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THE APPLICATION OF TRAFFIC SIGNAL PREEMPTION SYSTEMS FOR CONTROLLING BUS HEADWAYS

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PROJECT MEMORANDUM

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16. Abstract This report investigates the application of selective traffic signal preemption for controlling the headways of local service buses (buses with average time headways of less than 10 minutes). The preemption is selective in that it is granted to only "late" buses along a route, leading to a reduction in headway variance. The potential benefits of more evenly spaced bus headways include reduced passenger waiting times, reduced incidence of bus overloadings and more efficient fleet operation. Past application of traffic signal preemption systems have concentrated on reducing travel times for buses in Central Business District (CBD) grids and arterials. However, these systems have not been widely accepted and implemented, indicating that the amount of reduction in travel time has not resulted in a sufficient increase in ridership to offset the system costs and impacts on other traffic.

The analysis and simulation results in this report indicated that selective traffic signal preemption is a feasible method for controlling the headways of buses on short headway routes. Furthermore, selective preemption yielded equal or better transit system performance compared to unconditional preemption with less than half as many preemptions and preempted cycle time. Future plans are discussed for expanding the simulation model developed in this report and continuing the analysis. The output of this work is expected to be a quantification of benefits as a function of bus priority variables, traffic variables and route characteristics.

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1. INTRODUCTION

Signal preemption systems have been identified and tested as a means of reducing travel times for buses in Central Business District (CBD) grids and arterials,[1][2][3] however, these system applications have not been widely accepted because reduction in travel time has not been sufficient to warrant implementation, or the impact on other traffic has been large. The ineffectiveness of these systems has been generally due to the fact that buses have to stop frequently for passenger service, or because of traffic congestion.[4]

This study investigates the application of selective traffic signal preemption for controlling the headways of local service buses (buses with average time headways of less than 10 minutes), thus reducing the tendency of these buses to bunch, a common phenomenon along urban bus routes caused by variations in passenger loading. Effective control would provide more evenly spaced bus headways, reducing passenger waiting times and the incidence of bus overloadings and resulting in more efficient fleet operation. Further, a recent study[5] on technological innovations in transit service found that equalizing the numbers of passengers on buses <u>via</u> headway control yields a benefit equivalent to 0.4-3.8% additional buses and drivers.

The preemption is selective in that it is granted only to "late" buses along a route, leading to a reduction in headway variance. Thus, through selective preemption, real benefits to bus passengers in terms of more reliable service can be achieved. Because selective preemption is not exercised as frequently as unconditional preemption, a strategy designed to reduce bus travel time, potential negative impacts on other traffic can be minimized (i.e., less effective green time would be taken from the cross traffic signal phase).

Although limited analysis has been conducted on traffic signal preemption for bus headway control,[6] it does not appear that the concept has been sucessfully field tested. The goal of the current effort is to identify, develop, and field test effective headway control strategies and to provide benefit-cost tradeoff data on system alternatives. In this report, initial analysis and simulation results are discussed, followed by plans for further study. Chapter 2 discusses potential benefits obtainable with bus headway control. The benefits are estimated from an equation relating passenger waiting time to the bus mean headway and standard deviation, and also from a simplified bus-route model and control strategy. Chapter 3 describes a simulated bus preemption experiment, using field data to compare potential reductions in travel time with potential reductions in bus headway standard deviation for different types and levels of preemption. In Chapter 4, a simulation model of a representative bus route is developed. Various headway control strategies are also developed and evaluated in terms of passenger waiting time, bus load variance and bus in-service time. Chapter 5 discusses potential impacts on other traffic based on previous simulation experiments. Finally, Chapter 6 summarizes the results of the previous chapters and discusses further plans for expanding the simulation model developed in Chapter 3, continuing the analysis and field testing the preemption strategies developed. Some of the strategies provide a more comprehensive approach to headway control and may require real-time surveillance and control in the form of an Automatic Vehicle Monitoring (AVM) system. Such systems have already been tested to various degrees in Hamburg,[7] Chicago,[8] London,[9] and Philadelphia.[10]

2. ESTIMATED BENEFITS WITH BUS HEADWAY CONTROL

2.1 PASSENGER WAITING TIME EQUATION

On short headway bus routes (i.e., headways less than 10 minutes), the average passenger waiting time at each bus stop can be shown to be:[11]

$$W = \frac{h}{2} + \frac{\sigma^2}{2h} \quad (1)$$

where

W = average passenger waiting time

h = average bus headway

σ = bus headway standard deviation

Equation (1) assumes random and independent bus and passenger arrivals. Furthermore, the passenger arrivals are assumed to be uniformly distributed. These appear to be reasonable assumptions for short headway bus routes.

The average passenger waiting time thus increases with the bus headway standard deviation, and is at its minimum value when the average bus headway is equal to the headway standard deviation. On short headway routes, without effective control of the spacings between buses, buses will begin to bunch, producing large values of the headway standard deviation and average passenger waiting time relative to the average headway. However, the headway standard deviation (or variance) and thus the average passenger waiting time, can be effectively reduced by delaying early buses and/or advancing late buses. The former strategy can be employed by bus drivers at bus stops. The latter strategy can be employed with traffic signal preemption.

If the randomness of the bus arrivals could be eliminated (i.e., through perfect control of the bus headways), passenger waiting time would be reduced accordingly. The amount of the potential reduction in waiting time (in percent) is shown in Figure 1 as a function of the initial states of the average bus headway, h_0, and the standard deviation, σ_0. The waiting time reduction is obtained by reducing the headway standard deviation to zero and holding the average headway constant. Thus, starting with an average bus headway of 5 minutes and a headway standard deviation of 5 minutes, the maximum potential reduction in passenger waiting time would be 50%. With a headway average and standard deviation of 10 minutes and 5 minutes, respectively, the maximum reduction would be 20%. Although Figure 1 shows the potential reductions in terms of the initial states of the average headway and standard deviation, the percent reductions are dependent only on the ratio of the headway standard deviation to the average headway. Thus stated in more general terms, in situations where the headway standard deviation is equal to the average headway, the maximum potential reduction in passenger waiting time would be 50%, and in situations where the headway standard deviation is half the average headway, the maximum reduction would be 20%. Since these two examples perhaps represent the range of situations that would most likely occur in

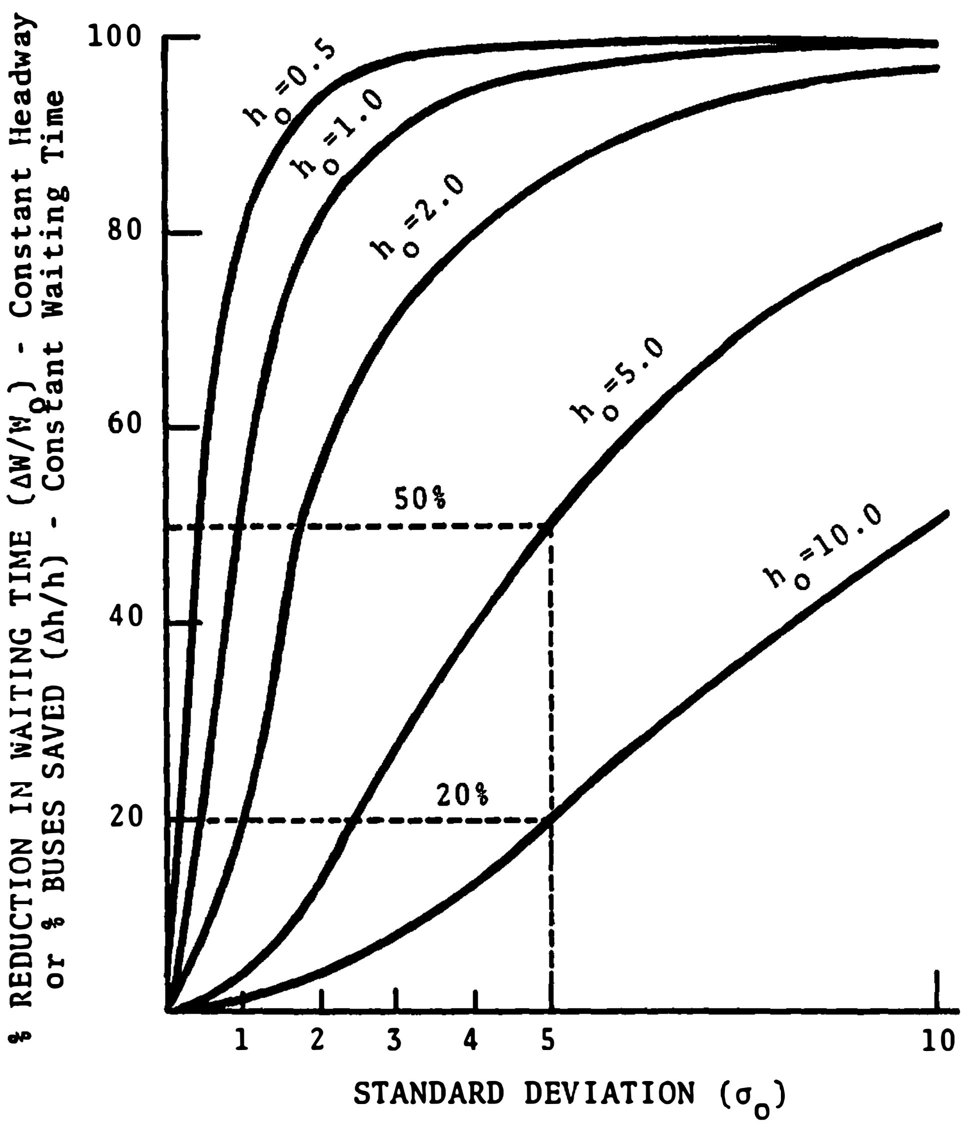

FIGURE 1. BENEFITS ACHEIVABLE THROUGH PERFECT HEADWAY CONTROL (COMPUTED FROM WAITING TIME EQUATION)

practice, 20-50 percent represents the maximum achievable reduction in passenger waiting time through perfect bus headway control. (The situation of multiple bus bunching is not specifically considered in this study. This perhaps represents a more extreme situation with more potential for improvement and where other measures, such as excessive passenger waiting time, may be more important).

Figure 1 also represents the maximum potential savings in buses that could be achieved by reducing the headway standard deviation to zero and holding the average waiting time constant. The potential savings in buses is determined by $(h_0-h)/h = \Delta h/h$, where h is the new headway computed from equation 1, and effectively assumes constant bus speeds. The methods for obtaining this type of control or for that mentioned in the preceding paragraph are not readily apparent but it is felt that limits portrayed by Figure 1 are helpful in providing information on relative potential benefits under various bus headway conditions. Thus, 20-50 percent also represents the maximum achievable reduction in buses through perfect bus headway control.

Since perfect headway control (i.e., 100% reduction in the headway standard deviation) is unachievable in practice, Figures 2 and 3 were generated to show potential benefits in terms of the amount of reduction in headway standard deviation.

Figures 2 and 3 represent, respectively, the percent reduction, in waiting time and buses saved, achievable through

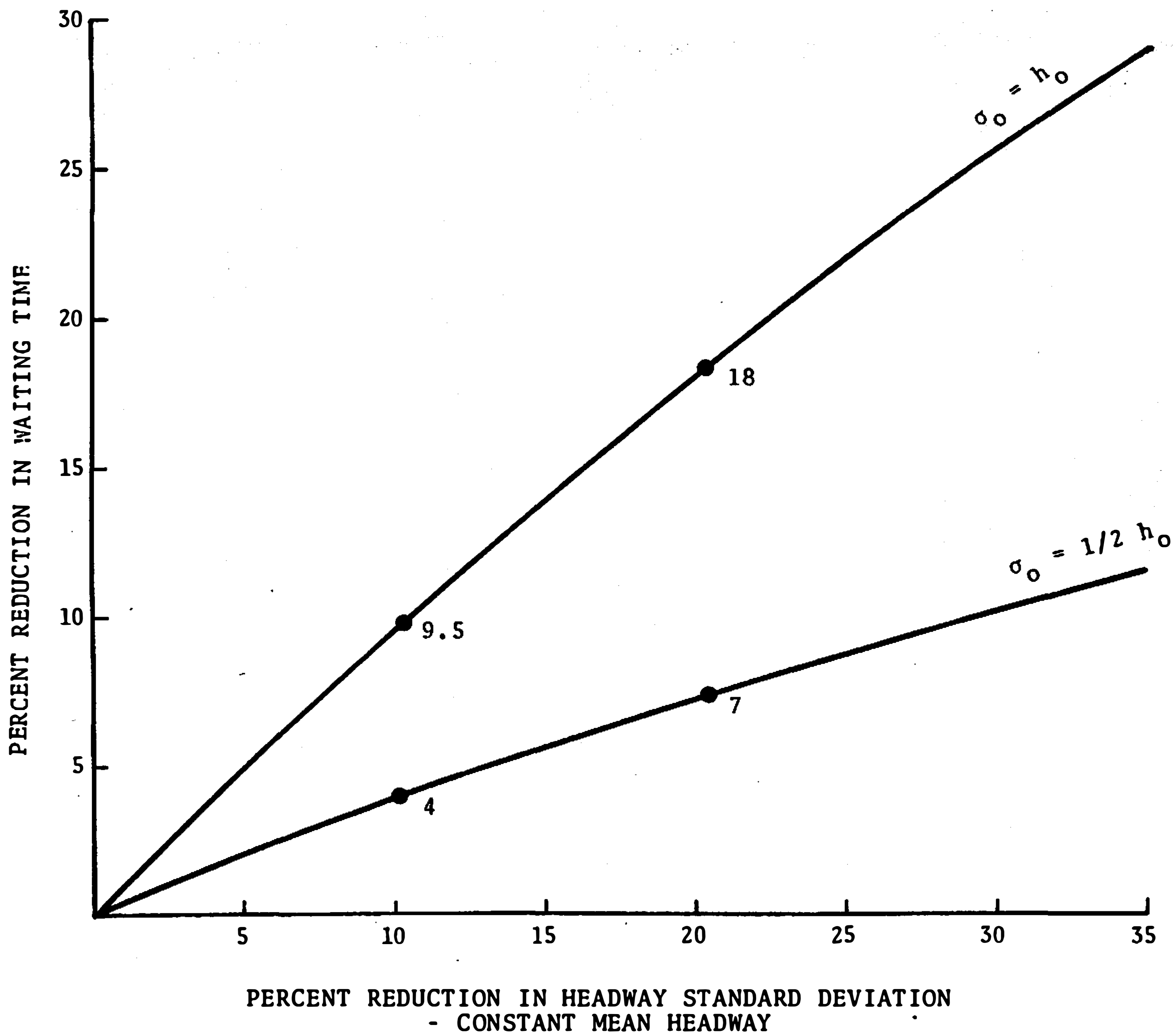

FIGURE 2. WAITING TIME BENEFIT WITH REDUCED HEADWAY VARIANCE

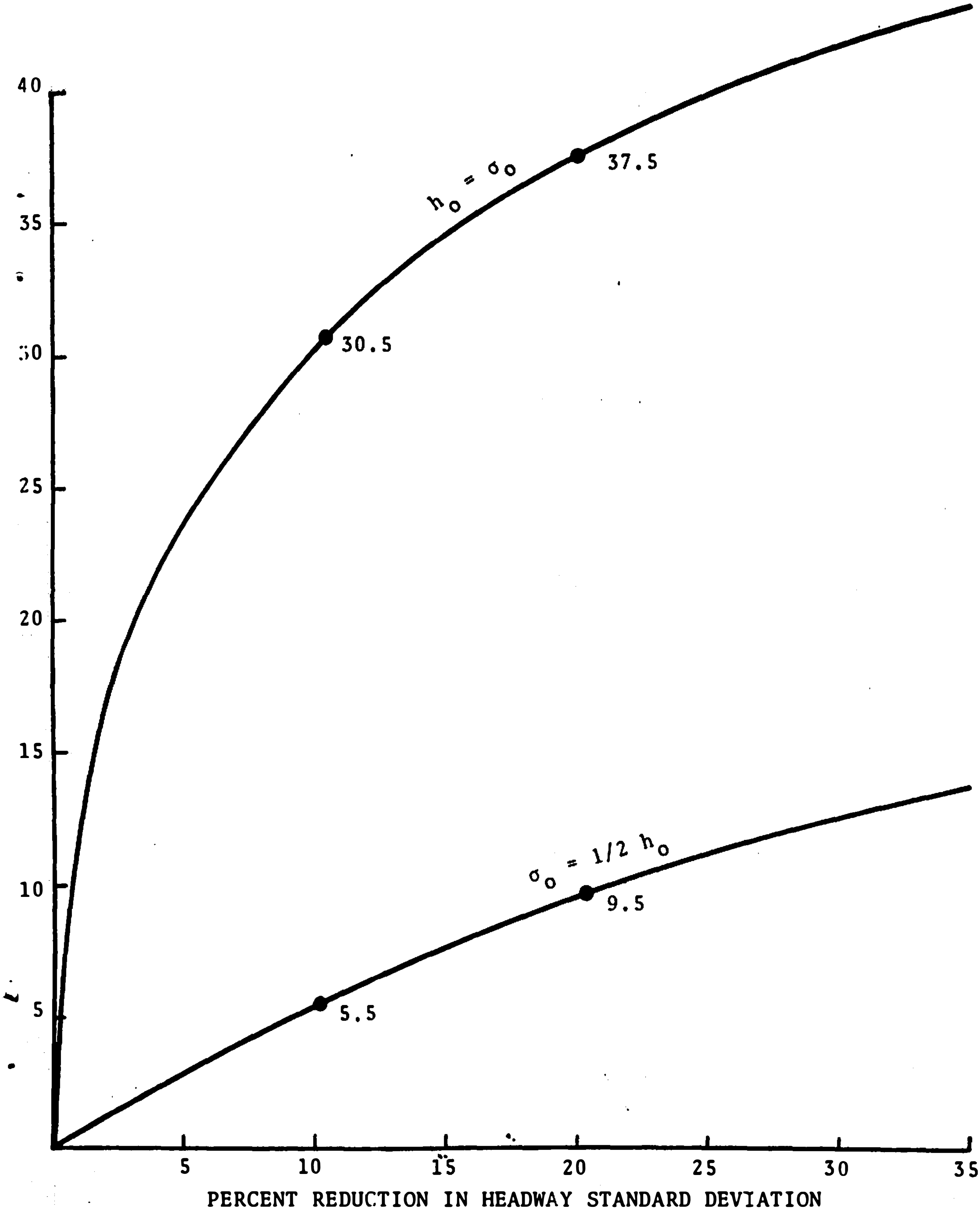

FIGURE 3. BUSES SAVED BENEFIT WITH REDUCED HEADWAY VARIANCE

percent reductions in the bus headway standard deviation. Again, the reductions were computed from the waiting time equation, keeping the headway constant for the waiting time computations and the waiting time constant for the "buses saved" computations. The reductions are shown for two situations: the first, where the initial state of the average headway and headway standard deviation are equal; and the second, where the initial state of the standard deviation is half that of the average headway.

From the figures, it is clear that additional potential benefit can be obtained from situations where the headway standard deviation and average are equal. This might be expected since this represents a "noisier" situation compared to the situation where the headway standard deviation is half the average. The curves do provide a quantification of the absolute and relative benefits for various headway conditions. As an example, from Figure 2, a 20% reduction in headway standard deviation will provide an 18% reduction in waiting time for situations where the headway standard deviation is equal to the headway average, but only a 7.2% reduction when the headway standard deviation is half the average. If the average headways were 5 minutes, this would translate into the following: for situations where the headway standard deviation is equal to the headway average, a 60-second reduction in the headway standard deviation (20%) would provide a 54 second reduction in average passenger waiting time (18%). For situations where the headway standard deviation is half the headway average, a 30 second reduction in the headway standard deviation (20%) would provide a 13.5 second reduction in average passenger waiting time (7.2%). The relatively diminishing benefits are thus apparent as the headway variance level decreases.

It is interesting to contrast the waiting time benefits of Figure 2 with the "buses saved" benefits of Figure 3. From Figure 3, a 20% reduction in headway standard deviation will provide a 37.5% reduction in buses (with a constant level of service or passenger waiting time) for situations where the headway standard is equal to the headway average, and a 9.5% reduction when the headway standard deviation is half the average. Thus, for small reductions in headway standard deviation, more relative benefit percent-wise is achievable in terms of buses saved compared to reduced passenger waiting time. However, the actual bus savings depend on the route characteristics (e.g., length, layover time) and cannot be determined within the scope of this simplified analysis. Nevertheless, tradeoffs will eventually have to be made between returning the potential benefits to passengers in terms of reduced waiting time or to fleet operators in terms of buses saved. Figures 2 and 3 may be used to provide comparative data for making these tradeoff decisions.

In summary, this section provided an indication of the level of benefits achievable through effective bus headway control on local service routes under various headway conditions and for different control levels. However, the analysis essentially represented a single bus stop location and did not identify or consider explicit control methods or strategies. The next few sections expand the analysis by developing models of bus movements along a route and by developing and evaluating more specific headway control strategies.

2.2 A SIMPLIFIED BUS ROUTE MODEL AND CONTROL STRATEGY

Bus headway control appears to be more amenable to analysis by computer simulation than by purely mathematical or conceptual models. Nevertheless, a mathematical model is available which has many of the elements of a realistic bus headway control situation.

Consider a very specific and simple model for bus motion on which will be imposed a model for schedule control: Suppose each bus moves forward at a constant average speed superimposed on a random walk. This is commonly known as random walk with drift. The case of a very short step-size random walk - known as diffusion - will be considered. The resulting motion is a Wiener process superimposed on a uniform drift velocity.[12]

The resulting model is a consistent, simple model of the motion of an object with a constant average speed which undergoes random fluctuation in its movement. This is probably the simplest model of continuous motion with two properties:

1. A constant average speed, and
2. A constantly changing random component to its motion.

The average or drift speed is not a precisely observable quantity for an individual bus, since the bus is constantly undergoing random motion as well. There will be a definite tendency for the bus to move forward at approximately a constant speed, but its actual motion can only be described in probabilistic terms. Let X(t) be the position of the bus at time t, which left point X=0 at time t=0 (i.e., X(0)=0). Then the average or expected position at time t can be denoted $\bar{X}(t)=Vt=\mu_t$, where V is the constant average or drift velocity. X(t) will be normally distributed about its mean value with a variance that also grows proportionally with time, thus: $\sigma^2_{X(t)}=kt=\sigma^2 t$. The foregoing properties of X(t) are properties of the random walk with superimposed drift. To recapitulate:

1. X(t) is normally distributed,
2. Its variance grows linearly with time: $\sigma^2_t=kt$, and
3. Its mean increases linearly with time: $\mu_t=\bar{X}(t)=Vt$.

The mathematical model is specified by the following conditional probability distribution:

1) $Pr\{X(t_2)<X_2 \mid X(t_1)=X_1\}$

$$= \frac{1}{\sqrt{2\pi k(t_2-t_1)}} \cdot \int_{-\infty}^{X_2} \exp\left(\frac{-\{U-[X_1+V(t_2-t_1)]\}^2}{2k(t_2-t_1)}\right) dU$$

where $(t_2>t_1)$

which states that if (i.e., conditioned on) $X(t_1)=X_1$, then $X(t_2)$ is normally distributed with mean $X_1+V(t_2-t_1)$ and variance $k(t_2-t_1)$. If it is assumed, as earlier, that $X(0)=0$, then:

$$2)\qquad Pr(X(t)<x) = \frac{1}{\sqrt{2\pi kt}} \int_{-\infty}^{x} \exp\left(\frac{-(U - Vt)^2}{2kt}\right) dU$$

which is a simpler and more convenient expression.

So far, a description of the mathematical model for the uncontrolled bus has been given. As noted, the variance of the position of the bus on the route, [X(t)], grows linearly with time. This has a correspondence with the hypothesis that the bus headway variance grows linearly with position on the route.[10]

Next, consider a simple control strategy. In an attempt to reduce headway variance, position variance (i.e., variance of X(t)) will be reduced by delays in accordance with a schedule. As the buses move independently according to the model described above (they may be initially dispatched at uniform or approximately uniform intervals), and since the control strategy will treat each bus independently (this latter is a feature of schedule control and not of general headway control), it follows that the headway variance can be readily obtained from the position variance of each bus.

The control strategy that will be evaluated in this section can be described as follows: the earliest time at which each bus can leave each location along a route is determined to be a linear function of the distance of the location from the beginning of the route. For the hypothetical bus leaving the beginning of the route at t=0 (i.e., for which $X(0)=0$), the control strategy is specified by $X(t) \leq V_0 t$, where V_0 is essentially a schedule velocity, and the control strategy is to ensure that $X(t)$ does not exceed its scheduled location $V_0 t$.

The control strategy just described mathematically can be pictured by the following physical model:

Suppose that a "pace car" travels in front of the bus at velocity V_0. The bus follows and may catch up to, but not pass, the pace car. The pace car defines the limit of motion imposed on the bus by this schedule control. The bus may occasionally catch up to the pace car, but since it may not, by the rule of the control strategy, go ahead of the pace car's position ($V_0 t$), the bus will, by the random influence of traffic, mostly be lagging behind the pace car by random amounts. In other words, even though the pace car travels at a constant speed, V_0 (this is a hypothetical vehicle), the bus, being subjected to the realistic random influence of traffic, will still have a random motion with variance, but the variance will be reduced below what is was in the uncontrolled situation (i.e., kt).

In practice, the control strategy may be implemented by employing Automatic Vehicle Monitoring (AVM) System technology with buses instrumented to provide appropriate schedule control information to the driver.

A simple tractable and, at the same time, instructive approach for determining the effectiveness of schedule control is to impose the constraint $X(t) \leq V_0 t$ and to observe the steady state solution.

If the bus route is very long, or if it is circular (cyclical), a reasonable choice for V_0 is slightly less than the free drift velocity (i.e., $V_0=V-v$). The parameter v can be optimized to achieve the best solution. One then expects a steady state distribution moving along with a speed V-v, but with unchanging variance after steady state conditions are achieved. In other words, the steady state or stable distribution will have a mean (i.e., location mean) which increases at rate V-v, but its variance is constant.

To analyze this model, a coordinate system moving with velocity V (the free flow velocity) is introduced. In this coordinate system, the free (uncontrolled) movement of the bus is pure random walk (diffusion) without drift (as the drift velocity has been removed). If ϕ represents the position density function, then it is known that for random walk without drift:

3) $$\frac{\delta^2\phi}{\delta x^2} = \frac{2}{k}\frac{\delta\phi}{\delta t}$$

Note that in this coordinate system (no drift velocity, so V=0), equation 2 becomes:

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$$3) \quad \frac{\delta^2 \phi}{\delta x^2} = \frac{2}{k} \frac{\delta \phi}{\delta t}$$

Note that in this coordinate system (no drift velocity, so V=0), equation 2 becomes:

4) $Pr(X(t)<x) = \frac{1}{\sqrt{2\pi kt}} \int_{-\infty}^{x} \exp\left(\frac{-U^2}{2kt}\right) dU$

5) If $\phi_u = \frac{d}{dX}$ $[Pr(X(t)<X)]$,

then ϕ_u satisfies equation 3. In general, equation 3 holds whenever the bus's motion is determined by the random processes alone (i.e., by the diffusion process between control actions).

The boundary conditions are determined by the control action, which requires (in the new coordinate system) that $X(t)\leq -vt$. The steady state solution will be a function of $X+vt$ as the entire steady state distribution moves along with velocity $-v$ while its shape is unchanging with time. Thus, for the controlled case, ϕ_u satisfies equation 3 as does ϕ_c (the controlled density function), but ϕ_c in the steady state must be of the form:

6) $\phi_c(x,t) = f(x+vt)$

From equation 6, equation 3, the boundary condition $X(t)\leq -vt$ and the normalization requirement, the following equation can be obtained:

7) $\phi_c(x,t) = \frac{1}{r} \exp[+r(x+vt]$

where $r = \frac{2v}{k}$ for $x<-vt$

The variance of the distribution defined by (7) is:

$$\frac{1}{r^2} = \frac{k^2}{4v^2}$$

Since the whole distribution moves along at speed V-v (back now to the ordinary coordinate system), the time variance for the bus arriving at a given location is derived by dividing its distance variance by $(V-v)^2$ to obtain $k^2/4v^2(V-v)^2$. The headway variance is obtained by multiplying the latter quantity by 2, since two independent buses contribute to the headway in this model. Thus:

8) $$\sigma^2 k = \frac{k^2}{2v^2(V-v)^2}$$

gives the headway variance under this type of schedule control. Note that the bus's average speed has been slowed from V to V-v. Thus, the headway is increased accordingly (for a constant number of buses on the route):

$$h_0 V = h(V-v),$$

where h_0 is the uncontrolled (undelayed) headway and h is the controlled headway. Thus:

9) $$h = h_0 \cdot \frac{V}{V-v} = h_0 + h_0 \frac{v}{V-v}$$

Equations 8 and 9 thus provide important tradeoffs between headway variance and average headway for the specified control strategy. Equations 8 and 9 can be used for determining average passenger waiting time from equation 1 in Section 2.1. Passenger waiting time provides a convenient criterion to optimize in order to find the optimal value of v in the control strategy. Substituting equations 8 and 9 into the waiting time equation gives:

$$10)\quad W = \frac{1}{2} h_0 \left(1 + \frac{v}{V-v} + \frac{k^2}{2v^2 (V-v)^2 h^2 V} (V-v)\right)$$

$$= \frac{1}{2} h_0 \left(1 + \frac{v}{V-v} + \frac{k^2}{2v^2 (V-v) V h_0^2}\right)$$

To simplify the analysis, it is assumed that $v \ll V$, so that:

$$11)\quad W = \frac{1}{2} h_0 \left(1 + \frac{v}{V} + \frac{k^2}{2v^2 h_0^2 V^2}\right)$$

$$= W_0 + \alpha v + \frac{\beta}{v^2} = W_0 + p + q$$

where $W_0 = \frac{1}{2} h_0$,

$\alpha = \frac{h_0}{2V}$,

$\beta = \frac{k^2}{4 h_0 V^2}$,

$p = \alpha v$, and

$q = \frac{\beta}{v^2}$

W is minimized when

$$12) \quad p = 2q$$

or

$$13a) \quad v^3 = \frac{2\beta}{\alpha} = \frac{k^2}{Vh_0^2}$$

If equation 10 is minimized with respect to v, without the approximation $v<<V$, the exact equation for the optimum value of v is:

$$13b) \quad v^3 = \left(1 - \frac{3}{2}\frac{v}{V}\right)\frac{k^2}{Vh_0^2} ,$$

or, in terms of the delay factor $d \overset{\Delta}{=} v/V$ (which represents the average increase in bus transit time due to the control strategy):

$$13c) \quad d^3 = \left(\frac{k}{V^2h_0}\right)^2 \left(1 - \frac{3d}{2}\right)$$

Returning to the simplified version for ease of discussion and illustration, Equation 13a thus provides the optimum value for v for the control strategy specified in this section. It is also interesting to point out that from Equation 12, the waiting time is optimized when that part of the waiting time due to increased average headway (resulting from delays imparted by the control strategy) - that is, p - is twice that part of the waiting time due to headway variance - that is, q. This result is consistent with that found in Section 4 for a more comprehensive computer simulation model of the bus route and different headway control strategies.

Equation 13 can be transformed into another interesting form. Note that k is the rate of increase of uncontrolled position variance with time ($\sigma^2=kt$) and so k/V^2 is the rate of increase of time variance with time. Setting

$$14) \quad \gamma = \frac{k}{V^2},$$

Equation 13 becomes

$$15) \quad v^3 \cong V^3 \frac{\gamma^2}{h_0^2}$$

In terms of the delay factor, d, Equation 15 can be represented as

$$16) \quad d^3 \cong \frac{\gamma^2}{h_0^2}$$

Letting τ^2 denote the amount by which the time variance will increase in the time interval of one headway, h_0, for an uncontrolled bus, then $\tau^2=\gamma h_0$. This means that if the bus operates without control for h_0 time units, its time headway variance increases by τ^2. Equation 16 thus becomes:

$$17) \quad d = \left(\frac{\tau^4}{h_0^4}\right)^{1/3}$$

which relates the optimum delay factor, d, to the rate at which the time headway variance grows in the space of one headway.

Probably the chief deficiency of the model developed in this section is the lack of an explicit representation of bus coupling due to passenger boarding. This effect may result in additional bus delays in order to achieve optimal control (i.e., tighter control to further decrease headway variance at the expense of mean headway).

Perhaps increased emphasis should be placed on headway variance over mean headways and instead of the waiting time, the payoff for headway control (with number of buses on the route held constant) should be measured by the amount of overloading (i.e., number of buses having excess passengers). Overloading is probably a stronger function of headway variance relative to mean headway than is mean waiting time.

Thus, both on the basis of changes needed for more realism in the model, and on the basis of changes needed for more realism in the criterion for optimality, greater emphasis on the importance of headway variance over that of mean headway may be needed for optimal control.

An example of the potential benefits in terms of average passenger waiting time, with the headway control strategy and bus route mode developed in this section, is presented next.

Let the transit time of the route be 25 minutes and suppose that the buses run with 5 minute average headways and that the standard deviation of an uncontrolled bus headway at the end of the route is 5 minutes. Thus, h_0=5 minutes and for T=25; $2kT/V^2=\sigma^2=5^2=25$. Thus:

$$\frac{2k\ 25}{V^2} = 25$$

and $\frac{k}{V^2} = .5$

For the uncontrolled route, the mean waiting time in the middle of the route is given by:

$$W_u = \frac{1}{2}h_0 + \frac{1}{2}\frac{\sigma^2_{u,T/2}}{h_0} = \frac{1}{2}h_0 + \frac{1}{2}\frac{25/2}{h_0} = \frac{1}{2}(5) + \frac{1}{2}\left(\frac{25/2}{5}\right) = 3.75$$

$$\left(\sigma_{u,T/2} = \frac{k(T/2)^2}{V^2}\right)$$

For the controlled route, equation 8 yields:

$$\sigma_h^2 = \frac{1}{2}\frac{k^2}{v^2(V-v)^2} = \frac{1}{2}\left(\frac{k}{V^2}\right)^2 \frac{1}{d^2(1-d)^2}$$

where $d = \frac{v}{V}$.

For the same parameters, equation 9 yields:

$$h = h_0 \frac{V}{1-v} = \frac{h_0}{1-d} = \frac{5}{1-d}.$$

The mean waiting time on the controlled route (after the stationary variance is achieved) is:

$$W_c = \frac{1}{2}h + \frac{1}{2}\frac{\sigma^2 k}{h} = \frac{5}{2}\left(\frac{1}{1-d} + \frac{.005}{d^2(1-d)}\right)$$

To minimize waiting time, set dW /dd = 0. So:

$$0 = \frac{5}{2}\left(\frac{1}{(1-d)^2} - \frac{.01}{d^3(1-d)} + \frac{.005}{d^2(1-d)^2}\right)$$

Or:

$$d^3 = .01 - .015d$$

(This equation is equivalent to equation 13c.)

This equation yields:

$$d = .1923$$

which, in turn, yields:

$$W_c = \frac{5}{2}\left(\frac{1}{1-d} + \frac{.005}{d^2(1-d)}\right) = 3.514$$

Compared with the mean waiting time at the center of the route for the uncontrolled case (i.e., 3.75), we find an improvement of:

$$\frac{3.75 - 3.514}{3.75} = 0.063$$

i.e., about 6%. Thus, the improvement in waiting time (for a constant number of buses on the route) is only 6% and this was achieved with a delay factor of 0.1923 (i.e., the average bus transit time is increased by more than 19%). These results indicate a broad minimum of waiting time witn respect to control intensity (i.e., the parameter d in the above example) and probably can be taken as a further indication that other benefits (bus overloading, etc.) which are stronger functions of headway variance, are of more importance in ultimately selecting an optimal control policy.

The relationships between average passenger waiting times, bus transit times and bus overloading are further investigated in Section 4 for various headway control strategies, including the application of traffic signal preemption.

3. SIMULATED BUS PREEMPTION EXPERIMENT

The objective of this experiment was to compare potential reductions in bus travel times with potential reductions in bus headway standard deviations for different types and levels of traffic signal preemption based on real-world data. Data were gathered on actual bus events (arriving times, departing times, passengers boarding and alighting, bus stop delays and signal delays) at a single intersection in Boston on the Harvard/Dudley bus route. This route is 3.7 miles long and is operated with headways of about six to seven minutes from 7:30-9:30 A.M. and from 1:30-7:00 P.M. and 12 minutes otherwise (except 20 minutes in the late evening). The route passes three major connection points with rapid transit and other bus routes. Also both terminals are connection points. Scheduled round trip times vary between 46 and 66 minutes. The scheduled layover times are 9 minutes at Dudley and 6 minutes at Harvard.

The observations were made between 7:30-9:30 A.M. and 4:00-6:00 P.M., on the northbound approach of Massachusetts Avenue at Beacon Street, on weekdays between June 28 and July 19, 1978. These times represent peak periods in terms of traffic volume. The traffic volume on Massachusetts Avenue varied between 1600-2200 vehicles per hour (VPH), while the Beacon Street volume varied between 500-700 VPH. Beacon Street is one way westbound at this location.

The traffic signals at this intersection are part of a computerized traffic responsive control system. There are three modes of operation: pre-timed, semi-actuated and fully actuated. During the observation times, the system basically operated in the pre-timed mode. There are 6 cycle lengths ranging from 60 to 120 seconds and five splits ranging from heavy main stream to heavy cross stream (70/30). During the observation times, the cycle lengths varied between 90 and 110 seconds with a signal split of 60/40 favoring the main stream (Massachusetts Avenue). The cycle included a 3 second yellow interval and concurrent walk/no walk phases.

A sample of 223 buses was observed. The headway average and standard deviation in this sample were 7 minutes 7 seconds and 3 minutes 41 seconds respectively. The reference point for computing the response measures (i.e., bus travel times and headway standard deviation reductions) was the time the bus entered the intersection relative to the traffic signal phase.

Three levels of traffic signal preemptions for buses were simulated.

Preemption Level 1 allowed a 10 second green extension.

Preemption Level 2 allowed a 10 second green extension or a 10 second red truncation.

Preemption Level 3 allowed unlimited preemption.

Thus the preemption levels ranged from a conservative system (level 1) to a liberal system (level 3) in terms of favoring the bus. The simulation did not include the effects of bus detector location or dwell time at the bus stop. Rather, the simulation of preemption was based solely on the observed traffic signal delay times. Thus if a bus were delayed 8 seconds, it would qualify to gain 8 seconds under preemption level 2 and preemption level 3, but no time under preemption level 1 (assuming a 100 second cycle and 60/40 split). If a bus were delayed 12 seconds, it would qualify to gain 10 seconds under preemption level 2, 12 seconds under preemption level 3 and no time under preemption level 1. Finally, if a bus were delayed 32 seconds, it would qualify to gain 32 seconds under all three levels of preemption.

Two types of preemption were granted.

Unconditional Preemption was granted to all buses delayed by the traffic signal regardless of the headway to the preceding bus, but subject to the constraints of the level of preemption.

Selective Preemption was granted only to those buses delayed by the traffic signal whose headway to the preceding bus was greater than the average headway (7 minutes 7 seconds), also subject to the constraints of the level of preemption.

The new headway averages and standard deviations after the simulated preemptions were computed by readjusting the raw data base (bus departure times) to account for the times gains from each preemption. "Estimated passenger waiting time saved" was determined from the waiting time equation presented in Section 2.1. It should be pointed out before examining the results of this simulated experiment that the intent of selective preemption is to reduce the headway standard deviation and, hence, the passenger waiting time. By contrast, unconditional preemption is generally employed to reduce the bus transit time.

The results of the simulated experiment are shown in Table 1. As might be expected, the average headway remained virtually unchanged regardless of the level or type of preemption. With unconditional preemption, the average time savings for the delayed buses ranged from 16-24 seconds and for all buses, 7-11 seconds. With selective preemption, these values were reduced by about half. Again, this was expected based on the assumption of a symmetric headway distribution (i.e., about half of the buses had headways to the preceding bus that were greater than the average headway).

The reduction in headway standard deviation ranged from .9% to 1.8% with unconditional preemption, and from 2.3% to 3.6% with selective preemption. The fact that the lowest percentage (.9%) occurred with the most liberal preemption level (level 3) with unconditional preemption is not altogether surprising: as mentioned above, the control technique with unconditional preemption is intended to reduce transit time but not necessarily the headway standard deviation. In fact, it is possible for the headway standard deviation to increase with unconditional preemption. The estimated passenger waiting time saved ranged from 1.1 seconds to 2.1 seconds with unconditional preemption, and from 3.0 seconds to 4.3 seconds with selective preemption.

Thus, selective preemption offers the advantage of reducing passenger waiting time by a factor of 2 compared to unconditional

TABLE 1. RESULTS OF SIMULATED BUS PREEMPTION EXPERIMENT

Preemption Level	Unconditional Preemption					
	Headway		Average Bus Transit Time Saved		Reduction in Headway Standard Deviation	Estimated Passenger Waiting Time Saved
	Mean	Standard Deviation	Delayed Buses	All Buses		
1	7 min. 7 sec.	3 min. 38 sec.	16 sec.	7 sec.	1.4%	1.6 sec.
2	7 min. 6 sec.	3 min. 37 sec.	21 sec.	9 sec.	1.8%	2.1 sec.
3	7 min. 6 sec.	3 min. 39 sec.	24 sec.	11 sec.	.9%	1.1 sec.

Preemption Level	Selective Preemption					
	Headway		Average Bus Transit Time Saved		Reduction in Headway Standard Deviation	Estimated Passenger Waiting Time Saved
	Mean	Standard Deviation	Delayed Buses	All Buses		
1	7 min. 7 sec.	3 min. 36 sec.	9 sec.	4 sec.	2.3%	3.0 sec.
2	7 min. 6 sec.	3 min. 33 sec.	11 sec.	5 sec.	3.6%	4.3 sec.
3	7 min. 6 sec.	3 min. 33 sec.	13 sec.	6 sec.	3.6%	4.3 sec.

preemption, but at the cost of increasing relative transit time by the same factor. Perhaps more importantly, selective preemption was accomplished with about half as many preemptions (101 vs 54 for level 3). The impact on other traffic would thus be expected to also be about half. Although the average savings may not be large (1-11 seconds), this analysis indicates that, with equal benefit weighting on transit time saved and passenger waiting time saved, selective preemption for bus headway control is more advantageous than unconditional preemption for reducing bus transit times. Furthermore, as mentioned earlier, passenger waiting time savings could be weighted more heavily than transit time savings on local service bus routes, thus making the advantage for selective preemption even greater.

4. DEVELOPMENT OF BUS ROUTE SIMULATION MODEL AND EVALUATION OF HEADWAY CONTROL STRATEGIES

This section describes the development of a bus route simulation model and evaluation of headway control strategies using the model. The model explicitly considers individual buses moving along a bus route, passengers interacting with each bus at bus stops along the route, and "delay" and "advance" strategies affecting each bus. The "advance" strategies essentially represent traffic signal preemption.

4.1 SIMULATION MODEL

Figure 4 shows the general functional inputs and outputs of the simulation. The model is structured to allow the variation in route length through the input of the number of links, a link being equivalent to a city block of roughly 750 feet. The simulation is run with 60 blocks (approximately 8.5 miles) for the purposes of these experiments. A mean travel time per block and an associated variance are specified. Buses travel along a link and stop for passengers to board and alight. Ten buses are on the route initially, equally spaced along the route. Buses are then dispatched at a constant rate of one every five minutes.

Passenger arrivals at stops are calculated from a probabilistic distribution specified by the user, while alightings occur at a rate of 10% of the load per stop. In this study, passengers arrive at each stop at a uniform random rate with a mean of 0.8 passengers per minute. A constant boarding

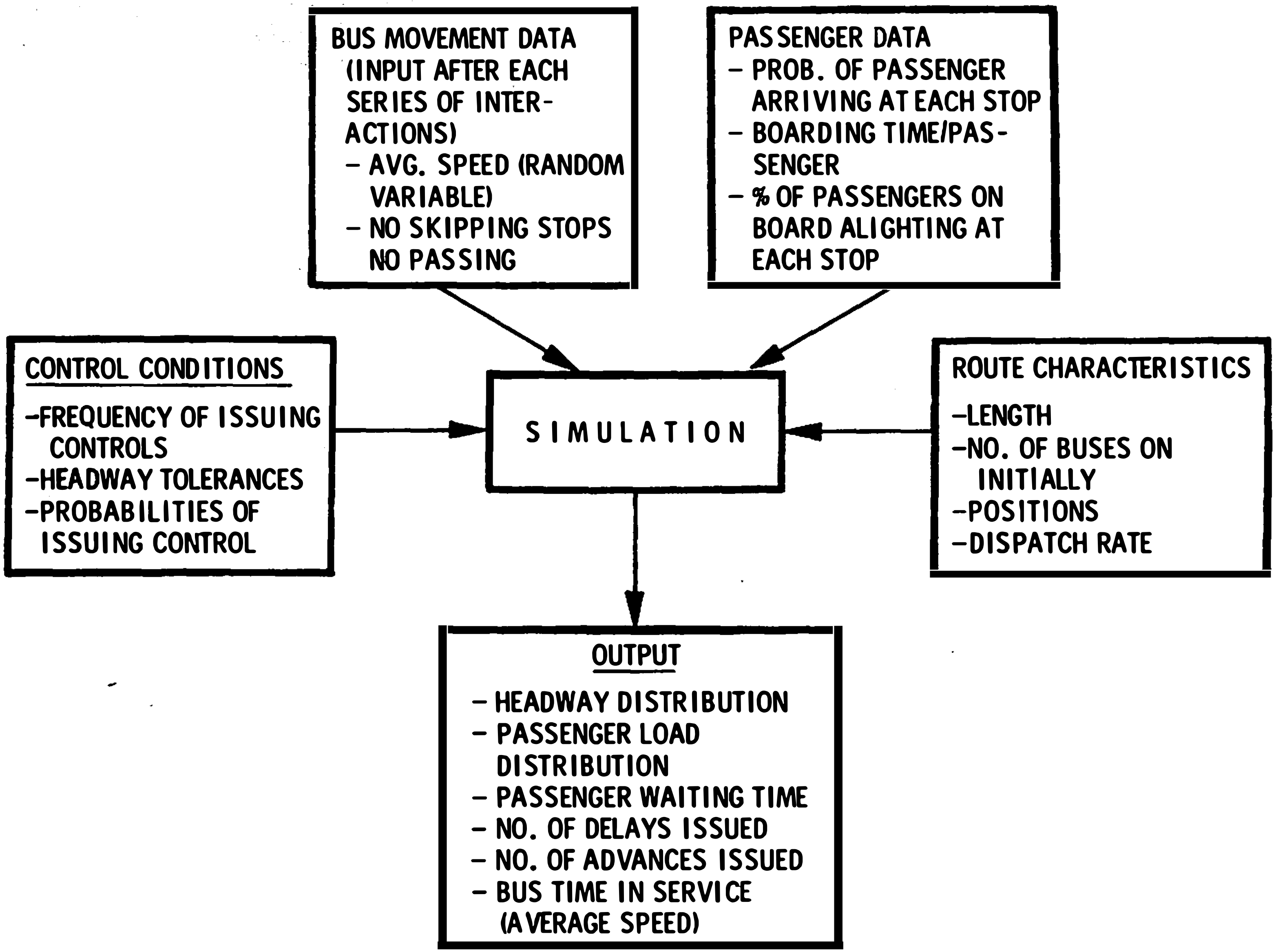

FIGURE 4. GENERAL SIMULATION STRUCTURE

time of 4.5 seconds per passenger is used in this study. Total transit time per block equals the random base transit time plus the time spent for passenger transactions.

No two buses can travel the same link simultaneously. Skipping stops and bus passings are not permitted. Initial route conditions, including the number of buses and their distribution along the route, are input at the start of the simulation.

In employing headway control, groups of three buses are examined with focus on the middle bus. This is essentially done for each bus on each link of the route (see next section). The headway to the bus ahead of the subject bus and to that of the bus behind are compared, and delays and/or advances are granted according to input conditions.

Two types of headway control strategies are investigated in this section. The first type of control delays buses that are running ahead of the average route headway. The second type of control "advances" buses that are running behind the average route headway. This "advance" control simulates signal preemption. The two types of control strategies are discussed further below.

4.2 DESCRIPTION OF THE EXPERIMENTS AND HEADWAY CONTROL STRATEGIES

Each experiment to test the effectiveness of a particular headway control strategy consists of fourteen 100-minute simulated runs. The program calculates the average headway, the headway variance, the mean passenger waiting time, the average and variance of load per bus per block, and the number of times each control was implemented. Relevant operational parameters were tabulated and reduced for analysis.

Five headway control strategies (including the base or free state with no control) are evaluated with the simulation model.

4.2.1 Free State - No Control

This experiment uses neither delay nor advance controls. Upon being dispatched at intervals of five minutes, buses proceed from stop to stop, allowing passengers to board and alight.

4.2.2 Delay-Only-Control

If the time difference from the subject bus to the bus ahead of it is greater than the time difference to the bus behind it by 90 seconds or more, (implying that the subject bus is running too fast in relation to the two adjacent buses), delays of 45 seconds are issued to the subject bus. This delay control is cancelled if the headway to the bus in front exceeds 5 minutes. This method of control effectively simulates a bus stop delay strategy and is typical of most transit operations, although scheduled vs. actual times at stops, rather than relative headway, is usually the initiating factor. This is primarily due to the ease of implementation. Headway control may be a more desirable means of rectifying bus distribution imbalances, especially on short headway routes where the frequency of buses is higher, and an imbalance in the arrival of a number of buses in a short period of time is more noticeable.

4.2.3 Advance Only Control

An advance of 15 seconds is granted in every block with a probability of 10% if the difference between the headway to the bus ahead of the subject bus and to the bus behind is greater than 30 seconds. This effectively simulates a very conservative signal preemption system (in terms of favoring the bus) at every intersection (block), or a liberal signal preemption system at every fifth intersection.

4.2.4 Delay and Advance Control

The same operational parameters relevant to the "delay-only" and the "advance-only" control initiate this combination of "delay and advance" control.

4.2.5 Delay and Unlimited Advance Control

This experiment is identical to the "delay and advance" control, except that advances are issued independent of the headway distribution of the buses (i.e., the above headway constraint is removed, but the 10% probability factor is still included). This strategy, together with the previous strategy, thus permits a direct comparison between selective preemption (headway constraint imposed) and unconditional preemption (headway constraint removed) which is the common type of signal preemption employed.

4.3 RESULTS OF EXPERIMENTS

Table 2 summarizes the results for each type of headway control strategy. In assessing the merits of each type of control, it should be pointed out that the "no control" strategy is probably not typical of most transit companies, since most already employ some degree of "delay" control. If such an uncontrolled route did exist, however, the improvement possible by utilizing the "delay-only" control would be substantial. Table 2 shows that waiting time decreases by 52%, while the load variance decreases by 88%. On the other hand, the "advance only" strategy yields only a 2.8% decrease in waiting time and a 14% increase in load variance. The differences between these two strategies are partially offset by the fact that the "delay only" strategy increases the transit time by about 17%, while the "advance only" strategy decreases the transit time by about 4%. (These figures are obtained from the average number and length of delays or advances.) However, the net result appears to be that the "delay only" strategy is substantially more effective than the "advance only" strategy when both are compared to "no control." These results are not unreasonable when one considers that the advance strategy (i.e., signal preemption) is quite limited in the level of time change, both practically and in the simulation model, when compared to the delay strategy.

TABLE 2. SUMMARY OF SIMULATION RESULTS

CONTROL STRATEGY	AVG. HEADWAY	HEADWAY VARIANCE (S.D.)	AVG. WAIT. TIME	AVG. LOAD/ BUS/LINK	LOAD VARIANCE	AVG. NUMBER OF DELAYS/ 100 MIN. RUN	AVG. NO. OF ADVANCES (PREEMPTIONS)/ 100 MIN. RUN
NO CONTROL (FREE STATE)	5.03	37.69 (6.14)	6.14	39.44	2444.62 (49.44)	0	0
DELAY ONLY	4.98	4.42 (2.10)	2.93	34.85	277.78 (16.67)	613.7	0
ADVANCE ONLY	4.96	34.98 (5.91)	5.97	39.82	2784.97 (52.77)	0	136.5
DELAY & ADVANCES	4.98	3.20 (1.78)	2.81	32.43	206.82 (14.38)	533.57	46.93
DELAYS & UNLIMITED ADVANCES	4.99	3.05 (1.75)	2.77	33.43	186.27 (13.65)	634.67	111.42

The "delay only" strategy produced results that are probably typical of operations on short headway routes where bus-bunching is not severe. Limited observations under such operating conditions have shown that the standard deviation of headways was roughly half the mean headway.[11] The "no control" strategy produced results that probably exemplify the multiple-bus-bunching situation, since this was observed in the simulation. Thus, results of the "delay only" strategy will be considered the base case from which the benefit of the "advance" control cases can be assessed. Accordingly, from Table 2, the "delays and advances" control strategy yields benefits in waiting times, load distribution, and transit time. Compared to the "delay only" strategy, waiting time, load variance and transit time decreased by 4%, 26%, and 3.5%, respectively, with "delays and advances" strategy. However, with the "delays and unlimited advances" strategy, the decreases were 5%, 31%, and 2.5%, respectively. This was surprising since a greater improvement in waiting time and load distribution was expected with the "delays and advances" strategy (advances were granted specifically to offset the headway imbalance with this strategy). Furthermore, a greater improvement in transit time was expected with the "delays and unlimited advances" strategy since, by design, more advances (preemptions) are allowed. Nevertheless, differences between the two strategies are minor and are due to the coupling effect between the delay and advance components of the control strategies. From Table 2, it is seen that, indeed, more advances are granted with the unlimited advances (111 vs. 47) and the difference between advances is even larger than that between the average number of delays (212 vs. 178). However, the overcompensating factor is the fact that the length of the delays (45 seconds) is larger than the length of the advances (15 seconds).

In summary, the "delays and advances" (selective preemption) strategy is perhaps superior to the "delays and unlimited advances" strategy since, essentially, the same improvement in terms of passenger waiting time, load variance and transit time can be achieved with either strategy, but the "delays and advances" (selective preemption) strategy requires less than half the number of preemptions required by the "delays and unlimited advances" strategy. This, of course, has favorable implications on the impact on other traffic.

The level of improvement of the "delays and advances" strategy over the "delay only" strategy is not large in terms of reduced passenger waiting time (4%) and reduced transit time (3.5%). However, as mentioned earlier, the advance strategy is conservative, and perhaps too conservative. The number of preemptions granted, (47) per 100 minutes, translates into about 1 preemption every two hours per intersection. It would seem that this could be relaxed somewhat, thus providing additional improvements without severely increasing the impact on other traffic. The tradeoffs between these parameters will be the subject of a follow-on effort to investigate the application of traffic signal preemption for bus headway control. Additionally, the relative importance of other measures, including load variance and its effect on bus overloadings, will be studied. The relatively large improvement in load variance (26%) suggests that this could be a more important measure of effectiveness than either passenger waiting time or transit time.

4.4 FUTURE SIMULATION DEVELOPMENT AND ANALYSIS PLANS

The extended effort mentioned above on studying the potential of bus headway control requires further simulation development. While the simulation model is currently suitable for making preliminary findings, certain assumptions were made in the development stages out of convenience that require refinement before more conclusive findings can be achieved. The model represents a route of sixty links, or blocks of equal length, with bus stops located at the end of the each block. Buses are dispatched at a fixed rate. Demand patterns, i.e., arrival rates at bus stops and alighting rates from buses, are equal for the entire route. These parameters or characteristics will be made variable in the simulation. Real-world data will then be utilized to calibrate the model, introducing realistic values for the operational parameters. Additional route characteristics will also be incorporated in the model. These include the following:

4.4.1 Passenger Demand

Realistically, passengers are more likely to board at the beginning of the route than at the end, and to alight at the end rather than the beginning. Passenger demands will therefore be represented by more typical boarding and alighting patterns (trip distributions).

4.4.2 Bus Acceleration/Deceleration

Currently, these rates are incorporated in average travel times. In the expanded model, buses will be represented microscopically. That is, the individual trajectories of each bus will be calculated for each block. This will provide a more accurate representation of bus time savings with signal preemption.

4.4.3 Traffic Signals

Currently, traffic signals are not specifically modelled. In the expanded model, simple traffic signal timing patterns will be represented (cycle lengths, splits and offsets).

4.4.4 Route Structure

The route will be structured to allow for variable block lengths, variable location of bus stops, multiple lanes, passing of buses and skipping of stops.

4.4.5 Bus Capacity

Currently, there is no limit to the number of passengers that a bus can accommodate. Realistic bus capacities will be incorporated into the expanded model. This parameter will affect both the waiting time and load variance parameters.

4.4.6 Other Traffic

Buses are the only vehicles currently modelled in the simulation. General traffic will be incorporated and described macroscopically, employing aggregate flow variables. This will permit a study of the impact that various headway control strategies have on other traffic.

With the expanded simulation model, specific evaluations of the incremental benefits of various signal preemption strategies will be performed, including the impact on other traffic. Parametric studies will be conducted involving bus preemption variables, traffic variables and route characteristics to determine their effect on potential benefits and impacts. The variables to be investigated will include location of bus stops, traffic signal cycle length, split and offset, bus dispatch headway rates, levels of preemption, traffic demand, passenger demand, spacing between intersections and number of traffic lanes.

5. POTENTIAL IMPACTS ON OTHER TRAFFIC

This section provides an estimate of the potential impacts on other (cross-street) traffic that different levels of preemption systems have in terms of increases in delay time and number of stops at intersections. The three levels of preemption systems range from liberal to conservative in terms of favoring the bus with a concomitant expected impact on other traffic. The estimates are based on simulation experiments conducted by the Mitre Corporation[13][14][15] between 1973-1976 using the Urban Traffic Control System (UTCS) bus priority simulation now called NETSIM. The Washington, D.C. urban street network shown in Figure 5 was used in the simulation runs. The bus preemption system detection zones are also shown; the signals affected by them are at the downstream nodes. The signal cycle length used throughout the network is 80 seconds, with approximately 50-50 splits. Twenty different bus routes traverse the network.

The three levels of preemption system (algorithms) examined were:

1. Unconditional preemption with return to timing pattern. Preemption is granted whenever a bus requests it. After all buses leave the detection zone, the algorithm returns to the interval that would have been in effect if no preemption had been granted, thereby retaining traffic signal coordination. The average bus headways during these tests were approximately four minutes.

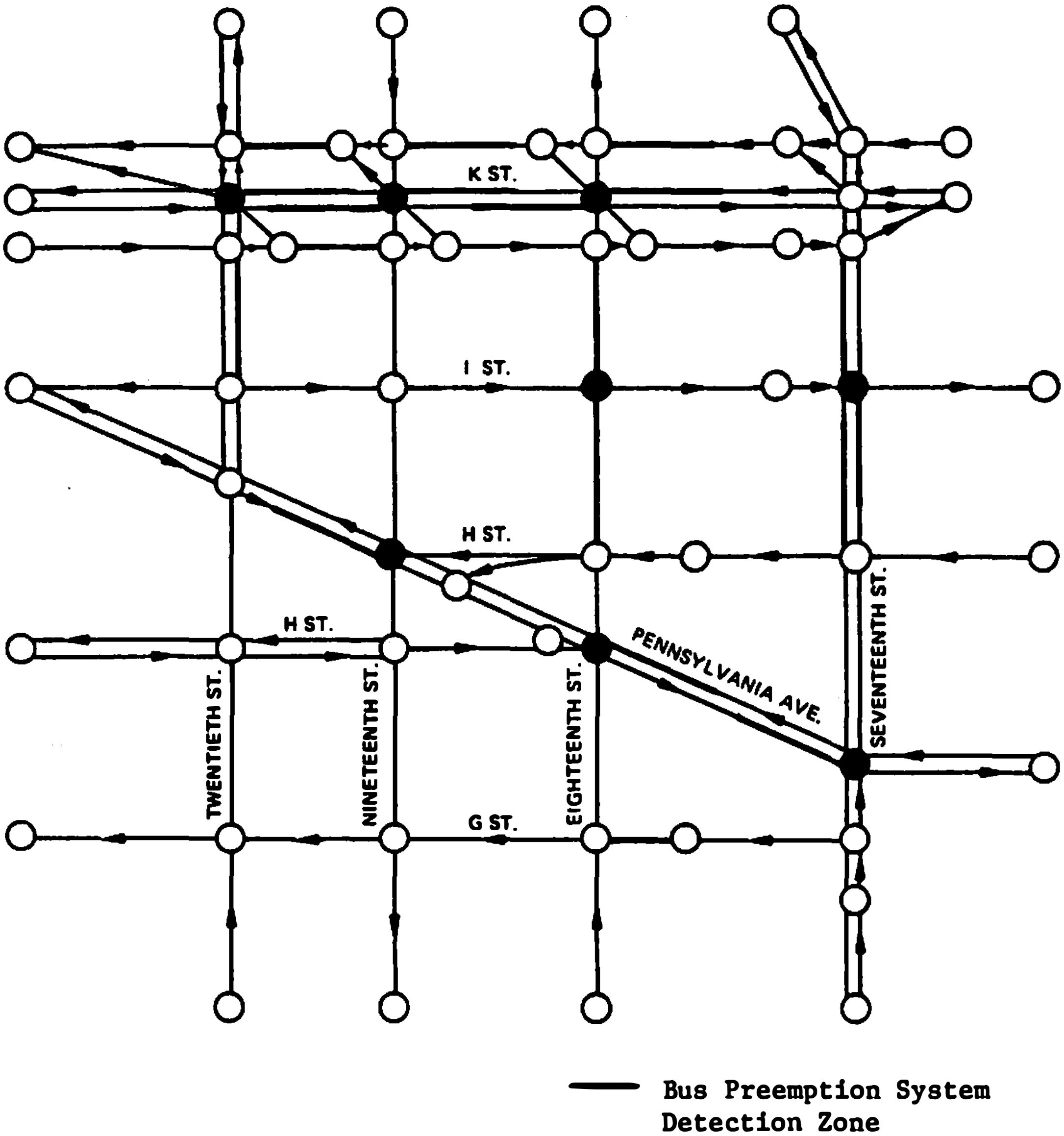

FIGURE 5. SIMULATION NETWORK

2. Green extension of 10 seconds.

A maximum extension of 10 seconds is granted if a detected bus is predicted to enter the intersection during the extension. Bus transit times and bus stop dwell times are considered in the prediction. No other changes occur in the timing pattern. The average bus headways during these tests were approximately four minutes.

3. reen extension of 10 seconds.

This system was the same as level 2, except that the average bus headways were somewhat greater than four minutes, and there were fewer intersections equipped to provide signal preemptions.

Each system was run on different bus routes, so only impact changes from the base conditions were examined. Four-minute headways corresponds to a bus arrival approximately every third cycle for the traffic network simulated. Also, the simulations of each system were run under A.M. peak period (heavy) traffic conditions.

The traffic impact results are shown in Figure 6. Increases in delay time and stops are shown as a function of preemption system level, and nearside/farside bus stop location.

The location of the bus stop had a substantial impact on other traffic. This was probably due to the longer preemptions required for preemption system level 1 and the added uncertainty

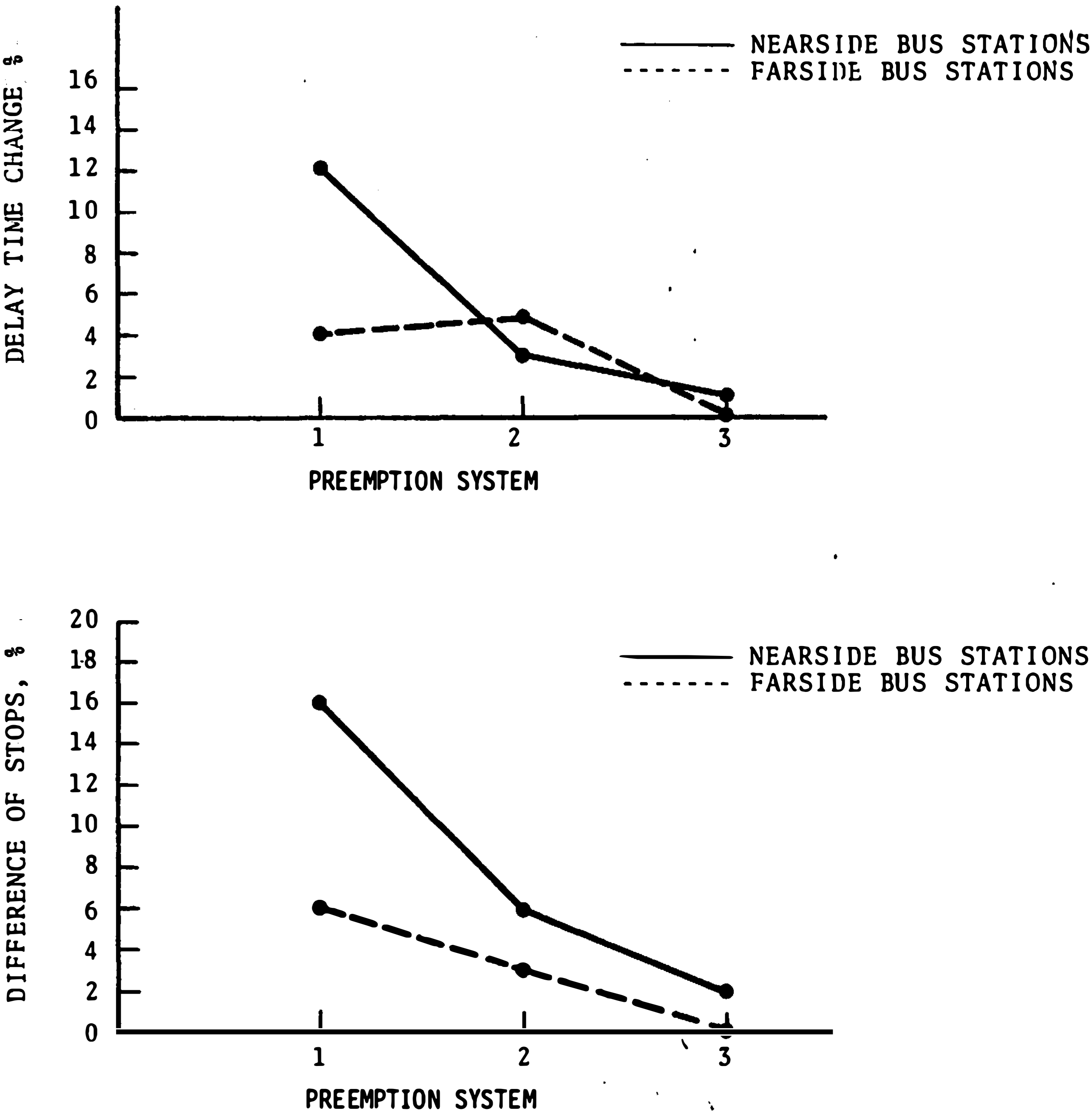

FIGURE 6. TRAFFIC IMPACTS WITH DIFFERENT PREEMPTION SYSTEMS

introduced in trying to predict bus arrivals at the intersections for preemption system levels 2 and 3.

Also, as might be expected, the liberal traffic preemption system (level 1) had the largest impact on other traffic, with delay time increasing by 12% and number of stops by 16% (for nearside bus stop locations). For the conservative system (level 3), the impacts were kept to within 2%. The author of the Mitre reports concluded that "most of the detrimental effect to cross-street traffic results from a few long preemptions that the 10-second maximum screens out. The damage done when this occurs cannot then be undone by hindering later preemptions... By simply incorporating a maximum allowable preemption time in an otherwise unconditional algorithm, most of the benefits of an unconditional bus preemption system are achievable and most of the harm to other vehicle traffic is avoided." Figure 6 thus provides an indication of the degree of impact on other traffic that might be expected with different levels of traffic signal preemption systems.

With a <u>selective</u> traffic signal preemption system for controlling the headway of buses, the degree of impact on other traffic would be expected to be half that shown in Figure 6 (due to the reduced requirement of selective preemption as discussed in the previous sections). Even further reductions in the impact on other traffic would be expected with average bus headways greater than four minutes. Thus, it is estimated that the impact on other traffic with selective traffic signal preemption (for controlling bus headways) and five-minute average bus headways would be about 5-6% with liberal preemption, and about 1% with conservative preemption.

6. CONCLUSIONS AND FUTURE PLANS

Analyses were conducted showing that traffic signal preemption is a viable concept for controlling the headways of buses on short headway routes, reducing passenger waiting time, bus load variance, and bus in-service time, while minimizing the impact on other traffic. The analyses included the following: an examination of passenger waiting time as a function of average bus headway and headway variance; the development of a simplified bus-route model and control strategy, a functional relationship between the control parameter and headway characteristics, and evaluation of the control strategy; a simulated bus preemption experiment to estimate the range of headway variance reductions with different levels of preemption; the development of a simulation bus-route model to evaluate various headway control strategies; and an assessment of the impact on other traffic based on previous simulation experiments. Although the benefits were not substantial, the analyses indicated that selective traffic signal preemption for controlling the headways of buses on local service routes provides a more cost-effective use of traffic signal preemption systems than unconditional preemptions for reducing the transit time of buses in CBD grids and on arterials.

Future plans call for the expansion of the simulation model to provide more realism to the analysis (e.g., with the addition of traffic impedances, bus capacity, acceleration and deceleration characteristics of the buses, and specific traffic signal timing patterns). The model will treat all buses microscopically (i.e., the individual trajectories of each bus will be calculated on each network link). General traffic will be described macroscopically, employing aggregate flow variables rather than explicitly considering individual vehicles. The model will be used for analyzing the effectiveness of general transit route control tactics and the incremental benefits of specific traffic signal preemption strategies. The potential impact on other traffic will also be analyzed. Evaluations will be conducted for both a generic data base and a site-specific data base. For the generic case, a parametric study will be conducted involving bus preemption variables, traffic variables,and route characteristics, to determine their effect on potential benefits and impacts. The variables to be investigated will include: location of bus stops, traffic signal cycle length, split and offset, bus dispatch headway rate, level of preemption strategies, traffic demand, passenger demand, spacing between intersections and the number of traffic lanes. The site specific case will be the Los Angeles Central Business District (CBD). Parametric analyses will be conducted as in the generic case where appropriate.

Field tests are also being planned to evaluate the most effective preemption strategies determined from the simulation results. The tests will be conducted on facilities with existing traffic signal preemption systems and also in the Los Angeles CBD as an adjunct to comprehensive tests and evaluations scheduled for an Automatic Vehicle Monitoring (AVM) system for multi-fleet users.[16]

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