Near Side, Far Side, Uphill, Downhill

Impact of Bus Stop Location on Bus Delay

Peter G. Furth and Joseph L. SanClemente

One of the factors affecting where bus stops should be located is the expected delay associated with the stop location. On hills, the effect of gravity on already weak diesel engines can lead to considerable additional delay if a bus has to accelerate from a stop. An empirical bus acceleration profile, modified to account for gravity, was applied to constant grade, sag curve, and crest curve profiles. The marginal impact of grade on stopping delay ranged from –4 to 11 s, depending on grade. At signalized intersections, a deterministic model was created that accounted for deceleration, acceleration, and queue interference. Relative to a stop placed away from an intersection, far-side stop placement either causes a very small reduction in delay or has no effect. Near-side placement can reduce delay in a few cases such as reserved bus lanes, but more often it increases delay, sometimes considerably depending on factors such as red ratio, volume:capacity ratio, cycle length, and stop setback. Measures that reduce interference with the queue tend to reduce the net delay from a near-side location; these measures include increasing stop setback, shortening cycle length, and giving the bus a (near) exclusive lane. Results are presented with default adjustments for hills and signalized intersections that can be used in the context of a stop spacing study.

A bus stop's location can make a difference in the extent to which a stopping bus is delayed. On upgrades, reduced acceleration upon leaving the stop increases departure delay. And when a bus stop is placed near a signalized intersection, interactions with the traffic signal and the queue affect the time needed to clear the stop and intersection. Although delay is not the only factor determining where stops should be placed, understanding the relationship of delay to stop location is important in evaluating alternative stop locations. In this study, kinematic models of vehicle movements were used to analyze the effects of grade profiles and signalization parameters on bus delays due to stopping.

This research was conducted to support a TCRP–IDEA project focusing on optimizing bus stop spacing. Stop spacing models found in the literature generally take stopping delay, which affects both passenger riding time and operating cost, as a constant. However, to the extent that grade and intersection interactions affect stopping delay, they can also affect optimal stop locations. The results presented here fill a gap by offering a means of estimating stopping delay that accounts for grade and intersection effects.

Stopping delay includes several components that can be summarized as time lost while a bus is stopped (for doors to open and close, for passengers to board and alight) and time lost during deceleration and acceleration. Grade and intersection interactions affect only the deceleration and acceleration components of stopping delay, and thus they were the focus of this study. If a bus is not impeded by traffic control devices or queues, deceleration and acceleration delay are usually modeled as follows:

$$d_{\text{full\_dec}} = \frac{0.5u_{\text{cruise}}}{a_{\text{dec}}}$$

$$d_{\text{full\_acc}} = \frac{0.5u_{\text{cruise}}}{a_{\text{acc}}} \qquad (1)$$

where $d_{\text{full\_dec}}$ and $d_{\text{full\_acc}}$ are "full deceleration" and "full acceleration" delay, that is, the time lost in going from full speed to rest and in returning to full speed from rest.

Equation 1 assumes that buses, if not stopping, will pass a stop at a cruising speed u_{cruise} and will decelerate and accelerate at constant rates a_{acc} and a_{dec}, respectively. Note that "time lost" is not the same as "time spent"; in fact, under the constant acceleration assumption, the time lost decelerating and accelerating is exactly half the time spent. Buses cover some distance while decelerating and accelerating; in the case of full deceleration and acceleration, these distances are

$$L_{\text{full\_dec}} = \frac{0.5u^2_{\text{cruise}}}{a_{\text{dec}}}$$

$$L_{\text{full\_acc}} = \frac{0.5u^2_{\text{cruise}}}{a_{\text{acc}}} \qquad (2)$$

Deceleration (acceleration) delay is the difference between time spent decelerating (accelerating) and the time that would have been needed to cover that distance at cruising speed.

Away from the influences of grade or traffic control, the sum of deceleration and acceleration delay tends to be about 11 s. As shown later, grade and intersection effects can change expected delay at a stop by up to 20 s and create a noticeable impact on operating speed and passenger travel time.

One of the reasons stop spacing models have taken stopping delay as fixed is that, until recently, bus routes were modeled as a continuum [e.g., Wirasinghe and Ghoneim (*1*)]. The effects of traffic signals and, to a lesser extent, grade vary sharply with position along a route, making these effects difficult to include in a continuum model. The present approach (*2*) involves a discrete location model that allows stopping delay to vary arbitrarily from one location to another and therefore can readily account for local factors affecting delay.

The question of near-side (upstream) versus far-side (downstream) stop placement is a long-standing controversy that did not end in

Department of Civil and Environmental Engineering, Northeastern University, 400 SN, 360 Huntington Avenue, Boston, MA 02115.

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spite of a 1971 *Traffic Engineering* article titled "Farside Bus Stops Are Better" (*3*). A 1996 TCRP report on bus stop location (*4*) listed many advantages and disadvantages of near-side and far-side placement, including pedestrian safety, pedestrian interference with bus movements, capacity effects on general traffic, and traffic safety effects related to right turns. Bus delay was also mentioned, but it was not quantified; in fact, the direction of the effect was not at all clear. The more recent *Transit Capacity and Quality of Service Manual* (*5*) similarly discussed near-side versus far-side placement without quantifying probably delay effects.

At signalized intersections, interactions among the stop, the signal, and the traffic queue can lead to buses experiencing highly variable delay. Consider the situation in which a traffic signal is red as a bus approaches. With a far-side stop, the bus will stop twice: once for the signal and then again for the stop. With a near-side stop, it may be possible for the bus to stop only once, serving the stop at the same time it waits at the red signal. This situation has been cited (*4*) as an advantage of near-side stops. However, another possible outcome, offered by others as a reason to avoid near-side placement, is the dreaded "triple stop": the bus stops first at the rear of a queue that blocks the stop; when released from the queue, it advances and stops at the stop; and then, before the bus can clear the intersection, the light turns red again, forcing a third stop and delaying the bus until the next green signal.

One of the objectives of this research was to reconcile these divergent opinions by constructing a model that accounts for both positive and negative outcomes. The present intersection model considers all of the points in a signal cycle at which a bus might arrive, averaging outcomes to determine the expected value and variance of bus delay for a given configuration, which represents a more reliable guide to stop placement than a focus on either extreme positive or extreme negative outcomes.

BUS ACCELERATION

Most American transit buses are powered by diesel engines. Industry practice is to specify rather weak engine performance when purchasing new coaches; a typical requirement for level-ground acceleration is only 1.5 mi/h/s (0.67 m/s²) for new coaches. The resulting slow acceleration can result in considerable delay as a bus departs a stop, especially if it is climbing a hill. Bus deceleration, in contrast, is limited by passenger comfort rather than by mechanical limitations. This analysis assumed a constant deceleration rate of 5.0 mi/h/s (7.4 ft/s², or 2.26 m/s²).

Motor vehicle engines do not generally deliver constant acceleration; rather, acceleration falls with speed. The level ground acceleration profile of a typical loaded new bus, formatted as speed versus time (see Figure 1), was obtained from New Flyer of America, Inc., a bus manufacturer. This profile was interpolated and recast as acceleration versus speed, yielding the function $a_o(u)$, which is instantaneous acceleration at zero grade at instantaneous speed u. In analyses of graded sections, instantaneous acceleration was modeled as a function of speed and grade:

$$a(u,G) = a_o(u) - gG \qquad (3)$$

where G = grade (e.g., $G = 0.08$ represents an 8% upgrade). The effect of some example grades on the acceleration profile is illustrated in Figure 1. Negative grades increase acceleration up to a passenger comfort limit (set at 6 mph/s).

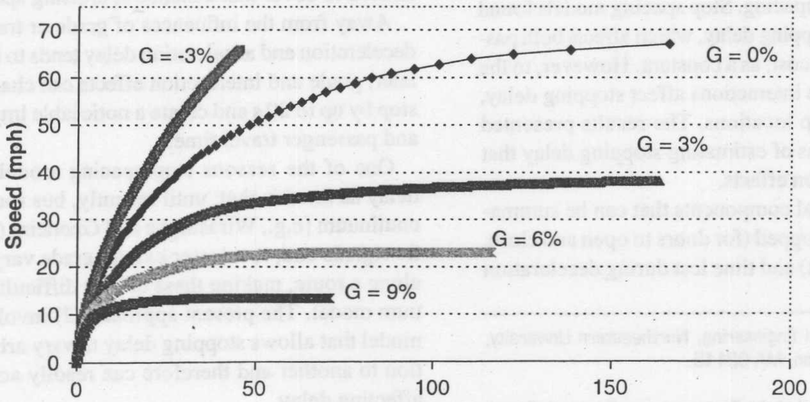

FIGURE 1 Acceleration profiles for various grades.

NET DELAY DUE TO GRADE

Through the use of an acceleration function that accounts for both speed and grade (Equation 1), a bus's travel time can be determined via numerical integration for an arbitrary roadway grade profile. In a stop spacing study, detailed roadway geometry data are unlikely to be readily available; therefore, in this study, some typical roadway profiles were analyzed to obtain a rough quantification of grade effect. Because grade was assumed to affect acceleration but not deceleration, grade affected only acceleration (departure) delay.

Three types of roadway profiles were examined, illustrated in Figure 2: constant grade, sag curve, and crest curve. Roadway sections were assumed to be 0.17 mi (267 m) long between two stops. The sag curve section begins with an initial stop at level grade followed by an immediate vertical curve to a grade G_f. On the crest curve section, the grade at the initial stop is G_i, followed by a vertical curve to level grade. Vertical curves follow parabolic profiles (uniform rate of grade change) in line with the minimum vertical curve lengths allowed for the respective curve types by the American Association of State Highway and Transportation Officials (*6*)

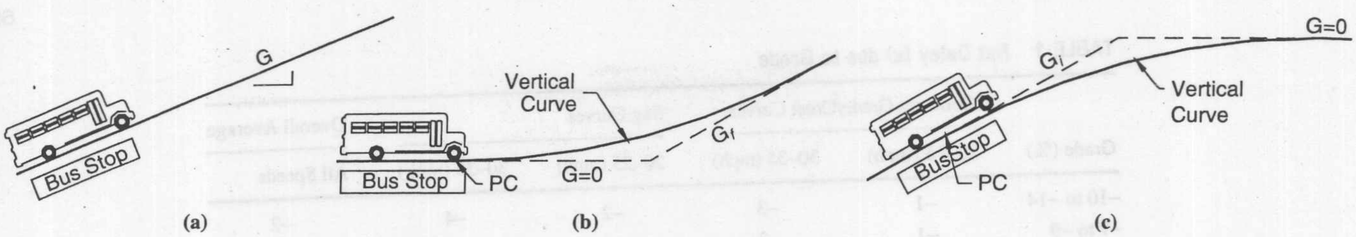

FIGURE 2 Grade profiles for (*a*) constant grade, (*b*) sag curve, and (*c*) crest curve (PC = point of curvature).

for a design speed equal to u_{cruise}. Following the parabolic profile, grade at any point in the curve is determined, from which speed and time throughout the section can be determined via Equation 1 and numerical integration.

For a given section, travel time from the initial to the final stop was determined for two cases: a bus starting from a stop at the initial stop and a bus passing the initial stop at speed u_{cruise}. In both cases, the bus stops at the final stop. The difference in travel time between the two cases is the departure delay for that particular grade profile. The departure delay calculated for a level grade section of the same length was then subtracted; that difference is d_{grade}, the net delay due to a stop being located on a grade.

The concept of net delay due to grade is best illustrated with an example for a constant grade section, using a cruise speed of 30 mph:

A. Travel time, 6% grade, start at rest: 36.69 s;
B. Travel time, 6% grade, start at cruise speed: 22.09 s;
C. Departure delay, 6% grade (A – B): 14.60 s;
D. Travel time, level grade, start at rest: 25.95 s;
E. Travel time, level grade, start at cruise speed: 20.00 s;
F. Normal (level grade) departure delay (D – E): 5.95 s; and
G. Net delay due to grade (C – F): 8.65 s.

When the bus is able to reach cruise speed, d_{grade} can more simply be calculated as the difference A – D.

Net delays due to grade for various grades and cruise speeds are shown in Figure 3. There is a general trend of increasing net delays with both grade and cruising speed up to a limiting grade, after which the difference holds constant.

It seemed counterintuitive that net delay should increase with grades up to 10% and then fall to a near-constant value. The explanation is that although steeper grades increase the travel time of a bus beginning at rest, they tend, beginning at moderate grades, to increase the travel of a nonstopping bus as well, because even at moderate grades terminal velocity can be well below nominal cruise speed.

Similar analyses were conducted for crest and sag curve profiles with various initial grades (for crest curves) and final grades (for sag curves). Results for crest curves were almost the same as for constant grade sections with the same initial grade, because grade early in acceleration is what mostly determines delay. Sag curves, which by construction begin at level grade, involved considerably less delay.

A summary of grade effects is presented in Table 1. For grades between 4% and 12% on constant grade sections or on crest curves with the same initial grade, grade adds 5 to 18 s to stopping delay. Sag curves rising from level grade can add up to 11 s to stopping delay. Downgrades can reduce stopping delay by up to 4 s.

One can see that grade impact is negligible at grades of 3% or less. Above 4%, the impact becomes large enough that it can make a difference in operating effects. For example, relocating four stops from the middle of a hill with an 8% grade to the top of the hill could reduce a trip's running time by more than a minute. This analysis shows the value of avoiding placing stops on steep upgrades when there is an alternative. In instances in which stops on steep grades are unavoidable, a transit company might want to consider specifying stronger engines or using electrically powered trolley buses that, lacking a transmission, can draw virtually unlimited power. The latter greatly benefit Seattle, Washington, bus routes that climb the steep hills rising from Puget Sound.

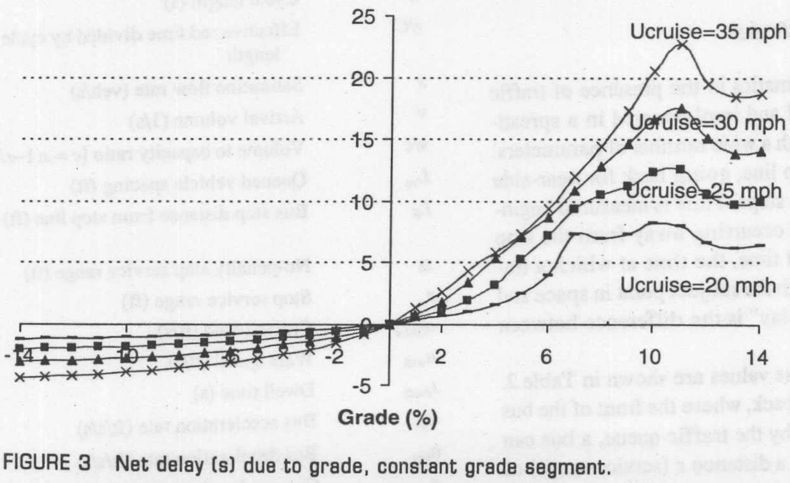

FIGURE 3 Net delay (s) due to grade, constant grade segment.

TABLE 1 Net Delay (s) due to Grade

	Constant Grade/Crest Curves		Sag Curves		Overall Average
Grade (%)	20–25 (mph)	30–35 (mph)	20–25 (mph)	30–35 (mph)	All Speeds
−10 to −14	−1	−3	−2	−4	−2
−7 to −9	−1	−3	−1	−4	−2
−4 to −6	−1	−2	−1	−3	−2
−1 to −3	0	−1	0	−2	−1
0	0	0	0	0	0
1 to 3	1	3	1	2	2
4 to 6	5	7	3	4	5
7 to 9	9	13	6	7	9
10 to 12	10	18	7	11	11
13 to 14	8	16	6	12	10

DELAY FOR STOPS NEAR SIGNALIZED INTERSECTIONS

For stops near an intersection, incremental stop delay is the difference between total delay and control delay (the latter being the delay that would occur with a bus not serving a stop), and net delay is the difference between incremental stop delay and the delay associated with serving a stop away from the influence of an intersection. Four chief interactions between a stop and a signal affect net delay:

1. Queuing may cause buses to approach a stop at less than cruising speed, lowering deceleration delay;
2. Time spent serving a stop during control delay does not contribute to net delay;
3. Stopping can make a bus miss a green light, increasing delay; and
4. Queues blocking a stop can increase the time needed to reach the stop.

With all these possible effects, it is not clear whether a bus stop near an intersection results in more or less delay than a bus stop not influenced by traffic control devices.

Description of Intersection Model

A deterministic model of bus kinematics in the presence of traffic signals and queues was developed and implemented in a spreadsheet to permit experimentation with a wide number of parameters. Distance is measured from the stop line, going back for near-side stops and going forward for far-side stops. Time is measured beginning at the start of red. For events occurring away from the stop line, time is expressed as projected time, the time at which a trajectory at speed u_{cruise} passing through the subject point in space and time would cross the stop line. "Delay" is the difference between two projected times.

Parameter definitions and base case values are shown in Table 2. For near-side stops, L_S is the stop setback, where the front of the bus normally stops. If a stop is blocked by the traffic queue, a bus can still serve it if the bus can get within a distance z (service range) of the stop; otherwise, the bus will have to wait to be released from the queue before it advances to the stop. If the bus stops within a distance z_o of the stop, boarding passengers are expected to able to get to the bus door without added delay; however, if it stops a distance x from the stop, where $z_o < x \le z$, a delay is assessed equal to the time needed for passengers to walk the distance $x - z_o$.

Dwell time includes lost time for doors to open and close. Vehicle arrival volume is specified through the volume:capacity ratio v/c. Buses and cars are assumed to travel at a speed u_{cruise} unless they are inhibited by the signal or the queue. Constant acceleration at a rate a_{acc} was assumed, with a_{acc} determined such that the time and distance involved in accelerating to cruise speed match the detailed level grade acceleration profile described earlier. Cars accelerate at a rate of $a_{\text{car}} > a_{\text{acc}}$. During queue discharge, these differential acceleration rates result in a gap:

$$h_b = 0.5u_{\text{cruise}}/a_{\text{acc}} - 0.5u_{\text{cruise}}/a_{\text{car}}$$

TABLE 2 Intersection Model Parameters

Parameter	Description	Base Case Value
C	Cycle length (s)	90
r/C	Effective red time divided by cycle length	0.5
s	Saturation flow rate (veh/s)	0.5
v	Arrival volume (1/s)	
v/c	Volume to capacity ratio [$c = s(1-r/C)$]	0.8
L_{vq}	Queued vehicle spacing (ft)	25.0
L_S	Bus stop distance from stop line (ft)	(near-side) 75.0 (far-side) 100.0
z_0	No-penalty stop service range (ft)	25.0
z	Stop service range (ft)	50.0
u_{cruise}	Cruise speed (ft/s)	44.0
u_{walk}	Walk speed (ft/s)	4.4
t_{dwell}	Dwell time (s)	15.2
a_{acc}	Bus acceleration rate (ft/s/s)	3.7
a_{dec}	Bus deceleration rate (ft/s/s)	7.4
a_{car}	Car acceleration rate (ft/s/s)	6.6

That is, whereas discharging cars follow each other at headway $1/s$, a bus after full acceleration follows the car ahead by a headway $1/s + h_b$. At default values, $h_b = 2.61$ s.

Queue dynamics follow a continuous model with uniform arrivals at rate v and uniform departures during queue discharge at rate s. There is no queue at time 0 (start of effective red). At time r (start of effective green), the front of the queue begins to move backward, and the queue disappears at projected time t_q:

$$t_q = r\frac{s}{s-v} \tag{4}$$

A bus with projected arrival time t_{arr} will face a queue whose rear point is located at

$$Q(t_{arr}) = t_{arr}\ v\ L_{vq} \quad \text{if } t_{arr} < t_q$$
$$= 0 \quad \text{otherwise} \tag{5}$$

The control delay of a bus with projected arrival time t_{arr} is

$$d_{\text{control}}(t_{arr}) = r - t_{arr}(s-v)/s + h_b \quad \text{if } t_{arr} < t_q$$
$$= 0 \quad \text{otherwise} \tag{6}$$

Delay Reaching a Near-Side Stop

For near-side stops, total delay is a sum of three parts: d_I (delay in reaching the stop), d_{II} (dwell time), and d_{III} (delay between departure from the stop and attainment of full speed beyond the stop line). Determining d_I requires considering five cases. If

$$Q(t_{arr}) \le L_s + z \tag{7}$$

the queue will not block the stop. The bus will stop to dwell at position

$$L_{\text{sactual}} = \max[L_s,\ Q(t_{arr})] \tag{8}$$

and so

$$d_I = d_{\text{full\_dec}} + \max[0, (L_{\text{sactual}} - L_s - z_o)]/u_{\text{walk}} \tag{9}$$

The other four cases apply when the queue blocks the stop (Equation 8 is not satisfied). In these cases, the bus will stop at $L_{\text{sactual}} = L_s$, and the distance between the rear of the queue and the stop is labeled $L_{Q\text{stop}} = Q(t_{arr}) - L_s$. Case 2, "long control delay, distant stop," applies when control delay is sufficiently long that a bus comes to rest at the rear of the queue,

$$d_{\text{control}}(t_{arr}) \ge d_{\text{full\_dec}} + d_{\text{full\_acc}} \tag{10}$$

and the rear of the queue is sufficiently far ahead of the bus stop that the bus reaches cruise speed when advancing from its position in the queue to the stop:

$$L_{Q\text{stop}} \ge L_{\text{full\_acc}} + L_{\text{full\_dec}} \tag{11}$$

Under Case 2, the bus experiences the full control delay, and so

$$d_I = d_{\text{control}}(t_{arr}) + d_{\text{full\_dec}} \tag{12}$$

Case 3, "long queue delay, close stop" (Equation 11 true, Equation 12 false), is illustrated in Figure 4. The bus leaves its position in the queue at point X accelerating along a trajectory that, if continued, would lead to normal signal delay $d_{\text{control}}(t_{arr})$. However, at point Y it switches (instantly) to decelerating, coming to rest at the bus stop at point Z. The speed at transition point Y can be shown to be

$$\Delta u = \sqrt{\frac{2L_{Q\text{stop}}}{\left(\frac{1}{a_{\text{acc}}} + \frac{1}{a_{\text{dec}}}\right)}} \tag{13}$$

The delay in reaching the stop is therefore

$$d_I = d_{\text{control}}(t_{arr}) - d_{\text{full\_acc}} + \left(\frac{L_{Q\text{stop}}}{\frac{\Delta u}{2}} - \frac{L_{Q\text{stop}}}{u_{\text{cruise}}}\right) \tag{14}$$

where the first two terms cover the delay in reaching point X, and the term in large parentheses is the delay involved in maneuver XYZ, shown in the figure as d_{XYZ}. Delay formulas for Cases 4 ("short queue delay with distant stop") and 5 ("short queue delay with close stop") were derived via similar logic.

Delay Leaving the Stop

On leaving a near-side stop, a bus will cross the stop line either (*a*) when its own acceleration would move it there or (*b*) after the light turns green and the cars ahead of it depart, whichever is later. Both the case of cars being permitted to overtake and queue in front of a stopped bus and the case of no overtaking were modeled in this analysis. The framework allows for the case of a bus with a projected departure time within the red period, which can happen when a bus crosses the stop line while still accelerating a short time before the light turns red.

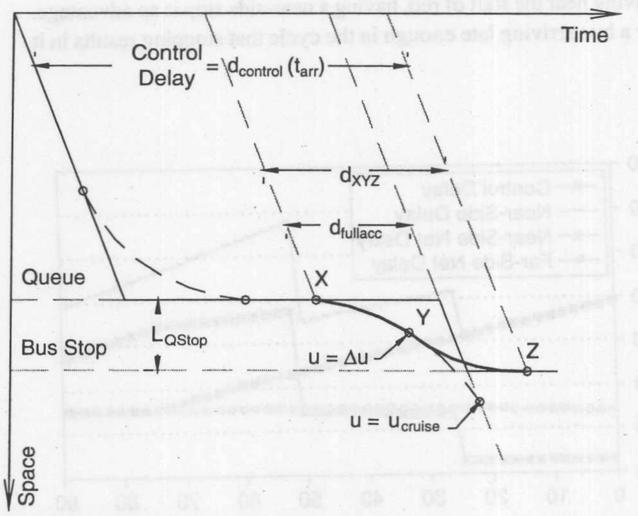

FIGURE 4 Long queue delay, close stop case.

Far-Side Stops

The equations used for near-side stops apply equally for far-side stops. As with near-side stops, the model includes the case in which a bus does not reach full speed between the queue and the stop, reducing deceleration delay.

Results

Base Case Results and Variations Within a Cycle

Because of the dynamics of the signal and the queue, bus delay varies strongly with the time in the cycle at which the bus arrives. In Figure 5, bus delay is plotted as a function of the bus's projected arrival time in the cycle, with base case values for a near-side stop without overtaking and for a far-side stop. The figure shows the delay for a stopping bus, control delay (Equation 7), and net delay, defined earlier as:

$$\text{net delay} = \text{total delay} - d_{\text{control}}\left(t_{\text{arr}}\right) - d_{o} \quad (15)$$

where d_o is normal stopping delay at a stop away from the influence of traffic, including dwell time and full deceleration and acceleration delay.

Net delay for near-side stops involves four distinct arrival time regions. First, for arrivals near the start of red, total delay will equal control delay (or be slightly greater if cars can overtake a stopped bus). Consequently, net delay in this region is strongly negative, in that the stop is served during control delay.

The second region begins when the queue effectively blocks the stop ($t_{\text{arr}} = 25$ s). Total delay roughly equals control delay plus normal stopping delay, and so net delay is near zero. The third region begins when serving the stop results in a bus missing the green (at $t_{\text{arr}} = 50$ s). Total delay makes a sharp jump, and net delay is strongly positive.

The fourth region begins at $t_{\text{arr}} = t_q$ (75 s). Control delay becomes constant (zero), resulting in net delay falling at a faster rate. However, net delay is still strongly positive.

Figure 5 shows both aspects of near-side stop delay. For a bus arriving near the start of red, having a near-side stop is an advantage. For a bus arriving late enough in the cycle that stopping results in it missing the green, a near-side stop is a clear disadvantage. Far-side stops, in contrast, are influenced only minimally by the signal, with a net delay near zero regardless of t_{arr}.

If one cannot control when in a cycle a bus will arrive, the overall effect of a stop near an intersection can be found by averaging over all possible arrival times. Base case results are shown in Table 3. For far-side stops, average net delay is about –0.5 s; for near-side stops, average net delays are about 11 s when overtaking is permitted and 9 s when it is not. For base case values of stop location, traffic, and signal cycle parameters, the disadvantageous aspect of near-side stop delay dominates, making it clearly inferior to far-side placement.

The standard deviation of total delay at an intersection does not increase when a stop is placed near side, because the additional delay caused by stopping is inversely correlated with control delay: When control delay is large (for arrivals just after start of red), a stop adds little or no delay, and when control delay is zero (for arrivals near the end of green), a stop adds a significant amount of delay.

Results for Other Parameter Values

Experiments were conducted with many variations in parameter values. For far-side stops, the simple result that average net delay is just below zero never changes. Near-side stop delay, however, is strongly affected by layout and traffic parameters. The most important parameters are those that determine (*a*) for how much of the cycle the queue blocks the stop and (*b*) how costly it is to have to wait for the next green.

In Figure 6, average bus delay is shown for a variety of bus stop setbacks, cycle lengths, and v/c ratios. With respect to setback, average net delay is worst with a small but nonzero setback in the range of 25 to 100 ft. Larger setbacks reduce delay by reducing the chance that a queue will block the stop. When the setback extends beyond the range of the queue, signals have no effect on stop delay. Alternatively, placing the stop at the stop line reduces delay by increasing the chances that a bus ending its service will be able to escape without waiting for the next green period because it will be able to cross the stop line without incurring any acceleration delay.

With a short cycle, net delay is smaller, because the penalty of missing the green is smaller and because the shorter resulting queues have less of an effect in terms of blocking stops. Finally, near-side net delay increases with v/c as a result of increasing queue length. The case of $v/c = 0.1$ represents a bus-only lane. Experiments showed a consistent result regardless of other parameters: With a bus-only lane, near-side stops yield negative net delay and are superior (with respect to delay) to far-side stops.

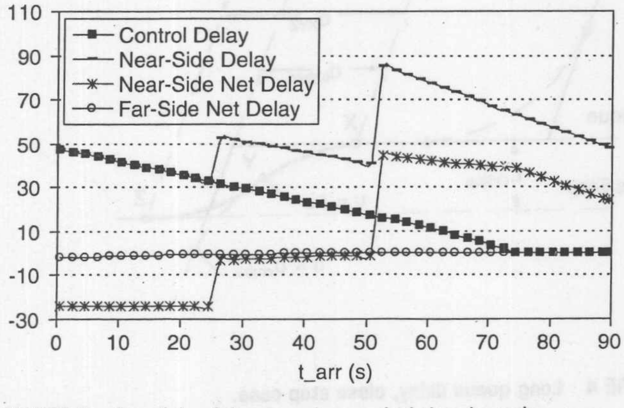

FIGURE 5 Bus delay (s) versus bus arrival time in cycle.

TABLE 3 Bus Delay: Base Case Results

	Near Side			
	No Overtaking	Overtaking	Far-Side	No Stop
E (delay) (s/bus)	53.8	55.6	44.5	20.7
Min. delay (s)	32.9	34.9	24.1	0.0
Max. delay (s)	86.1	86.1	69.3	47.3
Std. dev. (delay) (s)	14.4	13.8	14.8	15.3
E (net delay) (s/bus)	8.9	10.8	–0.4	—

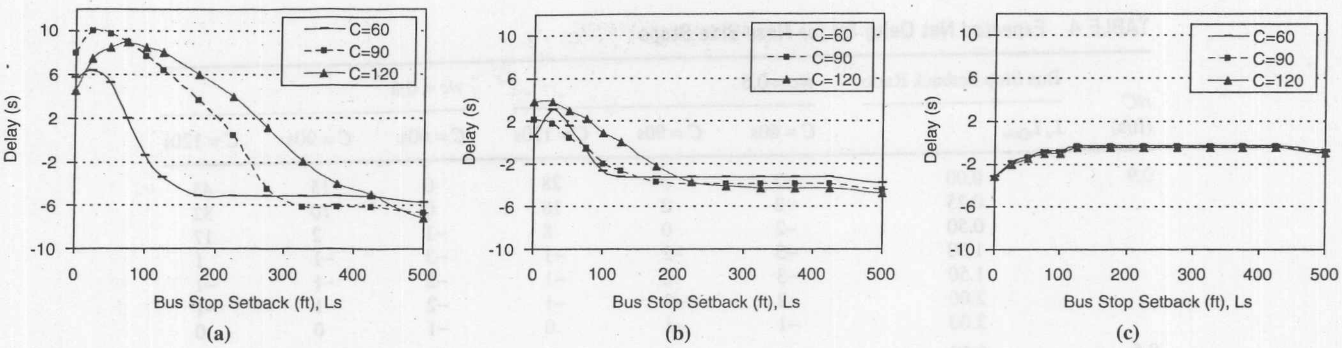

FIGURE 6 Near-side average net delay (s) versus setback with no overtaking permitted for (a) $v/c = 0.8$, (b) $v/c = 0.6$, and (c) $v/c = 0.1$.

In Figure 7, average net bus delay is shown as a function of the red ratio r/C. Base case parameters are used otherwise. For a given value of v/c, a large red ratio means a small volume, and a small red ratio means a large volume. With small red ratios (e.g., a major street intersecting a minor street), placing a stop near side imposes virtually no net delay because queues never become long and buses rarely miss the green. However, with long red ratios (e.g., a minor street intersecting a major street), near-side stops can cause large net delays because the "triple stop" becomes common. For buses facing a signal with a short green period, delay will be reduced significantly by placing a stop either far side or set back sufficiently far from the intersection that a queue rarely blocks the stop.

Experiments showed that dwell time duration can strongly influence average net delay depending on its "fit" with the cycle's green and red periods. Average delay varies with the ratio t_{dwell}/C roughly following a sine curve, with delay worst at a point in the range $t_{\text{dwell}} = 0.1C$ to $0.5C$ (depending on other parameters) and best in the range $t_{\text{dwell}} = 0.5C$ to $0.8C$. For base case parameter values other than t_{dwell}, there was a difference of about 20 s between best and worst cases, and the best case yielded an average net delay of −4 s. Unfortunately, however, neither transit nor traffic authorities have much power to "tune" the t_{dwell}/C ratio to its optimal value because of how dwell time varies with both random and systematic demand fluctuations and the need to vary cycle length with traffic and pedestrian demand. However, if one finds that buses at a certain intersection approach are often just missing the green, it may be worth trying to reduce delays by changing cycle lengths.

Results showed that the most of the variation in near-side average net stop delay could be explained by cycle length and three (nonindependent) ratios: v/c, r/C, and the bus stop setback ratio $L_S/L_{Q\text{ave}}$, where

$$L_{Q\text{ave}} = \frac{0.5 v t_q^2 L_{\text{veh}}}{C} \tag{16}$$

is the average reach of the queue (distance from the stop line) in a typical cycle. Expected net delay for different values of these four parameters for near-side stops is shown in Table 4.

CONCLUSIONS

Through analyses of some typical cases, net delay increments were developed to account for grade and intersection effects on stopping delay. Grades of 3% or less have no substantial effects. Steep upgrades can add 8 s or more to stop delays. At intersections, placing a stop far side is always a safe option, carrying essentially zero net delay. Near-side placement can add considerable delay, particularly when setback, traffic, and signal parameters are such that queues often block a stop and red periods are long, such as on a minor street crossing a major street. Near-side delay can be reduced by reducing queue interactions, either by increasing the setback or decreasing cycle time. When a bus has an exclusive lane, however, placing the stop at the stop line yields negative net delay, making it (slightly) superior to far-side placement.

The present model did not permit analysis of oversaturated intersections. However, inasmuch as the results show the importance of

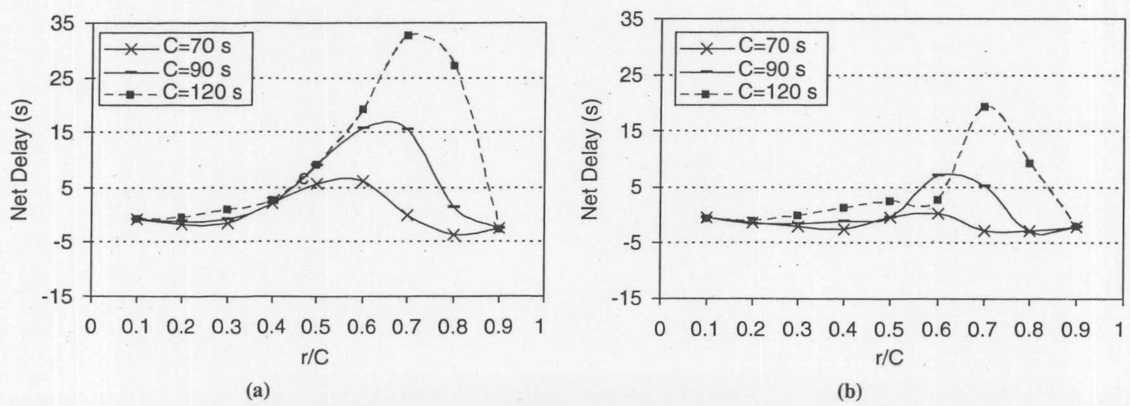

FIGURE 7 Near-side average net delay (s) versus fraction red with (a) $v/c = 0.8$ and (b) $v/c = 0.6$.

TABLE 4 Expected Net Delay (s) for Near-Side Stops

r/C (ft/s)	Bus Stop Setback Ratio $L_s L_{Qave}$	v/c = 0.6, C = 60s	v/c = 0.6, C = 90s	v/c = 0.6, C = 120s	v/c = 0.8, C = 60s	v/c = 0.8, C = 90s	v/c = 0.8, C = 120s
0.9	0.00	−2	3	28	0	15	43
	0.25	−2	2	18	0	10	32
	0.50	−2	0	8	−1	2	17
	1.00	−3	−2	−1	−3	−1	1
	1.50	−3	−2	−1	−2	−1	−1
	2.00	−2	−2	−1	−2	−1	−1
	3.00	−1	−1	0	−1	0	0
0.5	0.00	1	3	4	9	7	5
	0.25	3	3	5	8	11	10
	0.50	4	2	4	8	11	10
	1.00	3	1	3	2	8	8
	1.50	0	0	0	−1	4	3
	2.00	−1	−1	−1	−2	−2	0
	3.00	−1	−1	−1	−2	−2	−2
0.3	0.00	−1	0	1	−1	0	2
	0.25	−1	1	2	0	1	2
	0.50	−1	1	1	0	1	2
	1.00	−1	0	1	0	0	1
	1.50	−1	−1	0	−1	−1	−1
	2.00	−1	−1	−1	−1	−1	−1
	3.00	−1	−1	−1	−2	−2	−2

NOTE: Net delay for $v/c = 0.1$ is in the range −4 to −2 s, regardless of other parameter values. Results assume overtaking is permitted. If not, reduce net delay by 2 s.

queues blocking stops, it is possible to suggest an ideal location for a bus stop on an approach with frequent cycle overflows: near side and set back such that, on green, a bus queued at the stop will clear the intersection near the end of green. That location allows the bus the best chance of serving the stop while the bus is already stopped for the light, and the bus has a good chance of clearing the intersection once the stop has been served.

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