# Transfer Scheduling and Control to Reduce Passenger Waiting Time

Theo H. J. Muller and Peter G. Furth

**Transfers cost effort and take time. They reduce the attractiveness and the competitiveness of public transportation. The impedance of transferring should be limited, especially when low-frequency routes are involved. First, this paper shows the effects of planning the offset between the timetable arrival time of the feeder line and the timetable departure time of the connecting line on the transfer waiting time. An optimized buffer time reduces the probability of missing the connection to the point at which a further reduction would cause a still greater disbenefit by making passengers who make their connection wait longer. Second, the paper shows the effects of punctuality control on the routes on the transfer waiting time. If general operational control can reduce the punctuality standard deviations of arrivals and departures, it increases the reliability of the transfer. Third, the paper shows the effects of departure control at the interchange on the transfer waiting time. Holding connecting vehicles prevents missed connections because of early departures and holding just until the connection is made prevents unnecessary delays after passengers have transferred. Example results are derived by the use of a mathematical model.**

Because of how origins and destinations are dispersed, collective public transportation cannot provide direct connections for all relations. To reduce operational costs and to increase the efficiency and effectiveness of operation, only dense relations are served by transit routes. Other transit relations require one or more transfers. However, when passengers need to transfer, they must spend additional effort and waiting time, both of which reduce the attractiveness and competitiveness of public transportation.

Transportation planners have long known that passengers dislike making transfers. The General Motors Research Laboratory analyzed consumer attitudes toward a proposed new transportation system (*1*) and found that the predictability and the reliability of the arrival time at the destination, a short waiting time at the boarding stop, a short travel time, and also making a trip without changing vehicles were important. Research at the Delft University of Technology showed that the modal split is influenced by the travel time ratio (the total trip time by transit divided by the total trip time by a car), the frequency of operation, and the number of transfers (*2*). A mathematical formulation was found:

$$M = a_1 + e^{(a_2 + a_3 \cdot R + a_4 \cdot T + a_5/F)} \quad (1)$$

where

$M$ = market share (%),
$R$ = travel time ratio,
$T$ = number of transfers,
$F$ = frequency (number of vehicles per hour), and
$a_1$ to $a_5$ = constants.

For passengers with a car available (choice travelers), the influences of the number of transfers and the travel time ratio are shown in Figure 1.

Experience has shown that when the difficulty of transferring is reduced, user satisfaction and the amount of travel both increase. Transfers can be improved by several means, including through the use of better facilities, better institutional arrangements, and better operations (*3*). The findings of an investigation into intermodal passenger transfer facilities' operations and services in urban areas of California showed that besides safe and adequate facilities, including transfer information and fare ticketing systems, transfer waiting time and transfer reliability are, in particular, important items that attract passengers (*4*). This paper examines how better operations can minimize the transfer impedance.

A transfer requires transfer time. The timetable (scheduled) transfer time ($T_{1–2}$) is the difference between the timetable arrival moment $A_1$ of a feeder vehicle at the transfer stop and the timetable departure moment $D_2$ of a connecting vehicle:

$$T_{1-2} = D_2 - A_1 \quad (2)$$

This is shown graphically in Figure 2.

The scheduled transfer time ($T_{1–2}$) consists of a scheduled exchange time ($X_{1–2}$) for going from the alighting stop of Feeder Vehicle 1 to the boarding stop of Connecting Vehicle 2 and a buffer time ($B_{1–2}$) to reduce the probability of missing the connection. The exchange time depends, among other things, on the layout of the interchange and on the information systems and ticketing regime present and should account for

- Orientation time, which is the time required to collect information about the location and the departure times of connecting vehicles;
- Walking time; and
- The time required to pay fares or buy a ticket.

To minimize transfer impedance, a timed transfer coordinates the arrival time of a feeder vehicle with the departure of the connecting vehicle. Optimal scheduling involves a trade-off: by increasing the buffer, the probability of missing the connection will be low; however,

T. H. J. Muller, Delft University of Technology, Faculty of Civil Engineering and Geosciences, Stevinweg 1, Delft 2628 CN, Netherlands. P. G. Furth, Department of Civil and Environmental Engineering, Northeastern University, 306 Huntington Avenue, Room 400 SN, Boston, MA 02115. Corresponding author: T. H. J. Muller, t.h.j.muller@tudelft.nl.

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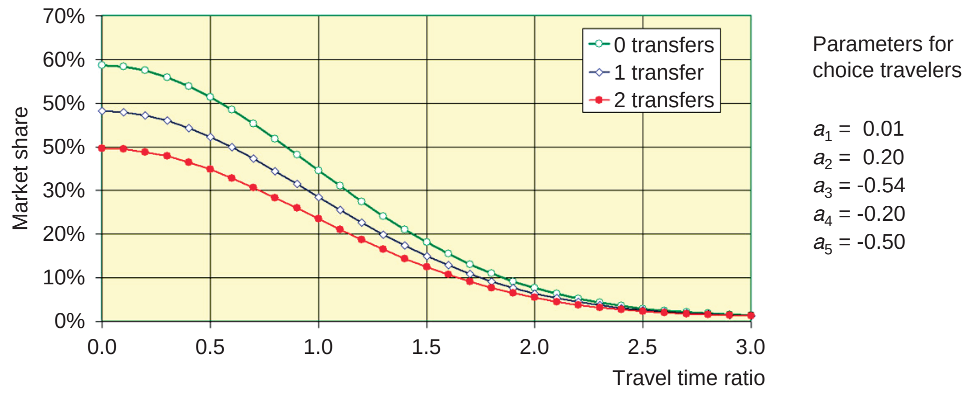


**FIGURE 1 Modal split versus travel time ratio with zero, one, and two transfers.**

at the same time, a larger buffer increases the transfer time for people who do not miss their connection.

## TRANSFER WAITING TIME MODEL

The impedance of transferring depends on, among other things, the transfer times experienced by passengers. Part of this time, the exchange time, is structural and for the remainder of this paper is assumed to be added to the arrival time of the first vehicle, so that arrival time can be interpreted as the time at which an arriving passenger is first able to depart on a connecting vehicle. The remainder is the transfer waiting time, which is affected by the schedule, the randomness of operations, and control actions taken to improve transfer reliability.

In the absence of operational control, the probability of missing the connection depends on the scheduled offset ($B$) and the probability density distributions of the arrival time of the feeder [$f(t_a)$] and the departure time of the connecting vehicle [$g(t_d)$], as illustrated in Figure 3. The time axis is such that the timetable arrival moment $A_1$ of the feeder vehicle (including whatever exchange time is needed) is at time ($t$) zero, and the timetable departure time of the connecting vehicle ($D_2$) is at $t$ equal to $B$, the scheduled buffer time. The variables $P_a$ and $P_d$ are the punctuality deviations of the feeder's arrival and the connecting vehicle's departure, respectively.

The expected arrival time of the first vehicle [$E(A)$] and the expected departure time of the second vehicle [$E(D)$] are therefore

$$E(A) = A + E(P_a) \tag{3}$$

$$E(D) = A + B + E(P_d) \tag{4}$$

Passengers are able to make their connection when $t_a$ is less than $t_d$, in which case their waiting time is simply $t_d - t_a$. Otherwise, they must wait for the next connecting vehicle. It is assumed that the probability that feeders will arrive later than the next connecting vehicle is zero.

Let $W(t_a)$ be the expected waiting time, given arrival at time $t_a$. The expected waiting time can then be formulated as the sum of two components: $E(W_{\text{conn}})$, the contribution from passengers who make their connection, and $E(W_{\text{miss}})$, the contribution from passengers who miss their connection:

$$\begin{aligned} E[W] &= E[W_{\text{conn}}] + E[W_{\text{miss}}] \\ &= p[\text{make}] * E[W|\text{make}] + p[\text{miss}] * E[W|\text{miss}] \end{aligned} \tag{5}$$

where $p$ is probability.

$$\begin{aligned} E[W] = & \int_{-\infty}^{\infty} f(t_a) * \int_{t_a}^{\infty} g(t_d) * [t_d - t_a] dt_d dt_a \\ & + \int_{-\infty}^{\infty} f(t_a) * \int_{-\infty}^{t_a} g(t_d) * [E(D) + H - t_a] dt_d dt_a \end{aligned} \tag{6}$$

This waiting time formula is illustrated in Figure 4.

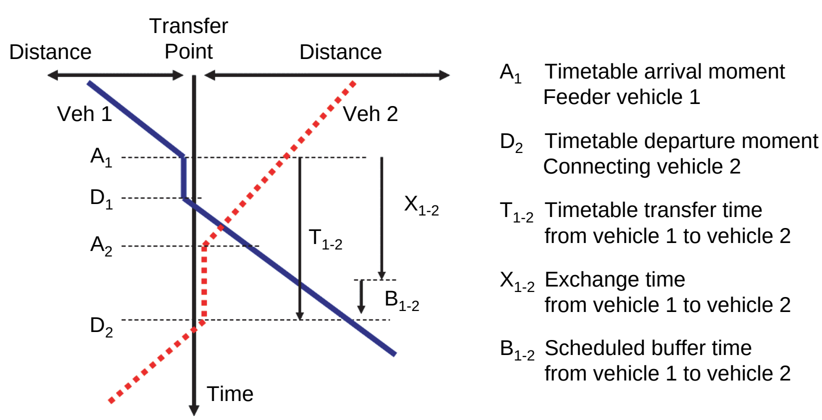


**FIGURE 2 Scheduled transfer time from Feeding Vehicle 1 to Connecting Vehicle 2.**

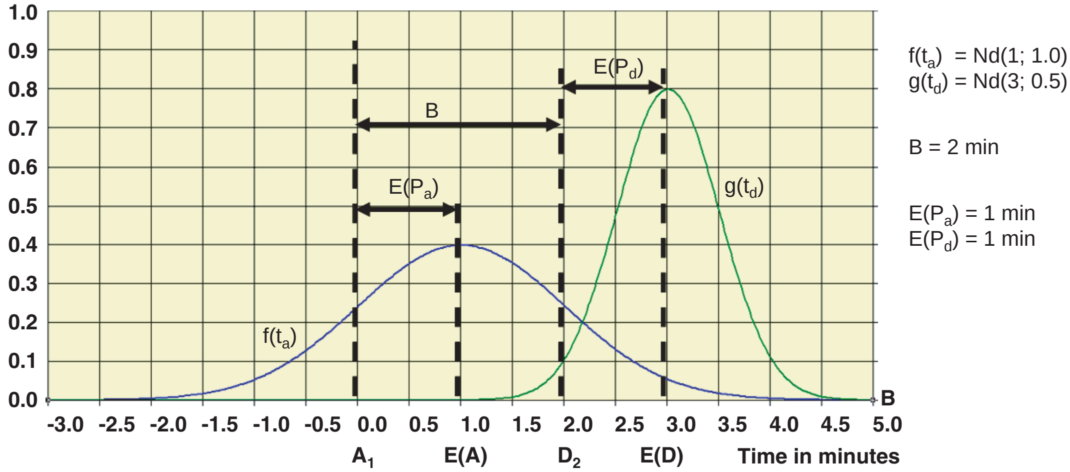


FIGURE 3 Probability density distributions of arrivals [$f(t_a)$] and departures [$g(t_d)$] ($N_d$ = normal distribution).

In Figure 4, arrival and departure time distributions are assumed to be normally distributed, with the parameters shown. The bimodal curve is the integrand of Equation 6, which represents the contribution to the expected waiting time for a given arrival time $t_a$. The area under this curve is the overall expected waiting time ($W_{tot}$). The dotted lines in Figure 4 are the integrands of $W_{conn}$ and $W_{miss}$, indicating the contribution to the expected waiting time from passengers who make and who miss their connection; the areas under those curves are $W_{conn}$ and $W_{miss}$, respectively. This graphical representation allows one to see clearly the two contributions to transfer waiting time.

In this example, the expected waiting time is 3.2 min, with components $W_{conn}$ equal to 2.0 min attributed to passengers who make the connection and $W_{miss}$ equal to 1.2 min attributed to passengers who miss the connection. The contribution from passengers who miss their connection is large compared with the small probability of missing the connection, which is only 3.7% in this example.

Equation 6 is based on the assumption that the number of transferring passengers is independent of punctuality deviations. In reality, one of the reasons that vehicles are late is that they encountered more passengers than expected, raising their contribution to the transfer waiting time. Because late arrivals are usually the main cause of missed connections, Equation 6 probably underestimates the expected transfer waiting time.

## Reducing Experienced Exchange Waiting Time

### *Quality of Planning*

The expected waiting time depends on how well the schedule coordinates the feeder vehicle arrival and the connecting vehicle departure. With a longer buffer, the probability of missing the connection falls, lowering $W_{miss}$ but at the same time increasing $W(t_a)$ and therefore $W_{conn}$. Figure 5 shows the difference in the expected waiting time when the buffer $B$ for the example used above changes from 2 to 1 min. The number of missed connections increases enormously, and the exchange waiting time increases from 3.2 to 6.8 min. This shows the sensitivity of transfer impedance to the quality of the planning of the offset of arrivals and departures.

If arrivals are normally distributed and departures are punctual, Knoppers and Muller (*5*) showed that the mean transfer waiting

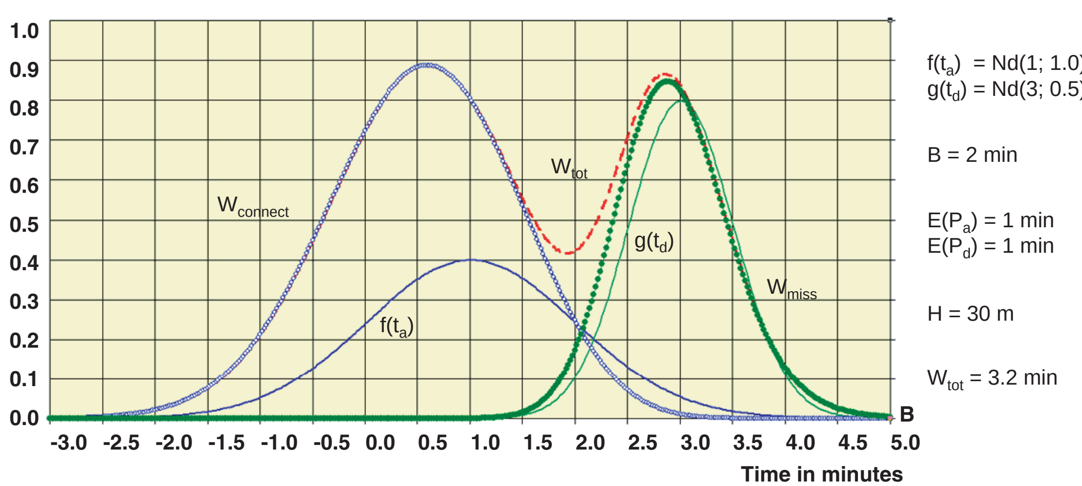


FIGURE 4 Waiting times according to the arrival and departure distributions.

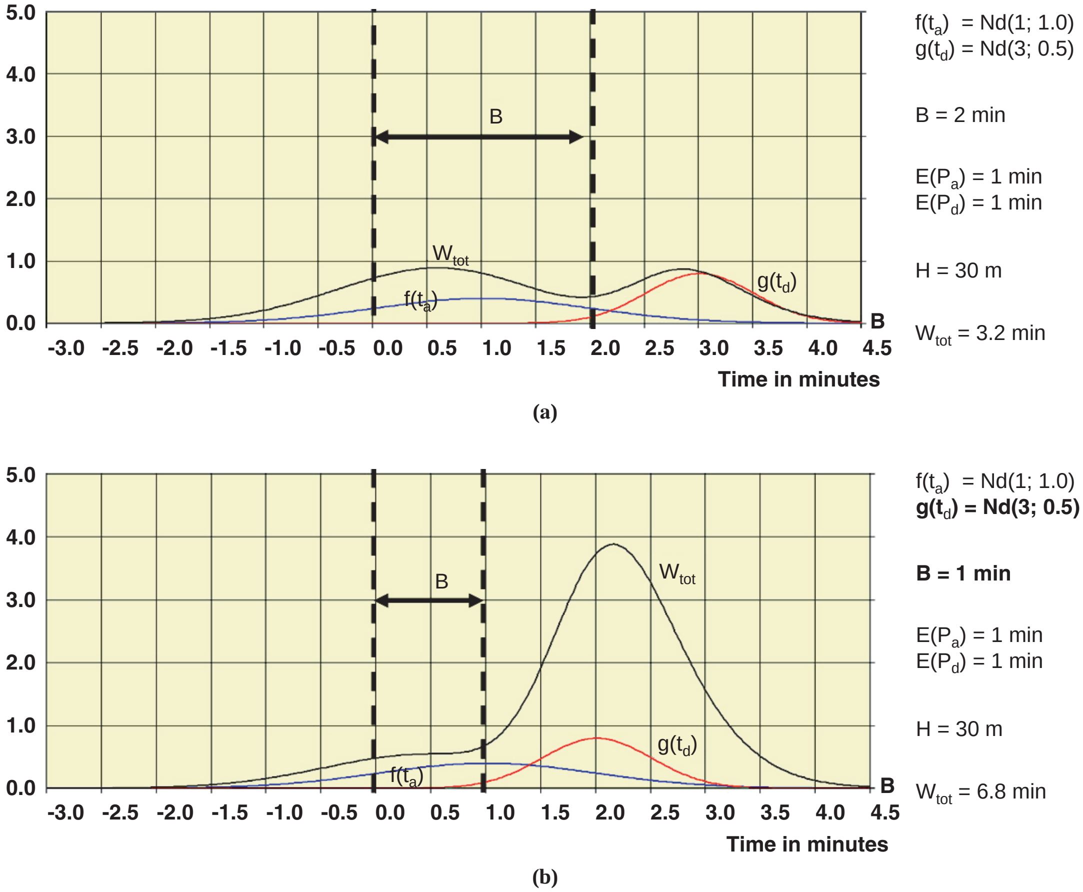


FIGURE 5 Expected transfer waiting times with buffers of (*a*) 2 min and (*b*) 1 min.

time [$E(W)$] is a periodic function of $E(B)$ with period $H$. With Equation 6 solved by using Fourier analysis, the expected waiting time is

$$E(W) = H \cdot \left( \frac{1}{2} + \sum_{n=1}^{\infty} \frac{e^{-2\left(\frac{n \cdot \pi \cdot \sigma}{H}\right)^2}}{n \cdot \pi} \cdot \sin \frac{n \cdot 2 \cdot \pi \cdot E(B)}{H} \right) \tag{7}$$

where σ is the standard deviation. This function can then be minimized with respect to $B$ to find the optimal buffer time. In this paper, the more general case of randomness in both the arrival process and the departure process is considered by using a direct numerical search to find the buffer that minimized the expected transfer waiting time.

Figure 6 shows how the expected transfer time varies with the buffer for the example used previously with normally distributed

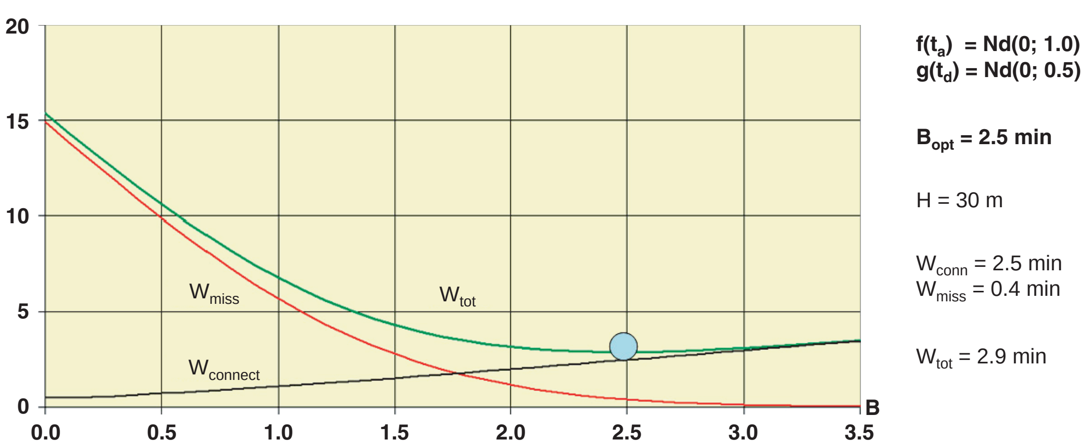


FIGURE 6 Expected waiting time versus scheduled buffer time *B*.

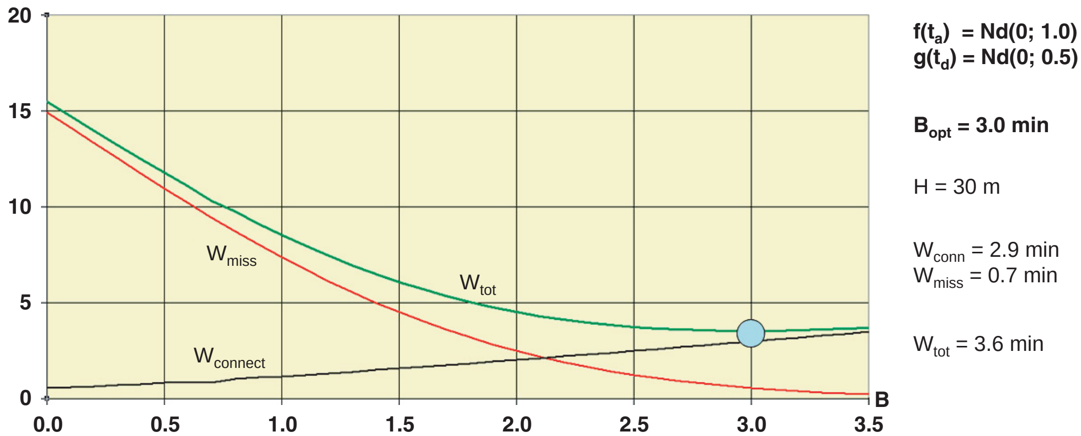


**FIGURE 7** Optimal offset with increased departure punctuality standard deviation.

arrival and departure time deviations. One can see that the optimal buffer is 2.5 min, resulting in an expected waiting time of 2.9 min. One can also see in Figure 6 the results of the previous example, in which the expected waiting time is far greater when the buffer is 1 min than when it is 2 min.

The shape of Figure 6 is characteristic: if the buffer is larger than optimum, the increase in the expected waiting time is small, but if the buffer is too small, the expected waiting time can increase rapidly. Because planning can never be perfect, it is therefore better to err on the side of a larger scheduled offset between a feeder vehicle arrival and a connecting vehicle departure.

### *Quality of Operation*

In addition to the quality of planning, the quality of operation, in terms of the variability of punctuality deviations $f(P_a)$ and $g(P_d)$, is important for the actual exchange waiting times that passengers experience.

Figure 7 shows the effect of increasing the variability of departure times on the transfer waiting time, with the standard deviation of departure punctuality increased from 0.5 to 1.0 min. With this increased variability, compared with the previous example, the optimal buffer grows to 3.0 min, and the minimal expected waiting time increases from 2.9 to 3.6 min.

Table 1 shows the optimum value of $B$ and the corresponding expected transfer waiting times $W$ for selected combinations of arrival and departure time variability. The mean punctuality deviation is assumed to be zero; if it is not, the buffer time should be adjusted accordingly. Table 1 shows that the greater that the standard deviations of the arrival and the departure punctuality deviations are, the larger that the optimum buffer $B$ is and the longer that the expected transfer waiting time $W_{tot}$ is.

The magnitude of service headway $H$ affects the waiting times of passengers who miss their connection, and therefore, with a longer headway, there is both a greater expected waiting time and a greater optimal buffer time. A repeat of the analysis whose results are shown in Table 1 but with a headway of 20 min instead of 30 min shows that the optimal buffer time and the expected waiting time are both about 10% less.

## Transfer Control

In addition to meticulous planning of the optimal offset and improving punctuality, transfer impedance can also be reduced by applying transfer control. Several control strategies can be distinguished.

**TABLE 1** Optimum Buffer Time *B* and Expected Waiting Time *W* as a Function of Arrival and Departure Time Standard Deviations

| | Departure σ | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | 0.0 min | | 0.5 min | | 1.0 min | | 1.5 min | |
| Arrival σ | *B* (min) | *W* (min) | *B* (min) | *W* (min) | *B* (min) | *W* (min) | *B* (min) | *W* (min) |
| 0.0 min | 0.0 | 0.0 | 1.1 | 1.3 | 1.4 | 2.0 | 1.1 | 2.5 |
| 0.5 min | 1.3 | 1.5 | 1.7 | 2.0 | 2.5 | 3.0 | 3.3 | 4.0 |
| 1.0 min | 2.3 | 2.7 | 2.5 | 2.9 | 3.0 | 3.5 | 3.6 | 4.3 |
| 1.5 min | 3.1 | 3.7 | 3.2 | 3.9 | 3.6 | 4.4 | 4.0 | 5.0 |
| 2.0 min | 3.8 | 4.7 | 3.9 | 4.8 | 4.2 | 5.2 | 4.5 | 5.7 |
| 2.5 min | 4.4 | 5.6 | 4.5 | 5.7 | 4.7 | 6.0 | 5.0 | 6.4 |

NOTE: Headway is 30 min.

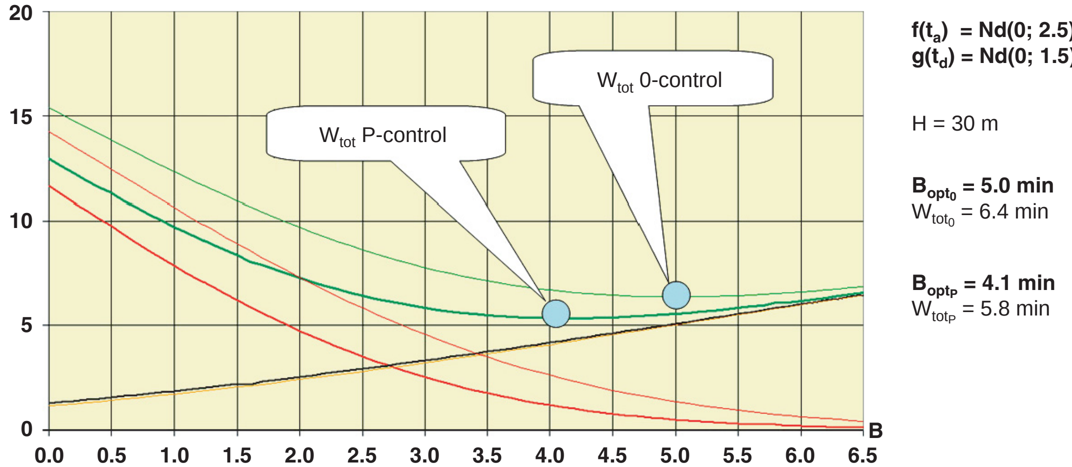


FIGURE 8 Expected waiting time versus buffer with and without departure punctuality control.

### *Departure Punctuality Control*

Some missed connections are caused by early departures on the connecting route. Departure punctuality control can prevent early departures by holding vehicles until the scheduled departure moment, in effect truncating the early part of the departure time distribution. The impact on the expected waiting time as a function of the scheduled buffer (offset) is shown in Figure 8 for the case of setting the scheduled departure time at the mean of the (uncontrolled) departure time distribution. In Figure 8, one can see that by applying departure punctuality control to prevent early departures of the connecting route, the optimum buffer time $B_{opt}$ is reduced from 5.0 to 4.1 min and the expected waiting time falls from 6.4 to 5.8 min.

The reduction in the expected waiting time due to departure punctuality control is illustrated in Figure 9, which shows the contribution to the waiting time of every possible arrival time for the

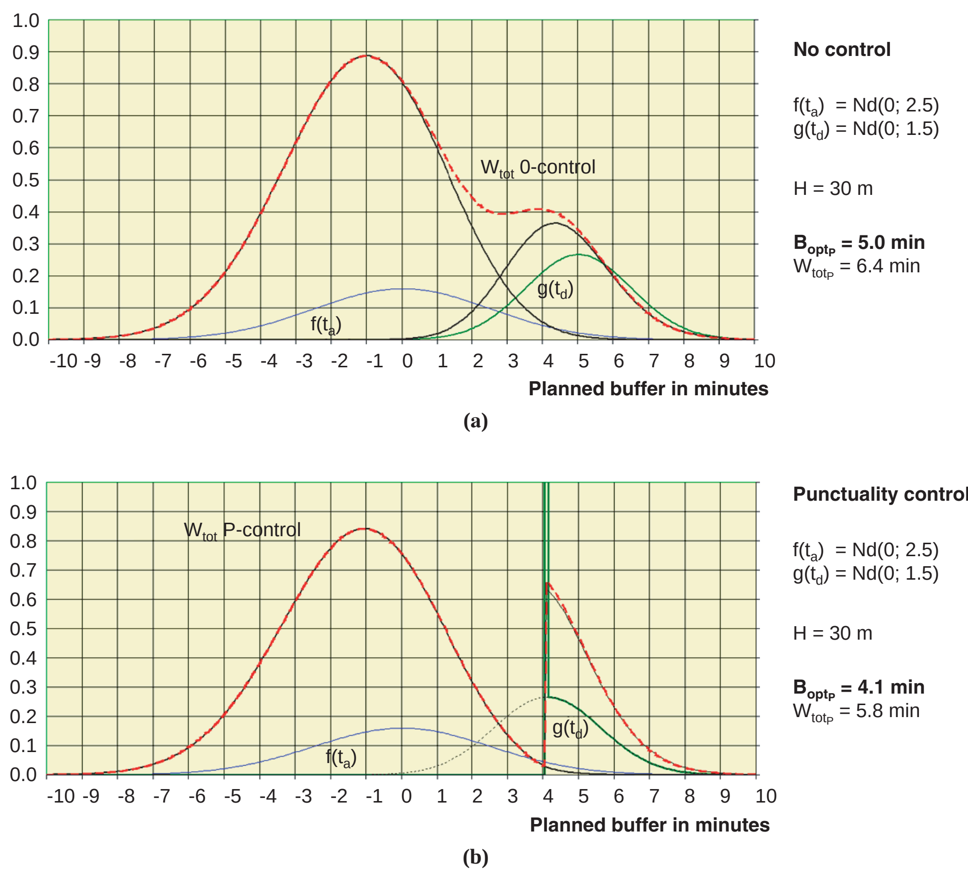


FIGURE 9 Optimum waiting time with no control and with punctuality control.

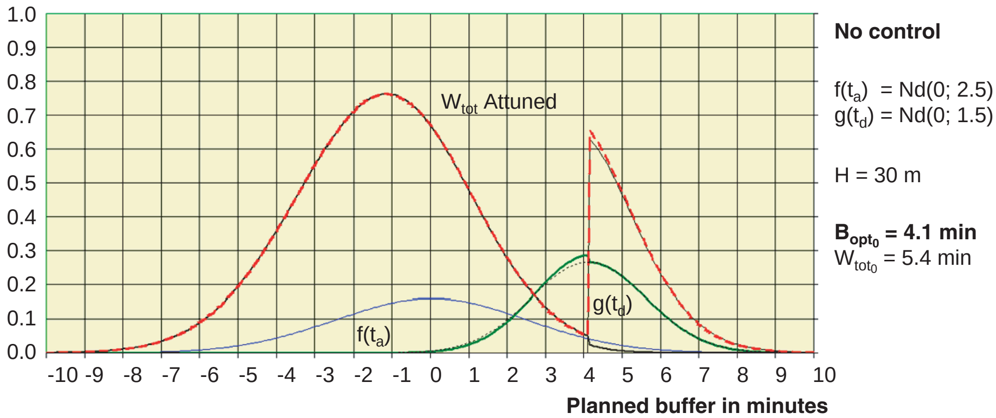


**FIGURE 10** **Probability density distributions of attuned departures.**

case of no control (Figure 9*a*) and departure punctuality control (Figure 9*b*). For each control case, the optimal offset is used. One can see the substantial reduction in the waiting time for passengers arriving within the 2 min or so before the scheduled departure time. The results of the comparison of the optimal offset and the corresponding waiting times (in minutes) are shown below:

| *Control Used* | $B_{opt}$ | $W_{tot}$ | $W_{conn}$ | $W_{miss}$ |
|---|---|---|---|---|
| No control | 5.0 | 6.4 | 5.1 | 1.3 |
| Punctuality control | 4.1 | 5.8 | 4.7 | 1.1 |

The average transfer waiting time $W_{tot}$ decreases from 6.4 to 5.8 min. Part of the gain comes from reducing the impact of missed connections, and part comes from having a smaller schedule offset that reduces the waiting time for connections that are made.

Departure punctuality control increases the transfer waiting time for cases in which the first vehicle has arrived but the connecting vehicle is still held until the scheduled departure time. This fact motivates the next strategy.

### *Attuned Departure Control*

With attuned departure control, departing vehicles are held only until the arrival of the feeder vehicle plus the necessary exchange time (which, again, is added to the arrival time in this analysis). As soon as the transfer is realized, the connecting vehicle can depart, even if it is before the scheduled departure time. This tactic requires an intelligent transportation system to predict the arrival time of the feeder vehicle and communicate that to the connecting vehicle. The communication system can be either a direct link between the feeder and the connecting vehicle or a control center. If the predicted arrival of the feeder bus is beyond the maximum delay, the connecting vehicle will not wait.

The contribution to the expected waiting time for every possible arrival time by the use of attuned departure control is shown in Figure 10.

By using the same parameters used in the previous example with departure punctuality control, the optimal buffer is still 4.1 min but the expected waiting time falls to 5.4 min (from 5.8 min).

### *Delaying Departure of Connecting Vehicle*

Attuned departure control can be made still more effective if the departing vehicle can be held up to a few minutes beyond its departure time if necessary to realize a connection. To prevent connecting vehicles from running too far behind schedule on the remaining sections of the route, delays in the departure of the connecting vehicle should be limited.

Figure 11 shows the contribution to the expected waiting time for every possible arrival time by using attuned departure control with

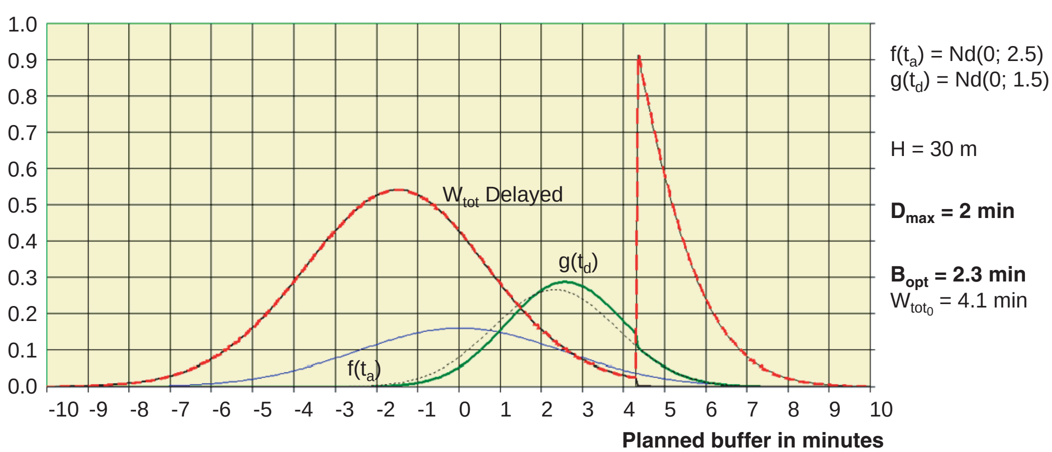


**FIGURE 11** **Probability density distributions of attuned and delayed vehicle departures.**

**TABLE 2 Comparison of Optimal Offset and Corresponding Waiting Times**

| Control Used | $B_{opt}$ | $W_{tot}$ | $W_{conn}$ | $W_{miss}$ |
|---|---|---|---|---|
| No control | 5.0 | 6.4 | 5.1 | 1.3 |
| Punctuality control | 4.0 | 5.8 | 4.6 | 1.2 |
| Attuning departures | 4.1 | 5.4 | 4.3 | 1.1 |
| Attuning and delay 1 min | 3.3 | 4.8 | 3.7 | 1.1 |
| Attuning and delay 2 min | 2.3 | 4.1 | 3.0 | 1.1 |

a maximum allowed delay of 2 min relative to the mean uncontrolled departure time. With this strategy, the optimal buffer has fallen to only 2.3 min, substantially reducing the expected delay for passengers who do not miss their connection.

Table 2 compares the results of the various strategies, including the attuned departure times with maximum allowed delays of 1 and 2 min with an optimized buffer time. Compared with the case for the no control, the application of attuned departure control with a maximum departure delay of 2 min reduces the average passenger transfer waiting time by 40% (to 2.3 min).

It is interesting that as the control becomes more attuned, there is relatively little reduction in the expected waiting time because of a missed connection. Instead, with better control, the optimal buffer (offset) becomes smaller, with the chief impact being a reduction in the expected waiting time for passengers who make their connection.

## CONCLUSION

This paper has described a simple probability model that shows the contribution to the expected transfer waiting time stemming from delays to passengers who make their connection (in which, in general, many passengers experience small delays) and passengers who miss their connection (in which a few passengers experience large delays). The model has also been used to show how the transfer waiting time can be reduced by careful planning of the schedule offset, using general operational control to reduce punctuality deviations, and exercising intelligent departure control.

Modeling of how the transfer waiting time varies with the schedule offset between the first vehicle's arrival and the second vehicle's departure shows how the optimal offset or buffer is a compromise between causing too much delay to passengers who make their connection and too much delay to those who miss their connection. It is also shown that the effects are not symmetrical, making it better to err on the side of having a buffer that is too long.

The paper also shows how general operational control efforts to reduce the arrival and the departure time punctuality deviations reduce the expected transfer waiting time and affect the optimal schedule offset.

Finally, three departure control tactics were described, and how they work to reduce the expected transfer waiting time was shown. The first tactic is holding departures until the scheduled departure time. The second is attuned holding, in which buses are held only until either the scheduled departure time or the arrival of the first bus (plus the necessary exchange time), whichever comes first. With attuned holding, an unnecessary delay to passengers who make their connections is eliminated. The third tactic is attuned holding, with the departing bus being held beyond the scheduled starting time, up to a given limit, if needed to wait for the arriving bus. Each of these strategies was modeled with respect to its impact on the optimal schedule offset and, by use of that offset, expected waiting time. It has been shown that with departure control, the probability that passengers will miss the bus declines, especially by use of the last strategy, as does the expected transfer waiting time. It was also shown that if one is allowed to hold a bus to make a connection, the optimal schedule offset decreases.

The analysis done in this paper used theoretical distributions of arrival and departure time deviations. For application, a measured probability distribution obtained by using an automatic vehicle location system can be used in the same way to help planners find the optimal schedule offset and to evaluate the impacts of various forms of operational control.

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