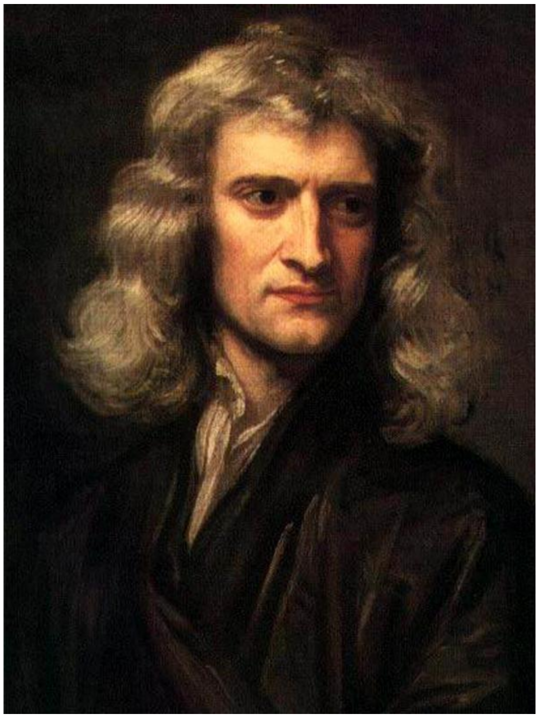
2012

Isaac Newton vs. Red Light Cameras



Short Yellow and Turns
Exposing the Traffic Engineer's Mistakes

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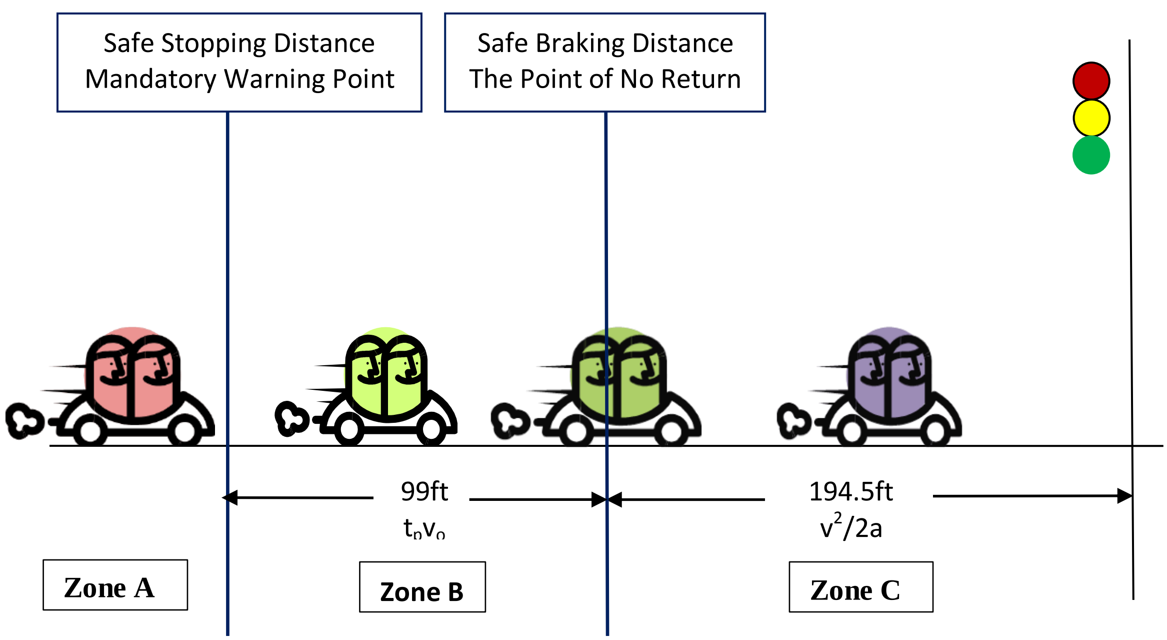
Yellow Light Defined

The yellow light interval equals the time it takes for a driver to perceive the light turning from green to yellow plus the time it takes for a driver to traverse the safe braking distance at the speed limit.[1]

The thing to get out of that definition is that the yellow time is *not* the time it takes for a driver to stop. That comes as a surprise to most people. The yellow time in fact, provides only half the time it takes a driver to stop. And that is the source of all the problems.

Problems with Short Yellows and Yellows for Turns

Figure 1 – Zones A, B and C



When the engineer shorts a yellow, the warning that a red light is about to appear comes too late. The driver may already be inside the Safe Stopping Distance (aka, the critical distance), where the driver has no option but to go, but the light can turn to yellow and then to red before the driver enters the intersection. The region on the road where engineer confronts the driver with an unsolvable decision problem[13] is called a *type I dilemma zone*[11]. No matter whether the driver decides to stop or to go, the driver will run a red light. This paper contains a mathematical proof of this statement.

Turning presents a similar problem. Turning is like shortening a yellow but by different means. When a driver approaches an intersection with intent to turn, he generally needs to slow down to initiate his turn. But his very act of slowing down consumes yellow time. Since the yellow light definition handles only cars proceeding at the speed limit; that is, with no provision for a car slowing down, the same thing happens to the turning driver as with the driver with a short yellow. The driver may already be inside the Safe Stopping Distance, where the driver has no option but to go, the light can turn to yellow and then to red before the driver enters the intersection. A yellow light duration set to ITE's yellow light equation automatically creates a *type I dilemma zone* in a turn lane. This paper contains a mathematical proof of this statement.

There is also the problem of the *type II dilemma zone*[12]. In a nutshell, a type II dilemma zone begins where the type I dilemma zone leaves off. While a solution is possible, the solution is not clear to the driver. The driver can easily and unintentionally choose incorrectly. This paper does not cover type II dilemma zones. It deserves its own paper.[8]

Engineers could prevent all the problems from ever happening by abandoning their faulty yellow light equation (equation 2), an equation which violates Newton's Second Law of Motion. All they would have to do to their equation is remove the "2" from the denominator. As it stands now, the equation is not an equation of motion. That is the source of all the problems.

I broke down the rest of this paper into two parts. The first part presents a typical poorly designed intersection from the Town of Cary. You can use this example to work the numbers for yourself. You will be able to see the problem.

The second part presents the General Case algebraically. With the equations from the General Case, given any speed limit, yellow time, perception time, deceleration constant and grade of road, you can determine the position and length of the segment on the approach, where if a driver so happens to be in it when the light turns yellow, the engineer will force him to run the red light. I have provided a spreadsheet[10] which computes the location of the segment for you.

ITE Created the Problem for Turning Lanes

The paper *Determining Vehicle Signal Change and Clearance Intervals* is the source of the mistakes which traffic engineers use to short yellow lights for turn lanes. The mistakes appear under the section "Use of Kinematic Formula for a Turn Lane."[2] The kinematic formula ITE is talking about is the Yellow Light Interval Equation. ITE's goal is to compute an adequate yellow time for a decelerating turning driver, but ITE fails in both its results and its methods.

Here is the pertinent excerpt from the paper:

> Consider two possible cases: [The first case:] A vehicle is approaching an intersection at a through speed, which we will assume is higher than what would be safely used to execute the turn. A green left-turn arrow is being displayed. The driver begins braking to slow the vehicle to the turning speed. The signal display changes to yellow . . . .
>
> In the first case, perception-reaction time is reduce[d] considerably as the driver's foot is already on the brake pedal . . . .
>
> The through vehicle procedure may produce an adequate initial yellow change interval length if the normal perception-reaction time is used and if the vehicle speed used is the average of the through vehicle speed and the turn execution speed. Vehicles decelerating from a through vehicle speed may be traveling faster, but the perception-reaction time may provide the necessary adjustment.[2]

Here are the errors:

Error	Description
1	ITE lists two cases. They missed the most important one. ITE omits the case where a vehicle approaches the intersection at the through speed and the driver's foot is still on the accelerator when the light turns yellow.
2	Because of the omission of the third case, ITE believes that all turning drivers already have their foot on the brake when the light turns yellow. The assumption is verified because ITE applies this assumption to all its turning lane yellow computations. The assumption is false. All turning drivers do not have their foot on the brake when the light turns yellow. The omitted case is the driver who just entered the approach segment with his foot on the accelerator. Since he is now located within the approach segment, the driver must proceed into the intersection. Now the light turns yellow. But because the yellow light does not provide time for a decelerating vehicle, deceleration being what a turning driver needs to execute a turn, the driver must enter the intersection under a red light. Even if ITE's assumption was correct--that drivers have their foot on the brake already, ITE's method to compute an adequate yellow time would still be wrong.
3	ITE removes perception-reaction time from the equation since all turning drivers have their foot on the brake when the light turns yellow. ITE transfers the perception-reaction time to the braking time, hoping that the time will be adequate. But since all turning drivers really do not have their foot on the

	brake when the light turns yellow, and since ITE believes that the foot location is the deciding matter, then the perception-reaction time cannot be transferred. The perception time must be remain perception time. Does ITE have any justification to consider that a driver's foot already being on the brake makes a difference? No. ITE doesn't have a justification. Whether the driver will decelerate with intent to enter the intersection, or decelerate more quickly and stop before the intersection, there is still is a *choice* that the driver has to make. If he decides to brake with intent to stop, there is the possibility of getting rear-ended. The driver will look in the rear-view mirror first. The perception-reaction time must remain.
4	ITE computes the average of the through speed and the turn execution speed and mistakenly plugs the result into the yellow light formula. ITE made a physics mistake. Using the average speed is a misapplication of the yellow light formula. The formula will yield a bogus result. ITE thinks that the yellow light formula accepts any velocity. ITE thinks that it can put any velocity from any situation from any vehicle location into the formula and the formula will magically compute the correct yellow time. That's not how the formula works. The yellow light formula requires a specific kind of velocity and it is not what ITE thinks. The velocity required by the yellow light formula is the velocity of the vehicle at a specific location. That location is where the vehicle enters the approach segment. The entry point of the approach segment is defined by the distance equation embedded inside the yellow light formula. The yellow light formula contains the distance equation: $t_p v + v^2/2(a + Gg)$

	The formula requires the vehicle's velocity at that distance. This distance is called the critical distance or the safe stopping distance. It is the closest distance to the intersection where a driver can stop safely. At the critical distance, a vehicle travelling at v can stop in time or proceed to the intersection at v. If the driver proceeds, he will arrive at the intersection at the moment the light turns red. Therefore v has got to be the velocity at the critical distance. The safe stopping distance for a vehicle travelling on a 45 mph road in North Carolina is 293 feet. That is just about the size of a football field. At a football field's distance from the intersection, you have a green arrow and a clear path. Are you going the speed limit? 100 yards is a long way. If you are going less than the speed limit, there will be a lot of angry drivers behind you giving you the birdie.
5	ITE mistakenly thinks that by plugging in the average speed, the yellow light formula is going to yield a time adequate for the vehicle to decelerate. The ITE formula computes the time it takes for a vehicle to traverse the critical distance at the speed limit. The formula does not compute the time it takes for a car to decelerate. Plugging in the average speed into the yellow light formula yields a bogus result. The bogus result undercuts the required yellow time, forcing drivers to run red lights.
6	While ITE confuses itself trying to figure out an adequate turning yellow duration, ITE forgets that turning drivers need to be able to stop from the speed limit too. ITE forgets that the yellow formula gives the minimum yellow interval needed for any driver going the

	posted speed limit to come to a stop. Just for purposes to come to a stop, the minimum yellow time has to be the formula yellow time with v being the speed limit. Turning drivers and going-straight drivers are indistinguishable before entering the critical distance. Both have their foot on the accelerator. Both are going the speed limit. Both drivers need at least the amount of time given by the yellow light formula as computed with the speed limit. That time will give them the distance to stop.
7	And the last problem is that ITE does not know the real way of computing the time required for a vehicle to decelerate. ITE does not know the laws of motion. Therefore in a sputter of pseudo-science strewn with disclaimers of “may produce”, “if”, “may provide” and “may offset,” ITE instructs traffic engineers to take the average speed and plug it into the formula. This singular piece of ignorance is the cause of millions of crashes. By the laws of physics, the time *required* for a vehicle to decelerate from v_i to v_f is: $$(a + Gg) = \frac{\Delta v}{\Delta t} = \frac{v_f - v_i}{t}$$ $$\boldsymbol{t = \frac{v_f - v_i}{a + Gg}}$$ Note that the time to decelerate has nothing to do with the yellow light formula. **Example 1.** If the speed limit is 45 mph and you need to decelerate to 20 mph before making a left turn, by the laws of physics you need 3.3 seconds to decelerate:

$$\frac{20-45}{-11.2}\left[\frac{5280\ ft/mile}{3600\ s/hr}\right] = 2.2 * 1.47 = 3.3 \text{ seconds}$$

11.2 ft/s^2 is NC's safe deceleration rate.

Add 1.5 second for NC perception time: 4.3 seconds.
(See error 3 for an explanation that perception time is still required.)

To allow the driver to *stop* from 45 mph, the yellow light formula still applies and requires the driver to have at least 4.5 seconds of yellow time.

The yellow time is the maximum of 4.5 seconds and 4.3 seconds.

The yellow time therefore is 4.5 seconds.

Example 2.

The speed limit is 45 mph and you need to decelerate to 10 mph because you are going to make a sharp U turn. By the laws of physics you need 4.6 seconds to decelerate:

$$\frac{10-45}{-11.2}\left[\frac{5280\ ft/mile}{3600\ s/hr}\right] = 3.13 * 1.47 = 4.6 \text{ seconds}$$

11.2 ft/s^2 is NC's safe deceleration rate.

Add 1.5 second for NC perception time: 6.1 seconds.
(See error 3 for an explanation that perception time is still required.)

The maximum of the yellow interval formula (4.5 seconds) and 6.1 seconds is 6.1 seconds.

The required yellow time for this specific driver therefore is 6.1 seconds.

Example 3

What then is the maximum amount of time a turning yellow must be?

In other words, what is the maximum time a driver needs to decelerate? We say this because we consider deceleration for turning vehicles, not proceeding at a constant speed as we do for straight-through movement vehicles.

Assume that the turn execution speed is the slowest it can possibly get without stopping. 1 mph. A driver needs 5.8 seconds to decelerate to 1 mph:

$$\frac{1-45}{-11.2}\left[\frac{5280\ ft/mile}{3600\ s/hr}\right] = 3.92 * 1.47 = 5.8\text{ seconds}$$

This value is greater than the yellow formula time because it has to be. The driver must enter the intersection because he closer to the intersection than the critical distance. Given that entering the intersection is a must, how long will it take the driver to get to the intersection by decelerating? Decelerating takes more time than proceeding at the constant speed limit. Therefore the turning yellow must be longer than the straight-through yellow.

What about adding the perception-reaction time to 5.8 seconds? Do we need that? Yes. It still makes sense. 5.8 seconds is the time the driver has his foot on the brakes. The driver still needs the time to react to the signal change and place his foot from the accelerator to the brake. If his foot is already on the brake, then the driver still needs to determine how hard he is going hit the brake. He must look in the rear-view mirror. He must have the perception-reaction time to do that.

The yellow light interval must be 5.8 + 1.5 = 7.3 seconds for such a driver.

The formula time is 4.5 seconds. The maximum of 4.5 seconds

	and 7.3 seconds is 7.3 seconds. The upper bound for a decelerating car on a 45 mph level road is 7.3 seconds. 7.3 seconds gives all turning drivers the deceleration time to execute whatever kind of turn they need. By the laws of physics, the turning lane yellow arrow must be 7.3 seconds.

Example: Westbound Cary Parkway at Kildaire Farms Rd.

Cary has a cornucopia of problematic traffic signals. For this example, I will use westbound Cary Parkway approaching Kildaire Farms Rd. The speed limit on Cary Parkway is 45 mph. The left-turn yellow is 3.0 seconds, 1.5 seconds too short according to Cary's yellow light equation. Refer to figure 1. When the light turns yellow . . .

1. Cary will force about 95% of the drivers in Zone B to run the red light.
2. Cary will force additional drivers in Zone B and C to run the red light when they choose to decelerate while in the lane.
3. Drivers in Zone A are okay. Cary expects them to stop. Drivers have enough distance. Cary should tell them where Zone A ends and B begins in order to avoid the dilemma zone.

Yellow Light Interval Equation Defined

The yellow light interval equals the time it takes for a driver to perceive the light turning from green to yellow plus the time it takes for a driver to traverse the safe braking distance at the speed limit.[1]

Definition by Words

$$\boldsymbol{Yellow\ Interval} = \boldsymbol{Perception\ Time} + \frac{[\boldsymbol{Safe\ Braking\ Distance}]}{\boldsymbol{Speed\ Limit}}$$

Definition by Math[3]

1. $Y = t_p + \frac{\left[\frac{v^2}{2a+2Gg}\right]}{v}$

2. $Y = t_p + \left[\frac{v}{2a+2Gg}\right]$

Where:

t_p = perception time in seconds
v = approach speed, the speed at the critical distance[14]
a = safe deceleration of vehicle
G = Acceleration due to Earth's gravity
g = grade of the road in %/100, downhill is negative grade

Safe Braking Distance—Expression of Newton's Law of Motion[6]

3. $S_b = \left[\frac{v^2}{2a+2Gg}\right]$

The Short Left-Turn Yellow

At the intersection of Cary Parkway and Kildaire Farms Rd, the Town of Cary sets the westbound thru-movement yellow interval to 4.5 seconds but shortens the left-turn yellow interval to 3.0 seconds. Can Cary do that?

No.

When Cary sets the yellow interval to 3.0 seconds, Cary decreases the amount of braking distance in which a driver must stop. Into what braking distance does 3.0 seconds confine a 45 mph car? Is it safe?

4. $Y = t_p + \left[\frac{S_b}{\mathrm{v}}\right]$
5. $S_b = v(Y - t_p)$
6. v = 45 mph = (45 mile/h) * (5280 ft/mile) * (1 h/3600 s) = 66 ft/s

7. S_b = (66 ft/s) (3.0s – 1.5s)

8. S_b = 99 ft

Cary expects a 45 mph car in the left lane to stop within 99 feet.

According to Cary, what is the required *safe* braking distance for a 45 mph car?

9. $S_b = \left[\frac{v^2}{2a}\right]$

10. $S_b = \left[\frac{66^2}{2(11.2)}\right]$

11. $S_b = 194.5 \text{ ft}$

According to Cary, the safe braking distance for a 45 mph car is 194.5 feet. But for left-turn lanes, Cary sets the braking distance for the same 45 mph car to 99 ft. According to Cary, it is not safe.

Cary believes that the immutable Laws of Physics change from lane to lane.

To brake *safely,* what speed limit does Cary's 3.0 second yellow interval represent?

Yellow time *Y* and safe braking distance S_b are a function of speed limit *v*. First solve for v, then solve for S_b. To make the arithmetic easier, we set the grade of the road to 0%. 0% means a level road.

12. $Y = t_p + \left[\frac{v}{2a}\right]$

13. $\left[\frac{v}{2a}\right] = Y - t_p$

14. $v = 2a(Y - t_p)$

15. t_p = 1.5 seconds. Cary, NCDOT and AASHTO standard

16. Y = 3.0 seconds according to the signal plan by R. Ziemba, 4/28/2009

17. $v = 2a(3.0s - 1.5s)$

18. $v = 2a(1.5s)$

19. a = 11.2 ft/s^2. Cary, NCDOT and AASHTO standard

20. v = 2(11.2 ft/s2)(1.5s)

21. v = 3(11.2ft/s)

22. v = 33.6 ft/s

23. v = 33.6 ft/s * (3600 s/h) * (1 mile / 5280 ft)

24. v = 22.9 mph

Cary's 3.0 seconds represents the yellow interval for a 22.9 mph car. 3.0 seconds provides a safe braking distance for cars approaching the intersection at 22.9 mph or less.

The Town of Cary assumes that all cars travelling down the left-turn lane at westbound Cary Parkway at Kildaire Farms Rd. approach the intersection at a maximum speed of 22.9 mph.

How far back on the approach does Cary assume the car is travelling at 22.9 mph? In other words, what is the Safe Stopping Distance for a 22.9 mph car?

25. $S_s = vt_p + v\left[\frac{v}{2a+2Gg}\right]$

26. $S_s = 33.6 * 1.5 + \left[\frac{33.6^2}{2(11.2)}\right]$ = 50.4 + 50.4

27. $S_s = 100.8\,ft$

Cary assumes that all cars in the left turn lane approach the intersection at a maximum of 22.9 mph as far back as 100.8 feet. In order for a 3.0 second yellow to work, cars in the left lane cannot exceed 22.9 mph starting from 100.8 feet from the intersection.

Even in a 45 mph zone.

This means that the Town of Cary does not allow a driver to go the legal speed limit.

If a driver is going 22.9 mph, 100.8 feet back from the intersection, with a clear path to the intersection, with a green left-turn arrow beckoning to him, he will have a train of rightfully frustrated tailgaters honking behind him.

The Thru-Movement Yellow Light Interval and Safe Braking Distance

According to Cary, the safe braking distance for a 45 mph driver is 194.5 feet (equation 11):

28. $S_b = 194.5 \text{ ft}$

What is Cary's required yellow interval for a 45 mph level road?

29. $Y = t_p + \left[\frac{v}{2a}\right]$
30. v = 45 mph = (45 mile/h) * (5280 ft/mile) * (1 h/3600 s)
31. v = 66 ft/s
32. $Y = 1.5\text{s} + \left[\frac{66\ ft/s}{2(11.2\ ft/s^2}\right]$
33. $Y = 4.5s$

For a 45 mph level road, the Town of Cary must set the yellow interval to at least 4.5 seconds.

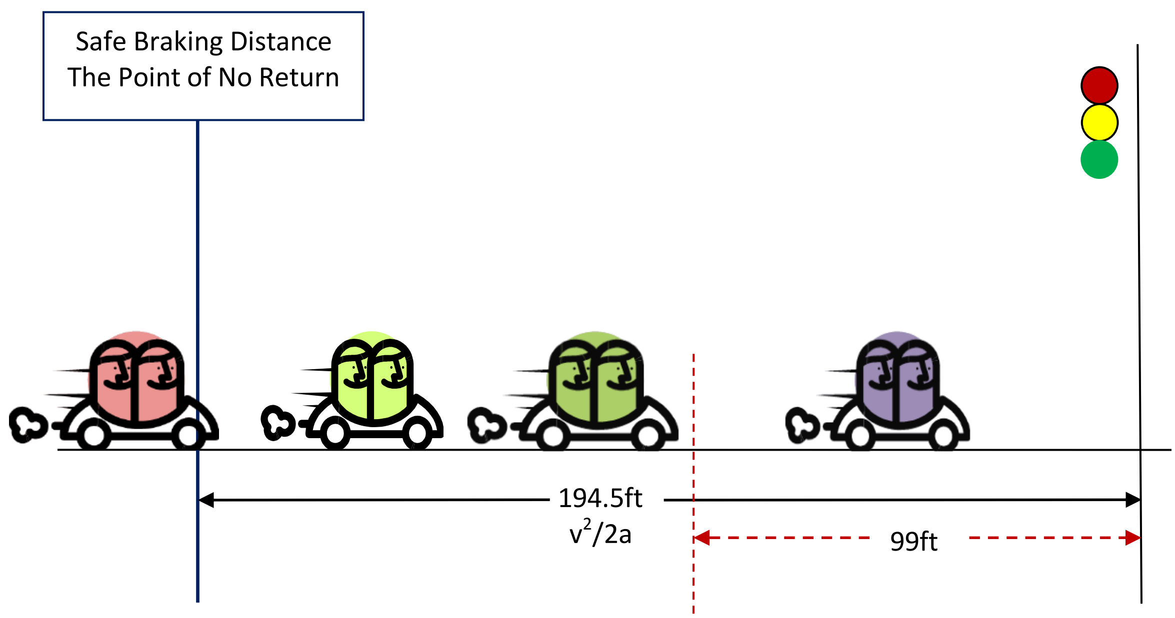
The safe braking distance equation (eq. 3), unlike Cary's other equations, is not arbitrary. One must use this equation without compromise. The safe braking distance equation part of the Yellow Light Equation is derived from Newton's Second Law of Motion. Everyone has no choice but to obey it.

Which Cars Does Cary Force to Run Red Lights?

Cary forces left and right turn lane drivers that approach the intersection at the speed limit, unhindered by slow cars in front of them, to run red lights.

That is because when Cary's traffic engineers set a turn yellow arrow time, they consider only cars waiting *in a queue*. Engineers assume that all cars turning left were once waiting at a red light. So when plugging in approach speeds to determine the yellow interval for the left-turn lane, engineers use speed of these queued cars, cars which enter the intersection very slowly--at 14-30 mph.[4]

The 45 mph left-turn lane with a 3.0 second yellow:



1. A 45 mph driver needs to apply his brakes at least 194.5 feet from the intersection in order to come to a stop. 194.5 feet is the Point of No Return. 194.5 feet is called the Safe Braking Distance. If the driver waits until he is closer to the intersection than 194.5 feet to stop, the driver will either stop too quickly causing a rear end crash, or he will skid through the intersection on a red.

2. It takes 1.5 seconds, Cary's perception time constant, for the driver to see the light turn yellow, decide what to do and then act. By the time the driver acts, there is only 1.5 seconds left of yellow remaining.

   $Y - t_p$ = time remaining

   3.0s – 1.5s = 1.5s

   Consider a driver who has passed the Point of No Return, he must proceed to through intersection, and with 1.5 seconds of yellow remaining . . .

   What is the maximum distance the driver can travel before the light turns red?

   a. rate * time = distance
   b. 66 ft/s * 1.5s = 99 ft

   The maximum distance the driver can travel before the light turns red is 99 feet. If the driver is within 99 feet from the intersection, then he can make it to the light before it turns red, but only *if he goes at least the speed limit.*

   Therefore, just when the perception time has passed, Cary forces all drivers who are between the Point of No Return and the point 99 feet from the intersection to run red lights. This is true for a short 3.0 second yellow on a 45 mph level road, for any lane.

3. Cary forces additional drivers to run red lights in turn lanes. Drivers in turn lanes usually must decelerate while in the lane before reaching the intersection. The little yellow time that remains, a driver eats up by decelerating.

   According to the NCDOT[3], the average initial left-turn *movement* speed is 25 mph. 25 mph is the speed at which the NCDOT expects the driver to start his turn. In the remaining yellow time of 1.5 seconds, at the NCDOT deceleration of *a*, is it possible for a driver to decelerate to 25 mph before the light turns red? What is lowest speed, $v_{e\text{-}min}$, to which a driver can decelerate when he enters the intersection?

a. $t = (v_o - v_e)/a$

b. $at = v_o - v_e$

c. $-v_{e\text{-}min} = -v_o + at$

d. $v_{e\text{-}min} = v_o - at$

e. $v_{e\text{-}min} = 66 \text{ ft/s} - 11.2 \text{ ft/s}^2 * 1.5\text{s}$

f. $v_{e\text{-}min} = 49.2 \text{ ft/s}$

g. $v_{e\text{-}min} = 49.2 \text{ ft/s} * (1 \text{ mile} / 5280 \text{ ft}) * (3600 \text{ s} / 1 \text{ h})$

h. $v_{e\text{-}min} = 33.5 \text{ mph}$

The driver's minimum possible speed at which a driver can enter the intersection is 33.5 mph. He cannot decelerate below 33.5 mph or Cary will force him to run a red light.

Cary expects drivers to enter the intersection at 25 mph. If a driver tries to do what Cary expects, Cary will either give him a ticket for skidding into the intersection or Cary will cause the car behind him to run into him.

4. What is farthest distance from the intersection where the driver can begin decelerating to 33.5 mph?

    a. distance = rate * time

    b. $d_e = (v_o + v_e)/2 * 1.5s$;   Where $(v_o + v_e)/2$ = average speed

    c. $d_e = [(66\ ft/s + 49.2\ ft/s)/2] * 1.5s$

    d. $d_e = 86.4\ ft$

If the driver is going to slow down to 33.5 mph, the driver can start hitting the brakes at 86.4 feet from the intersection.   He cannot hit the brakes any sooner.

If the driver is anywhere between 194.5 feet and 86.4 feet when the light turns yellow, and wishes to slow down, Cary will force him to run the red light.

If the driver is anywhere between 194.5 feet and the 99 feet when the light turns yellow, slow down or no, when the light turns yellow, Cary will force him to run the red light.

The Case Made

Shorting yellow lights forces drivers to run red lights. Shorting yellow lights in left-turn lanes further forces drivers to run red lights because deceleration while approaching the intersection consumes more yellow time. Shorting yellow lights applies to right-turn lanes as well. The Town of Cary will force even more right-turning drivers to run red lights because a right-turn is a sharper turn than a left-turn. Right turns require more deceleration.

Cary bestows upon these drivers unavoidable penalties and puts these drivers in harm's way.

Further Proof

To see graphs of this engineering failure, refer to *How Yellow Intervals Affect Red Light Running*.[9] By shorting yellows, the Town of Cary forces from 300% to 1000.0% more drivers to run red lights.

Seeing Is Believing

To witness the engineering failure firsthand, Cary offers a splendid vista at three intersections:

1. For westbound Cary Parkway at Kildaire Farms, park at Trader Joes.
2. For southbound Walnut St. at Meeting Place, park at McDonald's.
3. For westbound Maynard at Kildaire Farms, park at Rite-Aid.

   Watch the cameras flash all the unhindered left-turn lane drivers. Cary shorted all the left-turn yellows at these intersections.

   You will get the idea in 10 minutes.

Why does Cary Change the Yellow Light Rules for Left Turners?

1. Because ITE changes the rules under section "Use of Kinematic Formula for Turn Lanes" in the *Determining Vehicle Signal Change and Clearance Intervals*[2]. The NCDOT copies ITE. Cary copies the NCDOT. As shown a few pages ago, ITE's change of rules violates the laws of physics more.

2. Because there are technical writer errors in the NCDOT specs which imply to traffic engineers all over North Carolina that left-turn execution speed measured for all-red clearance intervals can be applied to yellow interval approach speeds. But approach speeds are to be measured at the critical distance, not at the intersection entry point.

3. Because traffic engineers sacrifice safety on behalf of traffic capacity. It's their motto. If traffic engineers can squeeze a few more cars through the intersection, even if means forcing cars to run red lights, they will do it.[5, 6]

4. Because MUTCD spec 4D.12 states that 3.0 seconds is the minimum yellow duration. Red light camera companies encourage legislators to put this MUTCD statement into the laws. Many traffic engineers and legislators take this out of context by thinking that 3.0 seconds is adequate for any yellow.

   Consider cooking meat. One has to cook different meats at different temperatures to kill bacteria. Steak requires 145°F. Ground beef requires 160°F. Chicken requires 165°F. In the Town of Cary, chicken is on the menu and cooks have set the oven to 145°F.

   The MUTCD's statement, in proper context, says this: If the computed yellow interval from the equation results in less than 3.0 seconds, then increase the yellow interval to 3.0 seconds. This increase comes into effect for speeds less than 22.9 mph, like in school zones.

The General Case

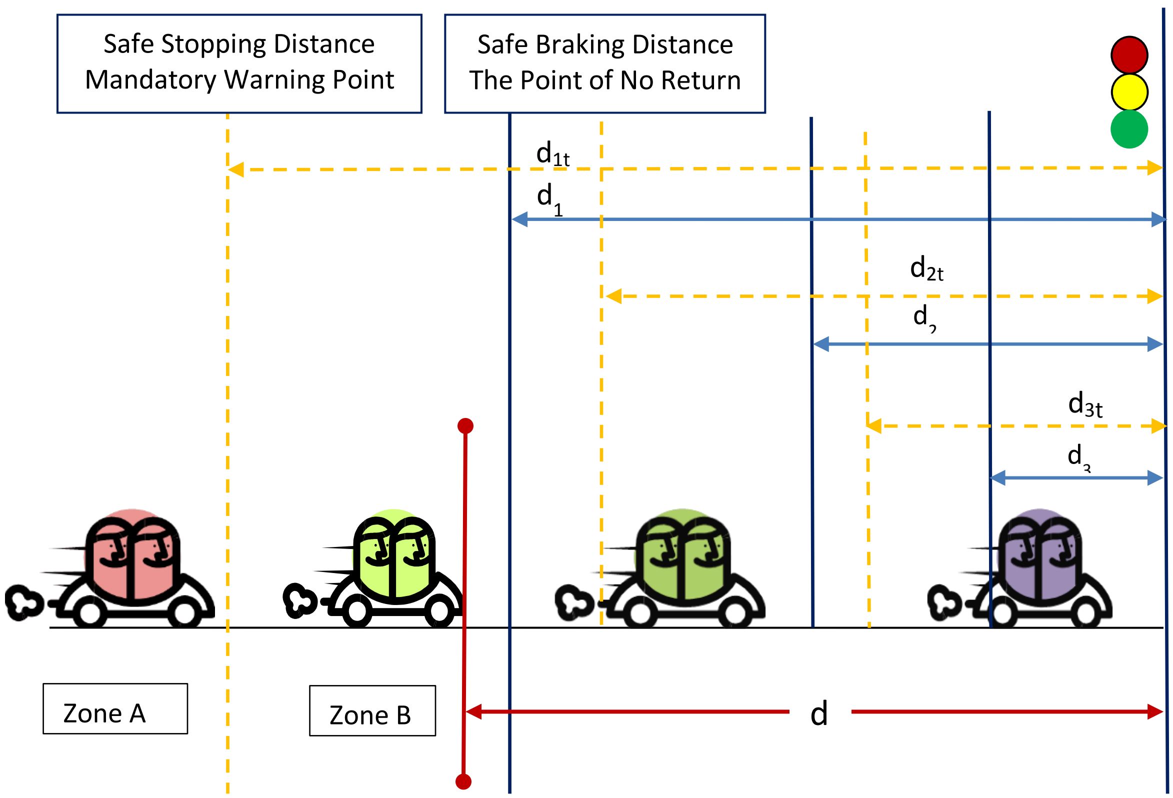


Table 1 – Short Yellows Force Drivers to Run Red Lights

Equation	Formula	Meaning
34	$d_{1t} = vt_p + \frac{v^2}{2\alpha}$	A green light must turn yellow at distance $\mathbf{d_{1t}}$ or farther for a driver to stop. $\mathbf{d_{1t}}$ is called the safe stopping distance. $\mathbf{d_{1t}}$ is the distance from intersection to the safe stopping distance. $\mathbf{d_{1t}}$ is the distance the driver travels at the speed limit during the time he perceives the signal changing to yellow, plus the safe braking distance.
35	$d_1 = \frac{v^2}{2\alpha}$	$\mathbf{d_1}$ is the distance from the intersection where the driver must begin to apply his brakes in order to stop safely at the intersection. $\mathbf{d_1}$ is called the safe braking distance. $\mathbf{d_1}$ is a derivation of distance travelled according to Newton's Second Law of Motion.[5] This equation does not allow any compromises.
36	$d_{2t} = vt_p + \mathrm{v}(\mathrm{T} - t_p)$	$\mathbf{d_{2t}}$ is the maximum distance a driver can travel during the yellow light. When the Town of Cary sets **T** according to the ITE Yellow Light Interval Equation[1,5]; in other words, Cary does not short the yellow, then: $d_{1t} = d_{2t}$

37	$\boldsymbol{d_2 = \mathrm{v}(\mathrm{T} - t_p)}$	**d_2** is the maximum distance a driver can travel during the yellow light after he perceived the light turning from green yellow.
38 	$\boldsymbol{d_{1t} \leq d \leq d_{2t}}$	At the time the light changes to yellow, the Town of Cary will force all drivers at distance **d** from the intersection to run a red light.
39	$\boldsymbol{D = d_{1t} - d_{2t}}$	***D*** is the size of the type I dilemma zone for straight-thru movement drivers.

Table 2 - Turning Forces Drivers to Run Red Lights

Equation	Formula	Meaning
40	$d_{3t} = vt_p + \overline{v}(\mathrm{T} - t_p)$	$\mathbf{d_{3t}}$ is the maximum distance a turning driver can travel during the yellow light. $\overline{v}$ is his average speed.
41	$d_3 = \overline{v}(\mathrm{T} - t_p)$	$\mathbf{d_3}$ is the distance a turning driver travels during the yellow light after he perceived the light turning from green yellow. $\overline{v}$ is his average speed. When turning, a driver decelerates on his approach in preparation to turning. Generally speaking, very few drivers can enter the intersection at the speed limit and still make the turn.
42	$v_e \leq v$	The driver's speed when he enters the intersection. For legal purposes, entry speed must be <= speed limit.
43	$\overline{v} = \dfrac{v + v_e}{2}$	Average speed from **v** decelerating to $\mathbf{v_e}$
44	$v_{e-min} = v - \alpha(T - t_p)$	v_{e-min} is the minimum speed which with a driver can enter the intersection.
45 	$v_e < v_{e-min}$	The Town of Cary will force all drivers who safely decelerated from the speed limit, but who enter the intersection at a speed less than v_{e-min} to run a red light.

46 	$d_{1t} \leq d \leq d_{3t}$	At the time the light changes from green to yellow, the Town of Cary will force all turning drivers at distance **d** from the intersection to run a red light.
47	$D_{turn} = d_{1t} - d_{3t}$	D_{turn} is the size of the dilemma zone for turning drivers.

Table 3 - Deceleration

Equation	Formula	Meaning
48	$\alpha = \mathbf{a} + \mathbf{G}\sin(\tan^{-1} g)$	For any grade **g**.
49	$\alpha = \mathbf{a} + \mathbf{Gg}$	For -10.0% <= grades <= 10.0%

Table 4 - Variables

Var	Meaning
d_{1t}	Distance from intersection to safe stopping distance
d_1	Distance from intersection to safe braking distance
d_{2t}	Maximum distance a driver can travel during the yellow light
d_2	Maximum distance a driver can travel during the yellow light after he perceived the light turning from green to yellow
D	The size of the type I dilemma zone for straight-thru movement drivers.
d_{3t}	Distance a turning driver travels during the yellow light
d_3	Distance a turning driver travels during the yellow light after he perceived

	the light turning from green yellow
D_{turn}	The size of the type I dilemma zone for turning drivers.
v	Speed limit. Traffic engineers often call this the approach speed. For the purpose of yellow intervals, the approach speed >= speed limit. Approach speed cannot be < speed limit because drivers can legally go the speed limit.
v_e	The speed the car enters the intersection
$\bar{v}$	The average speed of the car from v to v_e
$v_{e\text{-}min}$	The minimum speed the car can enter the intersection. Any safe deceleration from the speed limit to a speed slower than this minimum speed will force the driver to run the red light.
t_p	Perception time. North Carolina uses 1.5 seconds for this value. This value comes from AASHTO[6] but if falls 1.0 second short of AASHTO's *recommended* perception time.
α	Deceleration. Deceleration is a positive value.
G	Earth's gravitational acceleration constant. 32.2 ft/s^2
g	The grade of road. A grade of 1% means g = 0.01. Inclines are positive. Declines are negative.

Table 5 - Notes

#	Note
1	I assume that the driver uses all his perception time and only his perception time for perceiving.
2	I assume that the driver decelerates at the Town of Cary's accepted safe deceleration constant of 11.2 ft/s^2. Any deceleration greater than this will cause a rear-end collision or put the driver's head

	through the windshield.
3	The underlying physics premise of the safe braking distance equation is that a vehicle's brakes can always exert a force **F** capable of decelerating the vehicle at 11.2 ft/s^2 on a level road.
4 	The yellow light equation always assumes the road is dry. The safe braking distance equation does not compensate for rain or snow. In physics-speak, the safe braking distance equation does not include the coefficient of friction between the road and the tires of the car. In wet or icy conditions, the Town of Cary will force drivers to run red lights.

References

[1] *Determining Vehicle Signal Change and Clearance Intervals*, ITE Technical Council Task Force 4TF-1, Institute of Transportation Engineers, 1994, p. 3

[2] *Determining Vehicle Signal Change and Clearance Intervals*, ITE Technical Council Task Force 4TF-1, Institute of Transportation Engineers, 1994, p. 4

[3] *Traffic Engineering Handbook*, 6th Edition, Publication TB-010B, Institute of Transportation Engineers, 2010, p. 412

The basic equation is found in every state, federal and international department of transportation's signals manual. The "2" in the denominator is the give-away. The first *Traffic Engineering Handbook* the equation appeared in is the *Traffic Engineering Handbook*, 3rd Edition, Institute of Traffic Engineers, 1965, p. 407. The original formula came from an earlier. It is equation 9 in the paper, *The Problem with the Amber Signal Light in Traffic Flow*, by Denos Gazis, Robert Herman and Alexei Maradudin, GM Research Labs, 1959.

Here are some examples:

[3]*Traffic Signal Timing Manual*, Publication FHWA-HOP-08-024, Federal Highway Administration, 2008, p. 138

[3]*Intelligent Traffic Signal Systems Unit Design Manual*, North Carolina Department of Transportation, 2009, Standard 5.2.2, Sheet 4 of 4

[3]*Caltrans Traffic Manual*, California Depart of Transportation, Table 4D-102

[3]*Signal Policy and Guidelines*, Oregon Department of Transportation, 2009, Appendix K

[4]*Application of the ITE Change and Clearance Interval Formulas in North Carolina*, Steven M. Click, Ph.D, ITE Journal, January 2008, p. 20

[5] *Traffic Engineering Handbook*, 6th Edition, Publication TB-010B, Institute of Traffic Transportation, 2010, p. 412. In the fourth paragraph from the bottom of the page, ITE recommends that traffic engineers cut short the yellow light even when knowing it will force cars to enter the intersection on a red. For compensation, ITE recommends to increase the red clearance interval.

[6]*Derivation of the Yellow Light Interval Equation*, redlightrobber.com, Brian Ceccarelli, 2011. The yellow time is half the time required for a car to stop. Half the time you are stopping, the light is already red. This predisposes drivers to beat the light.

[7]*A Policy on Geometric Design of Highways and Streets*, American Association of State Highway and Traffic Officials, 2004, p. 110

[8]*Dilemma Zone*, redlightrobber.com, Brian Ceccarelli, 2011

[9]*How Yellow Intervals Affect Red Light Running*, redlightrobber.com, Brian Ceccarelli, 2011

[10]*Short Yellows and Turns Spreadsheet*, redlighrobber.com, Brian Ceccarelli, 2011

[11] *The Dilemma with Dilemma Zones*, Tom Urbanik, University of Tennessee; Peter Koonce, Kittelson and Associates, p. 2.

[12] *The Dilemma with Dilemma Zones*, Tom Urbanik, University of Tennessee; Peter Koonce, Kittelson and Associates, p. 3.

[13] The Problem with the Amber Signal Light in Traffic Flow, Gazis, et. al, GM Research Labs, 1959, p. 113

[14] The Problem with the Amber Signal Light in Traffic Flow, Gazis, et. al, GM Research Labs, 1959, p. 114. V_0 is the speed of the vehicle at the critical distance.