

Driver Decision Making at Traffic Signals

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The driving task at signalized road intersections is simplified substantially over that at nonsignalized ones. At the guidance level, the decision-making process consists mainly of the stopping/nostopping decision at the moment that the signal changes from green to yellow. Most red light running offenses appear to be related to this particular moment. The results of a 1-year before-and-after behavioral study in the northern part of the Netherlands demonstrate that a yellow interval of appropriate length (4 s for 50 km/hr and 5 s for 80 km/hr intersections) cuts the number of red light violations in half. Compared with fixed time control, vehicle-actuated signal control leads to a 1-s shift in the probability of stopping with respect to the potential time to the stopline at the onset of yellow, illustrating the role of driver expectancy in decision making. Through a comparison of these results with observed behavior at drawbridges and signalized railway grade crossings without gates, it is concluded that the absence of a separate yellow interval at railway grade crossings and drawbridges is disadvantageous. For all situations, a uniform stop signalization should be implemented. This signalization should consist of a steady red signal preceded by a yellow interval that is properly designed to serve the driver adequately in normal driving as well as to meet minimal driver needs in deteriorated circumstances.

For task analysis purposes, the driving task is generally divided into three performance levels: control, guidance, and navigation (1). In terms of the relationship with other traffic, the driving task at the guidance level for signalized road intersections is considerably simplified compared to that for nonsignalized intersections. However, at signalized intersections the road user has to deal with other tasks, such as processing information from traffic control signals. One of the important behavioral aspects of the driver's task is the decision whether to stop or to proceed when the signal changes from green to yellow and then to red. In an earlier study an optimal setting of the yellow interval was evaluated, and it was demonstrated that the type of signal control system (fixed time versus vehicle actuated) influences driver expectancy in this decision-making process (2).

The same kind of decision making is demanded when a driver approaches a drawbridge or a railway grade crossing at the onset of the red signal. The main difference in signalization in these cases, compared with roadway intersections, is the absence of a separate yellow interval. In this paper, by using the results of three studies dealing with driver decision making at road intersections, drawbridges, and railway grade crossings, it

will be argued that at least part of the problem of running red lights can be solved by applying simple measures.

STOPPING OR NONSTOPPING

The Traffic Rules and Traffic Signs Law in the Netherlands distinguishes among traffic control signals at road intersections, railway grade crossings, and drawbridges. In all these situations the required reaction to the red signal (either steady or flashing) is quite unambiguous, namely, "stop." At road intersections the red signal is always preceded by a yellow signal, which, as the law states, means "Stop; but those drivers who are close enough to the intersection that they are not reasonably able to stop may proceed."

The rationale for the yellow interval is, in principle, to prevent vehicles that are within a given (short) distance of the intersection from inevitably running through the red signal. At drawbridges the signal changes from off to steady or flashing red. This change is sometimes preceded by prewarning flashing amber signals at a given distance. At railway grade crossings the signal changes either from off (at railway crossings with gates) or from flashing white (at railway crossings without gates) to two signal heads alternately flashing red. The absence of a yellow phase at these stops is questionable, and the precise meaning of the flashing of a red signal can be questioned as well.

When the signal changes from green to yellow at a road intersection, a decision is demanded. The criterion for this decision (the distance within which it is not reasonable to stop) is not very precise, and for that reason it is subject to differences in interpretation. Although the yellow phase is absent at railway grade crossings and drawbridges, the decision-making process itself is not very different. Factors that may influence this process involve the driver's motivation and attitude, the amount of predictability of the situation, the estimate of the consequences of not stopping (likelihood of running red and getting a fine or of getting involved in a conflict with intersecting traffic or a collision with the grade crossing gate), and the estimate of the consequences of stopping (discomfort, waiting time, likelihood of a rear end collision or that braking will end in a stop within the intersection). Evaluating these factors also involves the driver's estimates of the required deceleration on the basis of the speed and distance to the stop line and the expectations of the duration of the yellow phase and the all-red period (or the time left until the gates close or the train arrives).

All of this discussion is based on the premise that the signals are implemented and positioned to be visible in due time for the approaching driver to make a decision. Also, the behavior of

other road users may influence the decision making. An example is the so-called "mitschleppeffekt," in which a nonstopping leading automobile influences the following automobile to continue as well (3, 4).

SIGNALIZED ROAD INTERSECTIONS

So that the decision-making processes at road intersections, drawbridges, and railway grade crossings can be compared, the results of the road intersection study with respect to the timing of the yellow signal and the type of traffic control strategy will be discussed briefly. More detailed information can be found elsewhere (2, 5).

Duration of the Yellow Interval

Extensive literature is available regarding the timing of the yellow interval. From an explorative study on the extent of the problem of red light running (6) and from a review of the literature on measures related to traffic signal control (5), it was concluded that the optimum yellow timing was 4 s of yellow for 50 km/hr intersections and 5 s for 80 km/hr intersections. Compared with current values in the Netherlands, this means that the duration of the yellow interval should be extended by 1 s to serve the driver appropriately in normal driving conditions and to meet minimum driver needs in deteriorated circumstances.

With this change in yellow timing the number of run red offenses would be reduced considerably, simply because 1-s prolongation of the yellow is not expected to change the drivers' behavior. Furthermore, more consistent decision making (in the sense that "emergency-type" braking and swerving are not needed anymore) might also be beneficial to traffic safety. On the other hand, the yellow time should not be longer than recommended because the stopping driver has to be "rewarded" with red (confirmation of appropriate behavior) and because an overlong yellow time might lead to greater variability in the decision making, resulting, for example, in an increase of the number of rear end collisions. Evidence for the latter has been found in literature on the safety effects of flashing green (3, 7).

Because the system is better adapted to "normal" behavior, enforcement measures might be much more effective. First, the group of offenders is expected to be much smaller, and second, the beginning of red no longer functions as a "necessary" extension of the yellow.

A 1-s extension of the yellow was evaluated in a 1-year before-and-after study in both urban and rural locations. All locations were provided with vehicle-actuated signal control. In the city of Leeuwarden, which has 23 signalized intersections, the yellow interval was changed from 3 to 4 s. The change was made without shortening the all-red time so that possible interfering effects would be prevented. The behavior of automobile drivers was observed at four selected intersections and was then analyzed quantitatively from time-lapse video recordings. The cameras recorded about 15,000 traffic signal cycles, in which 7,000 "deciding" vehicles (those nonstopping plus the automobiles that stopped first after the beginning of the yellow) were registered. The extension of the yellow interval at rural intersections from 4 to 5 s was evaluated on a rural route to

Leeuwarden that had seven signalized intersections. At two intersections the behavior of about 3,000 deciding vehicles was observed for about 4,500 traffic signal cycles. Details about method, procedure, and quantitative analysis may be found elsewhere (2, 8).

One year after the timing was changed, the number of run-red offenses at urban intersections appears to have been halved, from 1.1 to 0.5 percent of the total number of vehicles and from 13.4 to 6.7 percent of the number of deciding vehicles. At rural intersections the same reduction was achieved. The proportion of nonstopping automobiles with a stop line-passing time (TPS) greater than or equal to a given time t after the onset of yellow (Figure 1) shows a small shift of about 0.13 s for the urban intersections ($D_{\max} = 6.0$, Kolmogorov-Smirnov test, one-tailed, $p < 0.01$). Results for the "between" period (6 months after the extension of the yellow) differ by this same amount from the "before" period, but the between period does not differ significantly from the 1 yr after period. At rural intersections, no significant difference was found between the before and 1 yr after periods.

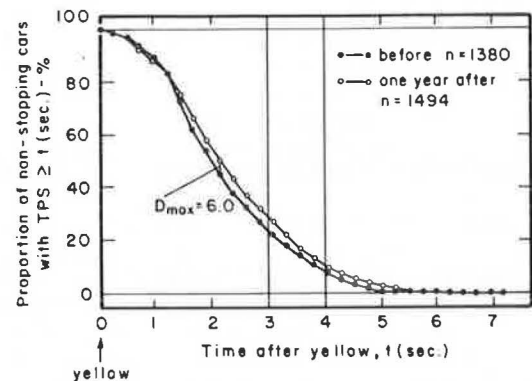


FIGURE 1 Proportion of the nonstopping cars with $TPS \geq t$ after the onset of the yellow, for before and 1 yr after the extension of yellow at urban intersections.

By including the information on the stopping drivers, the probability of stopping with respect to the potential time to the stop line (TTS) was calculated, taking into account the individual approach speed of each vehicle and assuming that vehicles will continue with a constant speed. A log-linear model fit resulted in a shift of 0.17 s between before and after situation. This (relatively small) change in driver behavior appears to be present for the after 6 months period as well and does not change thereafter.

From this field study it is concluded that a 1-s extension of the yellow time (from 3 to 4 s in urban areas and from 4 to 5 s in rural areas) cuts the total number of run-red offenses in half, although a small adaptation effect was also observed. However, after 6 months, no further change in driver behavior was found. The results are completely in agreement with the expectations of a simple model for calculating the required yellow time.

Type of Traffic Signal Control

It might be expected that different types of traffic signal control will differ in terms of exposure to potential offenses and will also perhaps differ in the process used by the drivers to decide

whether to stop or to proceed. If a vehicle-actuated control strategy is used, the green phase, in principle, will be extended as long as there are vehicles in a given detection area. When this control strategy operates well, it will result in much fewer potential red runners than does fixed time cycle control, in which the times selected for ending the green are independent of the traffic at the moment.

Zegeer and Deen (9) found a large reduction in the number of run red offenses when a green extension system was applied. The reduction was due mainly to the difference in exposure, but what about the differences in the discipline at the red light at the moment that the decision is required? The expectations of automobile drivers approaching the traffic light might differ for different types of control, resulting in different decision behavior in general, regardless of the duration of the yellow.

In the field study on the effects of yellow timing that was described in the previous section, all the traffic signal controls were vehicle actuated. In Figure 2, the probability of stopping at intersections with vehicle-actuated control is compared with data on fixed time control, available from the literature (10–12). All data sets are based on field studies, except those of Mahalel et al. (10). They conducted a laboratory experiment on the decision-making behavior of automobile drivers at traffic lights. A remarkable 1-s shift exists between the probability of stopping for a fixed cycle time control and that of stopping for a vehicle-actuated control. Evidently, a vehicle-actuated control leads to a shift in the criterion that drivers use. The drivers decide to proceed in an earlier stage of the approach process, when compared with the decision made for fixed-time control. In the field studies, it was observed that the characteristics of the decision process itself are not different, as is indicated by the similarity of the slopes of the curves at a 0.5 probability of stopping. The slope of the laboratory experiment at this point tends to be different, indicating a somewhat deviant behavior in more artificial circumstances (10).

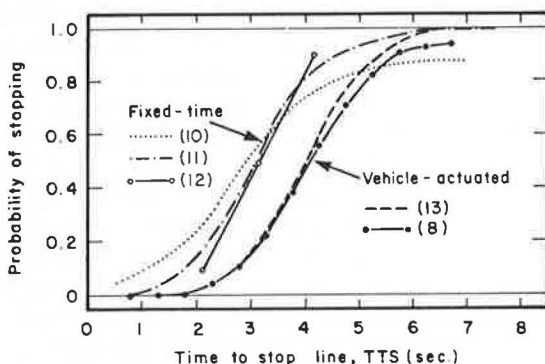


FIGURE 2 Probability of stopping as a function of the time to stop line (TTS) for fixed time (10–12) versus vehicle-actuated (8, 13) signal control systems.

Given this dependency of behavior on the type of traffic signal control, the hypothesis can be formulated that automobile drivers who are accustomed to vehicle-actuated control will adapt their behavior and expect to see a response when approaching the traffic signal during green. Contrary to the fixed time control situation, the drivers expect that the green interval will continue. Therefore, when the green phase ends

(that is, the maximum green extension period has been reached), their expectancy is violated, with consequences for their decision-making processes (1). It is expected that similar effects will occur in other situations. For example, in a string of interconnected signalized intersections (progressive signal control systems), the experience at previous intersections causes the expectancy that the driver will have or get the green interval at the next one as well.

To conclude, in spite of a negative effect on the decision-making behavior of automobile drivers per se, a vehicle-actuated traffic control system reduces the number of run-red offenses substantially in comparison with fixed time control. This reduction is mainly caused by a reduction in exposure, however.

RED SIGNALS AT DRAWBRIDGES

In the Netherlands, drawbridges are common. The operation of these bridges, especially on roads with heavy traffic flows, is sometimes problematic. On a freeway, for example, bridgekeepers sometimes have problems conducting the opening procedure because drivers persist in proceeding. The procedure is automatic once started by the bridgekeeper and consists of prewarning flashing signals (combined with a sign showing a drawbridge) located 900, 600, and 300 m before the bridge (the flashing starts successively about 30 s before the red signal), the onset of alternating flashing red lights above the stop line on the ramps of the bridge, the closing of the gates (8 s after red), and finally the opening of the bridge. The bridgekeeper can interrupt this procedure as needed if the descending gate threatens to hit a proceeding automobile. According to complaints by the bridgekeepers, 1 out of 5 or 10 closures has to be interrupted (14).

Why don't the drivers stop? In this case, it is not a matter of poor visibility of the signals or the gates. One assumption is that motorists, because they are familiar with this system and have visual contact with the bridgekeeper, know that the bridgekeeper is able to interrupt the procedure. The interaction between motorist and bridgekeeper and their mutual anticipation results in a nonstopping motorist. However, hiding the bridgekeeper behind one-directional curtains was not an effective countermeasure (14).

From video recordings, the behavior of the nonstopping automobiles was analyzed in more detail. Recordings of 82 closures with 348 nonstopping automobiles after the onset of the red signal were analyzed. Figure 3 gives the proportion of the nonstopping automobiles with a TPS greater than or equal to a given time t after the onset of red. It can be seen that 12 percent of the nonstopping automobiles pass the stop line after the gates begin to close (8 s after the onset of red).

If the behavior at this drawbridge is compared with that at signalized rural intersections with similar approach speeds, it is obvious that motorists make the decision to proceed much earlier at the drawbridge. On the basis of a speed of 100 km/hr, a reaction time of 1 s, and an average deceleration rate of 3 m/s², a clearance interval of 5.6 s would be sufficient. Yet 30 percent of the nonstopping automobiles pass the stop line later than this, compared to 6 percent for rural intersections. Even with a speed of 140 km/hr, drivers would be able to stop before the stop line at a time distance of 7.5 s. Yet 14 percent of the

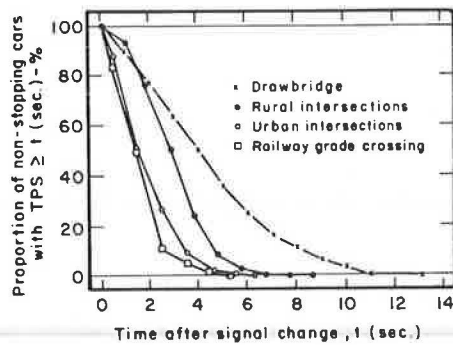


FIGURE 3 Proportion of nonstopping automobiles with $TPS \geq t$ after the onset of the yellow (for road intersections) or red (for drawbridges and railway crossings) signal.

nonstopping automobiles pass later. It appears that drivers are not *willing* to stop, rather than not *able* to stop. Given our knowledge of motorist behavior at signalized intersections, however, the functioning of the drawbridge signalization itself is questionable. About 30 s before the red signal is activated, the prewarning signal at 900 m starts flashing. Even when the prewarning signal is perceived, the uncertainty about the exact time that the red will appear is great because of the long interval (30 s) that passes with no complementary message to the motorist. The signaling system is in the same state at the end of the cycle, when the gates have been opened again. At the end of the cycle the warning lights are used as a warning for the queue of standing cars. In itself, this measure is effective to an extent, but it devalues the main function of these lights. Approaching drivers might be uncertain about whether the beginning or the end of the cycle is indicated.

At a speed of 100 km/hr, motorists who have just missed the warning signal will reach the stop line after 32.5 s. At that moment, the red signal is on for 2.5 s. Logically, it cannot be expected that those motorists will decide to stop at the onset of the red signal. They will proceed and inevitably run the red. Thus the meaning of the red signal is rather ambiguous. Following drivers see those automobiles in front running a red light. Because their situation is only marginally different (often heavy traffic flows with small headways), they are easily tempted to proceed as well (the previously mentioned *mitschleppeneffekt*). A separate yellow signal, preceding the red signal and combined with a much shorter warning time, might prevent a lot of these situations.

RED SIGNALS AT RAILWAY GRADE CROSSINGS

Recently, a study was conducted on the decision-making behavior of motorists who were approaching railway grade crossings that had signal control and were without gates (15). At this type of railway crossing, the yellow interval is absent: The signal changes directly from the safe situation (flashing white) to the unsafe situation (alternating flashing red). This is another situation in which road users may not be able to stop and therefore necessarily proceed through red.

The behavior of 660 motorists at the onset of the red signal was analyzed at two railway crossings. In contrast with the behavior at the drawbridge, motorists at this type of railway crossing are more willing to stop than those at signalized urban

intersections with comparable approach speeds (Figure 3). The probability of stopping at a given time distance appears to be higher at railway grade crossings, even in comparison with the data on fixed time control. At railway grade crossings the lack of a yellow phase seems to work in the opposite direction; that is, the obedience to the red light is better than at signalized intersections. However, a detailed analysis of the stopping vehicles indicated that some of the stops were realized only with a high deceleration rate ($> 4 \text{ m/s}^2$), and a few of them ended very close to the first railway track. Such "emergency" stops can easily lead to a stop on the track itself or to a rear end collision by a following automobile. Because of these risks, this kind of behavior is not desirable. It can be prevented by a separately signalized clearance interval with a yellow indication.

CONCLUSIONS AND RECOMMENDATIONS

At signalized road intersections, an extension of the yellow time by 1 s resulted in the number of run red offenses being cut in half. In the literature, evidence was found that 4 s of yellow for 50 km/hr zones and 5 s for 80 km/hr zones are optimum values. Longer times are not desirable because of expected secondary effects.

The comparison between behavior at vehicle-actuated and fixed time control systems indicates that motorists use expectations about the functioning of the signals and act accordingly. The relatively small number of run red offenses at vehicle-actuated signals is mainly due to a low exposure of deciding vehicles. Discipline at the red light per se appears to be less than for fixed time signals, probably because of a difference in expectancy.

Although the willingness of motorists to stop at drawbridges seems to be poor, at least some of the offenses can be explained by operational deficiencies of the signal system itself. The lack of a separate indication for the clearance interval is a major one. By introducing a yellow interval, only one interpretation of the red signal is possible, namely "stop." At railway grade crossings the absence of the yellow interval appears to have an opposite effect. The sudden onset of the red signal sometimes causes a kind of a panic reaction, with a very abrupt stop. This is especially the case with motorists who are so close to the railway track that proceeding would have been more appropriate. Although the obedience to the red light is better at grade crossings than at signalized intersections, large deviations from normal behavior occur. A separate yellow signal would therefore be advantageous at railway grade crossings as well.

Because the same behavior is demanded from the road user in all three examples given, one uniform signalization for stopping is recommended: a steady red signal preceded by a yellow interval that is properly designed to serve the driver adequately in normal driving as well as to meet minimal driver needs in deteriorated circumstances. Specifically, 4 s of yellow for 50 km/hr zones and 5 s for 80 km/hr zones are recommended.

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