Red Clearance Intervals

Theory and Practice

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At signalized intersections the red clearance interval has to be long enough to prevent accidents but not longer than necessary to ensure efficient traffic operations and encourage respect for the red indication. Because designers used a variety of methods to calculate clearance times, the association of Dutch traffic control engineers (Contactgroep Verkeersregeltechnici Nederland) initiated the development of a generally applicable method. The resulting method is based on a driver behavior model that involves five parameters. In contrast to the suggested Institute of Transportation Engineers (ITE) method, it determines red clearance time for each ordered pair of conflicting streams depending on the distance of the entering and exiting streams from the zone in which the two streams' paths overlap. The conflict zone method was calibrated by using field data collected at two intersections and was included in the 1996 Dutch guidelines for traffic controllers. In comparison with the ITE-suggested method, which gives the exiting stream enough time to clear the entire intersection, the new method is sensitive to the sequence in which traffic streams appear in the cycle and tends to call for less clearance time, improving intersection capacity and reducing delay. This approach is especially beneficial in improving efficiency of intersections with actuated control.

The vehicle signal change interval is "that period of time in a traffic signal cycle between conflicting green intervals" (*1*). This interval may consist of a yellow change interval only or both a yellow change interval and a red clearance interval (all-red interval). The red clearance interval is between the start of the red for one traffic stream and the start of the green for the succeeding conflicting stream. Although in the United States use of a red clearance interval is a matter of local policy, in the Netherlands the red clearance interval is always required. However, the applied lengths of red clearance intervals vary strongly in practice because of the lack of a generally accepted calculation method. For the United States, a similar situation is recognized by the Institute of Transportation Engineers (ITE) in its Publication IR-115 (*2*), which states that "there is currently no nationally recognized recommended practice for determining the change interval length, although numerous publications provide guidance."

To standardize the calculation of red clearance intervals, the association of Dutch traffic control engineers (Contactgroep Verkeersregeltechnici Nederland) in 1992 identified the need for a rational method grounded in both theory and observation of motorist behavior. In response, the Transportation Research Laboratory of the Delft University of Technology was funded by the national Ministry of Transport and the cities of Amsterdam and Rotterdam to carry out the needed research to develop a new method, which was subsequently accepted and published as a guideline by the Dutch Ministry of Transport (*3*).

The new method leaves unchanged the guidelines regarding the yellow interval. The long-standing Dutch practice is to time the yellow interval in order to avoid a dilemma zone, just as described in the 1994 ITE method (*4*). The yellow-time formula is

$$t_{\text{yellow}} = t_r + \frac{v_{\text{appr}}}{2|a_{\text{dec}}|} \tag{1}$$

where

t_r = reaction time,
v_{appr} = approach speed (85th-percentile approach speed is typically used), and
a_{dec} = deceleration rate.

However, this formula for yellow time demands a complementary formula for red clearance time, because the yellow-time formula is based on cars' entering the intersection throughout the yellow interval. The formula developed follows the general Dutch practice of determining needed red clearance time for each paired sequence of conflicting traffic streams and comparing the travel time for both traffic streams to the point at which their paths conflict. The innovative aspect of the new method is how it deals with the danger posed by drivers who see the signal turn green before they come to a stop and therefore enter the intersection at greater speed than drivers who came to a standstill before the signal turned green.

First, the driver behavior model is presented and from it the derivation of an equation for necessary red clearance time. Next, data collected at two intersections are analyzed to estimate parameters of the model and to verify that it matches observed driver behavior. Finally, a brief comparison of the new method with current U.S. practice is offered and conclusions are drawn.

NEW METHOD TO DETERMINE RED CLEARANCE TIME

With the yellow-interval timing formula (Equation 1) used by Dutch traffic control engineers and suggested by ITE, vehicles must be expected to enter the intersection (cross the stop line) during the entire yellow interval. The purpose of the red clearance interval is to ensure that traffic in the second stream can safely enter the intersection without colliding with the last vehicle from the first stream. Clearance intervals are important for safety, but they also affect traf-

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Transportation Research Record: Journal of the Transportation Research Board, No. 1867, TRB, National Research Council, Washington, D.C., 2004, pp. 132–143.

fic operations: they contribute to lost time and affect delays, queuing, and necessary cycle length. In principle, then, clearance times should be as small as possible while still allowing a traffic stream to safely follow a conflicting stream.

ITE's suggested red clearance time is based on the principle that traffic in the entering stream should wait until a vehicle from the previous stream that enters the intersection in the last moment of yellow completely clears the intersection; that is,

$$t_{\text{clearance}} = \frac{\text{distance to clear intersection}}{\text{speed}} \tag{2}$$

The new approach (the conflict zone approach) is more precisely targeted. The Dutch practice of stream-based vehicle-actuated traffic signal control requires that before a traffic stream can get a green indication, it must satisfy clearance times for every proceeding conflicting traffic stream. Red clearance times $t_{\text{clearance}}(i, j)$ must be supplied to the controller for each ordered pair of conflicting streams (i, j), where i is the index of the exiting stream and j is the index of the entering stream.

As an example, several traffic streams at a typical intersection are shown in Figure 1. If traffic streams southbound through (SB_{Through}) and northbound through (NB_{Through}) are followed by conflicting streams eastbound left (EB_{Left}) and eastbound through (EB_{Through}), and if the exiting streams begin the red simultaneously, stream EB_{Left} could not begin the green until clearance times $t_{\text{clearance}}(SB_{\text{Through}}, EB_{\text{Left}})$ and $t_{\text{clearance}}(NB_{\text{Through}}, EB_{\text{Left}})$ had both expired, and stream EB_{Through} could not begin the green until clearance times $t_{\text{clearance}}(SB_{\text{Through}}, EB_{\text{Through}})$ and $t_{\text{clearance}}(NB_{\text{Through}}, EB_{\text{Through}})$ had both expired. In practice, differences in clearance times between stream pairs often mean that one entering traffic stream gets the green slightly before another.

For a given ordered pair of conflicting movements, clearance time is based on the travel time of vehicles in the exiting and entering streams to that stream pair's conflict zone, the area within the intersection where paths taken by vehicles in the two streams overlap. If s_{exit} equals the distance a vehicle in the exiting stream must travel from the stop line to fully clear the conflict zone (including the vehicle length, commonly taken to be 12 m so as to represent a truck) and if t_{exit} equals an exiting vehicle's travel time from the stop line to just beyond the conflict zone, similarly, s_{entrance} equals the distance from the stop line of the entering stream to the conflict zone and t_{entrance} equals the amount of time the first vehicle from the entering movement needs to reach the conflict zone. To avoid a collision, the length of the red clearance interval, $t_{\text{clearance}}(i, j)$, must be

$$t_{\text{clearance}}(i, j) = t_{\text{exit}}(i) - t_{\text{entrance}}(j) \geq 0 \tag{3}$$

In the interest of safety, the exit time should concern a relatively slow vehicle, whereas the entrance time should pertain to a fast vehicle.

Figure 1 illustrates the importance of determining clearance time as a function of an ordered pair of streams. Considering the conflict zone between conflicting streams SB_{Through} and EB_{Through}, one can see that EB_{Through}'s stop line is much closer to the conflict zone than is SB_{Through}'s. Consequently, if EB_{Through} is exiting while SB_{Through} is entering, little or no red clearance will be needed, because EB_{Through} vehicles have a considerable amount of time to clear the conflict zone before an SB_{Through} vehicle arrives. However, if SB_{Through} runs first followed by EB_{Through}, a considerable red clearance time will be needed because an EB_{Through} vehicle could arrive very quickly at the conflict zone, well before the last SB_{Through} vehicle has cleared if it entered the intersection just at the end of the yellow. Stream EB_{Through} should be delayed by a red clearance interval.

In the remainder of this paper, the stream indexes i and j will be suppressed.

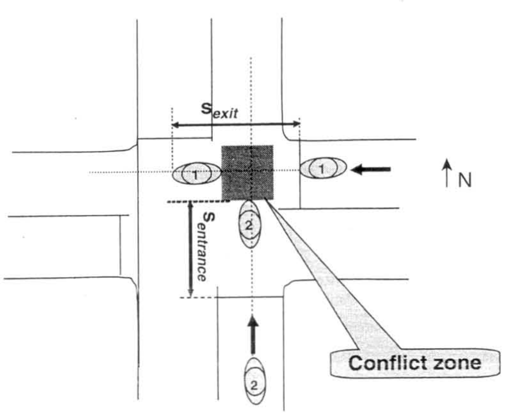


FIGURE 1 Traffic streams and conflict zones.

Determination of Exit Time

The new method does not change the calculation of exit time, which is determined rather straightforwardly as

$$t_{\text{exit}} = \frac{s_{\text{exit}}}{v_{\text{exit}}} \tag{4}$$

where v_{exit} equals the speed of a vehicle in the exit stream that crosses the stop line at the last moment of the yellow. Because such a vehicle was presumably unable to stop during the yellow interval, its speed is unlikely to be below the average approach speed; nevertheless, a somewhat conservative value may still be used.

However, no such generally accepted method existed for entrance time.

Determination of Entrance Time

In comparison with the calculation of exit times, the calculation of entrance times is more complex. For vehicles that decelerate to a standstill at the stop line before the light turns green, entrance time can be determined easily enough on the basis of an assumed acceleration trajectory. However, when a vehicle approaching the stop line has started to decelerate because the signal is red, but before it comes to a standstill the signal turns green, that vehicle can then begin to accelerate and enter the intersection at some speed. Such a vehicle may well reach the conflict zone sooner than it would have if it had been standing at the stop line when the signal turned green. Depending on the position and speed of the entering vehicle when the traffic signal turns green, the entrance time could differ. For safety, clearance time should be based on the smallest possible entrance time.

To determine clearance time according to the complex situation just described, a model of driver behavior is required. The following model is used:

- Drivers (with no traffic ahead) approach the intersection with an approach speed v_{appr}.

- Seeing the red signal, drivers decelerate as late as possible with constant deceleration a_{dec} following a trajectory that, if uninterrupted, brings them to a standstill at the stop line.
- When the signal turns green, drivers accelerate with the constant acceleration a_{acc} until they reach the speed v_{max}.
- A reaction time between the points when the light turns green and when acceleration begins may be taken into account.

To obtain safe values for the clearance time, the parameters for the described model should represent a rather aggressive driver.

Graphical Derivation of Minimum Entrance Time

A vehicle is considered that faces a red signal as it approaches an intersection with speed $v_{appr} = 50$ km/h, decelerating to a standstill at the stop line with $a_{dec} = -3$ m/s^2 and then immediately accelerating at $a_{acc} = 2$ m/s^2. If reaction time is assumed to be zero, it would imply that the vehicle came to a stop at the moment the signal turned green; if reaction time t_r is nonzero, it would imply that the signal turned green an interval t_r before the vehicle came to a standstill. The vehicle's deceleration to a standstill is completed during that reaction time, and so acceleration begins an interval t_r after the signal turns green. The vehicle's trajectory is plotted as the solid line in Figure 2*a*, where distance s is shown on the horizontal axis, with $s = 0$ at the stop line, and time τ is on the vertical axis. The origin of time, that is, $\tau = 0$, is placed at the moment of effective green, which is the moment of first possible acceleration, an interval t_r after the signal turns green. It should be noted that s and τ can be expressed as functions of each other.

For a given distance to the conflict zone $s = s_{entrance}$, $t_{entrance}(s) = \tau(s) + t_r$. Because of the coordinate system used, it is convenient to define adjusted entrance time as entrance time minus reaction time; that is,

$$t'_{entrance} = t_{entrance} - t_r \tag{5}$$

so that $t'_{entrance}(s) = \tau(s)$.

Next, if the light turned green early enough during the vehicle's deceleration that the driver had time to react and then begin accelerating before reaching the stop line, t_x is defined as the time interval between the moment at which the vehicle's deceleration trajectory would have led to a standstill if uninterrupted and the moment of effective green (when the vehicle begins to accelerate). For a vehicle that comes to a complete stop, t_x is positive, and for a vehicle that never comes to a complete stop, t_x is negative. The dashed line in Figure 2*a* represents the trajectory of a vehicle with $t_x = -1.5$ s. In comparison with the solid line, for which $t_x = 0$, it can be seen that both vehicles start decelerating at the same distance from the stop line. Until the moment of effective green, the dashed curve compared with the solid curve is simply shifted vertically by $-t_x$, the difference between the start of effective green for the two cases. For both vehicles, adjusted entrance time for a given entrance distance s can simply be read from Figure 2*a* as $t'_{entrance}(s) = \tau(s)$.

It can be seen in Figure 2*a* that for very small distances from the stop line, entrance time is smaller for the vehicle that comes to a standstill. For greater entrance distances, entrance time is smaller for the vehicle that passes the stop line with some speed.

In Figure 2*b*, trajectories are drawn on the same coordinate system for a range of values of t_x between 0 and -5 s, showing only the part of the trajectories occurring after the stop line. The upper envelope of these trajectories represents the minimum adjusted entrance time for any entrance distance. The analytical derivation of the curve representing this envelope will be discussed next.

Analytical Derivation of Minimum Entrance Time

Again, a vehicle approaching an intersection, facing a red signal, and following the behavior model described previously is considered. The coordinate system will now be adjusted by placing the origin of time τ at the moment when the approaching vehicle's trajectory would come to a stop at the stop line if that vehicle's deceleration is not interrupted by the signal's becoming green.

If τ_g is the start of the effective green (i.e., the start of the green plus the reaction time), under the new coordinate system,

$$t_x = \tau_g \tag{6}$$

Because, in accordance with the driver model, the vehicle's trajectory during deceleration is heading for the point ($s = 0$, $\tau = 0$), its speed and position at time t_x are given by

$$v(t_x) = t_x \cdot a_{dec} \tag{7}$$

$$s(t_x) = \tfrac{1}{2} \cdot a_{dec} \cdot t_x^2 \tag{8}$$

Of course, because both t_x and a_{dec} are negative, $v(t_x)$ is positive and $s(t_x)$ is negative.

At the moment that $\tau = t_x$, the vehicle begins to accelerate with constant acceleration a_{acc}. The vehicle's speed and acceleration at $\tau > t_x$ are then given by

$$v(\tau|t_x) = v(t_x) + a_{acc} \cdot (\tau - t_x) \tag{9}$$

$$s(\tau|t_x) = s(t_x) + v(t_x) \cdot (\tau - t_x) + \tfrac{1}{2} \cdot a_{acc} \cdot (\tau - t_x)^2 \tag{10}$$

It should be noted that the vehicle's speed and location are independent of v_{appr}, a parameter that turns out to be irrelevant. If Equations 7 and 8 are substituted into Equations 9 and 10,

$$v(\tau|t_x) = t_x \cdot a_{dec} + a_{acc} \cdot (\tau - t_x) \tag{11}$$

$$s(\tau|t_x) = \tfrac{1}{2} \cdot a_{dec} \cdot t_x^2 + t_x \cdot a_{dec} \cdot (\tau - t_x) + \tfrac{1}{2} \cdot a_{acc} \cdot (\tau - t_x)^2 \tag{12}$$

In the coordinate system being used, adjusted entrance time for a given entrance distance s is

$$t'_{entrance}(s) = \tau(s) - t_x \tag{13}$$

If Equations 12 and 13 are combined, entrance distance can be expressed as the function

$$s(t'_{entrance}|t_x) = \tfrac{1}{2} \cdot a_{dec} \cdot t_x^2 + t_x \cdot a_{dec} \cdot t'_{entrance} + \tfrac{1}{2} \cdot a_{acc} \cdot t'^2_{entrance} \tag{14}$$

Solving for adjusted entrance time (and taking the positive root),

$$t'_{entrance}(s, t_x) = \frac{-a_{dec} \cdot t_x + \sqrt{t_x^2 \cdot a_{dec}^2 - a_{acc} \cdot (a_{dec} \cdot t_x^2 - 2 \cdot s)}}{a_{acc}} \tag{15}$$

Figure 3 shows entrance times that follow from Equation 15 for several values of entrance distance s using the previously given

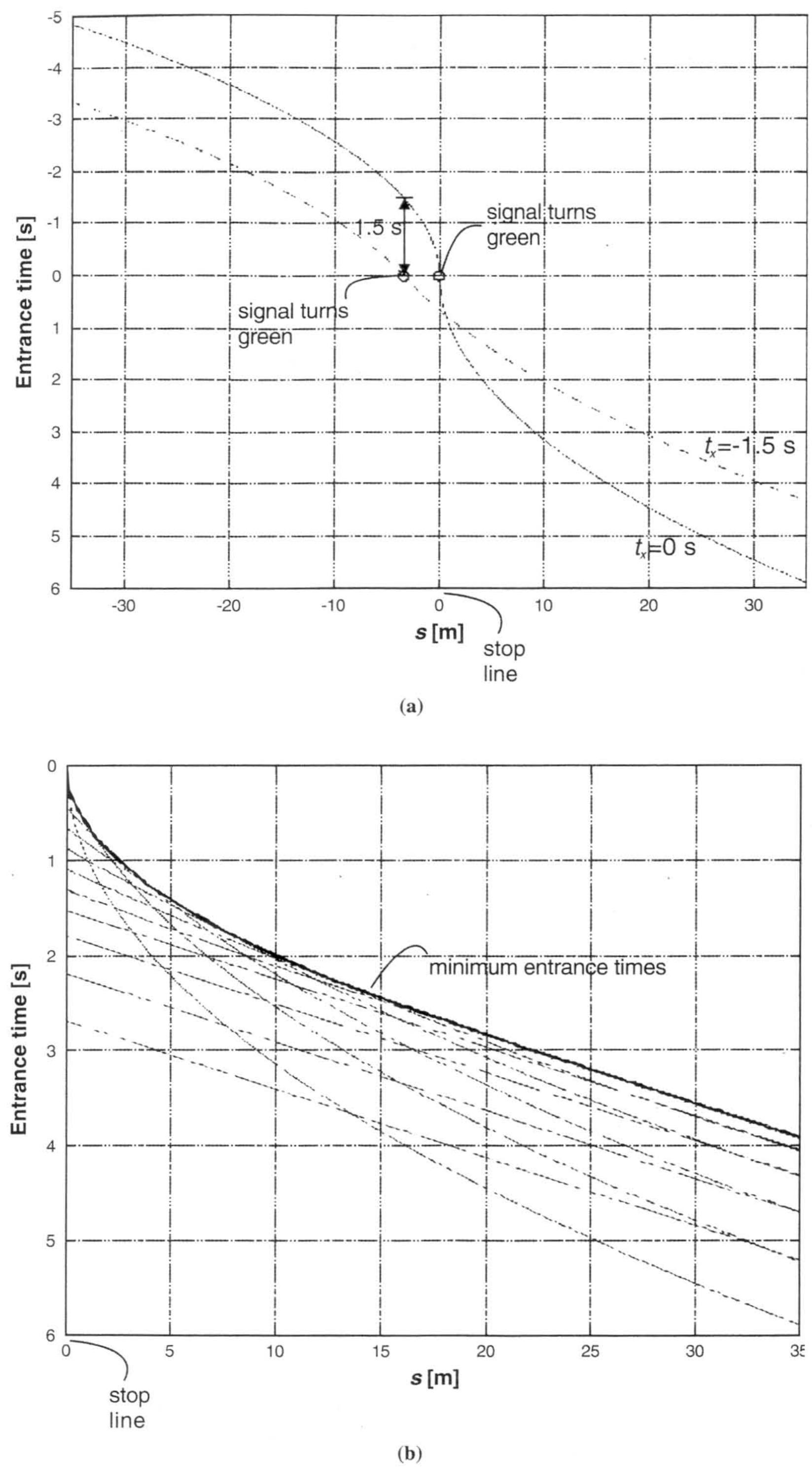


FIGURE 2 Entrance time derived from vehicle trajectories: (*a*) trajectories of two vehicles and (*b*) adjusted entrance time as envelope of trajectories.

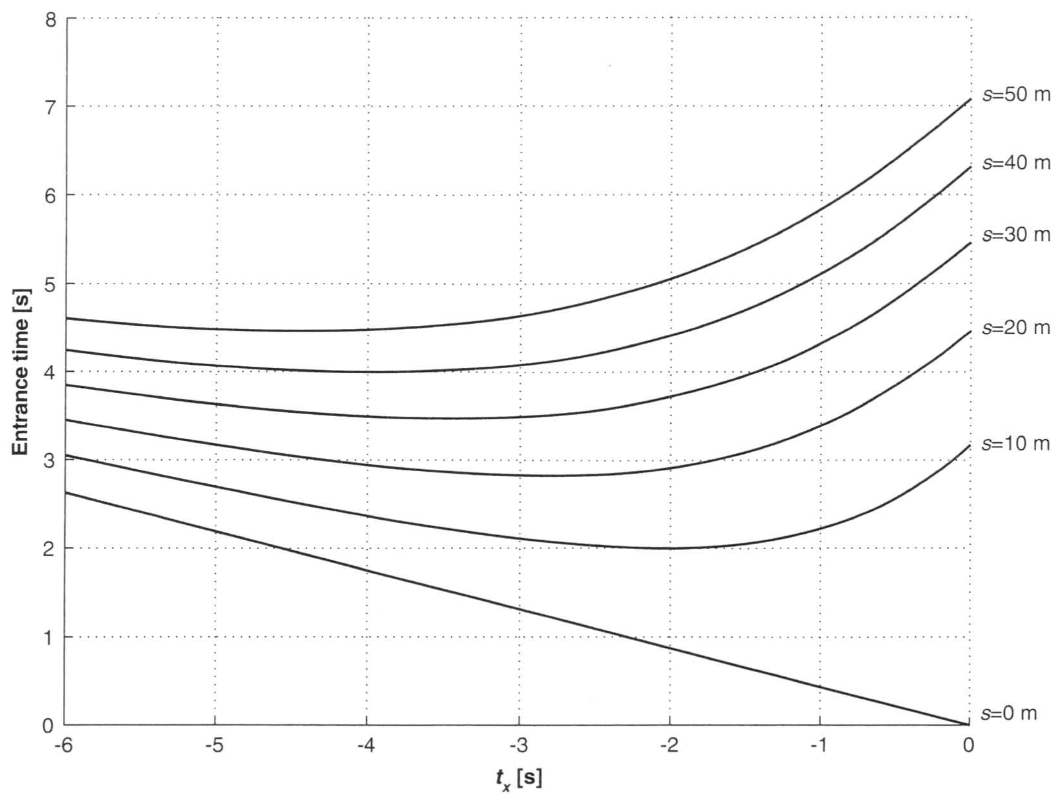


FIGURE 3 Entrance time as a function of moment at which traffic light turns green (t_x) and distance from stop line (s).

acceleration values. It can be seen that the critical value of t_x—the value that results in the minimum entrance time—differs for different values of s. The critical value of t_x for a given value of s, found by taking the derivative of the expression in Equation 15 with respect to t_x, is

$$t'_{x,\text{critical}}(s) = -\sqrt{\frac{2 \cdot s}{a_{\text{acc}} - a_{\text{dec}}}} \tag{16}$$

Substituting into Equation 15 and solving yields the adjusted minimum entrance time for a given entrance distance:

$$t'_{\text{entrance}}(s) = \sqrt{\frac{2 \cdot s}{a_{\text{acc}} - a_{\text{dec}}}} \tag{17}$$

Equation 17 is plotted in Figure 4; it replicates the envelope shown in Figure 2*b*.

Equation 17 does not yet take into account the limiting speed to which vehicles accelerate, $v_{\max}$. Because there is a limiting speed, the slope of the curve in Figure 4 should not exceed that of a vehicle running at speed $v_{\max}$, shown in Figure 4. There is therefore a critical distance s after which Equation 17 is not valid; it can be found by solving

$$\frac{dt'_{\text{entrance}}(s)}{ds} = \frac{1}{v_{\max}} \tag{18}$$

which yields

$$s_{\text{critical}} = \frac{v_{\max}^2}{2 \cdot (a_{\text{acc}} - a_{\text{dec}})} \tag{19}$$

For values of $s > s_{\text{critical}}$, it can be shown that the minimum adjusted entrance time is given by

$$t'_{\text{entrance}}(s) = \frac{s}{v_{\max}} + \frac{v_{\max}}{2 \cdot (a_{\text{acc}} - a_{\text{dec}})} \tag{20}$$

However, in practical intersection situations, entrance distances are unlikely to exceed s_{critical}.

Summary of New Method

In summary, clearance times can be calculated with the following equations:

$$t_{\text{clearance}} = t_{\text{exit}} - t_{\text{entrance}} \quad \text{(round negative values up to 0)} \tag{3}$$

$$t_{\text{exit}} = \frac{s_{\text{exit}}}{v_{\text{exit}}} \tag{4}$$

$$t_{\text{entrance}} = t_r + \sqrt{\frac{2 \cdot s_{\text{entrance}}}{a_{\text{acc}} - a_{\text{dec}}}} \quad \text{if } s_{\text{entrance}} \le s_{\text{critical}} \tag{21}$$

$$t_{\text{entrance}} = t_r + \frac{s_{\text{entrance}}}{v_{\max}} + \frac{v_{\max}}{2 \cdot (a_{\text{acc}} - a_{\text{dec}})} \quad \text{if } s_{\text{entrance}} > s_{\text{critical}} \tag{22}$$

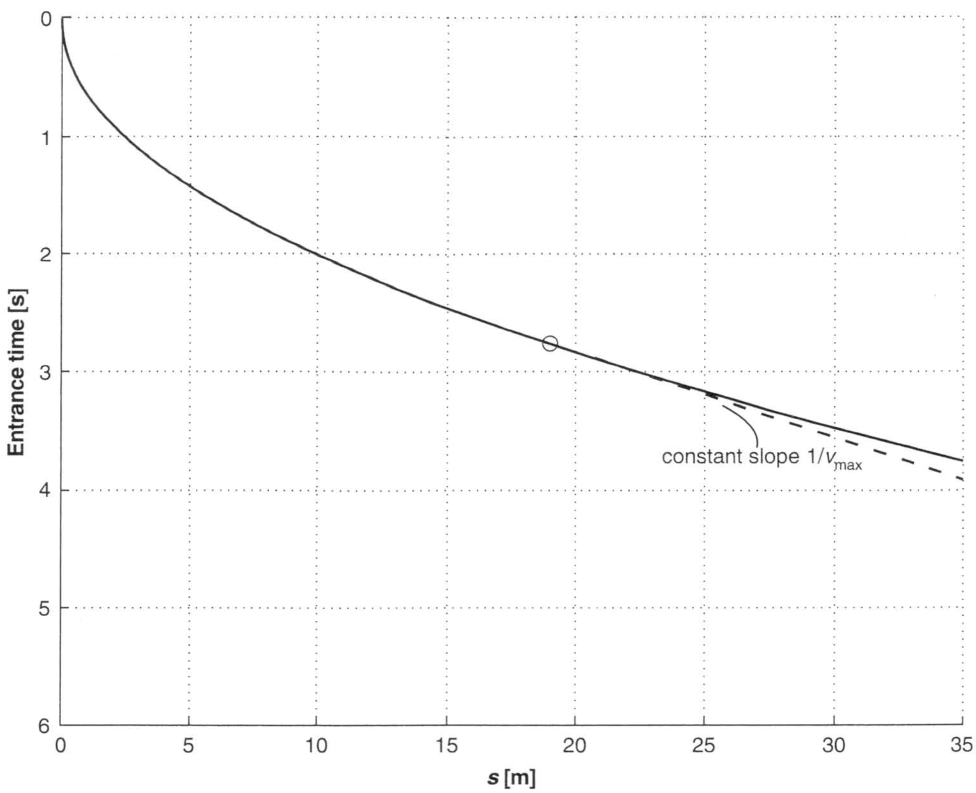


FIGURE 4 Adjustment of minimum entrance time curve for limiting speed v_{max}.

$$s_{critical} = \frac{v_{max}^2}{2 \cdot (a_{acc} - a_{dec})} \tag{19}$$

These equations include five parameters of the driver behavior model: v_{exit}, t_r, a_{acc}, a_{dec}, and v_{max}. However, because the acceleration rates appear only in the form of the algebraic difference ($a_{acc} - a_{dec}$) and because v_{exit} only affects exit time, which is not part of the new entrance time model, there remain three independent parameters to calibrate. It was decided that reaction time should be set to zero in recognition of motorists who, being familiar with the intersection, might anticipate the start of the green and react with almost no delay, leaving two parameters to calibrate. One of them, v_{max}, has little influence on the model's predictions for typical entrance distances. So the chief calibration parameter is the difference in accelerations, which can be seen as a measure of driver aggressiveness, because a high value is correlated with strong accelerations and decelerations. The data collection and analysis effort by which those parameters were estimated and the model was validated is described next.

CALIBRATION TO FIELD OBSERVATIONS

Field observations were carried out to establish whether the method's predictions are an acceptable approximation of how quickly drivers actually enter intersections and to calibrate the model's parameters. Only the entrance time part of the clearance time determination method was considered because this part was newly developed and there already existed considerable experience with the exit time formula.

Measurement Setup

The analytical method yields minimum entrance time as a function of distance from the stop line; this function is the one sought to be observed. The general approach was to observe and plot trajectories of vehicles that were the first to enter the intersection on the start of the green. For any given distance, 2nd-percentile observed entrance times were used to calibrate the model, that is, entrance times for which 98% of the observed vehicles took longer to enter than that. There are two reasons for selecting such an extreme value:

- As stated earlier, safety is enhanced by determining entrance time based on a relatively aggressive driver; and
- The model predicts that for any given distance from the stop line s, a variety of entrance times will be observed depending on each vehicle's experienced value of t_x, with entrance time tending to be smaller for vehicles experiencing a value of t_x close to the critical value. Only a minority of the observations should be expected to have the value of t_x that is favorable for a given entrance distance s.

Trajectories were determined by measuring the moment at which vehicles passed 10 cross sections in a 100-m section of road, beginning at the stop line. Passage moments were measured using infrared beams across the roadway that were interrupted by the wheels of passing vehicles. Detectors were placed closer together near the stop line because lower speeds were expected there. At some cross sections detectors were placed 1 m apart in order to measure speed and wheelbase (distance between axles) as well as passage moment.

Measurements were taken at two intersections, one in Delft and one in Haarlem. Both are cities of about 100,000 inhabitants located

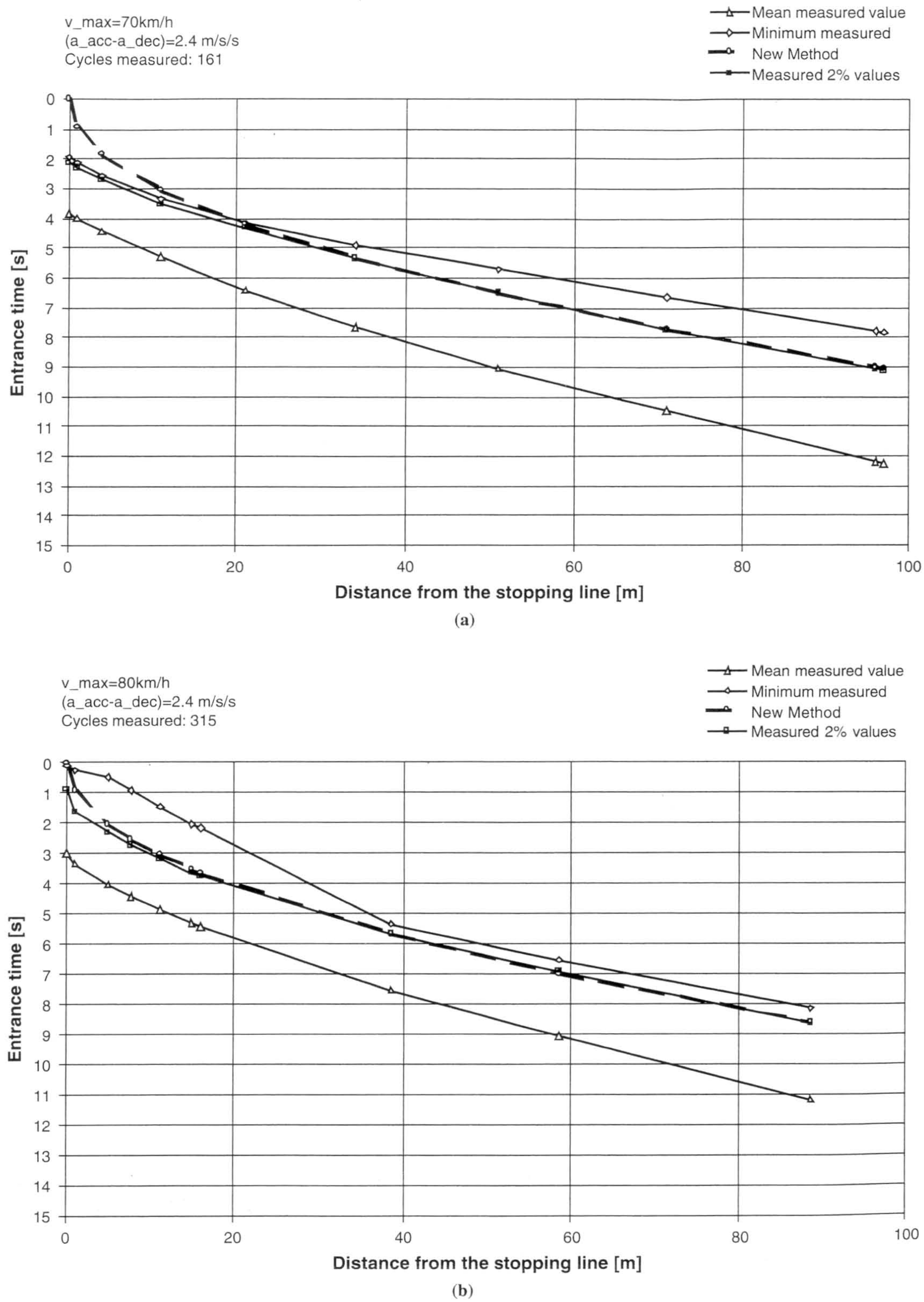
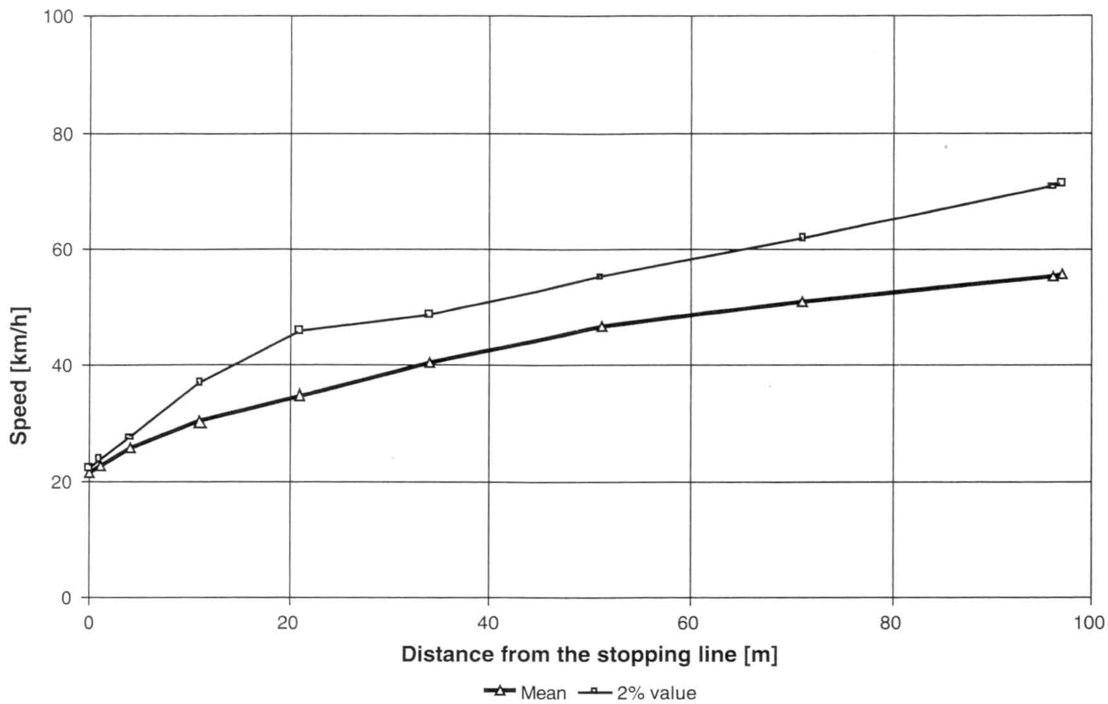
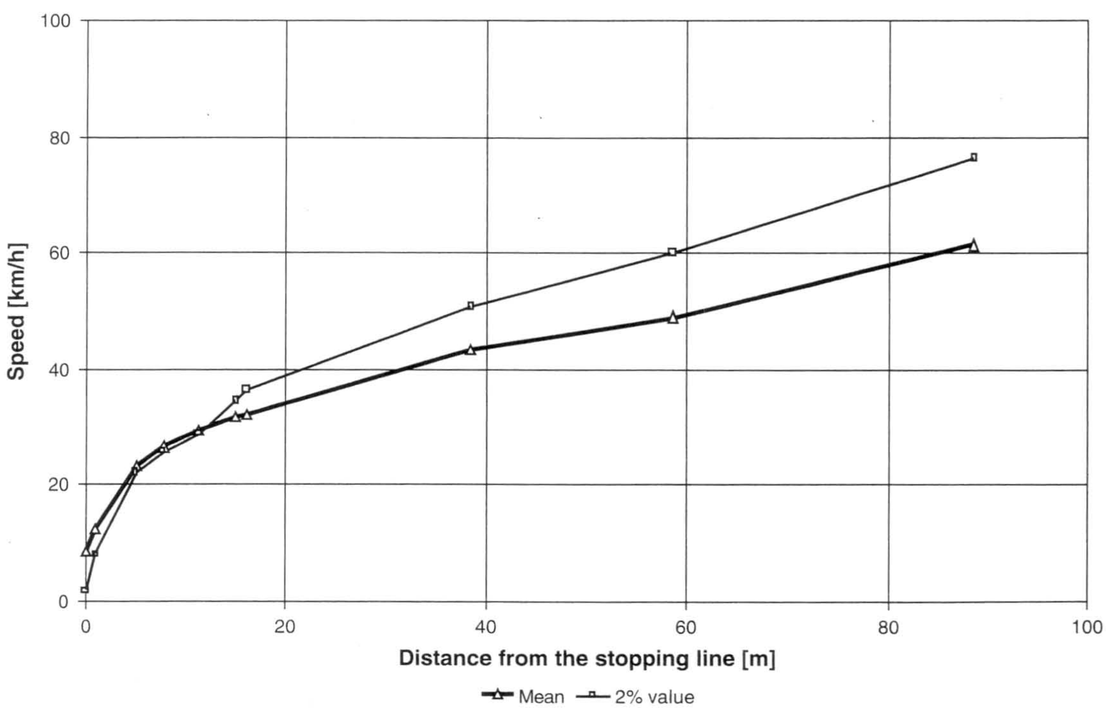


FIGURE 5 Observed versus predicted entrance times: (*a*) Delft site, (*b*) Haarlem site.



(a)



(b)

FIGURE 6 Observed mean and 98th-percentile speeds: (*a*) Delft site, (*b*) Haarlem site.

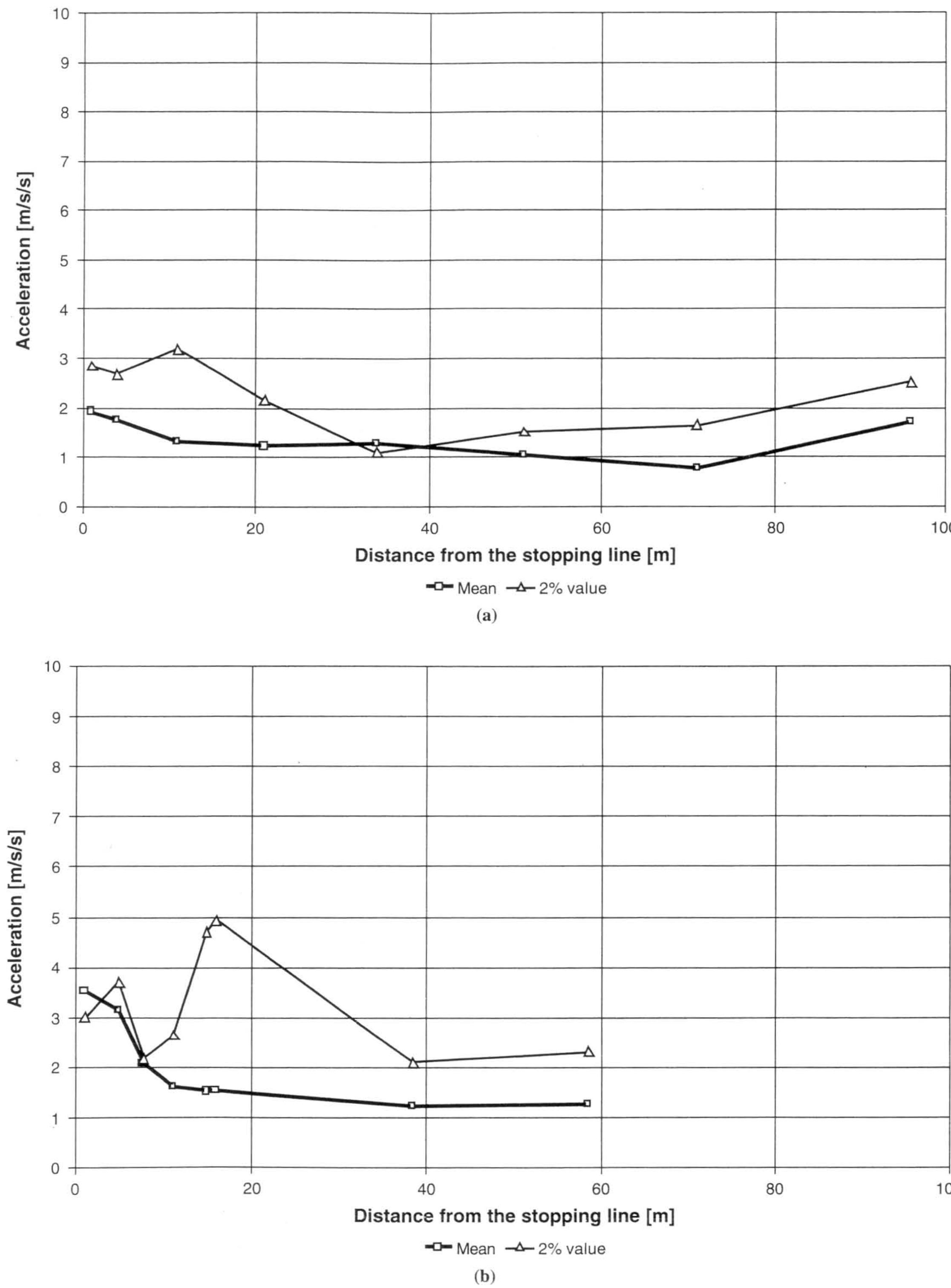


FIGURE 7 Observed mean and 98th-percentile accelerations: (*a*) Delft site, (*b*) Haarlem site.

rather low and is based on only two intersections, use of a locally calibrated value is suggested. Absent that calibration, a value in the range of 2.5 to 3.0 m/s^2 is suggested.

COMPARISON OF NEW METHOD WITH EXISTING PRACTICE

As mentioned earlier, the red clearance interval suggested by ITE is the time needed for the exiting vehicle to clear the entire intersection (Equation 2). This formula can lead to red clearance intervals that are considerably longer than needed to accomplish their purpose of avoiding collision between entering and exiting streams, unnecessarily affecting operations and perhaps encouraging red-light running. This issue is recognized in ITE Publication IR-073 (*4*), but possible adjustments are discussed only qualitatively. Further, Publication IR-073 addresses the choice of appropriate values for the two variables in Equation 2, but precise directions are not given. As a consequence, guidance for practitioners remains somewhat limited; however, it is clearly stated that it "does not constitute a recommended practice" (*4*).

To illustrate the conflict zone method for determining clearance time and contrast it to the ITE approach, the intersection in Figure 1 is considered. Each leg is assumed to have two through lanes, a left-turn lane, and two receiving lanes, all 3.5 m wide; a central median of 2.5 m; and a stop line set back 3 m from the first lane to allow for the crosswalk and planting strip. Overall distance is 20 m from the stop line to the edge of the opposite curb. Left turns are protected. Approach speed is taken to be 14 m/s (50 km/h) for through movements and 10 m/s (36 km/h) for left turns. The difference in accelerations is taken to be 2.8 m/s^2. Vehicle length is assumed to be 12 m with the conflict zone method and 5 m with the ITE method (this difference favors the ITE method).

First, the conflict zone approach is used to show the impact on clearance time of stream sequence. Two cases are examined: lagging left and leading left. For lagging left, the sequence of critical conflicts (conflicts that demand the most clearance time) is $SB_{Through}$-NB_{Left}-$EB_{Through}$-WB_{Left}-$SB_{Through}$. For leading left, the critical sequence is NB_{Left}-$SB_{Through}$-EB_{Left}-$WB_{Through}$-NB_{Left}. Because of the symmetry in this example, clearance time for the full cycle is simply twice the clearance time needed for the first two changes.

Necessary red clearance times for the alternative sequence schemes are shown in Table 1. It can be seen that lagging lefts demand almost no clearance time (0.4 s per cycle), whereas leading lefts require 4.6 s per cycle. This difference is significant in traffic operations. Using the sequence that requires a greater amount of clearance time may require a longer cycle, increasing vehicle delay; it will also diminish intersection capacity by 4% to 6%, depending on cycle length, further increasing vehicle delay.

Also shown in Table 1 is the amount of red clearance time demanded by the ITE method. Regardless of sequence (leading or lagging), 8.2 s of red clearance is needed per cycle. Compared with the conflict zone method with an efficient sequence, the ITE approach reduces capacity by 8% to 12%, depending on cycle length. Even more extreme is the difference in recommended cycle length following Webster's cycle length formula:

$$\text{Cycle length} = \frac{1.5(\text{lost time}) + 5}{1 - (\text{sum of critical } v/s)}$$

in which lost time is the sum of lost times between critical approaches. Assuming 3 s of start-up lost time for each of the four critical approaches, lost time is (12 + 0.4) in the conflict zone method with lagging lefts and (12 + 8.4) in the ITE method, regardless of sequence. As a result, the ITE method results in a Webster cycle length that is 51% longer than the more efficient sequence using the conflict zone method for determining clearance time, which implies substantially greater average vehicle delay.

As this example shows, the ITE approach can be quite inefficient, consuming considerably more capacity than needed because it treats the entire intersection as a conflict zone. The fact that the ITE method suggests the same clearance time regardless of stream sequence ignores the clearly greater risk of collision from a leading-left sequence (assuming that there was no red clearance time) compared with that from a lagging-left sequence. This is only one example of how stream sequence should affect clearance time. The unnecessarily long clearance times that result from the ITE method may also undermine efforts to control red-light running.

TABLE 1 Red Clearance Needs for Lagging Left, Leading Left, and ITE Method

	Exit Stream	Enter Stream	S-exit (m)	S-entrance (m)	T-exit (s)	T-enter (s)	T-clear (s)
Lagging Left (Conflict Zone Method)							
	SBT	NBL	22	20	1.57	3.78	0
	NBL	WBT	32	13	3.20	3.05	0.2
	Half-cycle total						0.2
	Cycle total						*0.4*
Leading Left (Conflict Zone Method)							
	NBL	SBT	33	4	3.30	1.69	1.7
	SBT	EBL	28	3	2.00	1.46	0.6
	Half-cycle total						2.3
	Cycle total						*4.6*
ITE Method							
	thru	(n/a)	28		2.00		2.0
	left	(n/a)	21		2.10		2.1
	Half-cycle total						4.1
	Cycle total						*8.2*

CONCLUSIONS

A new method to determine clearance times based on avoiding conflicts between exiting and entering traffic streams is presented. The main focus was on the calculation of entrance times. A simple driver model was constructed that involves a limited number of parameters. Field observations showed that although some differences existed, good correspondence between the model and measured clearance times was achieved. Further, this correspondence was found for two signalized intersections with rather different control strategies. Specifically, it seems that for the parameter ($a_{acc} - a_{dec}$), a value of 2.5 to 3.0 m/s^2 can be recommended. Further empirical research is recommended to test the applicability of that value to other intersections and to current times, since the original measurements were made approximately 10 years ago.

Compared with the ITE method of calculating red clearance time, the conflict zone method is more realistic, better reflecting intersection geometry and control sequence. It considers the traffic operations at intersections in more detail and takes into account both the exit and the entrance time. These considerations lead to realistic clearance times that are safe but not too large, which is important for efficiency and for promoting respect for traffic laws. At the same time, the method is not complex. It requires a limited number of parameters, which are easy to interpret and which can be calibrated to local conditions by field measurements.

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Publication of this paper sponsored by Traffic Signal Systems Committee.