Red Clearance Intervals: Theory and Practice

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ABSTRACT

At signalized intersections the red clearance interval has to be long enough to prevent accidents, but no longer than necessary in order to ensure efficient traffic operations and encourage respect of the yellow and red indication. Because designers were using a variety of methods to calculate clearance times, a Dutch association of traffic control engineers called CVN initiated the development of a generally applicable method. The resulting method is based on a driver behavior model that involves five parameters. In contrast with the suggested 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 zone within the intersection where the two streams' paths first overlap. The conflict zone method was calibrated using field data collected at two intersections, and has been 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 the 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, p. 295). This interval may consist of a yellow change interval only or both a yellow change interval and a red clearance interval (also called an all-red interval). While in the U.S. 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 lack of a generally accepted calculation method. For the U.S., a similar situation is recognized by (2, p. 33), stating 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, an informal association of Dutch traffic control engineers, the Contactgroep Verkeersregeltechnici Nederland (CVN), identified in 1992 the need to 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 the new method, which was subsequently accepted and published as a guideline by the Dutch Ministry of Transport (3).

The new method leaves unchanged guidelines regarding the yellow interval. Longstanding 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

$$t_{yellow} = t_r + \frac{v_{appr}}{2\left|a_{dec}\right|} \quad (1)$$

where t_r = reaction time, v_{appr} = approach speed (85-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, comparing the travel time for both traffic streams to the point where their paths conflict. The innovation 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 is analyzed to estimate parameters of the model and to verify that it matches observed driver behavior. Finally, we offer a brief comparison of the new method with current U.S. practice, and then draw conclusions.

A NEW METHOD TO DETERMINE RED CLEARANCE TIMES

With the yellow interval timing formula (eq. 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 -- the interval between the start of red for one traffic stream and the start of green for the succeeding conflicting traffic stream -- is to ensure that traffic in the second stream can safely enter the intersection without colliding with the last vehicle legally entering from first stream. While clearance intervals are important for safety, they also impact traffic operations: they contribute to lost time and, as such, 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 ("all red time") is based on the principle that traffic in the entering stream should wait until the a vehicle from the previous stream that enters the intersection in the last moment of yellow completely clears the intersection; that is,

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

The new approach, which may be called 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 conflicting traffic stream that just turned red. As an example, several traffic streams at a typical intersection are shown in Figure 1. Red clearance times must be supplied to the controller for each ordered pair of conflicting streams (i, j), where i = index of the stream getting the red (the "exiting stream") and j = index of the stream whose green immediately follows (the "entering stream"). If, in the Figure 1 example, traffic streams SBT and NBT are followed by conflicting streams EBL and EBT, and if the exiting streams begin red simultaneously, stream EBL could not begin green until clearance times $t_{clearance}$(SBT, EBL) and $t_{clearance}$(NBT, EBL) had both expired, and stream EBT could not begin green until clearance times $t_{clearance}$(SBT, EBT) and $t_{clearance}$(NBT, EBT) had both expired, where $t_{clearance}(i,j)$ = specified clearance time between the start of stream i's red start and stream j's green start. 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 stream to that stream pair's "conflict zone," the area within the intersection where paths taken by vehicles in the two streams first overlap. Let s_{esit} equal the distance from the stop line a vehicle in the exiting stream must travel to fully clear the conflict zone (including the vehicle length, commonly taken to be 12 m so as to represent a truck), and let t_{esit} equal an exiting vehicle's travel time from the stop line to just beyond the conflict zone; similarly, let $s_{entrance}$ equal the distance from the stop line of the entering stream to the conflict zone, and let $t_{entrance}$ equal 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, $t_{clearance}(i,j)$ must be

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

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

The sketch in Figure 1 illustrates the importance of determining clearance time as a function of an ordered pair of streams. Consider the conflict zone between conflicting streams SBT and EBT. As one can see, EBT's stop line is much closer to the conflict zone than is SBT's. Consequently, if EBT is exiting while SBT is entering, little or no red clearance will be needed, because EBT vehicles have a considerable amount of time to clear the conflict zone before a SBT vehicle arrives. On the other hand, if SBT runs first followed by EBT, a considerable red clearance time will be needed, because an EBT vehicle could arrive very quickly at the conflict zone, well before the last SBT vehicle had cleared if it entered the intersection just at the end of yellow, unless stream EBT traffic is delayed by a red clearance interval.

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

Determination of Exit Time

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

$$t_{exit} = s_{exit} / v_{exit} \tag{4}$$

where v_{exit} equals the speed of a vehicle in the exit stream that crosses the stop line at the last moment of 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. The next section describes the method that was developed to fill this gap.

Determination of Entrance Time

In comparison to 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 based on an assumed acceleration trajectory. However, consider a vehicle approaching the stop line that 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 described above, a model of driver behavior is required. The following model is used:

- a driver with no traffic ahead of it approaches the intersection with an approach speed v_{appr}
- seeing a 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 when the light turns green and 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

Consider a vehicle facing 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, that would imply that the vehicle came to a stop at the moment the signal turns green; if reaction time t_r is non-zero, that 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 an interval t_r after the signal turns green. The vehicle's trajectory is plotted as the heavy line in Figure 2(a). The coordinate system used for this figure shows distance s on the horizontal axis, with $s = 0$ at the stop line, and time τ 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. Note 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,

$$t'_{entrance} = t_{entrance} - t_r \qquad (5)$$

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

Next, consider what would happen 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. Define t_x as 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. Comparing with the solid line, for which t_x = 0, one can see that both vehicles start decelerating at the same distance from the stop line. Until the moment of effective green, the dashed curve, compared to the solid curve, is simply shifted vertically by $- t_x$, the difference between the start of effective green for the two cases. For the second vehicle as well as the first, adjusted entrance time for a given entrance distance s can simply be read from the figure as $t'_{entrance}(s) = \tau(s)$.

One can see 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, while 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 to -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. In the following subsection, the curve representing this envelope will be derived analytically.

Analytical Derivation of Minimum Entrance Time

Again, consider a vehicle approaching an intersection, facing a red signal, with no traffic ahead of it, and following the behavior model described previously. The coordinate system will now be adjusted by placing the origin of time τ at the moment at which 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 becoming green.

Let τ_g = start of effective green (i.e., start of green plus reaction time). Then, 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 $\tau = t_x$ the vehicle begins to accelerate with constant acceleration a_{acc}. The vehicle's speed and acceleration at $\tau > t_x$ are then given by

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

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

Note that the vehicle's speed and location are independent of v_{appr}, a parameter that turns out to be irrelevant. Substituting equations 7 and 8 are into equations 9 and 10 yields

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

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

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

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

Combining equations 12 and 13, entrance distance can be expressed as the function

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

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

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

Figure 3 illustrates entrance times that follow from equation (15) for several values of entrance distance *s*, using the previously given acceleration values. One can see 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

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

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

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

This equation 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}, as shown in Figure 4. There is therefore a critical distance *s* after which equation (17) is not valid; it can be found by solving

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

yielding

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

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

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

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

Summary of the New Method

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

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

$$t_{exit} = s_{exit} / v_{exit} \quad (4)$$

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

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

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

These equations include five parameters of the driver behavior model: v_{exit}, t_r, a_{acc}, a_{dec}, and v_{appr}. 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 familiar motorists who might anticipate the start of 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. The chief calibration parameter, then 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 next section describes the data collection and analysis effort by which those parameters were estimated and the model validated.

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 was the newly developed part, and there existed already 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 is the function we sought to observe. The general approach was to observe and plot trajectories of vehicles that were the first to enter the intersection upon start of green. For any given distance, we used 2-percentile observed entrance times 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
- 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 ten 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 in the metropolitan agglomeration called the Randstad, the main urbanized area of the Netherlands. Data were collected on a weekday morning in October, 1993 (Delft) and September, 1992 (Haarlem). Sample sizes were 161 (Delft) and 315 first vehicles (Haarlem). During the measurements weather and light conditions did not influence traffic operations negatively. While the data was collected 10 years ago, it is unlikely that the underlying traffic behavior it describes has changed. Further study would of course be welcome.

The Delft observation site was a three-legged intersection between the Kruithuisweg and the Provinciale Weg. Both are 4 lane divided urban arterials with speed limits of 70 km/h. Measurements were taken for the right through lane eastbound on the Kruithuisweg. The width of the intersection was approximately 40 m. Because neighboring intersections were 0.8 to 1 km distant, the signal control program was not coordinated with other intersection controllers. The controller was vehicle actuated, with cycle time varying constantly depending on traffic demand.

Observations in Haarlem were carried out on the left through lane of the northbound Provinciale Weg (unrelated to the road of the same name in Delft), a 4-lane divided arterial with an 80 km/h speed limit located just outside the city limits, at a four-legged intersection with the Vlaamseweg / De Ruijterweg, a 2 lane undivided suburban street with a speed limit of 50 km/h. The width of the intersection was, again, approximately 40 m. The controller was vehicle actuated, but the cross street green extension was limited in order to provide a northbound green wave. Consequently, it is likely that some familiar drivers would try to predict when their red interval would end. To limit platoon dispersion and to reduce traffic speed, the coordination offset was based on a speed slightly lower than the 80 km/h speed limit.

Calibration and Fit

Mean, 2-percentile, and minimum observed entrance times for different distances from the stop line are shown against the calibrated entrance time function in Figure 5. Part (a) shows the results for Delft; part (b), for Haarlem. As mentioned earlier, t_r was set to zero. For both sites, the best fit to the 2-percentile entrance times were found with v_{max} set equal to the speed limit (70 km/h in Delft, 80 km/h in Haarlem), and with $(a_{acc} - a_{dec})$ set equal to 2.4 m/s^2.

Looking at Figure 5, one can see that the fit is very good, except at very small entrance distances, where the model is conservative, underestimating the 2-percentile entrance time. The model tracks the 2-percentile entrance times almost perfectly beginning at about s = 15 m at the Delft site, and beginning at about s = 4 m in Haarlem.

To gain more insight into the driver behavior model, mean and 98-percentile observed speeds and accelerations at different entrance distances are shown in Figures 6 and 7. In those figures, 98-percentile statistics indicate behavior of the most aggressive drivers; however, as pointed out earlier, the vehicles with the smallest entrance times are not necessarily those with the greatest speed or acceleration, because a vehicle's entrance time also depends on its position and velocity at the start of green. At both sites, the velocity curves show the 98-percentile speed trajectory approaching the speed limit about 100 m from the stop line, while mean speed at that entrance distance is about 15 km/h smaller.

Analysis of Results

One can also see from both the velocity and acceleration plots that acceleration is greatest in the first 20 m or so, declining after that. Diminishing acceleration is a well-known property of vehicle performance due to power limitations and gear changing. The relatively good fit of the entrance time prediction function in spite of the simple acceleration model used is probably due to the offsetting effects of using a reaction time of 0 s, which makes the model conservative for short entrance distances, and constant acceleration. This effect is sufficient to explain the small differences (under 1 s) at the Haarlem site between observed and predicted 2-percentile entrance times at entrance distances of 8 m or less.

At the Delft site, however, observed entrance times at entrance distances of 8 m or less are considerably greater than predicted. In fact, short entrance times near the stop line did not occur; as shown in Figure 5, the smallest entrance time measured was 1.9 s. At the same time, one can see that at the Delft site, mean speed as vehicles crossed the stop line was not near 0 km/h as in Haarlem, but was about 20 km/h. These measurements are consistent with the general pattern of behavior observed at the Delft site: drivers approaching the intersection on red tended to decelerate to a low speed at a considerable distance upstream of the stop line, and then advance towards the stop line at low speed. When the signal turned green, they were still "crawling" at some distance from the stop line, so that it took a little longer for them to reach the stop line, which they crossed with some speed. Nevertheless, by the time the vehicles reached a distance of 12 m beyond the stop line, their entrance times matched those predicted by the model very closely.

At the Haarlem site, there is a considerable difference between the smallest observed entrance times and the 2-percentile entrance times, which the model tracks very well. These very small entrance times of a few vehicles may have been caused by drivers that did not intend to stop for the red light or that intended to brake extremely forcefully to stop in time if necessary. This behavior may be associated with the somewhat coordinated timing of the Haarlem signal with its upstream signal, which makes the start of green somewhat predictable. A caution, therefore, to applying the model is that it may overpredict entrance times for the most aggressive motorists who become confident that they can predict the start of green on a coordinated arterial.

Finally, we note that the calibrated acceleration difference, 2.4 m/s^2, is well below the "aggressive" limits of vehicle performance and human comfort (during braking). Our observations suggest that motorists who are the first to enter an intersection on start of green and who enter at some speed do not push vehicle performance to the limits, but exercise some restraint, perhaps because they consider the risk of collision. The fact that this parameter is not rooted in vehicular performance suggests that it should be calibrated locally and monitored over time. In particular, this parameter may change as the driving public becomes accustomed to clearance time policies.

Analysis Conclusion

The results from the calculation method and the field observations matched satisfactorily. The only significant discrepancy was for distances close to the stop line, for which the method calculates somewhat smaller and therefore safer entrance times than were observed in the field. While a more complex model of driver behavior might achieve a still better fit, it was concluded that the entrance time model with its simplifications was appropriate. This was further supported by the consistency in results between the two studied intersections in spite of their different traffic control strategies.

The most important parameter, the difference in accelerations, was calibrated at the two sites to be 2.4 m/s^2. Because this value seems 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 THE 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 impacting operations and perhaps encouraging red-light running. This issue is recognized in (4), but possible adjustments are discussed only qualitatively. Further, (4) 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, but, then, (4) clearly states that it "does not constitute a recommended practice."

To illustrate the conflict zone method for determining clearance time and contrast it with the ITE approach, consider the intersection illustrated in Figure 1. 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 stop line to edge of the opposite curb. Left turns are protected. Approach speed is taken to be 14 m/s (50 km/h) for through movements, 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 SBT-NBL-EBT-WBL-SBT. For leading left, the critical sequence is NBL-SBT-EBL-WBT-NBL. Because of the symmetry in this example, clearance time for the full cycle is simply double the clearance time needed for the first two changes.

Necessary red clearance times for the alternative sequence schemes are shown in Table 1. One can see that lagging lefts demand almost no clearance time (0.4 s per cycle), while 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 percent, 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 (lead or lag), 8.2 s of red clearance are needed per cycle. Compared to the conflict zone method with an efficient sequence, the ITE approach reduces capacity by 8 to 12 percent, depending on cycle length. Even more extreme is the difference in recommended cycle length following Webster's cycle length formula:

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

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 percent longer than the more efficient sequence using the conflict zone method for determining clearance time, implying 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 there were no red clearance time) compared to a lagging left sequence. The leading vs. lagging sequence example is only one example of how stream sequence should affect clearance time. The unnecessarily long clearance times that result from the ITE method at wide intersections may also undermine efforts to control red-light running.

CONCLUSIONS

This paper presents a new method to determine clearance times based on avoiding conflicts between an exiting traffic stream and an entering traffic stream. 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, a good correspondence 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 ten years ago.

Compared to 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 an intersection in more detail and takes into account both the exit and the entrance time. This leads to more realistic clearance times that are safe but not too large, which is important for efficiency and for promoting respect of traffic laws. At the same time, the method is not too complex. It requires a limited number of parameters, which are relatively easy to interpret, and which can be calibrated to local conditions by field measurements.

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LIST OF TABLES AND FIGURES

	Exit stream	Enter stream	S-exit (m)	S-entrance (m)	T-exit (s)	T-enter (s)	T-clear (s)
a. 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*
b. 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*
c. 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*

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

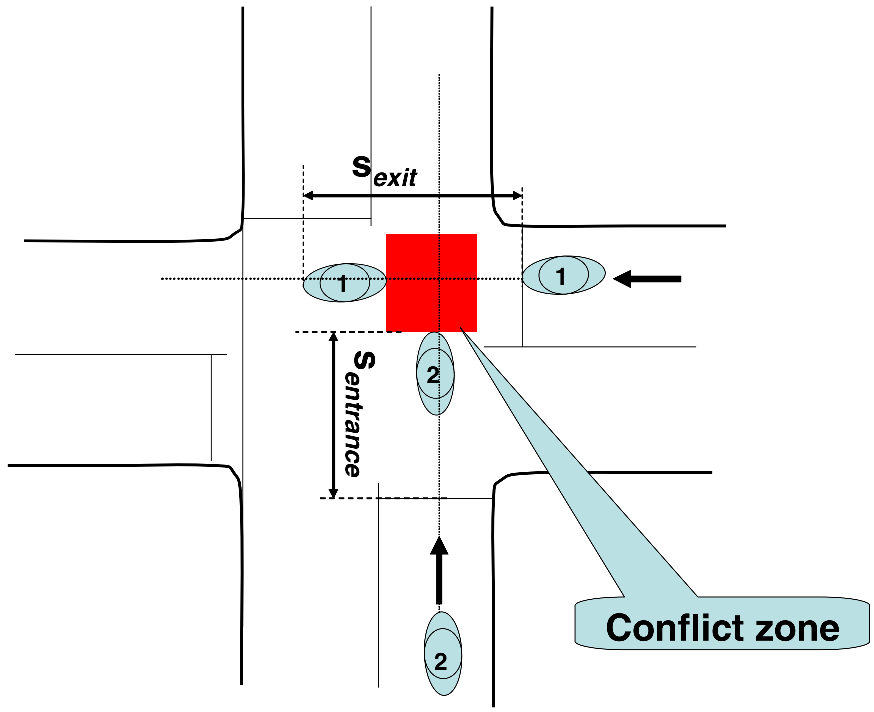
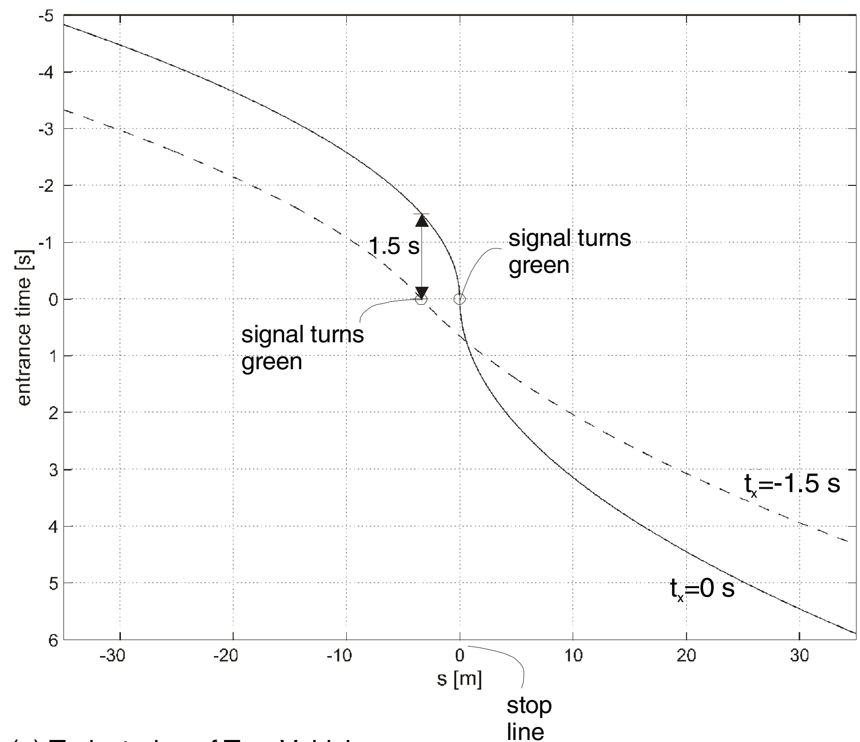
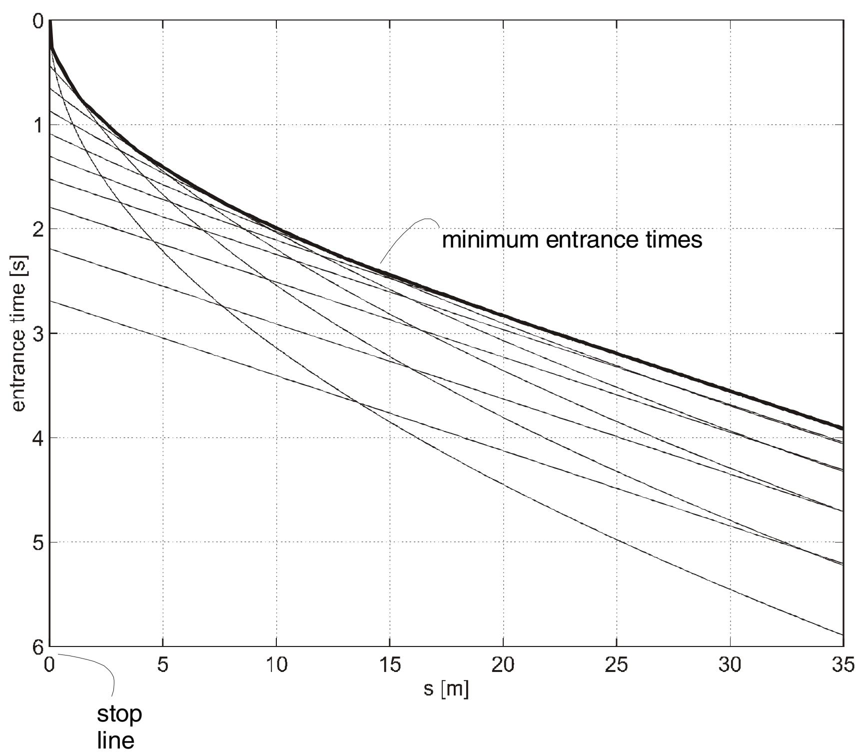


FIGURE 1 Traffic Streams and Conflict Zones



(a) Trajectories of Two Vehicles



(b) Adjusted Entrance Time as Envelope of Trajectories

FIGURE 2 Entrance Time Derived from Vehicle Trajectories

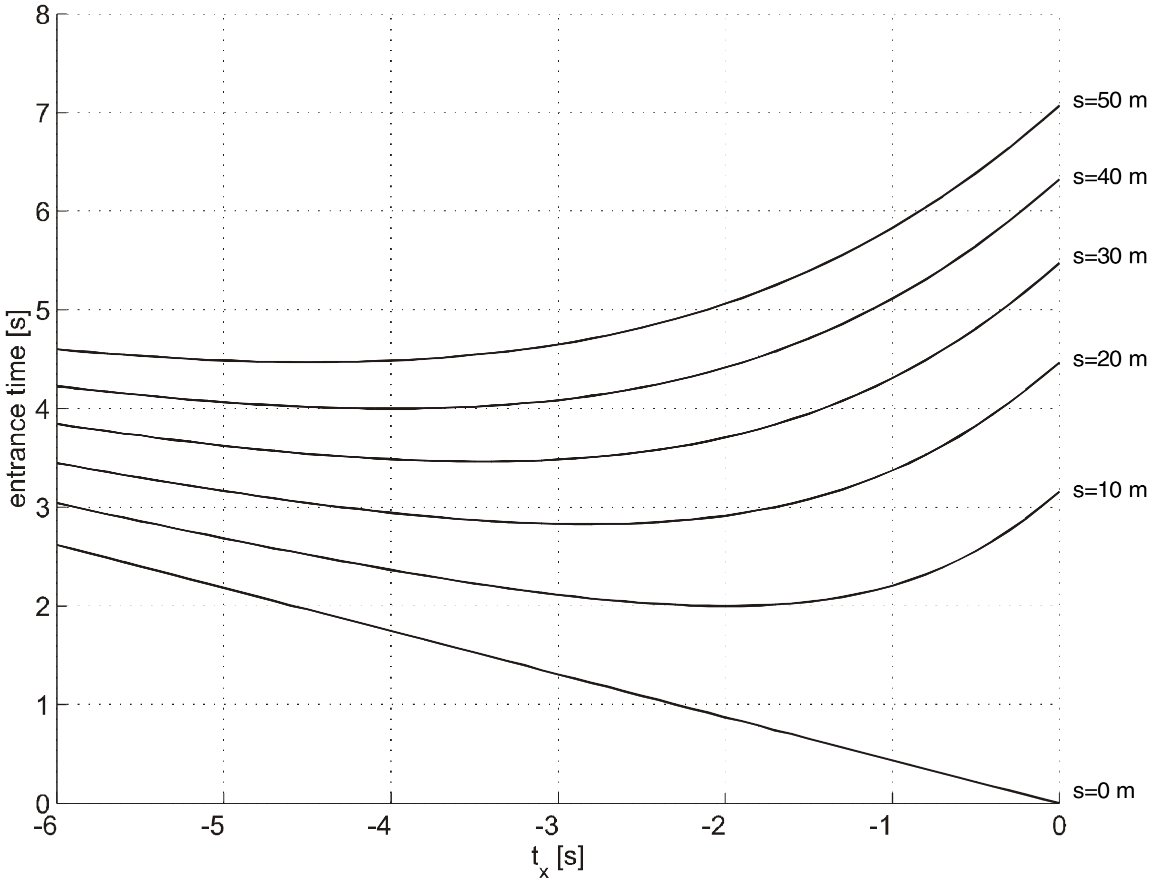


FIGURE 3 Entrance Time as a Function of the Moment at which the Traffic Light Turns Green *(t_x)* and Distance from the Stop Line *(s)*

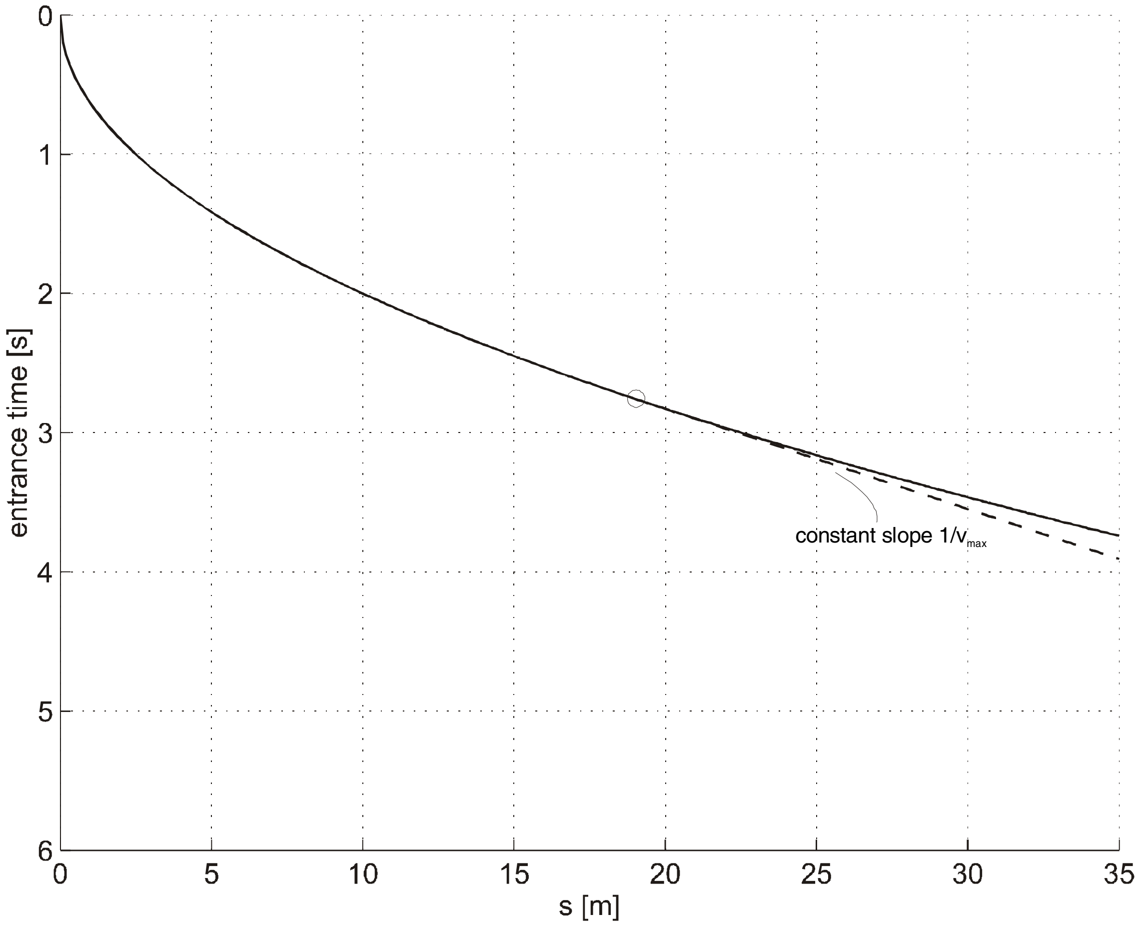


FIGURE 4 Adjustment of the Minimum Entrance Time Curve for Limiting Speed v_{max}

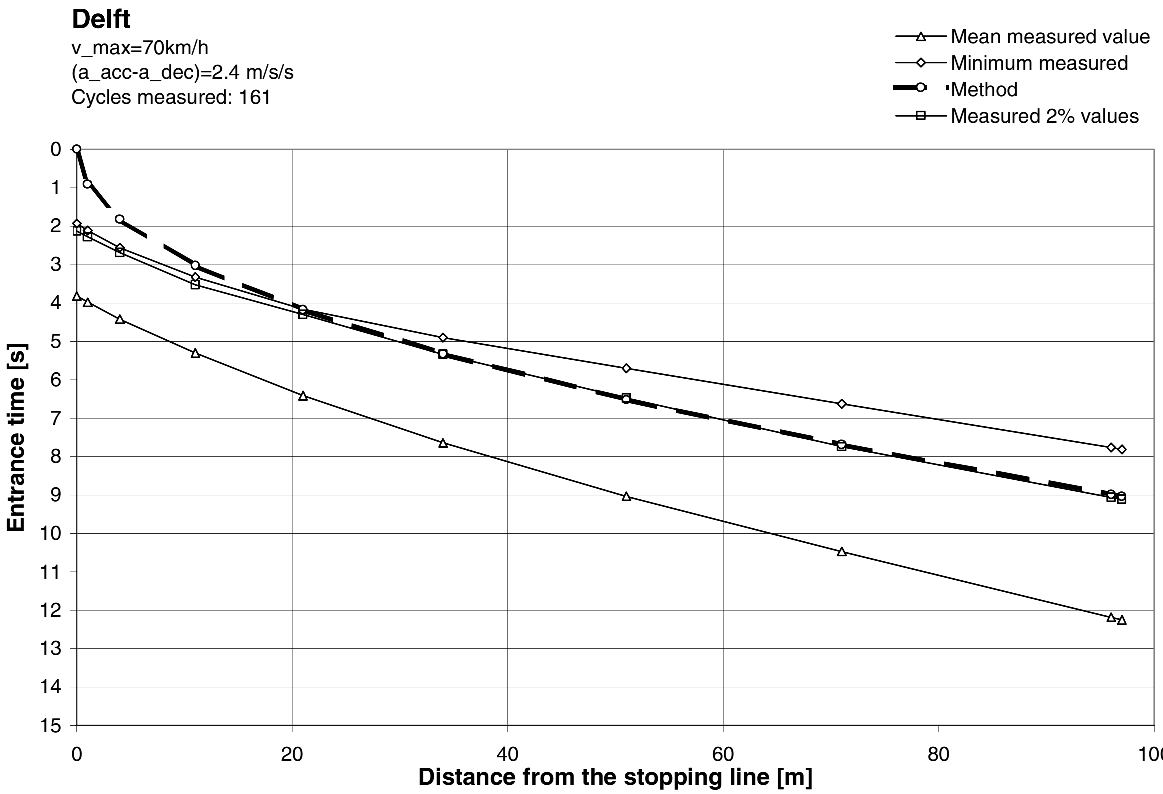


FIGURE 5 Observed vs. Predicted Entrance Times

(a) Delft Site

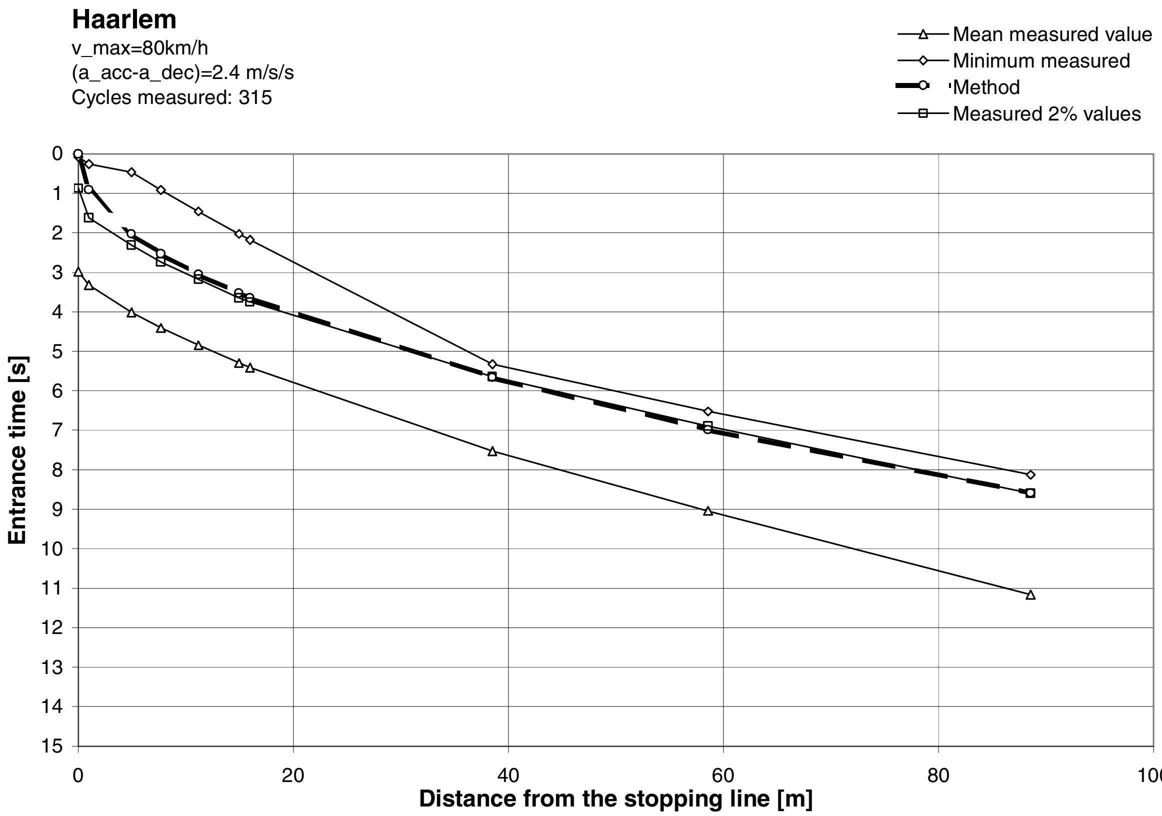


FIGURE 5 Observed vs. Predicted Entrance Times

(b) Haarlem Site

FIGURE 6 Observed Mean and 98-percentile Speeds

(a) Delft Site

FIGURE 6 Observed Mean and 98-percentile Speeds

(b) Haarlem Site

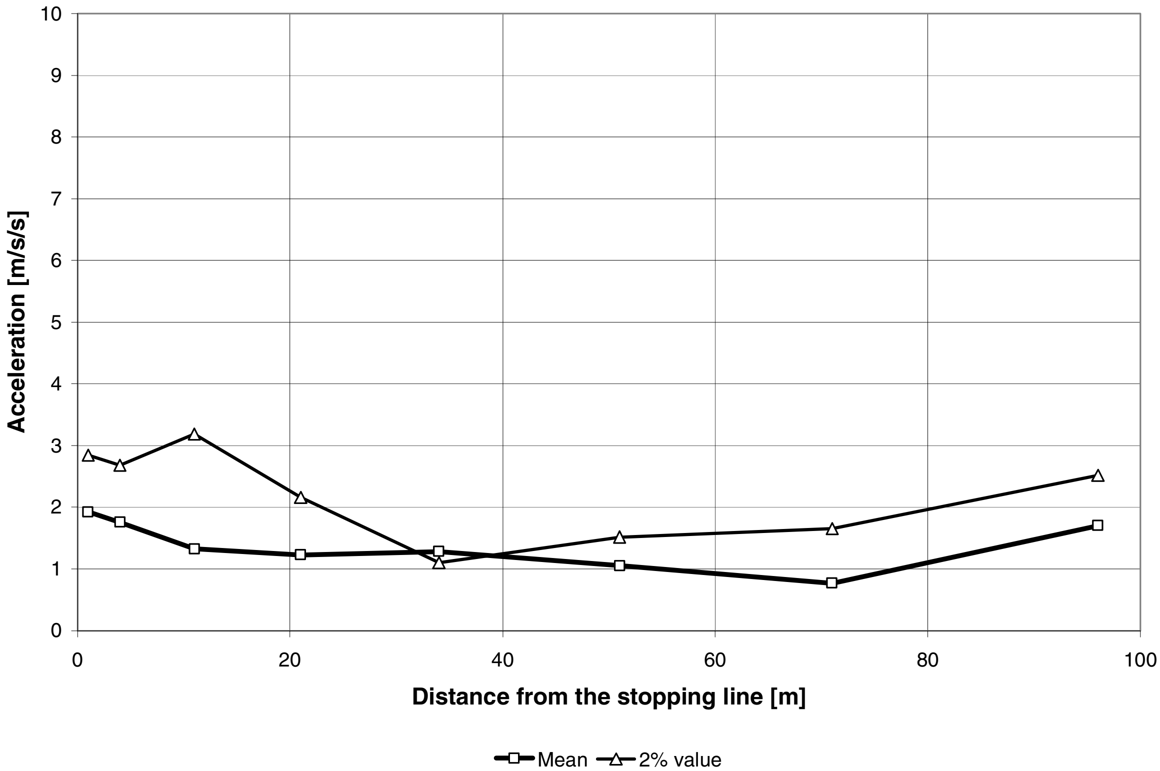


FIGURE 7 Observed Mean and 98-percentile Accelerations

(a) Delft Site

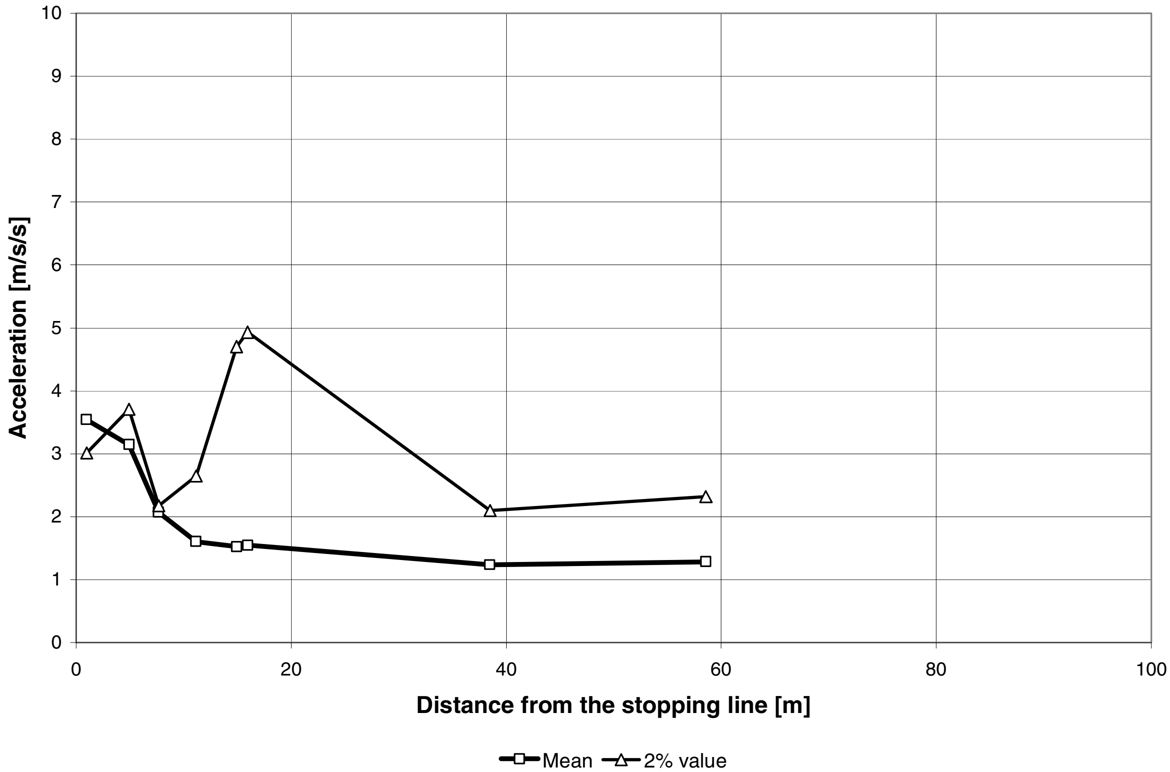


FIGURE 7 Observed Mean and 98-percentile Accelerations

(b) Haarlem Site