Case III). In both the Case I and Case III redesigns, consideration should be given to minimizing transfer times.

7.2.4 Rescheduling

Simple planning by the operator with regard to schedules may also lead to improved reliability. Increasing recovery time between runs and increasing the number of spare drivers and vehicles available for various contingencies will, from the transit user's perspective, involve tradeoffs between reliability and other service components. The net effect of rescheduling may be that traveler benefits derived from the improved reliability outweigh the disadvantages associated with a degradation of other service components. Such rescheduling may have little or no effect on the costs incurred by the operator.

A rescheduling demonstration would determine the actual effects on transit users and operators of making some simple changes on specific routes and systems. The key aspects of such a demonstration would be identifying and measuring all of the level of service tradeoffs experienced by transit users, and the cost implications for the operator.

7.2.5 Traffic Engineering Strategies

In addition to strategies which give buses priority over other vehicles, there exist other methods for improving bus flow and reliability. It would appear that any traffic improvement which removes causes of delay will have a beneficial effect on transit travel time variance as well. Thus, general improvements of roadway facilities should improve transit reliability.

Bus movements should be explicitly considered in the preparation of plans for general traffic improvements. It is not enough to locate bus stops so as not to interfere with other traffic and to remove pedestrians from interfering with the vehicular flow. Each traffic element, automobile, bus, and pedestrian must be specifically considered to design an "optimal" system. This consideration should, however, occur within the context of general improvements in the Transportation Systems Management (TSM) Element.

Specifically, improvements which may prove valuable in increasing reliability of transit operation include:

Improving physical condition of curb lanes -- to permit its use and thus speed up boarding in addition to reducing interference with other traffic.

Providing bus stops of adequate length -- to permit buses to load/unload immediately upon arrival and ease transfers between buses.

Providing adequate turning radii at corners -- to ensure smooth and quick turns into appropriate lanes.

Reorganizing bus stops -- to ease transferring and to reduce delay at stops.

Enforcing parking restrictions -- to clear bus lanes and stops.

Channelization where bus turning movements are heavy (even if few other vehicles make the turn) -- to reduce delays to buses at intersections.

Improving the location/phasing/control of pedestrian movements -- to minimize interference with bus flow.

Coordinating bus stop location and signal timing -- to reduce delays at signals (e.g., alternating near-side and far-side stops where two linked signals occur).

Improving bus stop location -- far side stops have been found to be preferable due to the following:

1. They reduce conflicts between right-turning vehicles and stopped buses.

2. They provide additional intersection capacity by making the curb lane available for traffic.

3. They eliminate sight-distance deficiencies on approaches to intersections.

4. They encourage pedestrian crossings at the rear of the bus.

5. They require shorter maneuvering distances for the buses to enter and leave moving traffic (where there is curb-side parking).

6. At signalized intersections, buses can find gaps to re-enter the traffic stream (where there is curb-side parking).

There are, however, some disadvantages to far-side stops and in some cases, near-side or midblock stops may be more appropriate.

In conclusion, there are a number of traffic engineering strategies that may improve bus flow and reliability. The effectiveness of each strategy has yet to be determined. Study of a sample corridor may assist in examining the impact of TSM strategies.

7.2.6 Reconfiguration of Demand Responsive Transit Service

Demand responsive transit (DRT) service has been identified in this report as having certain characteristics which can produce unreliable service. These include totally flexible and thus variable routing, immediate service with promised times, and the fact that an additional trip adds significantly to vehicle travel time (due to doorstep pick-up and drop-off). A possible strategy for reducing unreliability of demand responsive transit, short of conversion to fixed route, is the development of new hybrid service concepts which offer many of the advantages of dial-a-ride but which overcome some of its reliability problems.

Such modifications to the original many-to-many dial-a-ride service concept include:

1. Scheduled fixed stops with deviation service.

2. Many-to-few service.

3. Integrated service (zonal dial-a-ride & fixed route).

4. Restricted doorstep service to special needs groups/specified time periods.

Existing dial-a-ride services experiencing similar reliability problems might be selected to adopt these modified policies to test their effectiveness in improving reliability and to determine if perceived level of service is acceptable to current and potential users. In some cases these modifications may be made in a staged process to determine effects of each step in a natural progression of service changes. As a control, these changes could be implemented in a sector of a larger dial-a-ride service area.

7.2.7 DRT Multiple Service Options

Algorithms to assign passengers to vehicle tours based on specific preferences of service levels should be developed and tested. A demonstration could assess the ability of the computer dispatch system to improve total passenger satisfaction with service and possibly expand the market to those who previously found the service too unreliable in one respect or another. Interesting conclusions may be drawn from the resulting sub-"modal split" among available DRT options. The relative weighting of the variance and mean of service components for different user groups may become evident. Included in this demonstration could be the implementation of pricing schemes for the different service options provided. The goal of different prices for different services could be the maximization of either overall level of service, ridership on specific services, net revenue, or some combination of these. The demonstration could provide insight into the more effective pricing policies.

7.2.8 Restricted DRT Service

This demonstration would test the acceptability and efficiency of a service which strives for reliable service levels for regular users and puts other users on a stand-by basis at a lower level of service. It is related to the previous demonstration in distinguishing between user groups. This service would evolve towards subscription service with marginal or separate service for other users.

7.2.9 DRT Dwell Time/Rerouting Policies

This demonstration would experiment with alternate policies to deal with cancellations and no-shows on an existing dial-a-ride system. The objective is to develop policies which will minimize the effects of such perturbations on the other users. Such policies may include sounding the horn at arrival and leaving if no response is made within 30 seconds, or calling in to the dispatcher to request instructions if no one shows up within some specified time. If a no-show or cancellation occurs, policies may include proceeding to the next stop, reordering to drop-off some passengers first so as not to arrive early at a pick-up, or adding another pick-up to the tour list. The effects on service reliability would be analyzed for the alternative policies including any significant change in the occurrence of no-shows and cancellations which can be related to the change in policy.

7.3 CONCLUDING REMARKS

The findings of this study suggest that transit reliability has a significant impact on both the traveler and operator, and that transit service reliability improvement strategies can have significant beneficial impacts on both traveler behavior and transit operator efficiency.

There appear to be a variety of ways in which reliability improvements can be obtained. Some of these strategies have exhibited promise in the limited number of empirical and analytic studies which have been conducted.

However, major gaps in our knowledge of transit service reliability problems, improvements, and impacts still remain. The authors hope that the ideas and suggestions contained in this report will prove useful in enhancing our understanding of the effects of service reliability on various elements of travel, and will promote the design and implementation of more effective policies directed at improving transit travel and operator efficiency.

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2. Barnett, Arnold. "On Controlling Randomness in Transit Operations." Transportation Science. Vol. 8, No. 2, May 1974.

*Material on file: U.S.Department of Transportation, Transportation Systems Center, Cambridge,MA.

APPENDIX A

DERIVATION OF RELATIONSHIPS BETWEEN TRAVEL TIME AND TRAVEL TIME VARIABILITY*

Total actual trip time (T) experienced by the transit user is composed of the sum of mean trip time (M) plus random delays (D). The random delay facing the user can be expressed as the following probability distribution:

$$g(D) = \frac{1}{\sqrt{2\pi}\ V} \exp\left(-\frac{D^2}{2V^2}\right) \qquad -\infty < D^2 < \infty .$$

That is, D is approximately normal with mean zero and variance V^2. The traveler is assumed to be free to leave as early as he likes in order to be sure to arrive "on time." His premature departure time is denoted by P. His actual trip time is T = M+D. The total time he allows for his trip is A = P+M. Therefore, on average, he will arrive E(A-T) = E(P+M-M-D) = E(P-D) = E(P) = P hours ahead of time.** In any given instance, however, he may be very late if D is large positive or very early if D is large negative, for then P-D will be correspondingly large negative or positive respectively.

The traveler's tastes are assumed to be of the following form. The first component of disutility originates from the fact that his total time allowed for the trip (A) will be wasted time. Since this wasted time becomes harder to fit into his schedule as this block of time increases in length, this component of utility can be expressed as:

$$-wM^{\alpha}\ (M+P) \qquad \alpha \geq 0,\ w > 0$$

where w is his value of time, M^{α} is a factor which allows the loss per hour to increase as the average total trip time increases, and (M+P) is the total time allowed for the trip. Graphically, this component of disutility encompasses an entire family of functions as seen in Figure A.1. Note that the disutility per hour always increases.

The second component of disutility reflects the fact that since actual trip times have an element of randomness,

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*Summarized from Marfisi, et al., (1).

**E( ) is the expected value of the term in parentheses.

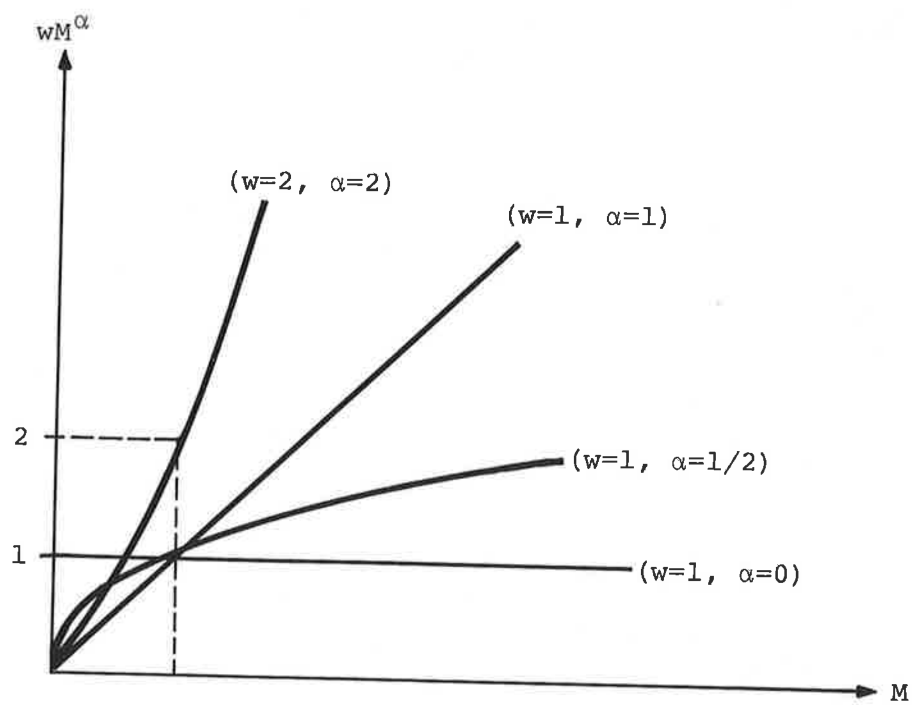

FIGURE A.1 GRAPH OF POSSIBLE DISUTILITY FUNCTIONS FOR DIFFERENT VALUES OF w AND α g(D), the traveler could easily arrive either earlier or later than he expected. If the latter occurs, there may be unfortunate consequences. If the former occurs, the traveler will have some free time which, to be sure, has some value, but is not likely to be as usefully spent as if he could count on having that extra time beforehand. The value the traveler places on a particular random delay can be represented by the following von-Neumann-Morgenstein utility function:

$$b\left\{1 - e^{c(d-P)}\right\} \qquad b,\ c > 0$$

This function is constructed so that if the actual delay (D) is precisely equal to premature departure time (P) there is no loss or gain from this component. The function embraces a wide family of functions depending upon the choice of b and c as is depicted in Figure A.2.

This function can be made as nearly linear as desired merely by allowing c to approach 0 while setting (-bc) at the desired constant slope -k. The rationale for this functional form is that longer delays in excess of premature departure times are more than proportionally costly to shorter ones. Similarly, longer "prearrival" times are less proportionally valuable to shorter prearrival times.

The second component of disutility can now be expressed as:

$$\int_{-\infty}^{\infty} b \cdot \left\{1 - e^{c(D-P)}\right\} \cdot g(D)dD$$

where each value of D is multiplied by the probability of its occurrence.

The traveler's total disutility, B, can now be expressed as:

$$B = -wM^{\alpha}(M+P) + \int_{-\infty}^{\infty} b \cdot \left\{1 - e^{c(D-P)}\right\} \cdot g(D)dD + K$$

$$= -wM^{\alpha}(M+P) + b - b\exp\left(-cP + \frac{c^2V^2}{2}\right) + K$$

where K is constant scaled so that B=0 when M and V are such that the trip is just worth making.

Assuming that the traveler desires to minimize his disutility, B, by an appropriate selection of a premature time P, $\frac{\partial B}{\partial P}$ is set equal to zero, and the solution for P is computed.

$$\frac{\partial B}{\partial P} = -wM^{\alpha} + bc\exp\left(-cp + \frac{c^2V^2}{2}\right) = 0 \quad .$$

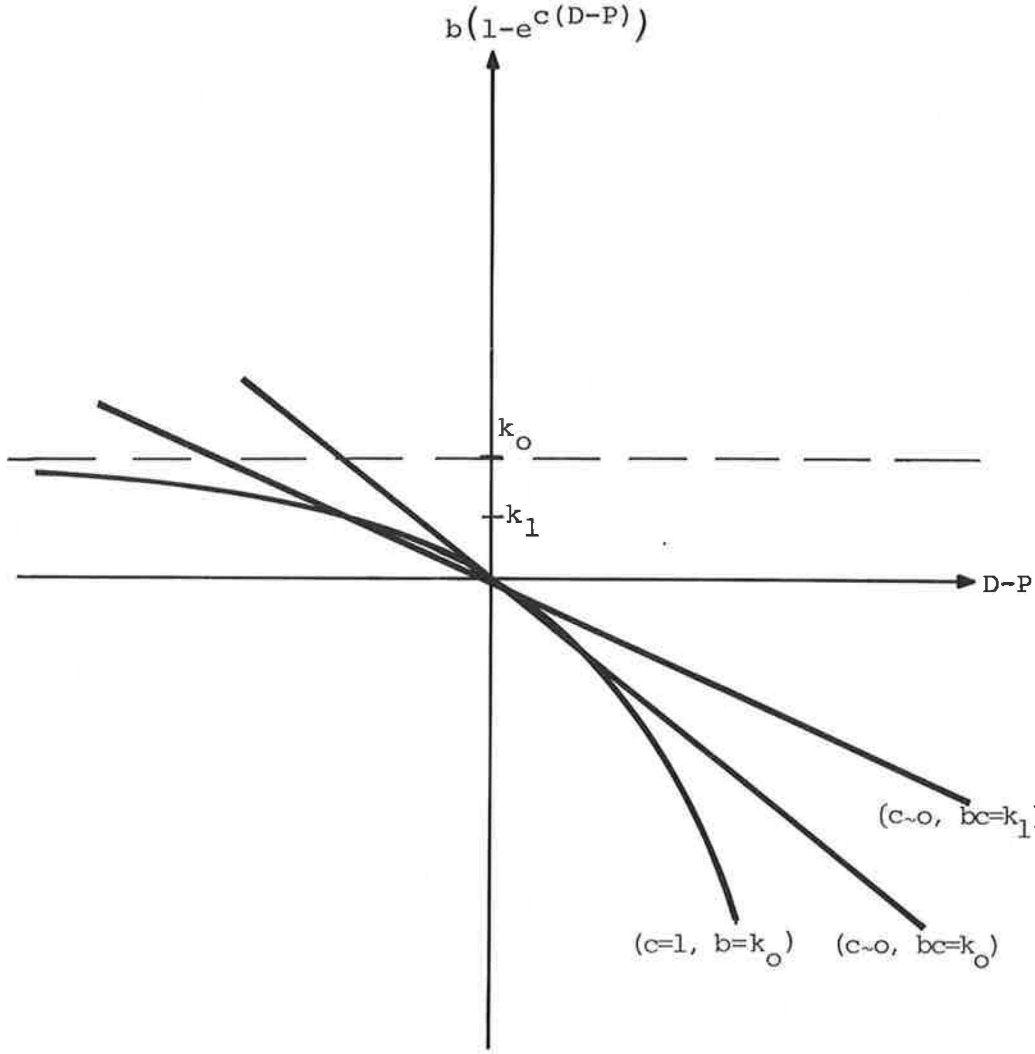

FIGURE A.2 GRAPH OF POSSIBLE DISUTILITY FUNCTIONS FOR DIFFERENT VALUES OF b AND c

Denoting P* as the optimal value of P,

$$P^* = -\frac{1}{c} \ln \left(\frac{wM^{\alpha}}{bc}\right) + \frac{cV^2}{2}$$

If the variance in actual delay approached zero, it would be expected that the traveler would schedule neither a positive nor a negative premature depature time. That is, as $V^2 \rightarrow 0$, $P^* \rightarrow 0$. This will occur if $b = \frac{wM^{\alpha}}{c}$.

This allows eliminating b from the set of parameters. The equation for P* can now be rewritten as:

$$P^* = \frac{cV^2}{2} \qquad c > 0$$

This equation indicates that the passenger will always schedule a positive premature departure time in the only case considered here, namely, that of positive "risk aversion" to delays.

APPENDIX B

DERIVATION OF TRAVELERS' MEAN WAIT TIME

Let $g_r(h)$ = headway distribution on route r

$\bar{w}(h)$ = average wait time for headway h

$n(h)$ = number of persons arriving in headway interval h

for interval h:

$$\bar{w}(h) = h/2 \qquad n(h) = kh$$

$$\text{Total \# of users} = \int_0^\infty n(h) \cdot g_r(h) \cdot dh$$

$$\text{Average wait time} = \bar{w} = \frac{\int_0^\infty n(h) \cdot \bar{w}(h) \cdot g_r(h) \cdot dh}{\int_0^\infty n(h) \cdot g_r(h) \cdot dh}$$

$$= \frac{k/2 \int_0^\infty h^2 \cdot g_r(h) \cdot dh}{k \int_0^\infty h \cdot g_r(h) \cdot dh} = \frac{E(h^2)}{2E(h)}$$

Since $Var(h) = E(h^2) - h^2$

$$E(w) = \frac{Var(h) + \bar{h}^2}{2\bar{h}} = \frac{\bar{h}}{2}\left(1 + \frac{Var(h)}{\bar{h}^2}\right).$$

Source: (Kulash, 2)

APPENDIX C

BARNETTS'S HOLDING POINT MODEL

A procedure has been developed to construct an approximate-optimal dispatching strategy for the control point (Barnett, 3). A description, application, and extensions of this procedure are discussed below.

The interarrival interval (or headway) between two consecutive vehicles at a point B, with respective lateness ℓ_1 and ℓ_2 and scheduled headway a, is:

$$h = a + \ell_2 - \ell_1$$

While ℓ_1 and ℓ_2 both have the same unconditional density function, it is unlikely that they are independent; presumably from the available data one can obtain the conditional distribution of ℓ_2 given by ℓ_1.

If passenger arrivals are assumed Pcisson distributed, the average waiting time is:

$$\bar{w} = \frac{E(h^2)}{2E(h)} = \frac{a^2 + E(\ell_1^2 + \ell_2^2 - 2\ell_1\ell_2)}{2a}$$

The only form of control being considered is the delay of individual vehicles at the contrcl point B. One can set the goal of a holding strategy to minimize an objective function, J, of the following form:

$$J = \alpha\ E_b(d) + (1 - \alpha) E_b(w)$$

where: $E_b(d)$ is the expected delay at B to passengers who boarded earlier and for whom B is an intermediate stop

$E_b(w)$ is the expected wait time for passengers who board at B

α is a weighting constant $(o \leq \alpha \leq 1)$

Since wait time varies linearly with headway variance, and since headway variation will build up proportionally along the route, reducing headway variation is the objective at point B most beneficial to passengers further down the route. Their expected wait can be shown to be proportional to that time at point B, and therefore, the expected delay and wait times at point B appropriately weighted are sufficient input to the objective function.

To simplify the problem, a two point model is developed for the lateness distribution, using parameters c, d, and p. c and d are the points and p the probability weight assigned to c ($c \leq d$).

Selection of c, d, and p are constrained by the following relationships:

$$u = cp + d(1-p)$$

$$v = c^2 p + d^2(1-p)$$

$$w = c^2(pp_{cc}) + 2cd(pp_{cd}) + d^2(1-p)p_{dd}$$

$$= c^2 p + d^2(1-p) - pp_{cd}(d-c)^2,$$

where: p = probability of delay c
p_{cc} = probability of delay c, given delay c on previous vehicle
u = mean lateness
v = second moment of lateness
w = expected product of two consecutive latenesses in the actual vehicle arrival pattern at point B.

We define $L = d-c$. The model is formulated as follows:

Possible Arrival Delay Sequences	Headway	Probability
c,c	a	p_{cc}
c,d	a+L	p_{cd}
d,c	a-L	$(1-p)\cdot p_{dc} = pp_{cd}$
d,d	a	$(1-p)\cdot p_{dd}$

Average wait at B satisfies

$$E_b(w) = \frac{E(h^2)}{2E(h)} = \frac{a^2 + E(\ell_1^2 + \ell_2^2 - 2\ell_1\ell_2)}{2a}$$

$$= \frac{a^2 + (2v-2w)}{2a} = \frac{a^2 + 2pp_{cd}(d-c)^2}{2a}$$

$$= \frac{a^2 + 2L^2 pp_{cd}}{2a}$$

in the model.

Thus variations around mean headway 'a' have increased expected wait time by $(L^2 p p_{cd})/a$ over its ideal value of $a/2$.

A simple strategy to reduce average wait time at B would be to regularize intervals by holding the second vehicle in a (d,c) sequence by some amount x (c_1 refers to a vehicle of lateness c immediately after one of lateness d).

Arrival Sequence	Associated Departure Headway	Prob. of Occurrence
(d,d)	a	$(1-p)\cdot p_{dd}$
(d,c_1)	$a-L+x$	$(1-p)\cdot p_{dc}$
(c_1,c)	$a-x$	$(1-p)\cdot p_{dc}\cdot p_{cc}$
(c,c)	a	$p p_{cc}^2$
(c_1,d)	$a+L-x$	$(1-p)\cdot p_{dc}\cdot p_{cd}$
(c,d)	$a+1$	$p p_{cc}\cdot p_{cd}$

The resulting value of the objective function is:

$$J(x) = \alpha x(1-p)p_{dc} + (1-\alpha)\frac{E(h^2)}{2E(h)}$$

J(x) is a minimum when:

$$x = \max\left\{0, \left(\frac{L(1+p_{cd})}{2} - \frac{\alpha}{1-\alpha}\left(\frac{a}{2}\right)\right)\right\}$$

(Note: for $L < a$, $0<x<a$)

The simple strategy described above leads to an overall reduction in average wait time. The overall average headway is unchanged and thus the system does not require additional vehicles or layover time. Some vehicles, however, are delayed and at some points in the sequence headway interval variation is increased.

This procedure was applied to a model of the northbound Red Line in Boston at Washington Street, the busiest stop on the line. Actual route operating data was used as input to the model. The scheduled headway, a, was 5 minutes for the analysis period. Lateness compared to scheduled time had a mean, u, of 0.7 min. and a second moment, v, of 1.7 min.^2. The expected product of two consecutive latenesses, w, was 0.3 square minutes.

An approximate two-point model was created. From the data, a graph of p_{cd} as a function of p was obtained and utilizing the values and equations for u, v, and w, the values of c, d, and p were obtained as well as p_{cd}, p_{cc}, p_{dc}, and p_{dd}:

$c = -0.4$
$d = 1.9$
$p = 0.48$
$p_{cd} = 0.58$
$p_{cc} = 0.42$
$p_{dc} = 0.54$
$p_{dd} = 0.46$

Average wait at Washington Street was:

$$- a/2 + (L^2 p p_{cd})/a = 2.8 \text{ min.}$$

Choosing $\alpha = 0.1$ to reflect the small number of passengers continuing through Washington Street, a one stage holding strategy of 1.54 min. can be determined. This results in a reduction of average wait to 2.62 min. and an average delay of 25 seconds for passengers passing through Washington Street.

After a few iterations of the model, multi-stage strategies yield a 10% reduction in average wait, to 2.53 min., very close to the ideal wait time value, 2.5 min. This is a drop of 90% in excess wait time.

Average holding time at Washington Street is under one minute, only a small fraction of typical buffer periods at terminals. An important side effect is the reduction of the average number of standees leaving Washington Street northbound by about 70%.

The simple control strategy that has been described above can be extended to include multi-stage holding strategies in which more than one vehicle is held to reduce the adverse effects. A more complex procedure has been developed to construct such multi-stage strategies and is easily programmable. The procedure for finding an approximate best dispatch strategy from the central stop is as follows:

1. The arrival delay distribution for vehicles is estimated by a two-point distribution that preserves those characteristics of the arrival pattern most relevant to the objective function.

2. An algorithm is used to obtain the best holding policy under the two-point model of vehicle arrival.

3. An elastic holding scheme is devised to implement as closely as possible in the actual situation the policy found best in the simplified model.

The procedure described above could be extended to include:

1. a more precise approximation of the vehicle lateness distribution (more than two points)

2. the use of more detailed information about future arrivals at the control stop, and

3. more control stops.

APPENDIX D

DERIVATION OF THE HEADWAY AT A PARTICULAR BUS STOP ON A ROUTE

Propagation of an initial deviation with number of stops along a route may be expressed as follows (Cohn, 4):

$$e_i = e_{i-1} + e_{i-1}(P \bullet b)$$

$$e_n = e_o(1 + P \bullet b)$$

where:
e_n = error in arrival at stop n
e_o = initial departure error
P = arrival rate of passengers at stops
b = boarding time per passenger.

This model can be extended to include:

1. probabilistic nature of passenger arrivals (let the number of passengers waiting to board be a function of the headway and a random variable P, the instantaneous rate of arrival);

2. probabilistic nature of travel times on all segments of the route.

Thus the expression for the error may be expanded to:

$$e_i = (e_{i-1} + t_i) + (e_{i-1} + t_i)(P \bullet b)$$

where:

t_i = a random variable which is a function of distance from i-1 to i. This represents a deviation from an expected travel time from i-1 to i.

P = a random variable representing passenger arrival rate at a stop.

Furthermore, an expression for headway may be developed:

Let: $H_i^{k-1,k}$ = headway at stop i between buses k and k-1

s = scheduled headway

Then: $$H_i^{k-1,k} = s + e_i^k - e_i^{k-1}$$

$$e_i^k = (e_{i-1}^k + t_i^k - e_i^{k-1})(1 + P \bullet b)$$

$$H_i^{k-1,k} = s + (1 + P \bullet b)(e_{i-1}^k + t_i^k - e_i^{k-1} - e_{i-1}^{k-1} - t_i^{k-1} + e_i^{k-2}).$$

APPENDIX E - FURTHER ANALYSIS OF JOLIFFE AND HUTCHINSON RESEARCH

A major finding of Joliffe and Hutchinson was that where bus arrivals are predictable, travelers may be able to minimize their wait time at the bus stop by arriving there at a particular time instead of randomly. They observed in several cases the coincidence of high passenger arrivals with resulting waiting times lower than the expected waiting time, w_{rand}, had the passengers arrived randomly. They calculated that, for each bus stop, there was a particular arrival time which would minimize the expected waiting time for the bus. This waiting time was called w_{min}.

On all of the bus routes observed, it was possible for a traveler to reduce his/her mean wait time by some amount. $g = w_{rand} - w_{min}$ was defined as the potential gain in reduced waiting time that could be obtained by a passenger with knowledge of the bus service who arrives at the optimal time.* Joliffe and Hutchinson observed that the actual waiting time, W, fell in between w_{rand} and w_{min}. They hypothesized that only a certain percentage of travelers were taking advantage of the time savings and the rest were arriving randomly. They developed the following scenario: a small percentage of the passengers, q, ran to catch the bus when it was in view, and had no waiting time at all; "p" percent of the remaining passengers, or $(1-q)p$ percent of all of the passengers, arrived at the optimal time and waited w_{min} for the bus; the remaining $(1-q)(1-p)$ percent arrived at random and waited w_{rand}. p was plotted against q for both peak and off-peak routes (see Figure E.1). Given the observed points and given that p (1) should always be in the range 0 to 1, (2) should be zero when g is zero, and (3) should be continuously increasing, a suitable function was found to be $p = 1 - e^{-\lambda g}$. The curves in Figure E.1 have this form, where λ is 0.131 for the peak and 0.015 for the off-peak.

It seems logical that when g is large, p is large, for two reasons: (1) the fact that a potential gain is available will be more easily perceptible, and (2) the incentive for arriving at the optimal time rather than randomly is larger. It is also expected that p is larger in the peak than in the

*Optimal time refers to the particular recurrent point in time at which a passenger would arrive at the bus stop so as to minimize his wait time.

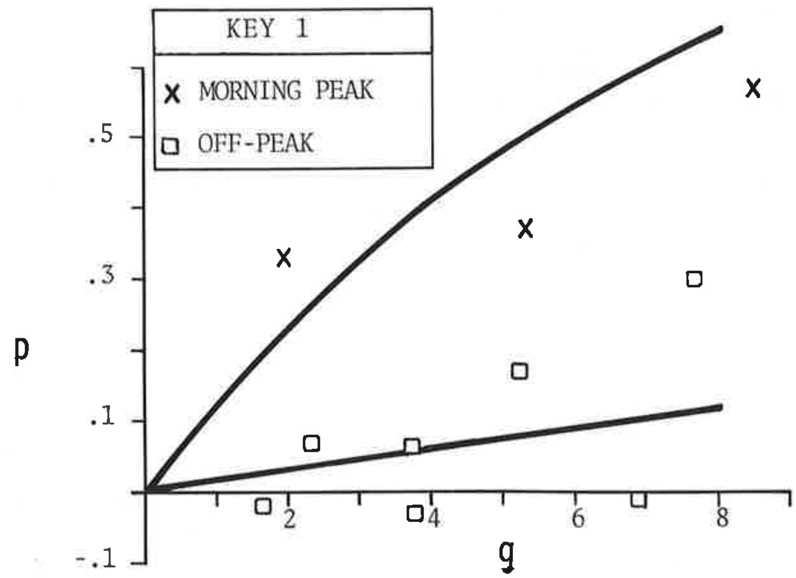

FIGURE E.1 PERCENT OF PASSENGERS ARRIVING AT THE OPTIMAL TIME AS A FUNCTION OF THE POTENTIAL GAIN IN REDUCED WAITING TIME off-peak, because of the greater proportion of regular travelers in the peak hours.

Joliffe and Hutchinson also found that w_{min} is positively correlated with Ω, the standard deviation of bus departure times excluding the effect of cancellations (see Figure E.2). If Ω were zero, then w_{min} should be zero also, since passengers could arrive at the same time as the bus. But this is only true if there are no cancellations. If some buses were cancelled, w_{min} would be positive even if Ω were zero, implying a positive intercept in Figure E.2. An exceptionally high proportion (33 percent) of buses at stop 9 were cancelled, giving rise to the outlying point at (3.1, 9.7). The authors of this report feel that this analysis would be strengthened if Ω', the standard deviation of bus departure times including cancellations, were used instead of Ω. With $\Omega' \geq \Omega$, all points would be shifted to the right, with the outlying point shifted the most (as indicated by the arrow in Figure E.2), and w_{min} would tend towards zero when Ω' was zero.

Joliffe and Hutchinson assumed that many travelers set their arrival time so as to minimize their expected wait time. However, at that time, the variability of wait time may not be minimized. Joliffe and Hutchinson did not explore this possibility. It might be that travelers will choose the time which minimizes their combined disutility for wait time and wait time variability.

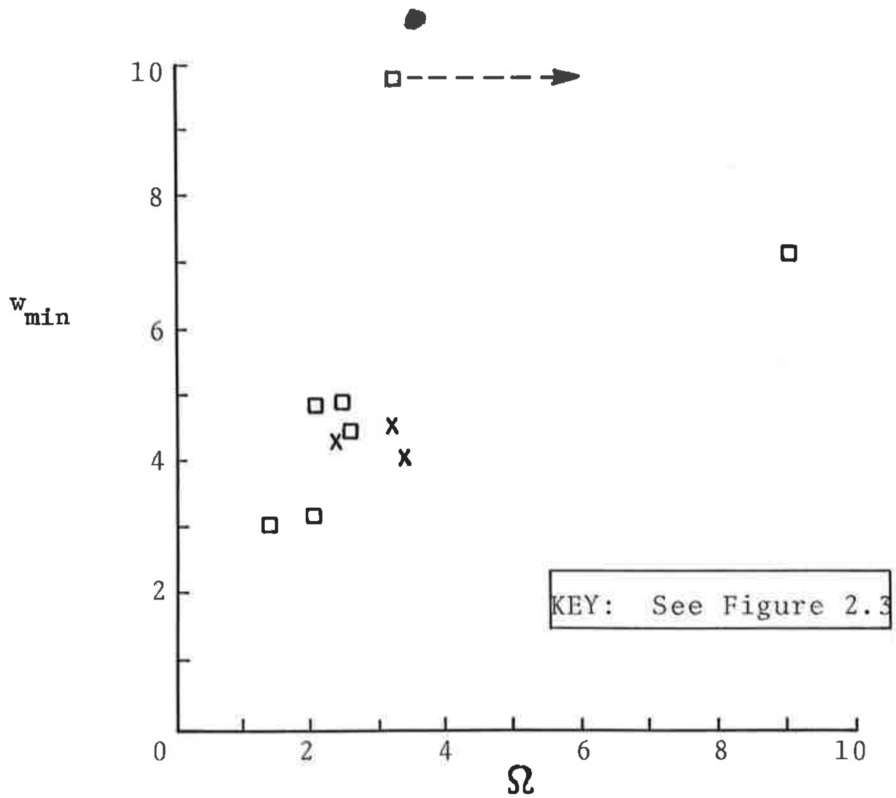

FIGURE E.2 RELATION BETWEEN STANDARD DEVIATION OF BUS DEPARTURE TIMES AND MINIMUM WAITING TIME

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