STATE OF NORTH CAROLINA

COUNTY OF WAKE

* * *

BRIAN CECCARELLI and LORI MILLETTE, individually and as class representatives,

Plaintiffs,

vs. CASE NO. 10-CVS-019930

TOWN OF CARY,

Defendant.

* * *

Deposition of ELIZABETH A. GEORGE, Ph.D., Witness herein, called by the Plaintiffs for direct examination pursuant to the Rules of Civil Procedure, taken before me, Kathy S. Wysong, a Notary Public in and for the State of Ohio, at the offices of Mike Mobley Reporting, 334 South Main Street, Dayton, Ohio, on Thursday, September 13, 2012, at 7:32 a.m.

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EXHIBITS MARKED

(Thereupon, Plaintiffs' Exhibit 1, affidavit of Elizabeth George, Ph.D. and Plaintiffs' Exhibit 2, curriculum vitae of Elizabeth George, Ph.D., were marked for purposes of identification.)..........	4
(Thereupon, Plaintiffs' Exhibit 3, graphs prepared by Brian Ceccarelli, was marked for purposes of identification.).....................	53
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APPEARANCES:

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ALSO PRESENT:

Richard Stevens, Videographer

* * *

THE VIDEOGRAPHER: We're on the record.

(Thereupon, Plaintiffs' Exhibit 1, affidavit of Elizabeth George, Ph.D. and Plaintiffs' Exhibit 2, curriculum vitae of Elizabeth George, Ph.D., were marked for purposes of identification.)

ELIZABETH A. GEORGE, Ph.D.

of lawful age, Witness herein, having been first duly cautioned and sworn, as hereinafter certified, was examined and said as follows:

DIRECT EXAMINATION

BY MR. STAM:

Q. My name is Paul Stam. I represent Brian Ceccarelli and Lori Millette, the plaintiffs in this case. I hand you what's been premarked as Plaintiffs' Exhibit 1 and 2 for your deposition and ask if you have prepared or seen those before?

A. Yes, I have.

Q. And is this an affidavit you've previously given in the case --

A. Yes.

Q. -- as Number 1, and Number 2, your curriculum vitae?

A. Yes.

Q. All right. First, is your -- please state your name, and is your address correctly stated on your curriculum vitae?

A. Yes. Elizabeth A. George, and those are my current work and home addresses.

Q. And that's in Springfield, Ohio?

A. Springfield, Ohio.
Q. Now, I understand there may be one slight update on your curriculum -- CV?
A. Yes. Since last year the university promoted me from assistant -- or sorry, associate professor to professor.
Q. What university is that?
A. Wittenberg University.
Q. All right. And if you would describe your training, education, and experience to become a professor at Wittenberg University.
A. Okay.
Q. First your education and training.
A. I have a bachelor's degree in physics from the University of Arizona. Master's in medical physics from the University of Colorado. And a Ph.D. in physics from the University of Wisconsin. And I have postdoctoral experience at the University of Wisconsin. And I've taught physics at the college level for nearly twenty years now.
Q. All right. How old are you?
A. I'm fifty-one.
Q. Do you -- what is your position at

the university?

A. I teach physics, and I'm also department chair of the physics department at Wittenberg.

Q. All right. What are your duties as department chair?

A. I manage the personnel of the department, which is four other faculty members, and then administrative assistant. I manage the budget for the department. I schedule courses. I make sure equipment is taken care of for the laboratories. There are lots of other things.

Q. What do you teach and how often do you teach?

A. I teach -- I share a position with my husband so I actually teach half time, which is an average of three courses a year. I teach all levels of physics from introductory physics for science and engineering majors all the way up through upper level physics courses.

Q. All right. Let's first talk about upper level physics. Do you have a particular concentration in physics?

A. I am a nuclear physicist by

training, an experimental nuclear physicist and -- so at the upper level I tend to teach laboratory courses and courses in nuclear physics, particle physics. But I've also taught courses on optics and electronics. And I've taught upper level mechanics courses and quantum mechanics courses.

Q. All right. When you talk about mechanics courses, to what do you refer?

A. Mechanics is the branch of physics that deals with motion and the causes of motion.

Q. Okay. And nuclear physics, is that particularly related to very tiny, small particles?

A. Yes. Nuclear physics deals with the fundamental particles that make up the atom.

Q. All right. How are the rules of motion or -- do you call them rules of motion?

A. Laws of motion.

Q. Okay. How do they compare in nuclear physics compared to the physics if I wanted to move this table?

A. Well, in nuclear physics actually

the laws of motion are very similar to the laws of everyday objects. You only see a difference when you're dealing with objects that are up very close to the speed of light, and actually in the atomic nucleus, the particles are not moving close to the speed of light, generally. There are a few exceptions.

Q.   I'm not going to go through all your publications, but have they typically been on -- there appears to be several dozen publications; is that correct?

A.   Yes.

Q.   And what is the general subject upon which you publish?

A.   The general subject is nuclear physics, is the forces and the causes of decay in atomic nuclei.

Q.   All right. The -- we're not going to be requesting opinions on nuclear physics today, but we are -- we will be requesting opinions on kinematics or mechanics, the laws of motion.

A.   Uh-huh.

Q.   So what is your experience in teaching those subjects?

A. I have taught the kinematics, the laws of motion, mechanics in general, that's the general discipline that covers the laws and the causes of motion, is typically taught in the first course that science and engineering majors take at the college level, and I've taught that course, I'd have to look back exactly, but probably six or seven times to different groups of students. And then because the laws of motion are so fundamental, they come up over and over again in following courses so nearly -- pretty much every semester I'm teaching a course that at least uses these laws of motion.

Q. You mentioned that you teach engineering majors. Is physics a prerequisite for the understanding of engineering?

A. Yes. Wittenberg doesn't -- doesn't give engineering degrees, but Wittenberg has what's called a dual degree program where students attend Wittenberg for three years and then go to an engineering school for two years, and those students are required to take a year of physics, and that includes the introductory course in which mechanics is taught.

Q. And why would engineering students be required to take a course in physics?

A. Because engineers -- since engineering is based on the way nature works and the laws and the models for how nature works, they need to understand those at a basic level in order to apply them in the real world.

MS. MARTINEAU: Objection. Move to strike.

BY MR. STAM:

Q. Is engineering the application of physics and other sciences?

A. Yes.

MS. MARTINEAU: Objection again.

BY MR. STAM:

Q. And just --

MS. MARTINEAU: Lack of foundation. I'm sorry.

BY MR. STAM:

Q. -- for your understanding, objections will be considered later by a judge --

A. Uh-huh.

Q. -- who will decide whether or not

you're qualified to explain the relationship, in this case, for example, between physics and engineering.

Is it possible to have a correct engineering solution that actually violates the laws of motion in the universe?

MS. MARTINEAU: Objection. Lack of foundation.

THE WITNESS: Correct, no, because it would not apply to the real world. It wouldn't work in the real world.

BY MR. STAM:

Q. Okay. Now, you're familiar through your affidavit, which is Deposition Exhibit 1, with what this case is about generally; and my question is not your affidavit yet but just on the subject. This calls for a certain amount of knowledge of physics or math and mathematics; and the question is, at what level would the laws of physics necessary to understand your affidavit -- your affidavit be taught? Is that a postgraduate -- postdoctoral course, graduate course, college course, freshman high school, or what?

A. The laws of motion that are required to understand the affidavit are taught in the very first college course that typically science and engineering majors take. It's also often taught in high schools.
Q. Okay. And is this branch -- is it usually referred to as mechanics or kinematics?
A. Mechanics is the general term for the area of physics that deals with the causes in nature of motion. Kinematics is specifically describing motion without worrying about what the cause of the motion is. If you include the cause of the motion, then that's called dynamics.
Q. Okay. Addressing your affidavit, which is Plaintiffs' Deposition Exhibit 1, do you recall signing that and swearing to that December 5th, 2011?
A. Yes.
Q. And we're going to have an opportunity for you to explain it in greater detail, but has anything changed in your opinion with regard to this affidavit?
A. No.
Q. All right. Would you -- do you

have an opinion -- do you know what a dilemma zone is?
A. Yes.
Q. Okay.
A. Yeah.
Q. All right. Do you have an opinion satisfactory to yourself based on your training, education, and experience concerning whether a vehicle traveling at a given speed requires a certain distance to stop safely?
A. Yes.
Q. All right. And what is that opinion?
A. Sorry. Are you asking specific -- in a specific case or for the general --
Q. Thank you. Good clarification. If you would discuss that in general first --
A. Okay.
Q. -- and then if you would opine on that subject specifically as it relates to the two intersections that you have examined or -- examined the facts concerning in Cary, North Carolina.
A. Okay.
Q. But if you would explain in

general how you arrived at your conclusions.

A. Okay. This is easier if I explain a little bit about the laws of motion, and so I will probably need to write a few equations if that's all right.

Q. As long as you explain --

A. Right.

Q. -- the equations and what the Ps and Qs mean.

A. Yes. So --

MS. MARTINEAU: Are we talking, just for clarification, general first? Is this your general --

THE WITNESS: General first.

MS. MARTINEAU: Okay.

THE WITNESS: General first, right.

MS. MARTINEAU: And then before you go into -- after she's done with the general, will you ask her what your specific question is?

MR. STAM: Yes, I will.

MS. MARTINEAU: Thank you. Go ahead.

THE WITNESS: Okay. So to determine the distance that a vehicle needs in order to stop safely, that's based on concepts of velocity and acceleration.

And velocity is defined as distance -- distance over time or -- the technical physics term is displacement over time.

And the acceleration -- the average acceleration is equal to the change in velocity over time. So change in velocity over time.

BY MR. STAM:

Q. Now, could you say what those different letters mean --

A. Yes.

Q. -- in case --

A. Yeah.

Q. -- counsel are not familiar -- in case I'm not familiar with what they mean?

A. Okay. So we represent velocity with a V and displacement is X and T is time. And then when I write acceleration, A, that's always an average acceleration. And then this means change in velocity over time.

If we're talking about deceleration, which we are going to be braking to a stop, then we can write that deceleration as the velocity that the object starts with, V not or V zero, minus the velocity the object ends up with divided by time. So that's the change in velocity over time. And it depends on the starting velocity and the initial velocity of the object and the time it takes to go from the initial to the final velocity.

So if we combine those equations and do a little bit of algebra, which I assume I can skip, we come up with an equation that relates the object's initial and final velocities to the acceleration and the distance it travels. So the square of the initial velocity minus the square of the final velocity is equal to two times the object's acceleration times the distance it travels while it's decelerating from its initial velocity to its final velocity.

And so if a car is going to stop, say, then the final velocity is zero and so there's a relationship between the initial speed of the object just before it starts decelerating and the rate of deceleration and the distance it travels. And so --

Q. So a vehicle that's decelerating cannot -- you cannot assume it will be going at its original speed the entire time?

A. That's right. Right. If the

vehicle decelerates to a stop, then over the time it's decelerating it actually averages the mean. The average is the -- is half of the initial velocity actually.

Q. Okay.

A. So if the car starts out with a certain speed, say, and we know what that is, then the distance that it travels before coming to a stop depends on the square of the initial velocity divided by twice whatever the acceleration is or the deceleration in this case.

Q. Is that 2a at the bottom?

A. That's a 2a at the bottom.

Q. Okay. All right. Now, are there other factors, perception time --

A. Yes.

Q. -- slope of the --

A. Right. So --

Q. How do other factors enter into the equation?

A. So this assumes that -- this is only the distance that's traveled while the car is braking, and this is assuming that there's no -- that the road is flat and so the only deceleration of the car comes from the braking.

If the object -- the car -- if it takes some amount of time for the car to begin to slow down, in other words, if it takes some amount of time for the driver to perceive that a light has changed and move the foot from, say, the accelerator to the brake, then the car will be traveling at that initial speed for some amount of time and so the distance that's traveled is going to be greater. So there will be the distance that's traveled while braking which is this V not squared over 2a term and --

Q. When you say V not, is not like zero?

A. Zero. Yeah. Sorry. That's the initial -- that's the speed that the object is traveling when it begins to decelerate --

Q. Okay.

A. -- V not or V zero.

Q. Divided by twice the rate of accel --

A. Acceleration, right.

Q. Right.

A. And that just comes from the definitions of velocity and acceleration.

Q. And is that true throughout the universe?
A. Yeah. As long as you have an object that's not moving near the speed of light --
Q. All right.
A. -- yes.
Q. Has anybody found anyplace on earth where that is not true?
A. No, not as far as I know. The only -- the only assumption that goes into this is that the car is decelerating at a constant rate.
Q. Okay. And, of course, the perception time?
A. And so -- yeah. Then --
Q. What do those letters mean that you have? T, what is T?
A. So T sub P is the perception time. That's the time it takes the driver of the car to actually begin to brake, and so at that -- during that time the car is not slowing down, the car is still traveling at its initial speed V not.
And so if you go back to the

definition of velocity and displacement or distance, then the distance that's traveled before the car starts to brake is that perception time T P times that initial velocity V not.

Q. Okay. Now, in this case the Institute of Traffic Engineers, they have a constant for a perception time?

A. Uh-huh.

Q. Are you aware of that?

A. Yeah. Is it one point five seconds, I think? I've seen several numbers.

Q. One point five at one place and one point two I've seen.

A. Okay.

Q. Is your opinion contrary to theirs on what the amount of perception time should be?

A. It seems like a reasonable number to me.

Q. All right. And you mentioned slope as well. Now, in this particular case I don't think there's issues of slope; but if you would just explain for the Court how slope would enter into this just so we have a complete record because at other intersections it might --

A. Sure.

Q. -- affect things.

A. Right. So if a car, say, is on a slope like that, then --

Q. Now, that's a downward slope?

A. That's a downward slope.

Q. Okay.

A. Right. Then say the car is traveling down the slope, the car's brakes can provide a certain acceleration but the slope is also going to provide an acceleration. If the car is going down a downward slope, then the slope itself, because of the gravitational -- part of the gravitational pull that's down the grade is going to make the total acceleration of the car a little bit smaller than it would be if there were no slope.

If the car is traveling up a slope, then the braking action and the pull of gravity are going to be at least partly in the same direction and so the total acceleration of the car will be a little bit greater than the value that would be on a flat surface.

Q. You can stop quicker --
A. You can stop quicker --
Q. -- if you're going uphill --
A. -- if you're going uphill because gravity is helping. And you take -- it's a longer distance to stop downhill because gravity is fighting the brakes.
Q. And is there a formula -- a physics formula to address that?
A. Yes, there is.
Q. If you would just tell us what that is or put it -- just write it right across the face of that slope, if you would.
A. Yeah. Let's see. So the way a physicist would write it is to say that the -- what -- this is maybe a little hard to see, but the acceleration that you'd have to use in this formula is the total acceleration, and that would be the acceleration you get from your brakes or deceleration you get from your brakes.
In the case of a downhill slope, you would add little G, which is the gravitational acceleration, it's nine point eight meters per second squared, which I guess

is thirty-two feet per second squared, times the sign of the angle of the slope, which is the angle from the horizontal.

Q. Okay.

A. And if you were -- if you were on an uphill slope, you would have to subtract G sign beta from the acceleration.

Q. Now, the --

A. Oops, I'm sorry. I said that backwards.

Q. Let's say it forward then.

A. Yes, let's say it forward. This equation here with the plus sign refers to the uphill slope where the acceleration from the braking and -- this is what I get for trying to do this upside down -- the acceleration from the braking and the acceleration provided by gravity are both in the same direction. So this equation that I wrote here actually works for the uphill slope. And for the downhill slope it would be the same equation except this plus sign would be a minus sign.

Q. Okay. In this case you're talking about deceleration?

A. Deceleration, right. Yeah.

Q. Now, the assumed rate of acceleration is -- you've seen in the documents --
A. Uh-huh.
Q. -- or have you --
A. Yes.
Q. -- what rate of acceleration they assumed?
A. Yeah, I think the number is, what, eleven point two feet per second squared, I'm not -- yeah, and that's about a third of the gravitational acceleration, more or less.
Q. And is that a reasonable assumption?
A. I don't know a -- yeah, it seems reasonable to me based on everything I've read and just my own sensation of braking in a car.
Q. Well, that would depend -- in other words, your opinions are not based upon challenging their assumed rates of --
A. That's right.
Q. -- acceleration or deceleration?
A. Yes. That's right.
Q. All right. All right. Referring you to paragraph seven of your affidavit, if

you just want to scan that a moment -- and, again, this is not specific to the case yet, but would you describe what is referred here as a type one dilemma zone?

A. Okay.

MS. MARTINEAU: I'm sorry, just for the record, I'm objecting to the admissibility of this testimony.

MR. STAM: Okay.

MS. MARTINEAU: Move to strike.

MR. STAM: And is that on paragraph seven?

MS. MARTINEAU: Yes.

MR. STAM: Okay.

BY MR. STAM:

Q. If you would basically explain paragraph seven of your affidavit.

A. Okay.

MS. MARTINEAU: Same objection.

MR. STAM: Continuing objection is fine.

MS. MARTINEAU: Thank you.

THE WITNESS: All right. So we -- so this goes back to the -- to the equation for stopping distance, which includes a braking distance and a distance traveled during reaction or perception.

With the assumption of the perception time and the safe acceleration that we've just talked about, you can then plug numbers into this formula depending on the initial speed of the car, that's the only other thing you need to know, and then this tells you the distance that the car will travel in stopping with those assumptions.

And if -- if the car is closer to the intersection than this distance, it can't stop safely if we assume, again, you know, the standard perception time and the standard acceleration.

BY MR. STAM:

Q. In both cases involved in this lawsuit the speed limit was forty-five miles per hour.

A. Right.

Q. So assuming that the plaintiffs were traveling at or around forty-five miles per hour, how would the math work out using those equations with respect to a type one dilemma zone?

MS. MARTINEAU: Same objection.

THE WITNESS: Okay. So what -- what

you can do is plug in numbers. So forty-five miles an hour I think is sixty-six feet per second, if I remember correctly, and if you plug in those numbers, you find -- can I pull numbers off of here?

BY MR. STAM:

Q. Sure.

A. Okay -- that this safe stopping distance comes out to be two hundred and ninety-three feet.

So a car that is farther than two hundred and ninety-three feet from the intersection has enough distance to stop safely with the assumptions about acceleration and perception time.

A car that's closer than that will travel into the intersection -- if that car tries to stop, it will travel into the intersection again with those assumptions about perception time and acceleration just because the laws of physics say that it must travel that distance before it comes to a stop.

Q. All right. Why is this called a dilemma zone?

A. The --

MS. MARTINEAU: Same objection. Sorry.
THE WITNESS: So if a car is closer than that distance, two hundred and ninety-three feet, then it can't stop safely before it gets to the intersection.
If the driver chooses to travel through the intersection, there needs to be enough yellow time -- time on the yellow light in order for the driver to physically cover that distance between the point where the driver sees the light turn and the intersection.
And if we go back --
BY MR. STAM:
Q. Now, when you say they can't do it, now, there's an assumed rate of deceleration?
A. That's right.
Q. I would assume if a person -- I'm going to assume that if a person jammed on his or her brakes very hard differently than the assumed safe rate of deceleration, that that could vary?
A. Yes, that's right. If the acceleration is greater, then the stopping

distance will be shorter.

Q. Or conversely, if the person is closer and jams on the accelerator and goes a hundred miles an hour --

A. Sure.

Q. -- they may be able to zip out the other end?

A. Yes. That's right. That's right.

Q. All right. So your assumption is not based on jamming on the brakes --

A. That's right.

Q. -- or accelerating beyond the speed limit?

A. That's right. I'm assuming in this dilemma zone that a car is already traveling the speed limit and, therefore, it can't legally speed up. And I'm assuming that jamming on the brakes -- the car isn't going to jam on the brakes either. I'm assuming this safe accel -- deceleration rate.

Q. And the safe deceleration rate was not chosen by you?

A. That's right. I'm using the assumptions in the traffic engineering literature.

Q. All right. Going now to a particular -- number nine, and giving you the assumption that the speed limit is forty-five miles per hour and that the yellow light -- amber light interval was four point oh seconds, do you have an opinion satisfactory to yourself whether or not a dilemma zone was created and the effect of that dilemma zone on a driver who is at certain distances away from the light when the amber light comes on?

MS. MARTINEAU: Objection to the -- objection to the question --

MR. STAM: Okay.

MS. MARTINEAU: -- regarding her ability to testify on issues of engineering, including dilemma zone.

MR. STAM: Got it.

BY MR. STAM:

Q. The question, remember, first, was do you have an opinion?

A. Yes, I do have an opinion.

Q. All right. What is that opinion and then please explain it?

A. Okay. My opinion is for these numbers and the standard assumptions about perception time and deceleration is that the law of motion that we've talked about pertaining to stopping says that a car has to be farther -- at least two hundred and ninety-three feet from that intersection in order to stop safely traveling at forty-five miles an hour.

But in the four seconds that the light is yellow, again, the laws of motion say that unless a car speeds up and exceeds the speed limit in that four seconds, the car can only travel two hundred and sixty-four feet.

And so unless -- unless -- if you're already traveling at the speed limit and you're between two hundred and sixty-four and two hundred and ninety-three feet from the intersection, you don't have enough time, without speeding up, to get to the intersection before the light turns red but the stopping distance is not sufficient to stop with the standard values of perception time and safe deceleration.

And so that -- you know, the terminology dilemma zone simply means that the laws of physics don't permit you to clear the intersection -- or get to the intersection at the speed limit, but they also don't permit you to stop with the assumed values of perception time and deceleration.

MS. MARTINEAU: Same objection. Move to strike.

BY MR. STAM:

Q. In other words, you can't -- for a certain number of people for whom a light changes between those distances --

A. Right.

Q. -- that far away from a yellow light --

A. Right.

Q. -- that person cannot simultaneously act lawfully and safely?

MS. MARTINEAU: Objection. Leading. Move to strike.

BY MR. STAM:

Q. Is that your opinion?

A. That's my opinion.

Q. Okay.

MS. MARTINEAU: Same objection.

BY MR. STAM:

Q. A second type of intersection

involved in this case involving Miss Lori Millette involves a left turn where the yellow light interval was three seconds but the speed limit was forty-five miles per hour.

Before opining on that particular situation, what -- what are the differences where there's a left turn signal as opposed to a straight-through signal from your knowledge of physics -- of the physics of motion, kinematics --

A. Right.

Q. -- mechanics, whatever?

A. Right. When -- when an object is turning, there's generally a safe speed at which it can turn because the friction between the tires and the road has to provide enough centripetal force to allow the car to make a turn.

Q. Explain your terms.

A. Okay. If an -- so this is a different -- this -- acceleration and deceleration relates not just to changes in speed but also changes in direction; and so for a car to change its direction, there needs to be a force on it. And if a car is turning in a circle or a part of a circle, there needs to be a force on the object pointing toward the center of the circle in which its turning.

And in the case of a car driving on the road, that force is provided between -- by friction between the tires and the road. And the amount of force that needs to be provided depends on how fast the car is going.

Q. Now, that's a new concept to me, the tire can provide force. Could you just explain that --

A. Sure.

Q. -- back up a little bit and explain how that is so.

A. Uh-huh. So the force we're talking about is the force of friction between the tire and the road. And if you think about the tires -- so here's the car making the turn, and I'm assuming the car is going this way. If you tried to push a car sideways, there would be resistance to that and that would be friction, static -- what we call static friction between the tires and the road. If there were no friction between the tires and the road, the car -- the car couldn't turn.

Even if you turned the steering wheel, the car would just continue in the direction it was originally going.

The force that --

Q. So, for example, if it's ice --

A. If it's ice, right, you can --

Q. -- there's no friction so --

A. -- there's no friction so there's no force that --

Q. Okay.

A. -- permits the car to turn.

There are standard values for how much this friction can be. It depends on the tire condition, the road condition. And so that sets a limit to how fast the car can go around the curve.

And so generally you have to be going slower to go around -- to make a turn than you would to cover the same distance in a straight line.

Q. Now, you've seen, have you not, in some of the documents that engineers should assume twenty to thirty miles per hour --

A. Uh-huh.

Q. -- for people making that turn?

A. Uh-huh.
Q. Does that sound reasonable to you?
A. Yeah. It depends so much on how sharp the turn is and the road conditions --
Q. Well, assume a ninety --
A. -- but, I mean, this is based on personal experience driving a car, it seems like a reasonable number.
MS. MARTINEAU: Objection to that question and move to strike as far as admissibility, relevance -- and relevancy.
BY MR. STAM:
Q. As a consequence of that additional factor that you're turning, does that mean a car traveling at forty-five miles per hour as the approach speed when the light goes on needs more time or less time in order to safely and lawfully either stop or safely and lawfully proceed through the intersection?
MS. MARTINEAU: Objection to the form of the question.
THE WITNESS: A car -- so a car traveling at a given speed, we had the equation for the car to stop, that's the same. The distance to stop is the same.

What's different, if a car slows down, then the time it takes to travel a given distance is longer. And so if you had two cars side by side, one going forty-five miles an hour that kept going forty-five miles an hour and one going forty-five miles an hour that slowed down to thirty miles an hour, the time it would take them to travel the same distance would be different because the average speed of the car that slows down is lower, which means --

BY MR. STAM:

Q. So --

A. -- that the -- for the same distance the time is greater.

Q. So if the two vehicles, one -- let's suppose one is planning to go straight through the intersection and one is planning to do a left turn presumably in a left turn lane, they have a forty-five mile per hour speed limit, if each vehicle plans to stop, then the stopping distance is the same --

A. Yes.

Q. -- is that correct? But if each vehicle is close enough that it has to proceed through, then what is the difference in the equation that leads you to your conclusion that you previously expressed that for turning it needs more time, not less?

A. Okay. So the relationship between velocity and distance traveled and time is still the same, but this velocity is the average velocity of the object.

So if the car traveling, say, at forty-five miles an hour continues traveling at forty-five miles an hour, then this is forty-five miles an hour.

If a car to turn needs to slow down, then this average velocity is going to be smaller. It's going to be -- if the car is braking -- braking at a constant rate to reach thirty miles an hour, then this speed would actually be the average of forty-five miles an hour and thirty miles an hour. That's smaller, and so in the same amount of time that car is going to travel a smaller distance which may mean that it doesn't -- it certainly is not going to go as far as the car that continues traveling at forty-five miles an hour. It will travel some smaller distance. Whether or not that's enough to, say, get through the intersection depends on the specific case.

Q. Okay. So if -- if it appears from the facts that the town of Cary and/or the North Carolina Department of Transportation allows four point five seconds yellow light for straight-through movement but three point oh seconds or in one case three point two seconds for a left turn movement, what would be your opinion about that?

MS. MARTINEAU: Objection to the form of that question. Lack of foundation.

THE WITNESS: That depends on the intersection and the conditions.

I can say from the laws of physics that if -- if cars are coming up -- are traveling at forty-five miles an hour in the left turn lane when the light turns yellow, then that's -- that three seconds doesn't provide enough time for all the cars that need to travel through the intersection to do so in that three seconds if they need to slow down in order to turn.

BY MR. STAM:

Q. And if they have -- if they're so close that they don't have the option of stopping, does this create a similar dilemma zone as you described as the type one dilemma zone --

MS. MARTINEAU: Objection to the form of the question. Also --

BY MR. STAM:

Q. -- for a left --

MR. STAM: I'll rephrase it.

MS. MARTINEAU: Go ahead.

BY MR. STAM:

Q. Does this create a dilemma zone for vehicles that are too close to safely stop in a left turn situation where the speed limit was forty-five miles per hour, the yellow light is three point oh seconds?

A. Yeah.

MS. MARTINEAU: Hold on a second. I'm just going to object. Objection to that question -- to the form of the question. Objection to the relevancy of the question. And objection to the ability of the -- or to the qualifications of the witness to provide meaningful testimony in answering the question. Go ahead.

THE WITNESS: Okay. My calculations using these equations that I've just described show that there's a distance from an intersection where the yellow light time is three seconds and the speed limit is forty-five miles an hour, that a car traveling forty-five miles an hour that needs to slow down in order to make a turn doesn't have the stopping distance to stop safely and does not have the time, again, according to the relationship between velocity, time, and distance, to travel through the intersection in that three seconds.

BY MR. STAM:

Q. Is that also a type one dilemma zone or is that a type two dilemma zone?

A. That's a type one --

Q. All right.

A. -- because there's a region where neither one of these equations has a solution under those assumptions.

Q. All right. If you would go to paragraph eleven of your affidavit and just briefly take a look at that.

A. Uh-huh.

Q. Is that the calculations that you made for that dilemma zone where there's a left turn and three seconds?

A. Yes.

MS. MARTINEAU: Objection to her testifying as to dilemma zone. Move to strike.

BY MR. STAM:

Q. All right. If you would now, after having taken a look at that, give us the actual -- I assume you calculated these --

A. Yes.

Q. -- at a previous time?

A. I did.

Q. All right. What are -- explain paragraph eleven.

A. Okay.

MS. MARTINEAU: Same objection.

THE WITNESS: So to calculate the stopping distance, this goes back to the equation that depends on the initial speed, the acceleration, and the perception time, and if we assume that a car traveling -- is traveling forty-five miles an hour and -- again, the standard assumed values for perception time and deceleration and we plug in -- plug those numbers into this equation, the stopping distance is -- comes out to be two hundred and ninety-three feet.

And, again, with those values for

acceleration and initial speed and perception time, there's no way that an object can travel less than that distance in coming to a stop.

So any car that is closer than two hundred and ninety-three feet, with those assumptions, can't stop before reaching the intersection.

BY MR. STAM:

Q. Now, you mean can't stop safely and legally?

A. Yes.

MS. MARTINEAU: Objection to legally. Move to strike.

THE WITNESS: It can't -- again, I'm assuming that the standard values for perception time and acceleration are -- are what constitutes safe. And under those assumptions two hundred and ninety-three feet is the minimum distance that a car traveling at that speed limit needs to stop.

But that same car, even if it continues traveling at the speed limit, which is the maximum legal speed it can travel, in three seconds it can only -- that car can only travel a hundred and ninety-eight feet.

So if a car is between --

BY MR. STAM:

Q. Now, is that -- just to be clear, is that pulling out the perception time or not, backing out the perception time?

A. The three -- perception time doesn't matter for a car that's going to travel straight through because we assume that the car --

Q. Okay.

A. -- continues to travel --

Q. I understand.

A. -- at the speed that it initially was.

Q. Okay.

A. So -- so, yeah. And so this doesn't allow for a moment of indecision where the driver starts to slow down. We assume that that driver is just going straight through at the speed limit. That's the best the driver can do and that -- that allows the driver to travel a hundred and ninety-eight feet. There's no way to travel more than that unless the driver speeds up, but we're already assuming that the driver is at the speed limit.

So any car between a hundred and

ninety-eight feet and two hundred and ninety-three feet, according to these calculations, doesn't have enough time to go straight through at the speed limit; but, again, assuming the values of perception time and acceleration, doesn't have the distance in order to stop.

Q. Now, the first example that you discussed involving straight through with a four point oh second versus four point five second --

A. Right.

Q. -- four point oh second, that dilemma zone appeared to be only twenty-nine feet?

A. Yes.

MS. MARTINEAU: Objection. Leading. Move to strike.

BY MR. STAM:

Q. Is that correct?

A. The -- if the yellow light time is four seconds, then the car can travel farther during that four seconds; and so, yeah, my calculation showed that there's a twenty-nine foot region where the driver can't stop safely but still can't travel straight through in that time.

Q. All right. In contrast with respect to left turn lanes where the speed limit is forty-five and the yellow light duration is three point oh seconds, what is the length of the dilemma zone?

A. So if the yellow light time is three seconds and the car can only travel a hundred and ninety-eight feet in that time, then the zone in which the car can't stop safely and can't also travel straight through, assuming at the speed limit, is -- that looks like ninety-five feet.

Q. Ninety-five feet. Okay. Well, what if the driver begins the approach below the speed limit, say at thirty miles an hour, knowing that he or she, in this case she, Miss Lori Millette, is going to be turning and might need to get down to thirty miles per hour, is there still a problem?

MS. MARTINEAU: Objection.

BY MR. STAM:

Q. And if so, what is your opinion on that problem?

MS. MARTINEAU: Objection. Assumes facts not in evidence. Move to strike.

THE WITNESS: If a -- so all of the previous discussion was for a car traveling at the speed limit. That's the V not in all of these equations. If we assume that's the -- so the V not is the initial speed when the light turns. If we assume that's the speed limit, then we get the numbers we just talked about.

If at the moment the light turns yellow the car is going more slowly, then the stopping distance is shorter; and the stopping distance actually gets shorter -- as the speed decreases, the stopping distance gets shorter more rapidly than the distance to travel straight through does so that shrinks that region where the driver can't safely do either one.

But at thirty miles an hour, I just -- again, the same equations and plugging in an initial speed, a V not of thirty miles an hour, I still get a region of twenty feet or so where there's not enough time to go straight through even maintaining that same speed but there's not enough stopping distance either.

BY MR. STAM:

Q. Now, you said straight through but we're talking about a left turn.
A. Yes.
Q. You mean -- would you --
A. To get to the intersection at that speed. I'm sorry.
Q. And proceed through?
A. Right. Right.
Q. You're not talking --
A. And that's, again, assuming that that's a car that is going thirty miles an hour at the instant the light turns and the car continues to travel at thirty miles an hour, whether the car is making a turn or not, I'm just assuming the distance to the intersection is the same.
Q. So if the town of Cary -- do you have an opinion satisfactory to yourself -- excuse me, satisfactory to yourself whether in the case of the town of Cary and/or the Department of Transportation having shorter yellow lights for left turns than for straight-through traffic at the same intersection, do you have an opinion whether that makes any sense at all?

MS. MARTINEAU: Objection to the form of the question. Just total objection.

BY MR. STAM:

Q. Let me -- let me rephrase that.

Do you have an opinion satisfactory to yourself whether with respect to an intersection that has both left turn and straight-through lights, and if the town of Cary and/or North Carolina Department of Transportation has a three second light for turning left but a longer yellow light for going straight through, whether that comports with the laws of motion?

A. All of these calculations depend on what the -- what the initial speed of the car is, which is the speed at the instant the light changes.

I don't know the intersection. If the intersection is such that it is reasonable for the driver to be coming up at -- you know, if the traffic is always heavy and when the light changes, the cars in the left turn lane are always going twenty miles an hour, then that might be okay because twenty miles an hour works with these equations.

But if the intersection is such that cars are routinely coming up in the left turn lane at thirty miles an hour or greater when the light changes, then my calculations show that there is a region where there's a problem.

Q. I should have added to my hypothetical that the stated speed limit for this intersection was forty-five miles per hour.

A. Right. And if cars are coming up in the left turn lane at forty-five miles an hour, then three seconds is too short a time to allow cars that are too close to the intersection to stop safely to travel through it.

Q. My question is a little bit different.

A. Okay.

Q. I'm not really addressing just whether three seconds is right or wrong. We have your figures on that. But whether -- if it's an initial speed of forty-five miles per hour, whether to have a shorter light for a left turn lane than for a straight-through lane, whether that comports with the known laws of motion of the universe?

A. If the straight-through time is set so that cars traveling at the speed limit that can't stop safely can just barely make it, then that's a problem for the left turn lane because cars making a turn have -- generally have to slow down from the speed limit. And in doing so, their average speed reaching the intersection is going to be lower and it's going to take them more time to get to the intersection, not less. Generally.

MR. STAM: Could we take about a five minute break?

MS. MARTINEAU: Sure.

THE VIDEOGRAPHER: We're off the record.

(Pause in proceedings.)

THE VIDEOGRAPHER: We're on the record.

MS. MARTINEAU: This is Elizabeth Martineau. I'm the attorney for the Town of Cary. While we were off the record a discussion was had between myself and Mr. Stam, and we agreed to stipulate that all questions are followed by a objection to relevancy as well as the qualifications of this witness to testify as an expert. And additionally, all answers are stipulated to be followed by a motion to strike so at the appropriate time a judge can determine whether or not her -- this evidence is relevant and can be admissible at the trial of this matter.

MR. STAM: And I agree to the stipulation.

MS. MARTINEAU: Thank you.

MR. STAM: Okay.

(Thereupon, Plaintiffs' Exhibit 3, graphs prepared by Brian Ceccarelli, was marked for purposes of identification.)

BY MR. STAM:

Q. Dr. George, would you take a look at what's been marked as Plaintiffs' Deposition Exhibit 3.

A. Uh-huh.

Q. Dr. George, you did not prepare these exhibits, did you?

A. I did not.

Q. I'll state for the record these are parts of exhibits to Mr. Ceccarelli's affidavit previously entered and that he prepared these exhibits; but assuming solely for purpose of discussion or hypothetical that they do illustrate what they purport to illustrate and that they come from data supplied by the Town of Cary, can you use these to illustrate any of your -- or to discuss any of your testimony?

A. Yes. So the first graph that shows Cary Town Boulevard and Convention Drive, this, I believe, is the case where the speed limit is forty-five miles an hour.

And if -- if I go back to my equations for stopping distance and for the relationship between speed and time and distance, a car that is closer than the calculated safe stopping distance at forty-five miles an hour, I calculate if that car continues traveling at forty-five miles an hour takes up to four point four five seconds to reach the intersection.

And so I see on the graph that there are two regions here, one where the straight-through yellow is four seconds, four point oh seconds. That's less than that amount of time that a car traveling the speed limit that's closer than the stopping distance would need to get to the intersection.

A car that's at the stopping distance would need four point four five seconds and so a car that's closer than that would need up to four point four five seconds.

And so if the yellow time is four seconds, I would expect that there would be cars in that region between the stopping distance and the distance that allows them to travel straight through during the yellow light who would reach the intersection -- they can't stop in that stopping distance, they would reach the intersection and the light might have changed to red up to half a second ago. And so I would expect to see a difference between having the straight through yellow set to four point five seconds, which my calculations say is the time it would take all those drivers to clear the -- to get to the intersection, and four seconds, which means that there are some drivers that can't get to the intersection in that time.

So the fact that the number of -- I assume these are citations, drops significantly when we go from four seconds to four point five seconds, makes sense with my calculations.

Q. All right. And that's the first page of Plaintiffs' Deposition Exhibit 3, which is also marked as Exhibit C?

A. Yes.

Q. All right. If you would take the second page, which is also marked Exhibit E --

A. Uh-huh.

Q. -- and this appears to be the intersection involving Plaintiff Lori Millette.

A. Right. So this, I believe, is also a forty-five mile an hour speed limit zone. And so for cars traveling straight through, again, the cars up to the stopping distance might require up to four point five seconds to reach the intersection at the speed limit, cars that would have to slow down from that to turn left would be traveling at a lower average speed and so they would require even more time. And so if the left turn yellow is set to three seconds, then it makes sense to me, based on my calculations, that there would be -- there would be a region where there would be cars that couldn't stop safely but would need more than that three seconds to get through the intersection.

Q. And is that reflected in the huge spike in citations at that intersection?

A. Well, it seems -- it seems consistent to me. The rate is fairly low until the left turn yellow has changed to three seconds and then the rate goes up by almost a factor of ten.

Q. Uh-huh. And then at some point there they turned off the light --

A. Right.

Q. -- or did something to take it to zero?

A. Zero, right.

Q. All right. Well, you know -- you said that -- you said the rate was low or relatively low; but if you compare that with Exhibit C, because, remember, here you're only allowing four seconds instead of four point five seconds --

A. Uh-huh.

Q. -- the scale of the graph is different but it's still four or five times higher than what it would be at four point five seconds. Am I reading that right?

MS. MARTINEAU: Objection to the form. Leading.

BY MR. STAM:

Q. Because the average appears to be maybe sixty, seventy, eighty per month.

A. For the four point oh second straight-through yellow?

Q. Yeah. Uh-huh.

A. Yeah. Sorry, I've lost the -- I lost the original question.

Q. Well, my question is, on Exhibit E --

A. Yes.

Q. -- whereas the four second left turn yellow was maybe one tenth as what it got to with the three seconds --

A. Oh, I see, you're comparing the first graph and the second graph.

Q. -- it's still like the precorrection Ceccarelli graph, somewhat?

MS. MARTINEAU: Objection. Move to strike.

THE WITNESS: Yeah.

MS. MARTINEAU: Counsel is testifying.

THE WITNESS: That's hard to say anything about.

BY MR. STAM:

Q. Hard to say. Hard to say. Okay. Let's go to the third page, which doesn't have a separate exhibit on it, but it's at that same intersection where it went from four point oh to three point oh. Can you use that to illustrate your testimony?

A. I assume this is the same speed limit?

Q. Same speed limit assumed -- may you -- if you assume it's the same limit.

A. If I assume it's the same speed limit --

Q. Forty-five miles per hour.

A. -- again, the calculations indicate that if the yellow light interval is three seconds, that there will be cars -- cars initially traveling at or close to the speed limit, especially those that have to slow down to make a left turn, will find that three seconds isn't long enough to reach the intersection.

Q. Now, the final page is labeled Walnut Street and Meeting Street. And, unfortunately, it doesn't have a seconds outside the shaded area so I'm not sure what you can say about that.

A. Yeah. And, again, I don't know whether -- if we assume the same speed limit, again, it --

Q. It shows three point two seconds for the shaded area.

A. Uh-huh.

Q. And if you will assume that that is a forty-five mile per hour --

A. Yeah.

Q. -- speed limit both for straight-through and a left turn --

A. Yes. And that makes sense because it says should be four point five seconds and four point five seconds is the number that it takes for a car going forty-five miles an hour to reach the intersection if it's just inside the stopping distance so --

Q. And that's with the other assumptions you made earlier?

A. That's with the other -- all of the other assumptions and assuming the car is not slowing down to make a turn or for other purposes. Yeah, four point five seconds.

So three point two -- if the yellow light interval is three point two seconds, again, I would expect, just based on those -- the laws of motion and the assumptions about deceleration and reaction time, that there would be a region where a car could not get through the intersection or even to the intersection in that three point two seconds that the light is yellow.

Q. And the scale of this graph is different than the others. This particular intersection has months where -- more than a thousand citations per month --

MS. MARTINEAU: Objection. Counsel is testifying.

BY MR. STAM:

Q. -- were written there.

MS. MARTINEAU: Move to strike.

BY MR. STAM:

Q. Is that what you read on this graph?

A. So the scale of this graph, yeah, goes up to over a thousand. That depends on numbers of cars and other factors so I'm not sure what I can say about that.

(Thereupon, Plaintiffs' Exhibit 4, Application of the ITE Change and Clearance Interval Formulas in North Carolina article, was marked for purposes of identification.)

BY MR. STAM:

Q. All right. If you would take a look at what's been marked -- that goes here -- as -- for identification as Plaintiffs' Exhibit 4.

A. Yes.

Q. And I'll stipulate that on the page one there's some handwritten stuff at that equation that was written by me and can be ignored. Have you had a chance to review this?

A. Yes, I have.

Q. I would direct your attention to the last page and the form determination of yellow change and red clearance intervals.

A. Uh-huh.

Q. Under notes.

A. Yes.

Q. With respect to the assumption about twenty miles per hour to thirty miles per hour, I guess it's the third paragraph under -- would you read -- so you know we're on the same --
A. So the -- for most left turn lanes, that part?
Q. Right.
A. For most left turn lanes assume a speed limit of twenty miles an hour to thirty miles an hour. For locations with unusual conditions, a higher or lower speed may be appropriate.
Q. All right. Now, do you know how they used that in their equation?
A. It -- from the numbers, it seems to me that they are assuming that that is the initial speed, what I called V not in these equations, and it looks like just V in these equations, the speed that the car is going when the light turns yellow.
Q. So what is the error that they're making here?
MS. MARTINEAU: Objection to the form.

BY MR. STAM:

Q. Do you have an opinion satisfactory to yourself whether whoever designed that form or that calculation made a basic error --

MS. MARTINEAU: Same objection.

BY MR. STAM:

Q. -- of physics?

A. The equation --

Q. Well, first, do you have an opinion?

A. I have an opinion. The equation --

Q. All right. What is your opinion?

A. The equation only works if the V in the equation is the initial speed of the vehicle at the time the light turns yellow.

If -- if cars are only going twenty to thirty miles an hour at the time the light turns yellow, then this equation gives a number for the yellow change interval that would allow those cars to travel to the intersection if they don't slow down further.

If there are cars that are traveling faster than that initially when the light turns yellow, then this -- this may not give enough time for them to clear the intersection if their initial speed is greater than twenty to thirty miles an hour.

Q. Is this a confusion between the approach speed and the speed within the intersection? Is that the problem?

MS. MARTINEAU: Objection. Move to strike.

THE WITNESS: It may be. If we -- if there's an intersection that is always so full of traffic that every time the light turns yellow the cars are going twenty to thirty miles an hour, then it's a reasonable assumption.

If that's not true, then it's not a reasonable assumption because the V in the equation has to be the initial speed that the fastest moving -- reasonably fastest moving car -- legally fastest moving car could have at that intersection.

MR. STAM: Could we label Dr. George's notes as Plaintiffs' Exhibit 5. How many pages of them are there?

THE WITNESS: That's three unless you want that one, too. That's the same equation. I just rewrote it so it would be easier to see.

(Thereupon, Plaintiffs' Exhibit 5, Elizabeth George's notes, was marked for purposes of identification.)

BY MR. STAM:

Q. All right. And there are -- Plaintiffs' Exhibit 5 is three pages, and we'll make copies later.

MR. STAM: The plaintiff is about to rest. Would you give me just one sec? More like a minute.

Plaintiff rests. Not rests. Plaintiff is through asking questions of the witness. Over to you.

MS. MARTINEAU: Dr. George, my name is Elizabeth Martineau. I'm an attorney and I represent the Town of Cary in this matter. I do have some questions for you.

CROSS-EXAMINATION

BY MS. MARTINEAU:

Q. How do you know Mr. Ceccarelli?

A. I was a classmate of his in college at the University of Arizona in several classes back in the early '80s.

Q. And since that time have you kept

in contact with him?

A. I have not.

Q. Okay. So tell me, how were you first contacted to provide an affidavit in this case.

A. Brian called me, I don't remember when exactly, and asked if I would look at some things that he had written and eventually to provide an affidavit as to the physics of the situation.

Q. So what is your understanding of what your role in this case is?

A. My understanding is that my role is to discuss the -- validate the basic physics behind the equations that are being used here and to show how they apply to the particular intersections that are under discussion.

Q. Have you ever been to these intersections?

A. I have not.

Q. Okay. Have you ever been to North Carolina?

A. I have.

Q. Okay. And when was that and what was the purpose for that?

A. That was in -- I don't remember the exact year. About 1992 I went to Triangle University laboratory to visit a researcher there who was working on a project that was similar to one I was working on. I was there for about a week.

Q. Did it involve traffic signal designs in any way?

A. No.

Q. Did it involve calculating yellow times for traffic signals in any way?

A. No.

Q. Okay. So you have a bachelor's in science and physics; is that right?

A. That's right.

Q. Okay. And then you have a master's in medical physics?

A. That's right.

Q. And then you got your Ph.D. in physics?

A. Right.

Q. Okay. And you teach -- you currently teach -- or share courses with your husband teaching physics classes?

A. Yes. I mean, we teach -- we don't

teach the same courses, but we teach half of a full-time teaching load at Wittenberg.
Q. Okay. And have you ever provided expert witness testimony before?
A. No, I have not.
Q. Are you licensed to practice engineering in any state?
A. I am not.
Q. Do you plan on giving engineering standard of care questions in this -- or opinions in -- strike that.
Do you -- yeah, do you plan on giving engineering standard of care opinions in this case?
A. No.
Q. Are you familiar with the North Carolina Board of -- North Carolina Board of Engineering and Surveyors?
A. Not as such, no.
Q. Have you ever sat -- have you ever sat for the boards in engineering in any state?
A. No.
Q. Are you -- are you a member of any engineering society?
A. No.

Q. Okay. How about the International Transportation Engineers Society, are you -- do you -- have you ever had the opportunity to work with them in your role as either a professor or researcher?
A. No.
Q. How about -- are you familiar with the engineering -- the professional engineering requirements for the state of North Carolina?
A. For the state of North Carolina, no.
Q. And you don't purport to practice engineering --
A. No.
Q. -- do you?
A. I don't.
Q. Do you know what the North Carolina law is regarding what -- because we -- Mr. Stam used the term lawfully from time to time. Do you know what the North Carolina general statute traffic law is regarding steady yellow lights?
A. Is this -- I'm not sure I do.
Q. Okay. And you just took a look at some material that you have. Can you -- I'm

over -- you know, I'm not sitting next to you, but can you go through what you have in your file, please?

A. I do have the Manual on Uniform Traffic Control Devices relating to yellow lights.

Q. And what is the date of that publication?

A. 2009, including revision one and revision two dated May 2012.

Q. Okay. What else do you have in your file?

A. I have my individual calculations for the data that was provided. Let's see what else do I have? I have the Institute of Transportation Engineer's Traffic Engineering Handbook. And the rest of this is, I believe, materials that Mr. Ceccarelli has written that are on the web and other places.

Q. And I don't want to take your file with me, but do you have any objection to me -- or after this deposition is over to copy your entire file that you brought and provide it to Mr. Stam so we can attach it as an exhibit to this deposition?

MR. STAM: We can probably do it today. It's very limited.
THE WITNESS: Yeah, that's --
MR. STAM: Let's do it before we go.
THE WITNESS: That's fine.
BY MS. MARTINEAU:
Q. Is that fine?
A. That's fine. Oh, I also have -- yeah. I have a paper by Denos Gazis, The Problem of the Amber Signal Light in Traffic Law.
Q. When is the first time you ever reviewed that paper by Denos Gazis?
A. Probably a little over a year ago. It was one of the materials that Brian Ceccarelli suggested that I look at, and I think he had it linked on his website.
Q. And that was solely in relation to -- the purpose of you reviewing that article was solely in relationship to either your affidavit or the work that you were going to be doing on this case?
A. Yes.
Q. Have you ever -- in your either education, your training, your teaching, or any

other additional continuing education credits that you may have received in your role as a physicist, have you ever had the opportunity to review that document before?

A. That document, no.

Q. Okay. You also indicated you have an ITE Traffic Engineering Handbook?

A. Some pages from it.

Q. Okay. And we will -- you know, once it gets copied, I'll have a better idea of what you have, but where did you get that from?

A. This I got from Mr. Stam.

Q. Okay. And when did you receive that from him?

A. Yesterday.

Q. And did you meet with Mr. Stam yesterday?

A. I did.

Q. And did you talk with Mr. Stam about what your opinions might be?

A. Yeah. I mean, he -- he had already seen the affidavit and it was basically that.

Q. Okay. And did you work with Mr. Ceccarelli in preparing the affidavit?

A. I did -- actually did not.
Q. Who did you work with in preparing the affidavit?
A. Mostly myself. I had my husband, who is a physicist, just check over my numerical calculations to make sure I hadn't plugged in an incorrect number anywhere.
Q. Who typed the affidavit?
A. I did.
Q. Okay. And so is it your position and testimony that your -- that you are here to give opinions and to provide physics equations related to the laws of motion?
A. Yes.
Q. Okay. Any other role in this case?
A. Well, the physics equations and as they apply to specific cases.
Q. When you say as they apply to specific cases, what do you mean?
A. I mean the applications of the general equations of motion to these specific -- some of the specific intersections.
Q. Have you reviewed the signal plans for these specific intersections?

A. I believe that some of that information was -- may be on the website -- Mr. Ceccarelli's website.

Q. Okay. So you've reviewed his website?

A. I have.

Q. And you think that some of those materials might be on his website?

A. I have -- I have a memory that they might be, but I might be wrong.

Q. Okay. Now, the Uniform -- excuse me. The Manual of Uniform Traffic Control Devices, you have part of that in your file today, do you use that manual at all in your -- in your current work?

A. No.

Q. Do you teach that manual at all to any of your students?

A. I don't -- I don't teach the manual. When we teach introductory physics courses that have to do with mechanics, we often work example problems and have the students do as homework problems that are similar to this. In a standard introductory physics textbook you would have, you know, a problem of how long it takes a car to stop or how far it can travel. But the manual specifically, no.

Q. Okay. And that's my question. So do you use the actual manual --

A. The actual manual, no.

Q. -- of Uniform Traffic -- and just for the purposes of the court reporter, if you could let me finish my question --

A. Oh.

Q. -- before you answer and then I'll give you the time to answer. It just makes for a better record. It's not how people talk but it does make for a better record.

A. Yeah. Sure.

Q. Okay. So do you use the Manual of Uniform Traffic Control Devices in any course that you teach?

A. No.

Q. Okay. In your publications that are attached to your CV, do any of those publications have to do with traffic signal design?

A. They do not.

Q. Has traffic -- other than -- prior

to being contacted by Mr. Ceccarelli, had traffic signal design ever been an interest of yours professionally?

A. Not -- not as a researcher. As a teacher, it's an interesting case to have students look at in introductory physics courses but not as a researcher.

Q. In your introductory physics courses do you ever -- do you ever teach students how to design traffic signal plans?

A. Not specifically.

Q. Okay. Now, do you have any opinion -- well, let me -- before I ask you that -- in your role as a professor at Wittenberg University -- is it --

A. Yeah, university.

Q. -- do you ever supervise either undergrad or graduate physics majors --

A. In --

Q. -- in terms of individually for --

A. In research?

Q. Yes.

A. Yes.

Q. Okay.

A. Undergraduate. We're only

undergraduate.

Q. Okay. And what type -- do those research students that you -- what would be the proper word? I just can't think of it when you're a professor and you have a student that you are sort of supervising in a research capacity.

A. Word for what I do or what they --

Q. What you do.

A. Mentor.

Q. Okay. Let's use -- when you're mentoring these students, what types of research would these undergrads be interested in or working on?

A. Some of them work on nuclear physics research that I'm involved in. I've had a number of students work on a project that we're doing with the geology department to study how changes to lowhead dams in Buck Creek affect the flow of the river. I've had some students work on projects in electronics to measure very short time intervals with electronic circuits. I've had students work on physics education projects. Projects to measure -- construct a pressure sensor that can measure underwater. So it's a variety.

Q. Okay. Would it be accurate to say that none of those research students that you are mentoring are -- do research in traffic engineering?

A. None of them have.

Q. And you don't -- you've never taught any course specific to traffic engineering?

A. No, not specifically to traffic engineering.

Q. And you've never taught any course that dealt with engineering standards of care?

A. Right.

Q. And you've never taught any course regarding engineering standards of practice?

A. Right.

Q. Are you -- so how did you -- what did you do when you got this case in order to -- well, prior -- let me back up.

Prior to Mr. Ceccarelli contacting you, were you aware of what ITE, the Institute of Traffic Engineers, recommended for designing yellow times and all red times and things like that?

A. No, I was not specifically aware of that.

Q. Okay. How about even generally, have you ever generally been aware of what ITE recommended?

A. No, I -- yeah.

Q. Okay. And how about the Uniform Manual on Traffic Control Devices, prior to being contacted by Mr. Ceccarelli, did you have any understanding of what the manual required or what their standard was for designing yellow times?

A. No, not specifically.

Q. Okay. How about just in general, did you ever, prior to Mr. Ceccarelli contacting you, ever refer to the manual for -- for how yellow times were to be determined?

A. I don't think I did.

Q. Do you know what the stat -- the North Carolina statutory requirement is for yellow times at intersections where Wake County municipalities install red light cameras?

A. I don't think so.

Q. Did you understand my question?

A. Yes.

Q. Okay.
A. And this is the specific legal statutory requirement?
Q. Right.
A. Yeah. No, I can't quote that.
Q. Okay. Do you have an opinion whether or not the signal plans at issue in this case -- the official signal plans were signed and sealed by a North Carolina licensed professional engineer?
A. I do not.
Q. Do you have an opinion of whether -- well, have you -- you said you looked at some of these signal plans. Did you look to see whether or not the signal plans complied with the MUTCD?
A. No, I don't think I did.
Q. Did you -- as you sit here today, do you know what the 2003 MUTCD requirements were for the length of yellow times?
A. 2003. No.
Q. Okay. How about 2009? Well, let me ask you this: Do you know what the date is of the official signal plan of record for Mr. Ceccarelli's intersection? Do you happen

to know what the date of that plan is?
A. No, I don't.
Q. Okay. Do you know which version of the manual was in effect at the time --
A. No, I don't.
Q. -- that signal -- I'm sorry -- that signal plan was designed?
A. No.
Q. Do you know what the standard of practice is for engineers anywhere for how often signal plans need to be redesigned?
A. No.
Q. Okay. Do you know what the 2009 version of the Manual of Uniform Traffic Control Devices, what they have to say about yellow times -- the design of yellow times?
A. No, I don't remember what that is. I think I've looked at it, but I don't remember.
Q. Okay. Do you recall in any of your investigations that you did for this case whether or not you saw that any of the -- any of the yellow times that you're aware that is at issue in this case exceeded the -- either exceeded or was not -- what's the opposite of

exceeded -- either were longer -- well, strike that. Let me ask a new question.
Do you know whether or not any of the signal plans that you looked at related to this case, whether any of those yellow times did not comport with the times allowed in the manual?
A. No, I don't know that.
Q. Okay. Are you -- I don't want to testify for you, but do you recall hearing that the manual required yellow times be between three and six seconds?
A. That's -- that's a -- those are numbers that I've read in a lot of documents. I can't tell you exactly which ones, but I do remember reading those general numbers.
Q. Okay. Are you aware of any yellow times at issue in this case that are less than three seconds?
A. No, I'm not.
Q. Okay. Do you know what the definition of -- or the purpose -- let me ask you differently.
Do you know what the purpose, according to the Manual of Uniform Traffic

Control Devices, either 2003 or 2009, what the purpose of the yellow time interval is?

A. No, I can't quote you that.

Q. How about in general? Do you have a general understanding of what the purpose of the yellow change interval is?

A. No. I have -- I have only my own understanding of what the yellow change interval is for, I guess.

Q. Sure. And what do you base what your understanding of what the yellow change interval is for on? Where does that come from?

A. Well, it comes from -- it comes from physics. It comes from understanding that there are going to be cars that are too close to the intersection to stop safely and that the yellow change interval should be long enough to let them get -- the yellow, plus the red, needs to be long enough certainly for them to get through the intersection safely. And the yellow itself, I assume, is to let them get to the intersection before the light turns red.

Q. Okay. Have you -- do you recall in your preparation for giving testimony today whether you came across any definition of -- or purpose -- either definition of or purpose of yellow change intervals to alert the driver that the -- that the -- that the signal -- that the color of the signal is about to change?

A. Oh, yes.

Q. Okay.

A. Yeah.

Q. All right. And that is different, you would agree, with a definition of a physics calculation, correct?

A. Well, if the only purpose of the yellow light is to alert drivers that the signal is about to change, then there doesn't need to be a minimum for the yellow light.

Q. Okay. That's a different question. Your answer -- I mean, that -- you answered a different question, but -- but my question --

A. I would say that's one of the purposes of a yellow light.

Q. Okay. And where -- okay. And have you ever been taught what the purpose -- have you ever in your education or your training or your background as a physicist, were you ever -- did you ever take any course or do you recall being taught what the purpose -- what the engineering purpose of a yellow change interval was?

A. Not in any course I took.

Q. And you also -- how about in terms of an all red signal, have you prior to being contacted by Mr. Ceccarelli in your -- any of the courses that you teach and any of the courses that you recall -- you know, any of the information you recall being taught as a physics student and any of the research that you've done in your professional life, was the study of red change intervals any -- ever a part of that?

A. Actually, I mentored a student in an electronics project where we had to get the electronics timing logic correct in order to produce red intervals of -- all red intervals of a certain amount of time, and there was an explanation there that the all red interval is to allow time for traffic to clear the intersection before traffic going in the other direction is released and that that might depend on the size of the intersection and other factors.

Q. So --
A. But not in any class I took ever.
Q. Okay. So --
A. This was something that I read as part of helping a student with a project.
Q. Have you -- prior to being contacted by Mr. Ceccarelli, have you done any research or study into the engineering problem of too -- of yellow times that are too long?
A. Not prior to being contacted by him.
Q. Since being contacted by him have you undertaken any either research or study into the engineering -- well, into -- into why engineers might not want yellow times to be too long?
A. I have read in some of these materials a little bit about that, particularly for high speed intersections, that simply applying the formula and having yellow lights that are too long might lead to results that are not desired. My memory is that those are for longer times, up to the six second maximum we talked about earlier.
Q. And this was -- so this was

something that you would -- did you get this information from reading engineering articles or journals about why yellow times -- you know, why yellow times should not be too long?

A. Yes. I think probably these traffic manuals and ITE documents.

Q. Do you know whether or not the yellow times that are on the signal plans of record that are at issue of this case, whether those are consistent with traffic engineering standards and/or practices promulgated by the ITE?

A. I -- my sense is that they're not consistent because they're not up in that upper level of times that would be considered to be too long.

Q. Okay. I'm not talking about -- okay. In terms just of the length of the yellow times at issue in this case that are on the signal plans of record, do you know whether or not -- in your investigation, did you come across any information to say that -- that would indicate that the yellow times on the signal plans of record in this case are not in conformance with ITE recommendations?

A. Not specifically.
Q. And I think you testified earlier that you came -- that you did -- in your investigation or your research for giving opinions in this case, that you did note that ITE recommended using an assumed speed for left hand turns between twenty and thirty-five miles an hour; is that correct?
A. That was in one of the documents I read. I'm not sure that that was an ITE recommendation.
Q. Okay. So you don't know where that came from but you saw that somewhere?
A. Uh-huh.
Q. Is that correct?
A. Uh-huh.
Q. Yes?
A. Yes.
Q. Have you ever published or sought to publish any scholarly articles or research related to traffic signal engineering?
A. No.
Q. Have you ever published or sought to publish any article -- scholarly article or research regarding traffic engineering standard

of care or practice for designing signal times?

A. No.

Q. Have you ever been hired by any organization that promulgates or publishes guidelines or practices or standards of care for traffic signal engineering?

A. No.

Q. You talked about -- you used the term to safely stop. And I think you actually at some point did give a definition of what you meant by safe. Can you just -- I didn't write it down. Can you tell me what -- again, what you mean when you say in your affidavit or in your testimony today to either safely stop or stop safely?

A. I am there using the -- what I understand to be the standard values for perception or reaction time and deceleration that is provided in the literature and the equations of motion that show how much time or distance it will take with those assumptions in order to stop.

Q. When you talk about the deceleration time provided in the literature, what do you mean by that?

A. The perception time or the --

Q. Well, you said deceleration time. Not perception -- well, you said perception/reaction, deceleration time provided in the literature. My question is related to the deceleration time.

A. Well, the deceleration time is calculated from the equations of motion using the perception or reaction time and the value of deceleration.

Q. Where do you get the value of deceleration from?

A. Various -- well, there -- I've seen various assumptions in various of these traffic engineering documents and codes. I think the number I used in my calculations was eleven point two feet per second squared.

Q. Where did you get that from?

A. I would have to look. It's one of -- it's one of these -- can I look?

Q. Sure.

A. Okay. Because I know it's one of these --

MR. STAM: May I refer her to the correct exhibit and page?

MS. MARTINEAU: Well, let -- she's -- I mean, I don't know.
THE WITNESS: Yeah, let me see if I can find it.
BY MS. MARTINEAU:
Q. While you're looking -- well, go ahead.
A. Yeah.
Q. You can --
A. For example, I see in the Traffic Engineering Handbook there's actually a deceleration rate of ten feet per second, which is less than the number I used, eleven point two. So the number I used was actually a little more conservative.
Q. And if I may, Dr. George --
A. And I -- my affidavit says I used North Carolina Department of Transportation values.
Q. So is it fair to say that you -- that you determined what the calculation was by going to and referring to engineering publications?
A. I determined the numbers to use in the calculations from engineering publications.

Q. Prior to being contacted by Mr. Ceccarelli, when would you have used those calculations before before that?
A. Well, we do calculations like that in the introductory mechanics course for, you know, typical -- so I probably have used typical numbers for -- I know I have used typical numbers for perception time and deceleration. And the numbers I found in the engineering literature were close to numbers that I've used before when teaching introductory physics.
Q. And does your introductory -- do you have your introductory physics class -- do you teach physics related to automobiles?
A. Partly. We use automobiles as examples in our introductory class.
Q. Okay. Is it your testimony that -- you talked about -- well, where -- had you studied dilemma zones prior to being contacted by Mr. Ceccarelli?
A. I wasn't familiar with the terminology; but, again, in introductory physics courses, we do calculations like this. But the term dilemma zone was not familiar to

me.

Q. Okay. And the term -- the engineering term dilemma zone was not something that you utilized -- that you utilized?

A. Not in those words.

Q. Okay. Right. So --

A. But the concept, yes, again, in teaching introductory physics that it may be possible for a car to not stop safety and then you can figure out how long it takes the car -- a car to get to the intersection under those conditions. The term dilemma zone, no, but that -- that concept is familiar.

Q. Okay. So the term dilemma zone is not a term that you used or use in teaching physics?

A. That's right.

Q. Okay. It was something that you came across in preparing for your research and testimony today?

A. That's right.

Q. And -- okay. And when you say stop safely, you don't mean to be able to -- well, strike that. I'm going to strike that.

Do you know what the laws of North

Carolina say about whether or not a driver in order to abide by the law has to stop the car prior to the red light being activated or just must enter the intersection prior to the red light being activated?

A. I -- no, I assume that a driver who is outside the stopping -- I don't know, but I assume that a driver that is outside the stopping distance, farther from the stopping distance who is still braking while the red light comes on is fine as long as that driver does not enter the intersection.

Q. Okay. What about can -- if the driver does enter an intersection on a yellow light and then that light turns red while they're in the intersection, do you know whether that violates the laws of North Carolina?

A. I don't know those laws of North Carolina.

Q. Okay. Do you have any information as to these intersections of crash rates at the intersections?

A. No, I don't.

Q. And you've never -- in your role

as a physicist and as a teacher and as a researcher, have you ever done studies regarding crash rates at intersections?

A. No, I haven't.

Q. From a physics point of view, are you aware that it takes -- if a car is stopped at a stoplight and then that stoplight turns to green, that some laws of motion would come into play as to when that car actually enters the intersection?

A. Sure. There would be a perception time and then acceleration.

Q. And do you know whether or not engineers use that perception time when -- or take into consideration that perception time when they do the traffic signal plans?

A. I don't know that.

Q. And, again, is that because you don't practice traffic signal engineering?

A. That's right.

Q. And you don't know what the standard of care is for traffic signal engineering?

A. Not for that.

Q. And it's not your -- it's not your

role to provide testimony today on engineering practices, correct?

MR. STAM: Objection --

THE WITNESS: Correct.

MR. STAM: -- solely to the redundancy.

THE WITNESS: That's right.

BY MS. MARTINEAU:

Q. Do you know how fast -- well, have you -- do you know how many of the red light camera citations that were issued by the town of Cary for the intersections at play, do you know how many of those people were in the dilemma zone --

A. I do not.

Q. -- at the time they -- or leading up to them receiving a citation?

A. I don't know that.

Q. So would you agree that -- well, I mean, so for those vehicles that were not within what you consider to be the dilemma zone, that those vehicles should have either been able to stop or continue through the intersection and not have received -- excuse me, could have either stopped or proceeded through the intersection safely?

A. I -- I don't know for sure. The dilemma zone, as I've defined it, assumes that a driver that proceeds through the intersection doesn't need to slow down. If that's the case at these intersections, then there probably were drivers -- there are regions -- there are still regions where a driver can stop or proceed through the intersection safely even if there is a dilemma zone.

Q. Okay. And you have no idea what percentage of drivers that receive red light tickets --

A. No.

Q. -- did that or not?

A. No.

Q. And that's not part of what you were asked to do today?

A. That's right.

Q. And Mr. Stam identified Plaintiffs' Exhibit 4 for your deposition. Had you seen this before, Plaintiffs' Exhibit 4?

A. I saw it yesterday.

Q. Okay. So you saw it yesterday for the first time?

A. Yes.

Q. Okay. Prior to seeing -- I said defendant's, I'm sorry. Prior to seeing Plaintiffs' Exhibit 4, had you been aware that the North Carolina section of the Institute of Transportation Engineers undertook a study?

A. No.

Q. Okay. And did you read in here that this study recommends the practice of using twenty miles an hour for an assumed left turn speed?

A. I read assume a speed of twenty miles an hour to thirty miles an hour. For locations with unusual conditions a higher or lower speed may be appropriate.

Q. Okay. And do you know what the qualifications -- or the engineering qualifications were for the members of this task force?

A. No.

Q. Do you know whether they were professional engineers or not?

A. No, I don't.

Q. Okay. To the extent that the licensed engineers who designed the signal plans at issue in this case used an assumed speed for left turns of twenty miles an hour, would you agree that that's consistent with what is recommended in Plaintiffs' Exhibit 4?

A. It's -- I don't have enough information to answer that. It's not inconsistent. It's the lower number of what is recommended here, and I don't know whether there are unusual conditions that might make that not applicable.

Q. Okay. But you would agree that if a licensed North Carolina engineer used twenty miles an hour for an assumed speed for a left turn when designing a yellow time, that twenty miles an hour is within the twenty to thirty miles an hour recommended by this publication, correct?

MR. STAM: Objection to form, and I'll be glad to tell you what it is.

MS. MARTINEAU: That's okay.

THE WITNESS: Twenty miles an hour is between twenty and thirty miles an hour.

BY MS. MARTINEAU:

Q. Do you know how fast Mr. Ceccarelli was when he first saw the yellow -- excuse me -- the light in his direction of travel turn from red to yellow?

A. I don't.

Q. Do you have an opinion of whether or not Mr. Ceccarelli could have stopped prior to the light turning red if he had wanted to?

A. Not knowing his initial speed and his position, I don't.

Q. Okay. And the same question for Miss Millette, do you know how fast Miss Millette was going --

A. No.

Q. -- when she first noticed the light in her left turn direction of travel to change from red -- excuse me, from green to yellow?

A. No.

Q. So you have no opinion of whether or not Miss Millette could have either stopped prior to the intersection -- excuse me, could have stopped before entering the intersection safely?

A. No.

Q. How about have you ever undertaken -- either before or after being contacted by Mr. Ceccarelli in this case, have you ever undertaken to do any traffic studies?

A. No.

Q. So you've not gone out to an intersection and watched left-hand turn drivers to see how fast they travel, correct?

A. That's correct.

Q. I'm almost done. Dr. George, do you have --

MS. MARTINEAU: Sure. Go ahead. We'll go off the record.

(Pause in proceedings.)

THE VIDEOGRAPHER: We're on the record.

BY MS. MARTINEAU:

Q. And, Dr. George, I already -- I'm going to ask -- I already asked you the question regarding your opinions on the 1991 signal plan where Mr. Ceccarelli received his citation, but I want to ask you about the other signal plans. I understand that you may or may not have reviewed them, but do you know or do you have an opinion of whether or not the '06 signal plan at Maynard and Kildaire Farm Road, whether the yellow time at that -- on the left-hand turns at those intersections, whether they are in full conformance with the requirements of the Manual of Uniform Traffic Control Devices?

A. No.

Q. You don't have an opinion whether or not --

A. I don't have an opinion.

Q. Dr. George, do you have an opinion of whether or not the yellow times on the signal plan at High House Road and Cary Parkway, whether those yellow times are in full conformance with the requirements of the -- set out in the Manual of Uniform Traffic Control Devices?

A. I don't have an opinion.

Q. Dr. George, do you have an opinion of whether or not the yellow times on the signal plan at play in this case for Kildaire Farm Road and Cary Parkway, whether those yellow times are in full conformance with the requirements of the Manual of Uniform Traffic Control Devices?

A. I don't have an opinion.

MS. MARTINEAU: Thank you,

Dr. George. Those are the questions I have for you.

MR. STAM: Dr. George, a few additional questions.

REDIRECT EXAMINATION

BY MR. STAM:

Q. I note on your CV that you are a reviewer for the nine chapters of the third edition of Knight book entitled Physics for Scientists and Engineers?

A. Yes.

Q. Why would they ask a physicist to review a book written for engineers?

A. Well, it's a -- it's a book for the introductory physics course that is taken by people who are in either science majors or engineering majors. Most -- most engineering majors, if not all engineering majors, have to take that introductory physics course.

Q. Why?

A. Because -- well --

Q. You design curriculum?

A. Yes. And have worked with students who have gone on to be engineers, and I -- they use those basic physics principles in their engineering.

Q. Engineering is applied physics and chemistry and --

MS. MARTINEAU: Objection to the form of the question. Move to strike testimony of Mr. Stam.

MR. STAM: I wasn't quite finished with my question.

BY MR. STAM:

Q. Is engineering applied physics and chemistry and other sciences?

A. Engineering is the application of science and math to real world problems.

Q. You were asked about the signal plan for the intersection where Mr. Ceccarelli -- the intersection -- the site plan for the intersection where Mr. Ceccarelli had his citation for not stopping at the red light.

Regardless of the date of that signal plan, did you know that that signal plan assumed a speed limit of thirty-five miles per hour when the actual speed limit was forty-five miles per hour?

MS. MARTINEAU: Objection. Testimony

of Mr. Stam.

THE WITNESS: I remember reading in some document that the yellow light interval had been created for a speed of thirty-five miles an hour, yes.

BY MR. STAM:

Q. And is the approach speed, which in this case I assume is the speed limit, what they used, if you miss on the V -- if you input the wrong variable there, will you get the wrong output on the equation?

A. All of those equations assume that that V is the speed that the vehicle is going when the light turns yellow. So, yes, if you use the wrong V, you get the wrong numbers.

Q. Garbage in, garbage out?

A. Right.

Q. Okay. Now, if the only purpose of a yellow light were to let you know that a green light is coming --

A. A red light.

Q. -- a red light is coming and presumably, therefore, a green light is coming --

A. Uh-huh.

Q. -- at the perpendicular road --
A. Uh-huh.
Q. -- and there's an eighteen-wheel trucker coming and is about to hit you if you don't get out of the way, I guess you would be alerted if it were only two seconds so that you could prepare for death?
MS. MARTINEAU: Objection. Move to strike.
BY MR. STAM:
Q. Is that why there's other purposes for a yellow light?
MS. MARTINEAU: Same objection, as well as her qualification to testify as to the engineering reason -- purpose of a yellow light.
THE WITNESS: If the only purpose of the yellow light is to tell you that the red light is coming and that the green light is coming the other way, then I wouldn't -- it could be -- it could be -- the yellow light could be very short. It would not have to have any length that has anything to do with the speed limit or anything else like that. It could be, yeah, as short as -- as short as you want if the only purpose is to alert you that the light is going to change.

(Thereupon, Plaintiffs' Exhibit 6, Traffic Engineering Handbook, 6th Edition, was marked for purposes of identification.)

BY MR. STAM:

Q. I'll show you what's been marked for identification as Plaintiffs' Exhibit Number 6 and ask if this is also a document that has been provided to you?

A. Yes. I have seen this document before.

Q. And it appears to be certain pages from what?

A. The 6th Edition of the Traffic Engineering Handbook, Institute of Transportation Engineers.

Q. If you would take that along with -- pages four twelve and four thirteen of that publication and then also look at Plaintiffs' Exhibit 4, page twenty-four, and compare, I guess I'll say, the factual assumptions for reaction time and deceleration rate.

A. Uh-huh.

Q. Are they different or similar or the same?

A. They're not the same. The reaction time in the traffic engineering handbook says typically one second and in the other document typically one point five seconds.

Q. Now --

A. And --

Q. Is that because one it says reaction time and the other says --

A. Perception/reaction time.

Q. -- perception/reaction time, or is that just a difference of opinion amongst engineers whether it should be one second or one and a half seconds, if you know?

A. I don't. I don't know.

Q. All right.

A. I -- just based on the use of the equation, I assume it's referring to the same thing, that is the time it takes the driver to put the brakes on after the light is perceived to be yellow.

Q. Okay. So you take that as just a change in the opinion of engineers whether -- how long it will take?

A. Yes. That's what I would assume.

Q. Okay. And you -- either one -- does your formula work with either one? I might not be asking the question right.
A. The formula is the same. The numbers that I quote -- quoted in the affidavit and that I quoted earlier are assuming the longer time --
Q. The one point five?
A. -- the one point five seconds because that gives a more conservative estimate of the --
Q. Okay. And that's the one that's specific to North Carolina --
A. Okay.
Q. -- as I understand it; is that correct?
A. Yeah. Well, that's --
Q. All right.
A. And that's the number I've been using.
Q. Would you also look at the deceleration rate.
A. Uh-huh. So in the Traffic Engineering Handbook it says typically ten feet per second squared and in the ITE journal

eleven point two feet per second squared.
Q. Okay. And is that what you used, the eleven --
A. I used the eleven point two. Again, that's more conservative.
Q. Now, when you say conservative, you're not referring in any political sense?
A. No.
MS. MARTINEAU: You're not?
BY MR. STAM:
Q. Okay.
A. Not that I know of. I haven't read the Republican party platform.
Q. On physics. Okay. Now, they both appear to be addressing the same question, do they not?
A. Yes.
Q. Of how to calculate the yellow light interval?
A. Right.
Q. Both of them in the -- V in the actual -- what do you call that, a formula or an equation?
A. Either one.
Q. All right. Say V equals design

speed and is that --

A. Feet per second.

Q. -- feet per second?

A. Uh-huh.

Q. All right. Is that talking about the design speed when you're in the middle of the intersection using the friction of your tires to help you decelerate or is that talking about the design speed at which you first see the yellow light?

A. The equation -- in this equation V is the speed when you first see the yellow light.

(Thereupon, Plaintiffs' Exhibit 7, Manual on Uniform Traffic Control Devices for Streets and Highways, 2009 Edition, was marked for purposes of identification.)

BY MR. STAM:

Q. I'd like to show you one other exhibit. That goes here.

If you would take what's been marked as plaintiffs' Exhibit 7. Were you provided this prior to your deposition?

A. Yes.

Q. And you were asked about this on

cross-examination, I believe; is that correct?
A. Yes.
Q. Now, just tell us what it is for the record?
A. This is a page from the 2009 Edition Manual on Uniform Traffic Control Devices.
Q. All right. Do you have page five twelve?
A. Five twelve.
Q. What does page five twelve say about how the standard -- what the standard is for the duration of the flashing yellow interval to be determined by engineering judgment?
MS. MARTINEAU: Objection. Mischaracterization of the testimony.
MR. STAM: I'm sorry.
MS. MARTINEAU: Move to strike.
MR. STAM: I'm sorry. I'll withdraw that.
BY MR. STAM:
Q. Would you read from point 05 through point 07?
A. Sorry.

Q. About two-thirds of the way down.
A. Yeah. Does that start with the standard?
Q. It would start with the duration.
A. The duration.
Q. Actually, if you would go --
A. The study?
Q. -- right above that. Guidance.
A. So guidance, the duration of the flashing yellow interval should be determined by engineering judgment.
Q. Okay.
A. Standard, the duration of the steady yellow change interval shall be determined using engineering practices. Guidance, the steady yellow interval should have a minimum duration of three seconds and a maximum duration of six seconds, see Section 4D.26. The longer interval should be reserved for use on approaches with higher speeds.
Q. Is there a big difference between three seconds and six seconds in the use of your formula?
A. Yes.
MR. STAM: Okay. No further

questions.

RECROSS-EXAMINATION

BY MS. MARTINEAU:

Q. Dr. George, do you know when the 2009 Edition of the Manual on Uniform Traffic Control Devices was first published?

A. No.

Q. Are you -- do you know if you meet the qualifications in any state to sign and seal traffic signal plans?

A. I do not.

Q. You don't know?

A. No, I don't -- I don't meet the standards. I know I don't.

Q. Okay.

A. Well, okay. I don't know all state laws. I don't know.

Q. Okay. How about, did you look -- how about North Carolina, do you know if you meet the standards in North Carolina -- well, let me ask you, are you qualified in North Carolina to sign and seal traffic signal plans?

A. No. Well, I don't know.

Q. You don't know? And I think I asked you this: And as far as -- do you know what the North Carolina statutory definition of the practice of engineering is?

A. No.

MS. MARTINEAU: Okay. Thank you very much.

MR. STAM: Just shall we -- are these the copies of her --

MS. MARTINEAU: Are we done?

MR. STAM: Yes. Oh, I want to ask you a question.

FURTHER REDIRECT EXAMINATION

BY MR. STAM:

Q. Dr. George, do you claim to be an engineer?

A. I do not.

MR. STAM: Thank you. No further questions.

THE VIDEOGRAPHER: We're off the record.

(Thereupon, Defendant's Exhibit A, Elizabeth George's file material, was marked for purposes of identification.)

(Thereupon, signature was not waived.)

(Thereupon, the deposition was

concluded at 9:58 a.m.)

I, ELIZABETH A. GEORGE, Ph.D., do hereby certify that the foregoing is a true and accurate transcription of my testimony.

_ _ _ _ _ _ _ _ _ _ _ _ _ _

Dated _ _ _ _ _ _ _ _ _ _ _ _ _ _

STATE OF OHIO)
COUNTY OF MONTGOMERY) SS: CERTIFICATE

I, Kathy S. Wysong, a Notary Public within and for the State of Ohio, duly commissioned and qualified,

DO HEREBY CERTIFY that the above-named ELIZABETH A. GEORGE, Ph.D., was by me first duly sworn to testify the truth, the whole truth and nothing but the truth.

Said testimony was reduced to writing by me stenographically in the presence of the witness and thereafter reduced to typewriting.

I FURTHER CERTIFY that I am not a relative or Attorney of either party, in any manner interested in the event of this action, nor am I, or the court reporting firm with which I am affiliated, under a contract as defined in Civil Rule 28(D).

IN WITNESS WHEREOF, I have hereunto set my hand and seal of office at Dayton, Ohio, on this _ _ _ _ day of _ _ _ _ _ _ _ _ _, 2012.

_ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _

KATHY S. WYSONG, RPR
NOTARY PUBLIC, STATE OF OHIO
My commission expires 12-1-2013

EXHIBIT

2

PLAINTIFF'S EXHIBIT

1

KW 9-13-12

STATE OF NORTH CAROLINA | **IN THE GENERAL COURT OF JUSTICE**
SUPERIOR COURT DIVISION
10-CVS-019930

COUNTY OF WAKE

BRIAN CECCARELLI,
individually and as class representative,

Plaintiffs,

v.

TOWN OF CARY

Defendant.

AFFIDAVIT OF ELIZABETH GEORGE

ELIZABETH GEORGE, being first duly sworn, deposes and says:

1. Based on my education, training, and work experience, I have knowledge of the facts hereinafter stated and am competent to testify as a sworn witness to the matters contained herein. I am over the age of 18 years.

2. I received a Ph.D. in Physics in 1993 from the University of Wisconsin – Madison.

3. I am currently employed by Wittenberg University as an Associate Professor and Chair of the Physics Department and have been with the university since 1998.

4. My Curriculum Vitae, including a list of publications, is attached to this Affidavit as Exhibit "A."

5. Based on my education and training in physics, I am qualified to testify regarding the dilemma zones created by the yellow light duration formula used by traffic engineers.

6. My conclusions are based on basic principles that I teach in my physics courses.

7. When a traffic light changes from green to yellow, a vehicle traveling at a given speed requires a certain distance to stop safely. If the vehicle is closer to the intersection than this critical distance, the driver cannot safely stop short of the intersection and has to continue through the intersection instead of stopping. When the yellow light duration is too short for a vehicle traveling at this speed to clear the intersection before the light turns red, a Type I dilemma zone is created, in which a driver cannot stop safely, but also cannot get through the intersection before the light turns red without speeding up.

8. When the yellow light duration is set to the ITE yellow light change interval based on a design speed lower than the speed limit, Type I dilemma zones are created for vehicles traveling between the design speed and the speed limit. Drivers in a dilemma zone do not have enough room to stop safely, and also do not have enough time to clear the intersection before the light turns red without speeding.

9. The eastbound Cary Towne Blvd. and Convention Drive intersection under the 1991

signal plan is an intersection with such a dilemma zone. With a yellow light duration of 4.0 seconds and a speed limit of 45 mph, a driver needs to be at least 293 feet from the intersection to perceive that the light has turned yellow and stop safely. Drivers closer than this distance must continue through the intersection, but at 45 mph a driver can travel only 264 feet in the 4.0 seconds that the light is yellow. (Standard NCDOT values for perception time and deceleration rate have been used in this calculation.) Thus, drivers traveling at the speed limit between 264 and 293 feet from the intersection at the instant the light turns yellow can neither stop safely nor reach the intersection at the speed limit before the light turns red. If drivers are required to completely clear the intersection before the light turns red, the dilemma zone is even larger.

10. When the yellow light duration in a turn lane is set to the ITE yellow light change interval based on the speed limit for vehicles traveling straight through, a similar Type I dilemma zone is created. Drivers in this zone are too close to the intersection to stop safely, but because they have to slow down below the speed limit in order to turn safely, the yellow light interval is not long enough to allow drivers to clear the intersection while making a turn before the light turns red.

11. Such a dilemma zone exists at the northbound Cary Parkway and Kildaire Farms intersection with the yellow light duration set to 3.0 seconds in the left turn lane. Drivers approaching at the speed limit of 45 mph who are closer than 293 feet from the intersection at the instant the light turns yellow cannot stop safely and must continue through the intersection, but even if they do not need to slow to make the turn they can travel only 198 ft at the speed limit before the light turns red. Slowing to make the turn makes the distance that can be traveled in 3.0 seconds even shorter than 198 feet, so there is a very large dilemma zone for drivers who plan to turn left at this intersection. Even for drivers who have already slowed to 30 mph when the light turns yellow there is still a dilemma zone in the region between 132 and 152 feet from the intersection.

This the 5th day of December, 2011.

Elizabeth George
Elizabeth George

STATE OF OHIO
COUNTY OF Clark
Sworn to and subscribed before
me this 5th day of December, 2011.
Connie Ross
Notary Public
My Commission Expires: Connie S. Ross
Notary Public, State of Ohio
My Commission Expires 1/29/2016

11/23/2011; last update 11/22/11

EXHIBIT

tabbies

A

PLAINTIFF'S DEPOSITION EXHIBIT

PENGAD 800-631-6989

2

KW 9-13-12

Elizabeth A. George

Work:
Physics Department, Wittenberg University
PO Box 720, Springfield, OH 45501
(937)327-7854
egeorge@wittenberg.edu

Home:
1223 N Lowry Ave
Springfield, OH 45504
(937)215-2743 (cell)
eageorge@uwalumni.com

Education:

Ph.D. Physics, University of Wisconsin—Madison, 1993
Minor: Distributed (Mathematics and Computer Science)
Thesis: "A New Determination of the Asymptotic *D*-state to *S*-state Ratio of the $^3H \rightarrow$ n+d Cluster Wavefunction Using Sub-Coulomb $(\vec{d}, t)$ Reactions"
Thesis advisor: Lynn Knutson

M.S. (Radiology [Medical Physics]) University of Colorado, 1986
Thesis: "Application of Fractal Geometry to the Evaluation of Lung Airway Morphology and Anatomy"

B.S. Physics, University of Arizona, 1983 (With Highest Distinction)
Minor: Mathematics

Professional experience:

2010-	Interim Assistant Provost (part-time), Wittenberg University
2003-	Chair, Physics Department, Wittenberg University
2002-	Associate Professor, Wittenberg University
1998-2002	Assistant Professor, Wittenberg University
1995-8	Assistant Professor, University of Wisconsin—Whitewater
1993-5	Visiting Assistant Professor, Richard Stockton College of New Jersey
1987-93	Research Assistant, University of Wisconsin—Madison (Physics)
1986-7	Teaching Assistant, University of Wisconsin—Madison (Physics)
1982-4	(summers) Undergraduate Research Assistant, University of Missouri Research Reactor

Professional affiliations, offices held:

- American Physical Society
  Secretary, Ohio-Region Section 2004-10
- American Association of Physics Teachers
  Executive Committee, Southern Ohio Section, 2000-
- Project Kaleidoscope Faculty for the 21st Century, class of 1997
- Advanced Lab Physics Association (ALPhA)
  Board member, 2011-

Academic honors and awards:

- Finalist, Sigma Xi Graduate Research Award, University of Wisconsin, 1993
- Phi Beta Kappa, elected 1982 (Alpha of Arizona)
- Outstanding Student, Faculty of Sciences, University of Arizona, 1983

Peer-reviewed publications:

"A superconducting beta spectrometer," L.D. Knutson, G.W. Severin, S.L. Cotter, L. Zhan, P.A. Voytas, and E.A. George, Rev. Sci. Instrum. **82**, 073302 (2011)

"The half-life of ^{66}Ga," G.W. Severin, L.D. Knutson, P.A. Voytas, and E.A. George, Phys. Rev. C **82**, 067301 (2010)

"Scattering lengths for p-^{3}He elastic scattering from an effective-range phase shift analysis," E.A. George and L.D. Knutson, Phys. Rev. C **67**, 027001 (2003)

"The A_y problem for p-^{3}He elastic scattering," M. Viviani, A. Kievsky, S. Rosati, E.A. George, and L.D. Knutson, Phys. Rev. Lett. **86**, 3739 (2001)

"Determination of the ^{6}Li $\rightarrow \alpha + d$ *D*- to *S*-state ratio by a restricted phase-shift analysis," E.A. George and L.D. Knutson, Phys. Rev. C **59**, 598 (1999)

"Cross section and analyzing powers for ^{6}Li-^{4}He elastic scattering at 5.5 and 19.6 MeV," E.A. George, D.D. Pun Casavant, and L.D. Knutson, Phys. Rev. C **56**, 270 (1997)

"Measurement of the longitudinal analyzing power for noncoplanar *p-d* breakup," E.A. George, J. Frandy, M.K. Smith, Y. Zhou, L.D. Knutson, J. Golak, H. Witała, W. Glöckle, and D. Hüber, Phys. Rev. C **54**, 1523 (1996)

"New determination of the asymptotic *D*-state to *S*-state ratio of the triton using $(\vec{d},t)$ reactions at sub-Coulomb energies," E.A. George and L.D. Knutson, Phys. Rev. C **48**, 688 (1993)

"Neutron interferometric search for quaternions in quantum mechanics," H. Kaiser, E.A. George, and S.A. Werner, Phys. Rev. A **29**, 2276 (1984)

"Direct measurement of the longitudinal coherence length of a thermal neutron beam," H. Kaiser, S.A. Werner, and E.A. George, Phys. Rev. Lett. **50**, 560 (1983)

b) Peer-reviewed and invited publications in conference proceedings:
"Observing students' use of computer-based tools during collision experiments," Elizabeth A. George, Maan J. Broadstock, and Jesús Vázquez-Abad, Proceedings of the 2001 Physics Education Research Conference, Rochester, NY, July 2001

"Learning energy, momentum, and conservation concepts with computer support in an undergraduate physics laboratory," Elizabeth A. George, Maan Jiang Broadstock, and Jesús Vázquez Abad, International Conference of the Learning Sciences, Ann Arbor, MI, June 2000

<u>Selected Conference Presentations (* denotes undergraduate student):</u>
"Investigation of Light-Induced Atom Desorption," Timothy Uher*, Paul Voytas, and Elizabeth George, Ohio-Region Section APS meeting, Flint, MI, April 2010

"Upper-level lab sequence at Wittenberg University: paths to student independence," Elizabeth George, Paul Voytas, and Jeremiah Williams, Topical Conference on Advanced Laboratories, Ann Arbor, MI, July 2009 (peer-reviewed)

"Determining the half-life of ^{40}K from the activity of salt substitute," Elizabeth George and Paul Voytas, Topical Conference on Advanced Laboratories, Ann Arbor, MI, July 2009 (peer-reviewed)

"Investigating Tangential Acceleration in the Laboratory with a Rotation Wheel," Elizabeth George and Paul Voytas, Summer AAPT meeting, Ann Arbor, MI, July 2009

"Buck Creek River Flow Analysis," Yasas Dhanapala*, Elizabeth George, and John Ritter, Ohio-Region Section APS meeting, Ada, OH, April 2009

"Achieving Nanosecond Timing with the Vernier Method," Rebecca Cooper*, Elizabeth George, Paul Voytas, Ohio-Region Section APS meeting, Ada, OH, April 2009

"Calibration of a superconducting beta spectrometer using ^{66}Ga," Gregory Severin, Lynn Knutson, Elizabeth George, Paul Voytas, Sean Cotter, APS Division of Nuclear Physics meeting, Oakland, CA, October 2008

"Recent Results on the Branching Ratio in the Beta Decay of Oxygen-14," Matthew Kowalski*, Elizabeth George, Paul Voytas, Lynn Knutson, Gregory Severin, Sean Cotter, Ohio-Region Section APS meeting, Miami University, Oxford, OH, October 2007

"Modeling a new superconducting beta spectrometer for a CVC test in ^{14}O beta decay," P.A. Voytas, E.A. George, L.D. Knutson, and S.L. Cotter, APS Division of Nuclear Physics meeting, Chicago, IL, October 2004

"Design and Calibration of a Superconducting Beta Spectrometer," S.L Cotter, L.D. Knutson, E.A. George, and P.A. Voytas, APS Division of Nuclear Physics meeting, Chicago, IL, October 2004

"Properties of Biological Media Determined from Polarization Properties of Backscattered Light," Landon Locke*, Ohio Section APS meeting, Athens, OH, April 2004

"Studying the Motion of Rising Bubbles with Video Capture," E.A. George, Ryan Greer*, P.A. Voytas, Summer AAPT meeting, Madison, WI, August 2003

"Adapting RealTime Physics," Elizabeth A. George, Daniel A. Fleisch, Paul A. Voytas, William E. Dollhopf, Ohio Section APS/Southern Ohio Section AAPT Joint Meeting, Columbus, OH, October 2001

"Observing students' use of computer-based tools during collision experiments," Elizabeth A. George, Maan J. Broadstock, and Jesús Vázquez-Abad, Summer AAPT meeting, Rochester, NY, July 2001 (invited talk)

"Student understanding of momentum, mechanical energy, and conservation principles in a computer-supported undergraduate physics laboratory," Jesús Vázquez-Abad, Elizabeth A. George, and Maan J. Broadstock, AERA annual meeting, Seattle, WA, April 2001 (peer-reviewed)

"Learning momentum and energy conservation principles with computer support in an undergraduate physics laboratory," Maan J. Broadstock, Elizabeth A. George, and Jesús Vázquez-Abad, NARST annual meeting, St. Louis, MO, March 2001 (peer-reviewed)

"Learning momentum and energy conservation in a computer-based laboratory," Elizabeth A. George, Maan J. Broadstock, and Jesús Vázquez-Abad, NSTA annual meeting, St. Louis, MO, March 2001 (peer-reviewed)

"Student learning in motion detector- and video-based collision laboratories," Elizabeth A. George, Maan J. Broadstock, and Jesús Vázquez-Abad, Summer AAPT meeting, Guelph, Ontario, August 2000

"Learning momentum and energy conservation principles with motion detectors and video," Elizabeth A. George, Theresa Conway*, Maan Jiang Broadstock, and Jesús Vázquez-Abad, Winter AAPT meeting, Kissimmee, FL, January 2000

"Four Strategies for Exploiting Computers in a Science Core Course," D. Waechter-Brulla, E. Drexler, L. Urven, F. Luther, R. Helwig, E. George, and J. Bak, 162nd National Meeting of the AAAS, Washington, DC, Jan. 1996 (peer-reviewed)

Other presentations:
"Nuclear beta decay and the weak interaction," Wright State University Physics Department seminar, May 5, 2006

"Phase shift analyses and scattering lengths for p-^{3}He," seminar at Institute for Nuclear and Particle Physics, Ohio University, January 27, 2004

"Using spinning nucleons to investigate the strong force," Physics Department seminar at Denison University, Jan. 31, 2002

Grant proposals funded:
Co-principal investigator (lead investigator: Paul Voytas) for "A mono-energetic neutron facility for investigating radiation damage to Si and SiC devices," submitted to Analex, a support service contractor to NASA Glenn Research Center, funded August 2004-September 2005

Principal investigator for "Computer-aided active engagement learning in an introductory physics sequence for science majors," National Science Foundation, Division of Undergraduate Education, CCLI-A&I program, funded 2000-2003 (co-principal investigators: W.E. Dollhopf, P.A. Voytas)

Principal investigator for "Effects of instructional technologies on student learning in the undergraduate physics laboratory," National Science Foundation, Division of Research, Evaluation and Communication, REPP program, funded 1998-2001 (co-principal investigator: Jesús Vázquez-Abad, Université de Montréal)

Courses taught at Wittenberg:
General education courses: Physics Through Experimentation; Chaos and Fractals (first-year seminar); Patterns in Nature (first-year seminar)
Honors course: Chaos and Fractals (team-taught)
Introductory physics courses: Mechanics and Waves; Topics in Contemporary Physics (algebra-based course); Thermodynamics and Optics; Intermediate Physics Lab; Special Relativity and Applications; Modern Physics
Upper-level physics courses: Wave Phenomena; Electronics; Digital Electronics; Nuclear Physics; Particle Physics; Junior/Senior Seminar

Community and professional service contributions:
- Reviewer, American Journal of Physics (2005-)
- Reviewer, Europhysics Letters (2011-)
- Reviewer for nine chapters of third edition of Knight, Physics for Scientists and Engineers, 2010
- Reviewer, U.S. Civilian Research and Development Foundation 2005 Cooperative Grants Program
- National Science Foundation review panels: Division of Research, Evaluation and Communication CAREER program, October 1999; Information Technology Research program, February 2001; Assessing Student Achievement program, July 2001 and January 2002
- Steering Committee, 2009 and 2012 Advanced Labs Topical Conferences, American Association of Physics Teachers
- Member of Audit Panel for K-12 science education review, Oakwood School District, 2010-11
- Coordinated and led physics activities for Girl Scout Science Night at Wittenberg, 2001-4, 2007-9
- Helped organize SOS/AAPT meeting at Wittenberg, March 2002

University committees and task forces:
- Diversity Advisory Committee, 2011-
- Strategic Planning Implementation Task Group A, 2008-10
- Provost's Advisory Committee, 2009-10
- Hearing Board on Academic Freedom and Tenure, 2002-5; 2008- (Chair, 2003-2005, 2009-11)

- Faculty Executive Board, Fall 2007 (sabbatical replacement)
- Curriculum Review Committee, 2006-7
- Task group on the Mission Statement, 2004-6
- Strategic Planning task groups on Attracting High-Performing Students and on Promoting Student Excellence, Persistence and Success, 2003-4
- Committee on Admissions/Financial Aid, 2001-3
- Facilities and Environment Committee, 2001-3 (Chair, 2002-3)
- Library Policies Committee, 1999-2001 (Chair, Spring 2000)

Other contributions to the University:

- Chief Information Officer search committee, 2009
- Panelist/ co-presenter for the following Wittenberg Faculty Development events: "Keys to a successful sabbatical," 2007; "The arc of a teaching career," 2009; "Radical pedagogies," 2010; "How Do We Respond? A Collection of Response Strategies for Papers and Oral Presentations," 2010; "3 principles and 9 strategies for the bimodal classroom," 2011
- Faculty Retreat planning group and co-presenter of session on "Research-based teaching strategies," 2008; co-organizer of session on "Faculty Workload," 2011
- Academic advising: Advised four groups of 6-18 first-year students; currently major advisor for 10 students

Responsibilities as Interim Assistant Provost (2010-11)

- Led faculty groups developing new Environmental Science major and investigating the feasibility of an Environmental Sustainability major
- Supervised International Education office
- Responsible for departmental non-staffing budget requests
- Provost's office liaison for grant administration; Grant administrator (Fall 2011)
- Interim Director for Computational Science minor program
- Ex-officio member of Facilities and Environment Committee

EXHIBIT
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PLAINTIFF'S DEPOSITION EXHIBIT
3

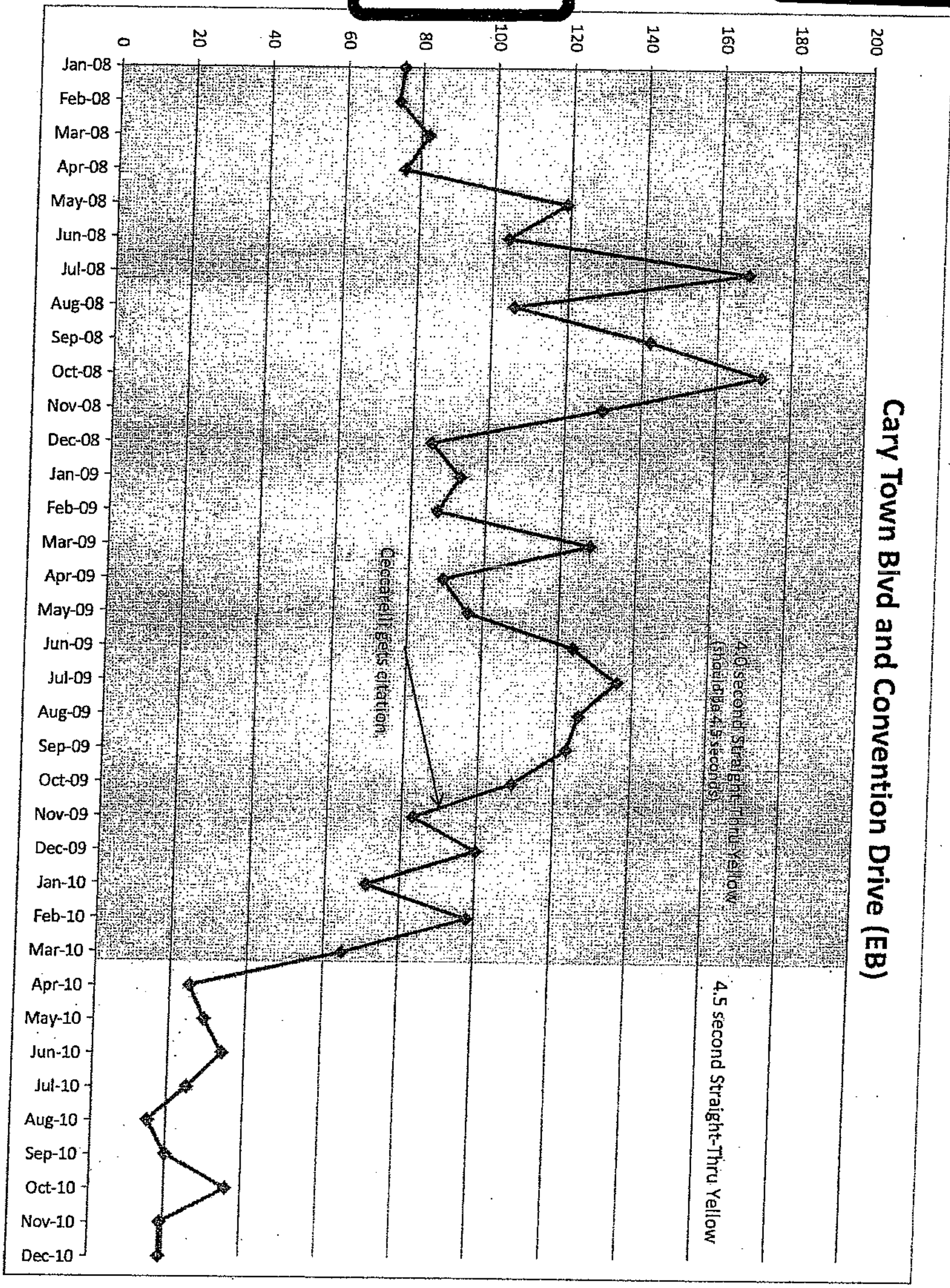
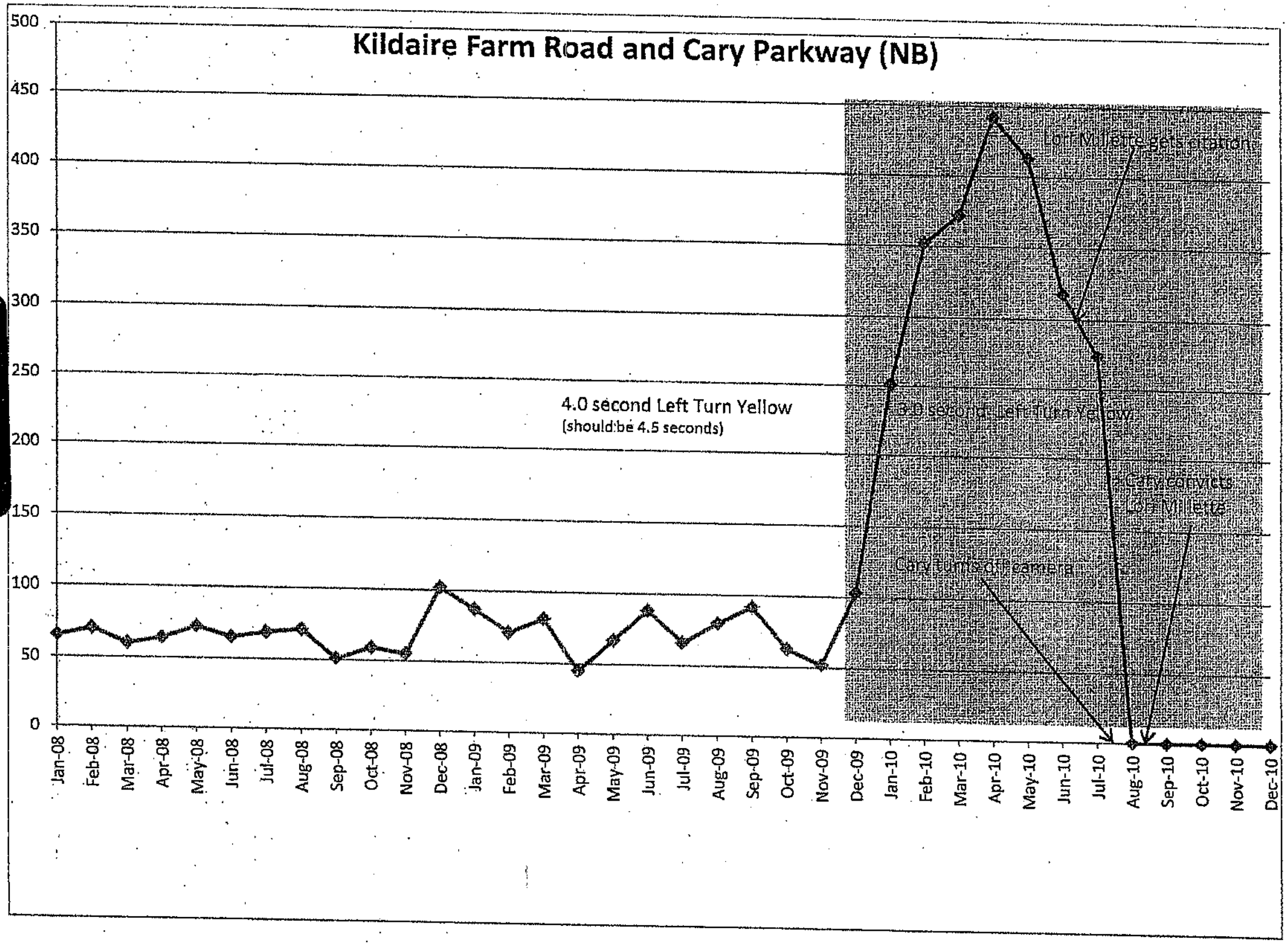


EXHIBIT E



Kildaire Farm Road and Cary Parkway (NB)
4.0 second Left Turn Yellow
(should be 4.5 seconds)
3.0 second Left Turn Yellow
Lori Millette gets citation
Cary convicts Lori Millette
Cary turns off camera
0
50
100
150
200
250
300
350
400
450
500
Jan-08
Feb-08
Mar-08
Apr-08
May-08
Jun-08
Jul-08
Aug-08
Sep-08
Oct-08
Nov-08
Dec-08
Jan-09
Feb-09
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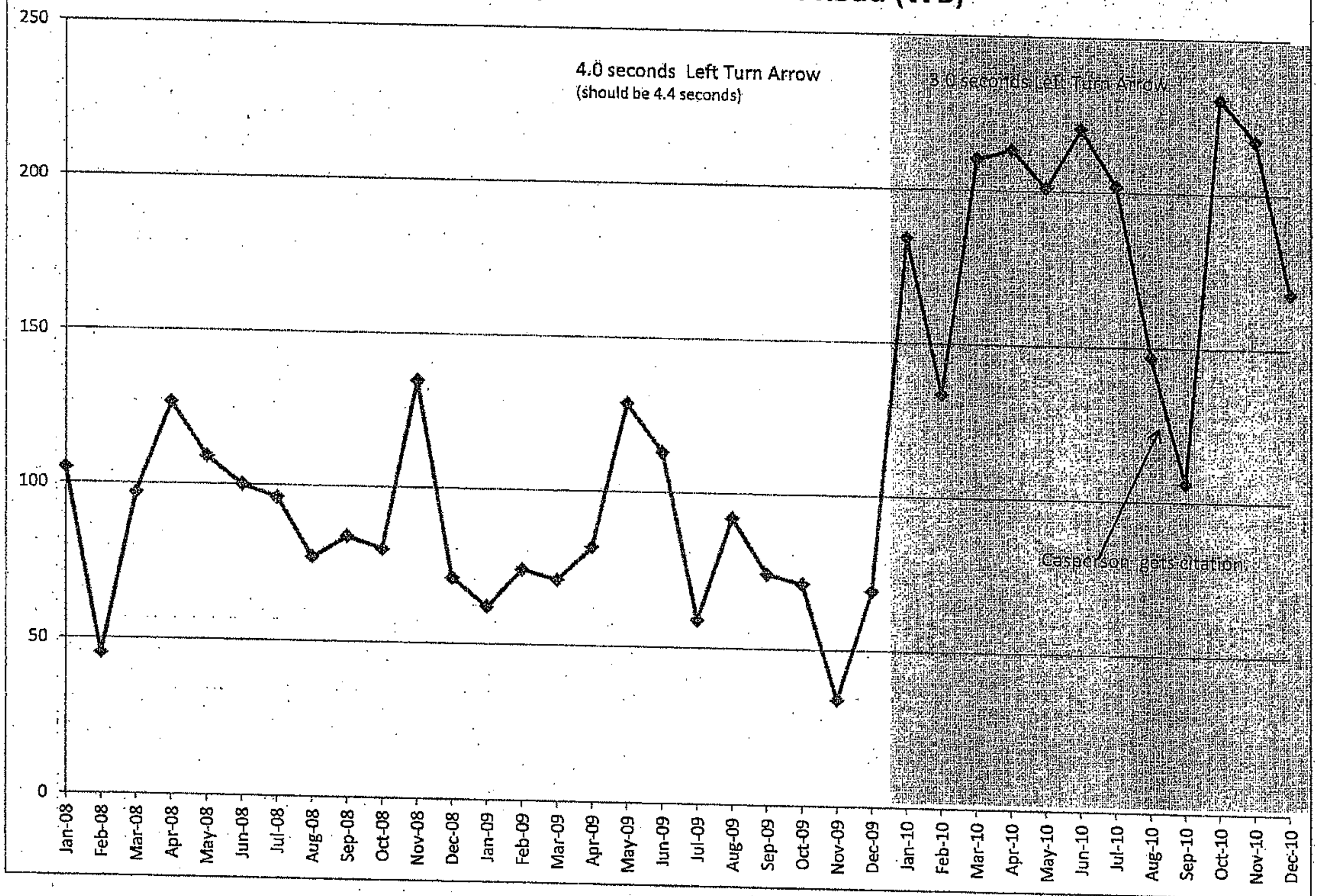
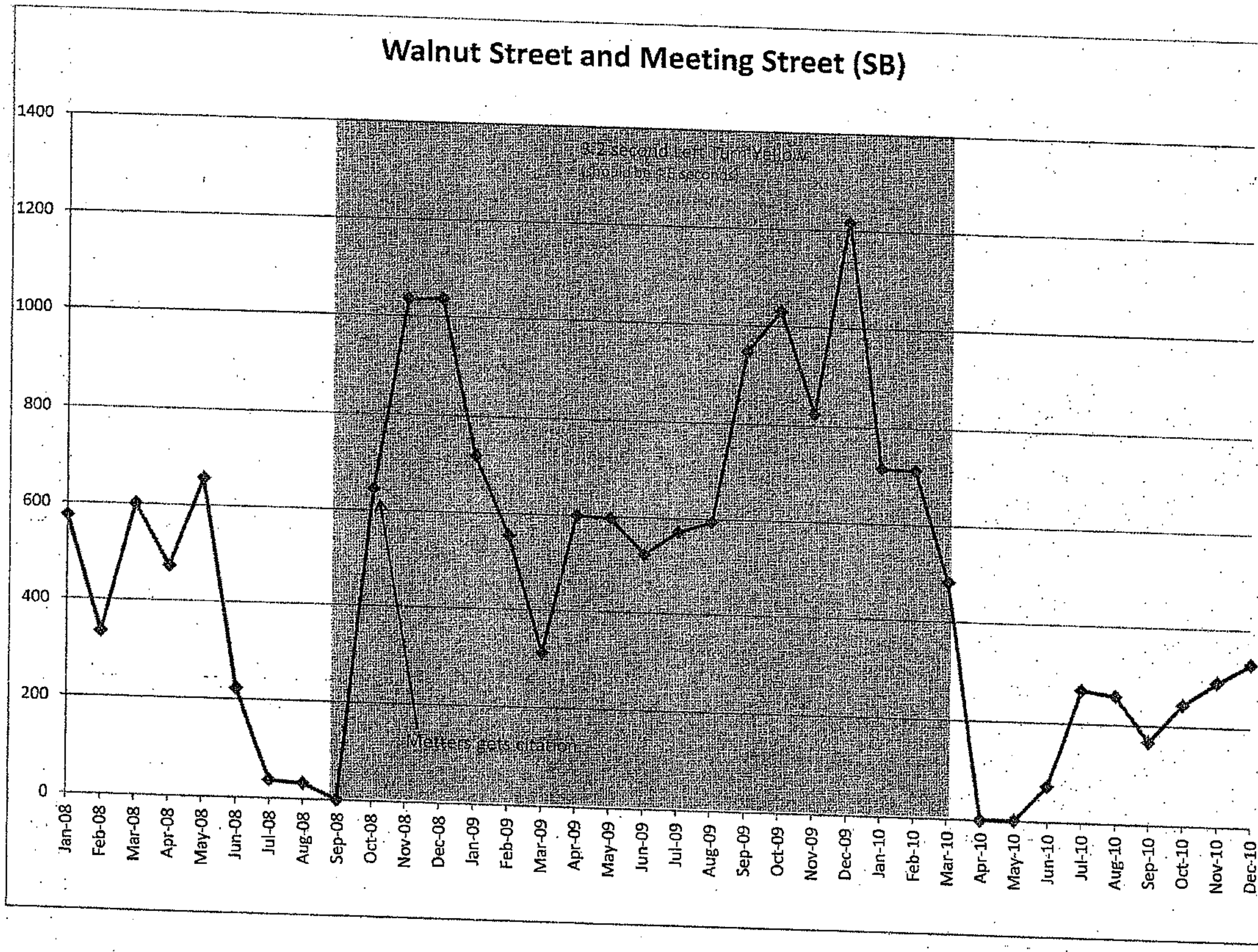
Dec-10

Cary Parkway and Kildaire Farm Road (WB)





Walnut Street and Meeting Street (SB)
3.2 second Left Turn Yellow
Metters gets citation
1400
1200
1000
800
600
400
200
0
Jan-08
Feb-08
Mar-08
Apr-08
May-08
Jun-08
Jul-08
Aug-08
Sep-08
Oct-08
Nov-08
Dec-08
Jan-09
Feb-09
Mar-09
Apr-09
May-09
Jun-09
Jul-09
Aug-09
Sep-09
Oct-09
Nov-09
Dec-09
Jan-10
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Mar-10
Apr-10
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Jul-10
Aug-10
Sep-10
Oct-10
Nov-10
Dec-10

Application of the ITE Change and Clearance Interval Formulas in North Carolina

DURING 2005, THE NORTH CAROLINA SECTION OF ITE CONVENED A TASK FORCE TO INVESTIGATE AND RECOMMEND A PRACTICE FOR DETERMINING YELLOW CHANGE AND RED CLEARANCE INTERVALS. THIS FEATURE BRIEFLY SUMMARIZES KEY DELIBERATIONS AND DECISIONS OF THAT TASK FORCE. THE METHODOLOGY AS IMPLEMENTED BY THE NORTH CAROLINA DEPARTMENT OF TRANSPORTATION ALSO IS PRESENTED ALONG WITH SAMPLE YELLOW AND RED TIMES RESULTING FROM ITS APPLICATION.

BY STEVEN M. CLICK, PH.D., P.E.

INTRODUCTION

In December 2004, in response to a formal request by the North Carolina Department of Transportation (NCDOT), the Traffic Engineering Council of the North Carolina Section of the Institute of Transportation Engineers (NCSITE) announced a task force to investigate and recommend a practice for determining yellow change and red clearance intervals at signalized intersections in North Carolina. The purposes of this feature are to briefly summarize key deliberations of that task force and present the resulting methodology as implemented by NCDOT.

BACKGROUND

One issue in determining appropriate yellow and red intervals is that, despite the existence of several well-recognized guidance documents, there is no national standard. The *Manual on Uniform Traffic Control Devices* (MUTCD), which typically provides prescriptions for device operation, does not stipulate the manner in which yellow or red intervals should be determined. It does, however, require the use of a yellow interval; require that the duration of the yellow and red intervals be predetermined; and suggest durations of 3 to 6 seconds for yellow and, at most, 6 seconds for red.[1]

Calculation methods are available in the *Traffic Engineering Handbook* and other sources.[2] A recent survey by ITE suggests that, by far, the most common method in use today is based on what is termed the "ITE formula," shown below:[3]

$$Y + R = t + \frac{v}{2a + 2Gg} + \frac{w + l}{v} \quad (1)^{4}$$

where:

Y = yellow change interval (seconds [sec.])
R = red clearance interval (sec.)
t = perception-reaction time (sec.)
v = design velocity (feet/sec.)
a = deceleration rate (feet/sec.^{2})
G = acceleration due to gravity (32.2 feet/sec.^{2})
g = grade in decimal form (1 percent = 0.01)
w = clearance distance (feet)
l = vehicle length (feet)

In discussion of the yellow and red intervals, the *Traffic Engineering Handbook* goes on to suggest a typical application of the first two terms to determine the yellow and the last term to determine the red.

The ITE formula has been published, with timely revisions, since the first edition of the *Traffic Engineering Handbook* in 1941. Beginning in 1965, the formula appeared in its present form, although without the effect of grade. In this same year, ITE suggested the use of a red interval under certain conditions. The inclusion of the effect of grade on the yellow and red intervals appeared in 1982. In all, the formula has been updated eight times since 1941.[5] Still, the *Traffic Engineering Handbook* has not accrued any legal status.

Although the NCDOT documentation covers only the more recent practices for calculation of yellow and red, it gives clear evidence of its desire to provide both safe and efficient operation. One source, from February 1990, summarizes a meeting NCDOT hosted to discuss change and clearance intervals, involve traffic engineers from across the state and examine current practice. At the time of the meeting, NCDOT and most other state agencies were using the ITE formula as the foundation of their practice.[6]

More recently, NCDOT has worked to improve signal design consistency through publication of the *Traffic Management and Signal Systems Unit Design Manual*.[7] The purpose of the manual is to highlight standards of practice in signal design and operation. Although all the design manual editions have required the use of the ITE formula, specific division of the resulting total clearance into yellow and red times has not been consistent over the last 15 years and has been, at varying levels, left to the discretion of the design engineer.

The result is inconsistent yellow and red timing throughout the state.

The resulting inconsistencies, differing preferences among designers and a general consensus among NCDOT design and field personnel that these intervals are becoming too long all were factors in the decision to request a recommendation from NCSITE.

RECENTLY, NCDOT HAS WORKED TO IMPROVE SIGNAL DESIGN CONSISTENCY THROUGH PUBLICATION OF THE *TRAFFIC MANAGEMENT AND SIGNAL SYSTEMS UNIT DESIGN MANUAL.*

THE NCSITE TASK FORCE

In December 2004, a call went out for volunteers for the NCSITE Task Force. The NCSITE mailing list offered a representative pool of traffic engineering professionals from all over North Carolina, with a wide cross-section of relevant experience and knowledge. The resulting volunteer membership included:

- municipal engineers: 11
- consulting engineers: 10
- NCDOT engineers—central office: 7
- NCDOT engineers—field forces: 2
- non-profit organizations: 1
- research organizations: 1
- students: 1

The full NCSITE Task Force met a total of four times between January and June 2005 and divided into subcommittees to help meet the prescribed 6-month deadline. During the first task force meeting, a discussion and brainstorming session provided a list of issues to be addressed. Subcommittees held teleconferences and in-person meetings to discuss their topics and conducted data collection and reduction efforts in support of their tasks.

Issues Addressed by the Task Force

For purposes of organization, the issues tackled by the task force are presented in the sequence that they would be encountered using the methodology, beginning with text from the written recommendation and ending with summaries of key issues.

The ITE formula for the calculation of the total change plus clearance interval should be the basis for NCDOT practice. Both NCDOT's long history and the recent ITE surveys suggested the ITE formula was the logical starting point for use in the methodology.

Calculation of the yellow change and all-red clearance intervals should not vary based on the presence or absence of enforcement devices. At this time, NCDOT does not operate or intend to operate automated enforcement devices (such as red-light cameras); however, individual municipalities can petition the state legislature for the authority to install such devices. The recommended practice should result in safe and efficient intervals, independent of enforcement.

The NCSITE Task Force also discussed the option of including a grace period at automated enforcement locations, but it decided to leave such choices to the operating agency. NCDOT does recommend a break-in period to allow drivers to become accustomed to any changes made as a result of the new practice.

Separate practices should not exist for different regions of the state, unique vehicle streams (such as a high percentage of heavy vehicles), or left-turning vehicles versus through vehicles. Because one of the primary motivations for the task force was consistency, there was little discussion of this issue. The recommended practice should result in safe and efficient intervals, independent of region, stream, or movement.

Calculation of the yellow change interval should be performed using the first two terms of the ITE formula, with the result rounded up to the next 0.1 sec.

$$Y = t + \frac{v}{2a + 2Gg} \qquad (2)$$

The yellow and red intervals serve different functions; therefore, the calculation should be made as independently as possible. In past practices, time might be shifted from the red to yellow, but not in the new practice. Independent calculations are needed to help prevent excessive yellow time from contributing to disrespect of the yellow change interval.

The 2001 constants from the American Association of State Highway and Transportation Officials (AASHTO) for deceleration (11.2 feet/sec.^{2}) and perception/reaction time (1.5 sec.) are sound. The longer perception/reaction time responds both to the aging driver population and to the increasing number of distractions in the driving environment. At higher speeds, the higher deceleration rate does help offset the additional perception/reaction time.

The NCSITE Task Force also looked into the performance characteristics of trucks. Although no specific information could be found related to "comfortable" stops, AASHTO constants were within the expected performance capabilities of trucks.

The effect of positive grade should be factored into the yellow calculation. In past practice, NCDOT included the detrimental effects of negative grades but ignored the beneficial impacts of positive grades. None of the ITE publications suggests that positive grades should be ignored in calculations, and the Federal Highway Administration's *Signalized Intersections: Informational Guide* clearly indicates that positive grades can be used.[8]

The minimum value for yellow should be 3.0 sec. Not only does MUTCD recommend this minimum value, it also is required by the National Electrical Manufacturers Association Standards Publication.[9] Note that when the calculated yellow is less than 3.0 sec., the time difference is not shifted from red: In other words, the yellow increases without a change in the red.

Current practice in the Signals and Geometrics Section for selection of vehicle speeds, "v", was reviewed and retained in this application. For through movements, current practice uses the posted speed limit as the design speed unless a speed study has been specifically performed. When provided, the design speed will be taken as the 85th-percentile speed, up to a maximum of 10 mph above the posted limit. Because NCDOT does not signalize facilities with

Site	Left Turn Angle	Single or Dual	Collection Method*	Sample Size	Speed					
					Min	15%	Avg	StDev	85%	Max
1	125	Dual	All	39	14	15.0	**18.9**	**3.4**	21.3	30
2	110	Single	All	40	11	12.0	**15.6**	**2.7**	18.0	24
3	120	Single	All	71	12	16.0	**18.4**	**2.9**	21.0	26
4	110	Single	Sample	120	14	16.0	**18.1**	**2.1**	20.0	23
5	100	Single	Sample	120	9	11.0	**13.6**	**2.2**	16.0	20
6	100	Dual	End Car	80	14	17.0	**19.0**	**1.8**	21.0	23
7	70	Dual	End Car	160	10	13.0	**14.6**	**1.6**	16.0	20
8	115	Dual	End Car	80	13	16.0	**18.7**	**2.3**	21.0	26
9	130	Dual	End Car	156	14	17.0	**19.3**	**2.3**	22.0	25
10	85	Single	End Car	160	12	15.0	**17.2**	**2.0**	19.0	23
11	90	Dual	End Car	80	13	16.0	**17.4**	**1.8**	19.2	21
ALL	-	-	-	**1106**	**9**	**14.0**	**17.1**	**2.9**	**20.0**	**30**

*** Collection Methods:**
All = Speed recorded for all vehicles making the left turn
Sample = Speed recorded for an initial vehicle, a mid-queue vehicle, and an end-of-green vehicle
End Car = Speed recorded for the last vehicle using the phase each cycle

Figure 1. Left-turn speed data.

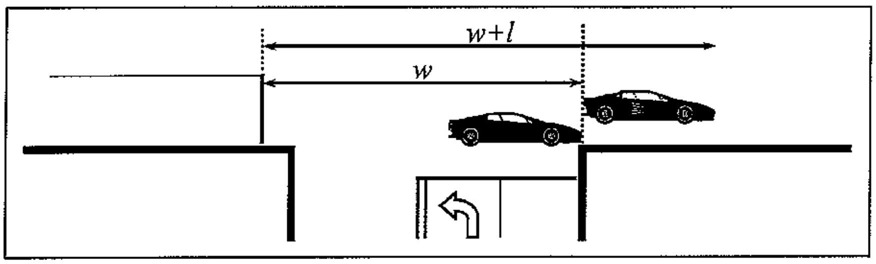

Figure 2. Effect of removing "l" from red calculations.

speed limits greater than 55 mph, the highest allowable design speed is 65 mph.

For left-turn movements, past editions of the *Traffic Management and Signal Systems Unit Design Manual* suggested a speed between 20 and 30 mph, with 20 mph the almost universal selection. Many expressed concern that 20 mph was overly conservative and led to excessive red intervals, so a field investigation was conducted. Unexpectedly, the study results, shown in Figure 1, indicated typical speeds slightly lower than 20 mph but not low enough for the task force to justify changing current practice.

Calculation of the all-red clearance interval should be based on the third term of the ITE formula, but with the following modification: The vehicle length should be removed from the all-red formula, and the result rounded up to the next 0.1 sec.

$$R = \frac{w}{v} \qquad (3)$$

Unlike MUTCD, which does not require the use of a red interval, the North Carolina Supplement to the MUTCD does.[10] As noted above, NCDOT design and field personnel shared the belief that reds were becoming too long, and NC-SITE Task Force discussions showed this sentiment was shared by both municipal and consulting engineers within the state.

The culprits: increasing intersection widths and the need to provide protected phases for left turns. The causes: increasing corner curve radii standards; the separation of crosswalks with two handicapped ramps on each corner; and increasing facility size in terms of number of lanes. To be clear, neither accident nor ticketing issues had developed to draw public attention to the problem; however, the task force members wished to correct any problems before such statistics evolved.

As modified, the red interval serves to carry the front bumper of a last-instant legal intersection entry to the far edge of the conflict zone. Originally, any vehicle equal to or shorter than the assumed length would be carried past the conflict zone. The resulting difference is shown in Figure 2.

The obvious advantage to removing the assumed vehicle length is a reduction in the red interval. Past NCDOT practice used 20 feet as the assumed vehicle length. Removing this results in a 0.7-sec. reduction at 20 mph; 0.4-sec. at 35 mph; and 0.2 sec. at 55 mph.

Despite this anticipated reduction, the formula still allows the red to increase without bound. Left-turn clearance distances of 200 ft. currently exist, resulting in red intervals of 6.9 sec., much longer than acceptable to the task force.

If the initial calculation results in an all-red clearance interval greater than 3.0 sec., the all-red clearance interval should be recalculated as follows:

$$R = \frac{1}{2}\left(\frac{w}{v} - 3\right) + 3 \qquad (4)$$

Discussion of reducing excessive red times consumed a large portion of the NC-SITE Task Force effort. The recommended method was determined to best balance competing concerns related to overly short and overly long red times. The result of this mitigation was that all of the first 3 sec. calculated for the red interval are used, but only half of the portion above that. So, if the initial calculation resulted in 4.0 sec. of red, the mitigation will reduce it to 3.5 sec. As with the other calculations, the result is rounded up to the next tenth.

The only other method receiving serious consideration was the reduction of red time based on expected time to conflict point. Although a preliminary field study looked positive, investigation of current literature, notably Muller et al., provided only minimal adjustments.[11] Faced with minimal benefits and questions about proper application, the task force discontinued its investigation into this option.

The clearance distance should be measured to the far side of an exclusive right-turn lane.

- *In the presence of a crosswalk with pedestrian signals, the clearance distance should be taken to the near side of the crosswalk*
- *A crosswalk without pedestrian signals should not be considered when determining clearance distance.*

These recommendations did not represent a change from past practice. This includes clearance distance measurements using the "straight line" method rather than a vehicle turning arc. A preliminary comparison of the straight line method to an outside wheel arc method resulted in an average difference of +2.2 feet, only +0.07 sec. at 20 mph. The task force agreed to continue using the straight-line method.

Past practice left consideration of crosswalks to the discretion of the design engineer. The task force felt it was important to always consider crosswalks with pedestrian signals when determining clearance distance. The decision to not consider crosswalks without signals was based on two factors: unsignalized crosswalks typically have insignificant pedestrian volume; and unsignalized crossings provide no guidance, so pedestrians cannot be expected to cross during any particular interval, reducing the probability of providing protection.

The *Traffic Management and Signal Systems Unit Design Manual* gives specific guidance for calculating clearance distances, shown in Figure 3.

The minimum value for all-red clearance intervals should be 1.0 sec. Prior practice suggested at least 1.0 sec., so this was not a significant change.

The proposed implementation of a yellow change interval longer than 6.0 sec. or a red clearance interval longer than 4.0 sec. is cause for a "stakeholder discussion" to provide advance notification and involvement to stakeholders and provide an opportunity to consider possible countermeasures.

Field personnel should be involved in developing and applying the practice. Stakeholder discussions help ensure these personnel are not surprised by new installation of long intervals.

Although countermeasures for reducing the yellow are difficult, typically involving the reduction in grade over the stopping distance or making geometric and enforcement changes to reduce travel speed, identification of excessive yellow at an intersection can provide an opportunity for present or future mitigation.

The opportunity for reducing the red is more likely, with lower cost solutions such as reduced median widths, positive offset left turns and channelized right-turn lanes.

For a "shared clearance" phase (when a phase serves multiple movements needing different yellow change and all-red clearance intervals), the following procedure should be applied:

- *Calculate each movement's change plus clearance intervals as if it had a dedicated phase.*
- *Use the largest yellow value; then subtract this yellow value from the largest total change plus clearance to determine red.*

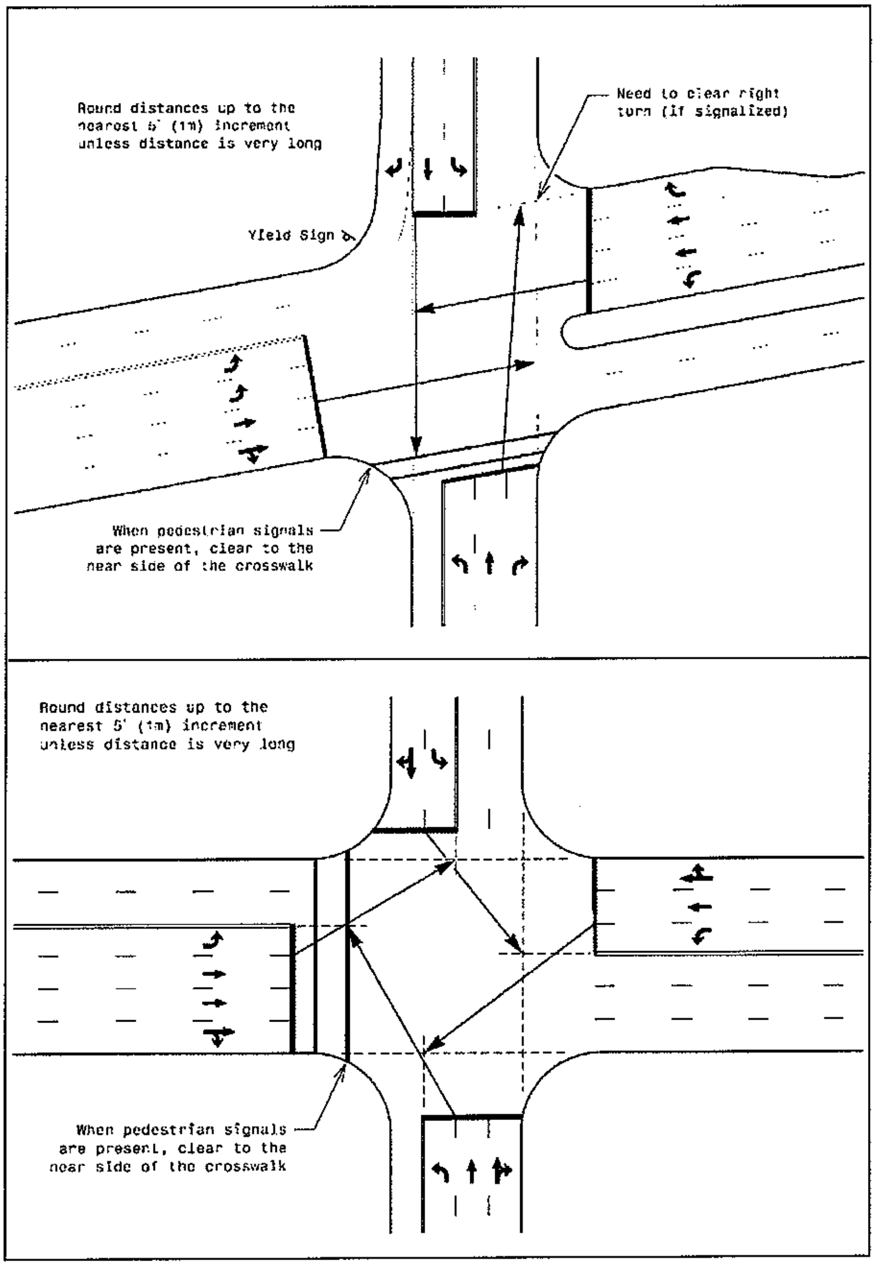

Figure 3. Measuring clearance distances.

Although this is not a change from past NCDOT practice, this confirms that mitigation of excessive red clearance intervals will take place for each movement before the shared change plus clearance is determined.

The Task Force considered but rejected both the use of the longest yellow change with the longest red clearance interval and the use of the yellow change and red clearance interval associated with the longest total clearance. The former option was rejected because it was incompatible with the goal of reducing interval length; the latter was rejected to ensure that every movement received sufficient yellow change time.

CONCLUSION

After receipt of the NCSITE Task Force recommendations, Greg A. Fuller, P.E., of the Intelligent Transportation Systems and Signals Unit of NCDOT, officially adopted the revised methodology, and the *Traffic Management and Signal Systems Unit Design Manual* was revised accordingly. The resulting methodology is presented in full in Figure 4, and a sample set of yellow and red intervals is presented in Figure 5.

Determination of Yellow Change and Red Clearance Intervals

Yellow Change Interval

Yellow interval = $t + \frac{v}{2a + 64.4g}$

t = perception reaction time, typically 1.5 seconds
v = design speed*, in ft/s
a = deceleration rate, typically 11.2 ft/s2
g = grade

Round up to nearest 0.1 second.

Minimum yellow change interval is 3.0 seconds.

Hold stakeholder discussion** when calculated yellow change interval is longer than 6.0 seconds.

Red Clearance Interval

Red interval = $\frac{w}{v}$ w = width of intersection, in feet; v = design speed*, in ft/s

If the initial calculation results in an all red time longer than 3.0 seconds, recalculate the red time as follows:

Recalculated red interval = $\frac{1}{2}(\frac{w}{v} - 3) + 3$

Round up to nearest 0.1 second.

Minimum red clearance interval is 1.0 seconds.

Hold stakeholder discussion** when recalculated red clearance interval is longer than 4.0 seconds.

Notes

*Design speed is the speed limit unless a speed study determines that the 85th percentile speed is faster or intersection geometrics compel vehicles to traverse the intersection slower.

**The purpose of a stakeholder discussion is to provide advance notification and involvement to stakeholders and provide an opportunity to consider possible countermeasures.

For most left turn lanes, assume a speed of 20 mph (32 kph) to 30 mph (48 kph). For locations with unusual conditions a higher or lower speed may be appropriate.

For separate left turn phases, calculate yellow and red intervals.

For left turns without a separate phase, calculate yellow and red times for both the through movement and the left turn movement. Use the highest yellow and enough red to equal the highest total time.

Where existing times are higher than calculated times, use the calculated values unless there is a documented history of the need for higher times. If approach is high speed and existing times are significantly higher than the calculated times, use the calculated values but consider adding a note to the plan to direct field forces to reduce the time incrementally. Include in the note how much and how often to reduce time until the final value is reached. (Ex. Existing Yellow Change Interval for phase 2 may be decreased by 0.2 seconds per week until the required value is reached.)

Where revising a location or adding a new signal along a corridor, consider comparing clearance times at adjacent intersections to new calculations to meet driver expectations.

Sources:
Traffic Engineering Handbook, Fifth Edition, Institute of Transportation Engineers, 1999.
A Policy on Geometric Design of Highways and Streets, Fourth Edition, American Association of State Highway and Transportation Officials, 2001.

Change and Clearance Intervals
SIGNALS & GEOMETRICS SECTION
TRAFFIC ENGINEERING AND SAFETY SYSTEMS BRANCH
NORTH CAROLINA DEPARTMENT OF TRANSPORTATION

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Figure 4. The revised methodology, as adopted.

Speed mph	Speed fps	Grade -6%	-3%	0%	3%	6%
20	29.3	3.1	3.0	2.9*	2.8*	2.7*
25	36.7	3.5	3.3	3.2	3.1	2.9*
30	44.0	3.9	3.7	3.5	3.4	3.2
35	51.3	4.3	4.1	3.8	3.7	3.5
45	66.0	5.1	4.8	4.5	4.3	4.1
55	80.7	5.9	5.5	5.2	4.9	4.6
65	95.3	6.7+	6.2+	5.8	5.5	5.2

* Less than 3.0 second minimum, increase yellow time to 3.0
\+ Greater than 6.0 sec threshold, requires stakeholder meeting prior to approval

Speed mph	Speed fps	Clearance Distance (feet) 50	75	100	125	150	175	200
20	29.3	1.8	2.6	**3.3**	**3.7**	**4.1+**	**4.5+**	**5.0+**
25	36.7	1.4	2.1	2.8	**3.3**	**3.6**	**3.9**	**4.3+**
30	44.0	1.2	1.8	2.3	2.9	**3.3**	**3.5**	**3.8**
35	51.3	1.0	1.5	2.0	2.5	3.0	**3.3**	**3.5**
45	66.0	0.8*	1.2	1.6	1.9	2.3	2.7	**3.1**
55	80.7	0.7*	1.0	1.3	1.6	1.9	2.2	2.5
65	95.3	0.6*	0.8*	1.1	1.4	1.6	1.9	2.1

Shaded cells indicate mitigated red intervals
* Less than 1.0 second minimum, increase all red time to 1.0
\+ Greater than 4.0 sec threshold, requires stakeholder meeting prior to approval

Figure 5. Sample yellow and red intervals.

With the adoption of this practice, NCDOT has established a consistent method for calculating yellow and red intervals that will provide safe and efficient operation. Because of the prohibitive cost associated with an immediate statewide change, the new practice will be used for new signals and phased into existing signals as they require other revisions, with a review of closely spaced signals to help promote the desired consistency. ■

References

1. *Manual on Uniform Traffic Control Devices for Streets and Highways.* Washington, DC: Federal Highway Administration (FHWA), November, 2004.

2. *Traffic Engineering Handbook, Fifth Edition.* Pline, J.L. (ed.). Washington, DC: Institute of Transportation Engineers (ITE), 1999.

3. Tarnoff, Philip J. and J. Ordonez. *Signal Timing Practice and Procedures: State of the Practice.* Washington, DC: ITE, 2004.

4. *Traffic Engineering Handbook,* note 2 above.

5. Eccles, K.A. and H.W. McGee. *A History of the Yellow and All-Red Intervals for Traffic Signals.* Washington, DC: ITE, 2001.

6. North Carolina Statewide Stakeholder Meeting on Clearance Intervals. Unpublished Meeting Minutes, 1990.

7. *Traffic Management and Signal Systems Unit Design Manual.* North Carolina Department of Transportation (NCDOT), 2004. Note: The former Traffic Management and Signal Systems Unit since has been renamed the ITS and Signals Unit, and the manual has been renamed the accordingly.

8. *Signalized Intersections: Informational Guide* (FHWA-HRT-04-091). Washington, DC: FHWA, 2004. Accessible via www.tfhrc.gov/safety/pubs/04091.

9. *NEMA Standards Publication TS 2-1998: Traffic Controller Assemblies with NTCIP Requirements.* National Electrical Manufacturers Association, 1998.

10. *2004 North Carolina Supplement to the Manual on Uniform Traffic Control Devices.* NCDOT, 2004.

11. Muller, T.H.J., T. Dijker and P.G. Furth. "Red Clearance Intervals: Theory and Practice." *Transportation Research Record,* No. 1867 (2004): 132–143.

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$$V = \frac{X}{t} \qquad a = \frac{\Delta V}{t} = \frac{V_0 - V_f}{t}$$

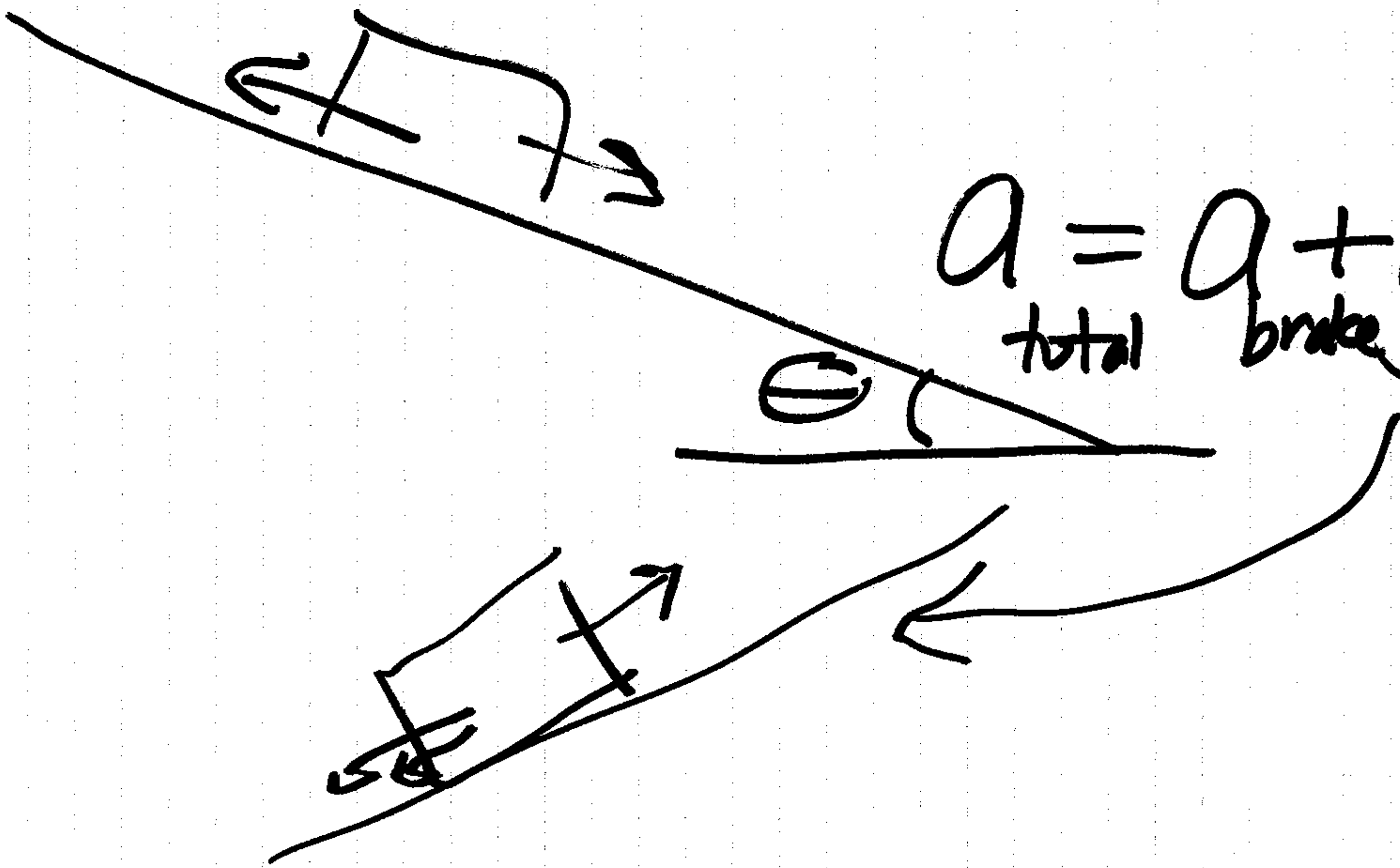
$$V_0^2 - V_f^2 = 2aX$$

$$V_f = 0$$

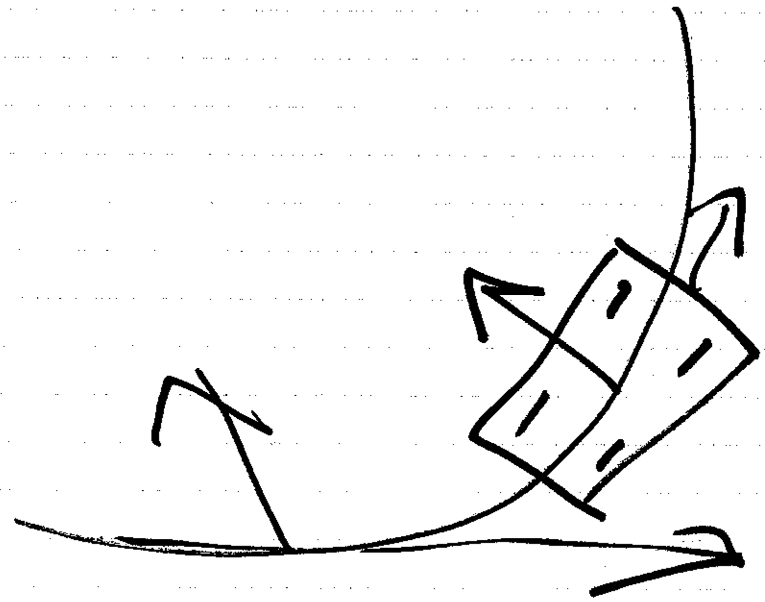
$$V_0^2 = 2aX$$

$$X = \frac{V_0^2}{2a}$$

$$X = t_p v_0 + \frac{v_0^2}{2a}$$



$$a_{total} = a_{brake} + g\sin\theta$$



TRAFFIC ENGINEERING HANDBOOK

6TH EDITION

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a head start or the pedestrians can be held until the initial queue of vehicles has been served. However, such controller phasing may have a detrimental effect on vehicle flow and, if part of a system, on system capacity.

The goals of traffic safety and traffic capacity must be balanced when determining controller phasing for an intersection. The following section describes the various components of controller phasing. More in-depth discussion can be found in the *Manual of Traffic Signal Design* and *Signalized Intersections: Informational Guide*.[14,15]

Green Interval. Ideally, the length of the green display on each approach to an intersection will be sufficient—but not excessive—to serve all the vehicles and pedestrians queued during the red interval. Several PC-based computer programs are available to assist in determining the green interval timing.

For semi- or fully-actuated controllers, a minimum and maximum amount of green time must be determined and allocated for each phase and programmed into the controller. These values are derived from the analysis results of the timing software or other method of analysis used by the designer.

For pre-timed signal controllers, the length of the green display is based on engineering judgment. Traffic and pedestrian counts for a specific period of time are often used in determining the signal timing.

Yellow Change Interval. The purpose of the yellow change interval, which is required to be the first interval following every circular green or green arrow indication, is to warn approaching traffic of the termination of the related green interval or that a red signal indication will follow (see "Vehicle Detector Placement").

MUTCD states that yellow change intervals should have duration of 3 to 6 sec.[16] To determine the appropriate yellow time for the approach, this should be calculated using the Kinematic Model—Formula 1 found in ITE's *Determining Vehicle Signal Change and Clearance Intervals*:[17]

$$Y = t + [v/(2a+2Gg)]$$

where:
Y = yellow clearance interval (sec)
t = reaction time (typically 1 sec.)
v = design speed (ft./sec.)
a = deceleration rate (typically 10 ft./sec.^{2})
g = acceleration due to gravity (32.2 ft./sec.^{2})
G = grade of approach (percent/100, downhill is negative grade)

The equation shown above includes a reaction time, a deceleration element and an intersection clearing time. In view of the operational history of the yellow change interval and the assumptions used in the formula, applying the formula requires the exercise of engineering judgment.

Because a long yellow change interval may encourage drivers to use it as a part of the green interval, maximum care should be used when exceeding 5 sec. If the interval is too short, rear-end crashes may result. When the calculation for yellow change interval time indicates a time longer than 5 sec., a red clearance interval typically provides the additional time.

Some jurisdictions time the yellow change interval to enable a vehicle to clear the intersection before the onset of a conflicting green display. Other jurisdictions allow a conflicting green display to be shown before the intersection is cleared. Still others allow a conflicting green display to be shown after the vehicles have cleared the center line of the conflicting approach. Engineering judgment should be exercised in selecting the operation of the yellow change interval to ensure safe passage of vehicles in the intersection.

As can be seen from the formula above, slower speeds result in higher values of yellow clearance time. When calculating the needed time, consideration should be given to the values for the 15th-percentile speed, particularly at wider intersections.

The calculations for steep downgrades will yield values that some drivers may consider excessive. Simply reducing the interval times may create dangerous operating conditions. The engineer should consider lowering the approach speeds by reducing the speed limit or by the use of a warning beacon or other measures.

Red Clearance Interval. The red clearance interval is an optional interval that follows a yellow change interval and precedes the next conflicting green interval. The red clearance interval is used to provide additional time following the yellow change interval before conflicting traffic is released.

MUTCD states that the red clearance interval should not exceed 6 sec.[18] The appropriate red time for the approach should be calculated using the following formula found in ITE's *Determining Vehicle Signal Change and Clearance Intervals*:[19]

$$R = (w+L)/v$$

where
R = all red interval (sec.)
w = width of stop line to far side no-conflict point (ft.)
v = design speed (ft./sec.)
L = length of vehicle (typically 20 ft.)

For exclusive turn movements, the value of w should be measured along the vehicle turn path from the stop line to the no-conflict point.

The decision to use a red clearance interval is determined by intersection geometrics, crash experience, pedestrian activity, approach speeds, local practices and engineering judgment.

6. Left Turns

Three operational modes are available when provisions for left turns are made in the phasing of a traffic control signal:

1. **Permissive (permitted) mode only**—in which drivers may turn left after yielding to conflicting traffic or pedestrians during the circular green indication, along with the parallel through movements. A separate left-turn lane is often provided but not required. No regulatory sign is required, but an informational sign may be used.

2. **Protected (exclusive) mode only**—during which left turns are permitted only when a left green arrow is displayed. There is no conflicting vehicular or pedestrian traffic. Typically, a separate left-turn lane is provided. If the left-turn movement occurs when the adjacent through movement is shown a circular red indication, a separate left-turn lane must be provided.

   A separate left-turn signal face must be used where the signal sequence does not provide for the simultaneous movement of the parallel through traffic. The change interval display may consist of either a yellow left arrow or a circular yellow. The yellow indication must match the green indication; that is, if the separate left-turn face provides a circular green, a circular yellow is provided. If the separate left-turn signal face provides a green left arrow, the yellow indication must be a left arrow. MUTCD requires that all green arrow indications must be followed by yellow arrow indications. The red interval may use a red arrow only if a yellow arrow indication is used. Otherwise, a circular red is required.

   When a separate signal face is used, it should be positioned in line with the turning movement approach. A left-turn signal sign (R10-10) is required unless the signal face consists of arrows only or unless it is properly hooded, shielded, or louvered to ensure that conflicting circular yellow or red indications are not readily visible to motorists in the through lanes.

3. **Protected/permissive (exclusive/permitted) mode**—a combination of both the protected and the permissive modes whereby left turns may be made during the green display as defined under the respective modes. Green and yellow arrow indications are required for this type of operation.

   The controller phasing for protected/permissive mode is the most complicated of the three modes in that it combines the other two modes. Four distinct controller-phasing schemes are commonly employed:

- lead-left turn with parallel, non-conflicting through traffic;
- simultaneous lead-left turns with no parallel through traffic;
- lag-left turn with parallel, non-conflicting through traffic; and
- simultaneous lag-left turns with no parallel through traffic.

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for Streets and Highways

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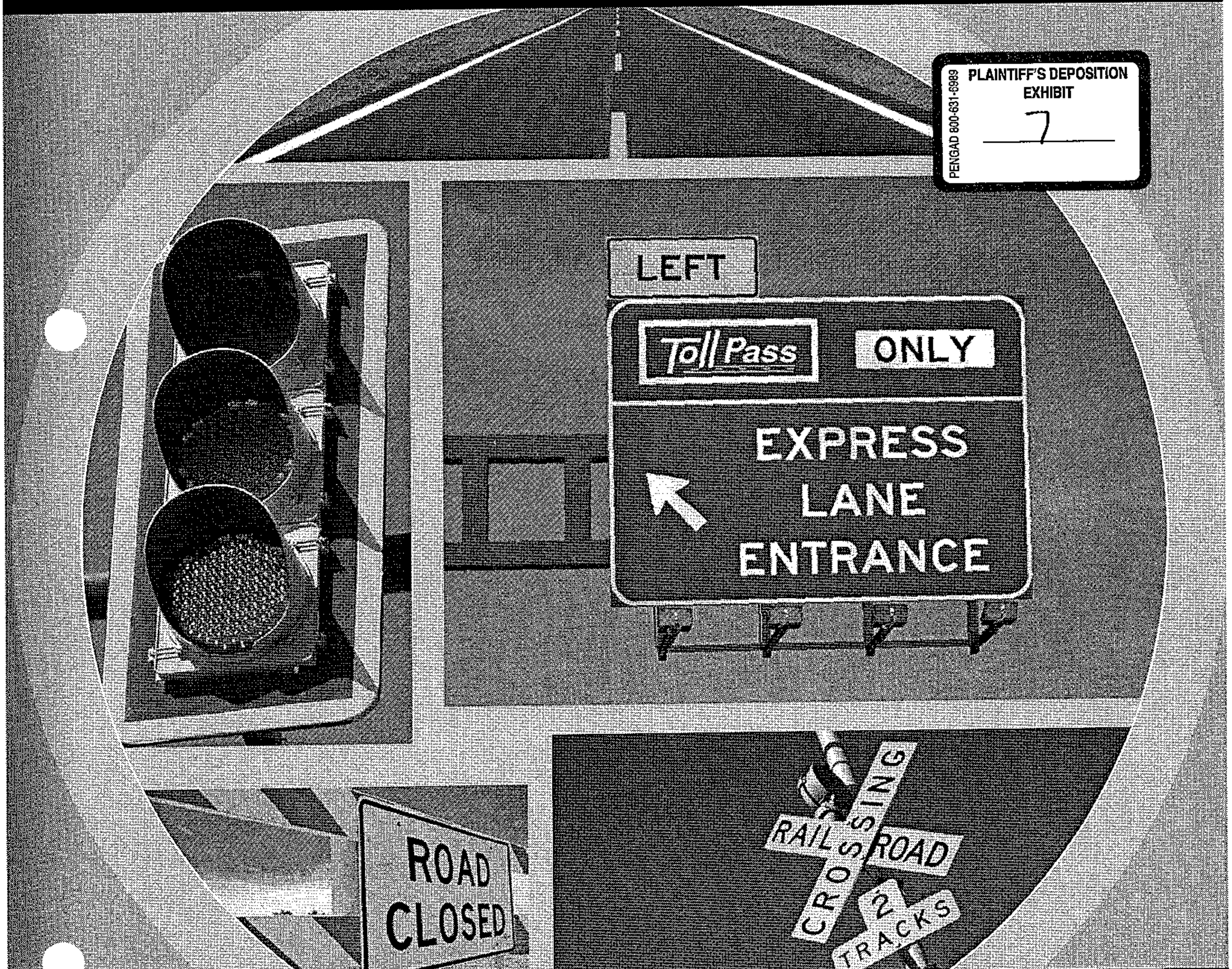

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03 **Except as provided in Paragraph 4, the pedestrian signal heads shall continue to display a steady UPRAISED HAND (symbolizing DONT WALK) signal indication when the pedestrian hybrid beacon faces are either dark or displaying flashing or steady CIRCULAR yellow signal indications. The pedestrian signal heads shall display a WALKING PERSON (symbolizing WALK) signal indication when the pedestrian hybrid beacon faces are displaying steady CIRCULAR RED signal indications. The pedestrian signal heads shall display a flashing UPRAISED HAND (symbolizing DONT WALK) signal indication when the pedestrian hybrid beacon faces are displaying alternating flashing CIRCULAR RED signal indications. Upon termination of the pedestrian clearance interval, the pedestrian signal heads shall revert to a steady UPRAISED HAND (symbolizing DONT WALK) signal indication.**

Option:

04 Where the pedestrian hybrid beacon is installed adjacent to a roundabout to facilitate crossings by pedestrians with visual disabilities and an engineering study determines that pedestrians without visual disabilities can be allowed to cross the roadway without actuating the pedestrian hybrid beacon, the pedestrian signal heads may be dark (not illuminated) when the pedestrian hybrid beacon faces are dark.

Guidance:

05 *The duration of the flashing yellow interval should be determined by engineering judgment.*

Standard:

06 **The duration of the steady yellow change interval shall be determined using engineering practices.**

Guidance:

07 *The steady yellow interval should have a minimum duration of 3 seconds and a maximum duration of 6 seconds (see Section 4D.26). The longer intervals should be reserved for use on approaches with higher speeds.*

I affirm that, in regards to the duration of yellow lights and signalized intersections that,

1. Setting the duration to that less than the ITE Yellow Light Change Interval confronts drivers with an impossible decision problem, forcing drivers to run red lights. That such a duration creates a region on the road where if the driver is in at the time the light turns yellow, the driver neither has enough distance to stop nor the time to proceed to the intersection at the maximum allowable speed or less and still enter the intersection while the light is still yellow.

   - The name of such a region on the ~~road is called a~~ *type I dilemma zone*. No matter the decision of the driver, the driver will run a red light. There is no solution. or speed

   - The *maximum allowable speed*, also known as the *design speed* or *approach speed*, is at least the speed limit for purposes of using the ITE Yellow Light Change Interval.

2. Setting the duration to that less than or equal to the ITE Yellow Light Change Interval for left and right turn lanes, confronts turning drivers with an impossible decision problem, forcing drivers to run red lights. That such a duration creates a type 1 dilemma zone, a region on the road where if the driver is in at the time the light turns yellow, the driver neither has enough distance to stop, nor enough time to proceed to the intersection at the maximum allowable speed or less, nor enough time to compensate for the driver's necessary act of slowing down from the maximum allowable in order to begin turning. The driver cannot enter the intersection while the light is still yellow.

   Turning (U, left and right) drivers require up to twice as much yellow duration as the ITE Yellow Light Change Interval provides, certainly no less than that the formula provides. The Yellow Light Change Interval only provides enough yellow time for drivers to approach the intersection from the critical distance at the maximum allowable speed, no less. The Yellow Light Change Interval does not provide enough yellow time for drivers who intend to enter intersection, who also need to *slow down* before entering the intersection.

   - The *critical distance* is the distance the driver needs to stop from the maximum allowable speed. It includes the distance he travels while decelerating, and the distance he travels at the maximum allowable speed while he perceives the light turning from green to yellow.

3. Setting the duration to that less than or equal to the ITE Yellow Light Change Interval at an intersection which is close by another intersections creates a type 1 dilemma zone.

   The ITE Yellow Light Change Interval only provides enough yellow time for drivers to approach an intersection from the critical distance at the maximum allowable speed, no less. Any

PENGAD 800-631-6989 DEFENDANT'S EXHIBIT A KW 9-13-12 obstacle that interferes with a driver's constant procession to the intersection at the maximum allowable speed, forcing him to slow down for a period, creates a type 1 dilemma zone for that driver. The length and location of the dilemma zone depends on when and where the obstacle appears. A close-by intersection whose light is currently green is not an obstacle. A close-by intersection whose light turns is not green is an obstacle. Any driver travelling within that zone when the obstacle manifests itself, will be forced to run a red light.

The obstacle is usually another intersection whose approach, as defined by the ITE Yellow Light Change Interval, overlaps or is just outside the approach of the first intersection. The obstacle could be backed up cars waiting at the next intersection, feeder roads, or mall exits—anything that obstructs the drivers progress to the intersection from the critical distance at the maximum allowable speed.

in other cases

4. Setting the duration to exactly the ITE Yellow Light Change Interval leaves no margin of error. The ITE Yellow Light Change Interval yields the absolute minimum length for a yellow duration for a driver traversing the critical distance at the maximum allowable speed. This minimum duration represents the instant a safe decision first becomes available at all points along the approach. That means that at one infinitesimally-thin line on the road, the decision to stop gets replaced with the decision to go. There exists a viable decision, but there is no play. If the driver makes a decision to go just before crossing the thin line, he will run a red light and possibly cause a t-bone crash. If the driver makes a decision to stop after crossing the thin line, the driver either skids into the intersection, stops abruptly or possibly causes a rear-end crash. Setting the yellow to the ITE Yellow Light Change Interval means that a decision is available, but it also means that it is not clear to drivers what the decision should be. Since traffic engineers do not mark this line on the road, the driver is forced to guess. Half the time the driver guesses wrong. This predicament is called a type 2 dilemma zone.

(1) 4.0 s @ 45 mph

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(2) 3.0 s @ 45 mph

---

braking to stop at 45 mph = 66.0 ft/s = V_0

should be ≥ 4.45 s

(1) $t_0 = 1.5$ s

$a = 11.2$ ft/s² (0.348 g)

$\Delta x = 1.5 V_0 + \frac{V_0^2}{2a}$ = 99 ft + 194 ft = 293 ft

$\stackrel{?}{=} 66 \times 1.5 - \frac{1}{2}(15.2)(1.5)^2$

travel in 4.0 s : 264 ft at 45 mph

So between 264 ft + 293 ft can neither stop safely nor reach intersection before light turns red (ignores width of intersection/ length of car)

↳ would need to brake at 13.2 mph (?)

---

w/ left-turn light set to 3.0 s

(2) travel in 3.0 s = 198 ft at 45 mph

so if between 198 – 293 ft can't stop –

~~need to be~~

RL

1.5(66) + (87) + 186

in 1.5 s at 11.2 ft/s² $\Delta V = a\Delta t$ = 16.8 ft/s

can only slow to 49 ft/s = 34 mph

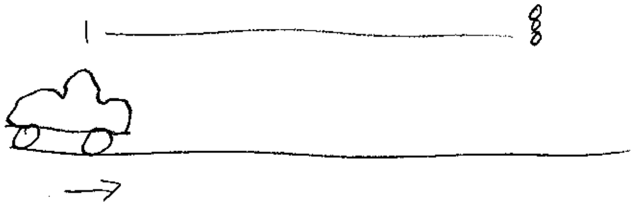
travel, brake

30 mph = 44 ft/s

stopping distance = 66 + 86 = 152 ft

travel: 132 ft

} 132–152 can't stop / can't go thru



45mph @ 4 sec → $\frac{45\,mi}{h} \times \frac{5280\,ft}{mi} \times \frac{1\,h}{3600\,s} = 66$ ft/sec

264 ft. = travel dist @ 45mph during yellow w/o changing speed

---

1.5 s reaction time before braking → 99 ft travel befor decel.

"Decel" @ 11.2 ft/s²

Dist to stop:

$$v_f^2 = v_0^2 + 2a\Delta x \quad (v_f \to 0)$$

$$\Delta x = \frac{-v_0^2}{2a} = -\frac{66^2}{2(-11.2)}$$

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

$$+99$$

$$\overline{293.5 \text{ ft}}$$

So to go safely through before red, w/o brake must be closer than 264 ft.

But to stop safely before intersection, must be 293.5 ft or <u>farther</u>.

Dilema zone betw 264 + 293

3 sec, 45mph

66 ft/s × 3 sec = 198 ft travel @ 45 for 3sec

· Decel: 1.5 sec RX time → 99 ft

Stop dis → all same → 293.5 ft

so worse dilema zone (198 ft to 293.5 ft)

3 sec 30 mph → 44 ft/sec × 3 sec = 132 dist trav @ 30mph in 3 sec

1.5 s RX × 44 → 66 ft travel during RX

$$\Delta x = \frac{(44)^2}{2(11.2)} = 86.4 \text{ ft to brake}$$

+ 66 = 152 ft

dilema zone 132 – 152 ft

Response to Vanasse-Hangen-Brustlin Comments on Brian Ceccarelli's *Derivation of the Yellow Light Equation*

by Brian Ceccarelli

April 29, 2012

The letters in the outline below (A, B, C . . .) refer to the red tab marks I made on Vanasse-Hangen-Brustlin's comments. I put VHB's comments at the end of the outline.

Vanasse-Hangen-Brustlin [VHB]
Brian Ceccarelli [BC]

A. VHB: "His thesis is based on a misunderstanding of the yellow change interval—that this interval is equal to the time needed for a vehicle to stop before the intersection before the yellow signal indication terminates."

   BC: The thesis VHB is talking about is from an early edition of my *Derivation* paper—from February 2010. In February 2010 I did believe what VHB claims. I did believe that traffic engineers *meant* for the yellow change interval to be equal to the time needed for a vehicle to stop. I certainly did not believe they actually intended it to be what the formula says: *half* the time needed for a vehicle to stop. I believed that traffic engineers had made an innocent math goof. I could not imagine professional engineers making such a heinous mistake. My misunderstanding of what traffic engineers *meant* does not make a difference in my conclusion. The formula is wrong no matter what their intention is. In my February 2010 paper, I gave traffic engineers the intellectual grace that they couldn't have meant what their formula means.

   But in July 2010 H.F. Van Der Brinten of Houston convinced me that traffic engineers *purposed* the yellow interval to be half the time it takes a vehicle to stop. That was a shock. Engineers are not innocent. These guys just do

Setting the Length of the Yellow Light

Your Department of Transportation sets the length of the yellow light according to an equation published by the Institute of Traffic Engineers (ITE). The Institute of Traffic Engineers is an international organization. ITE was established in the United States in 1930. The yellow light equation has been in all editions of ITE's Traffic Engineering Handbook since 1965. Most cities in the world apply this equation to their traffic lights.

In the realm of traffic engineering, the goals of traffic safety and the goals of traffic capacity often compete. ITE's yellow light equation is an example of where the goal of traffic capacity usurps traffic safety. For the goal of traffic safety, the yellow light equation is wrong. Setting yellow light intervals to this equation intentionally risks our lives.

For ITE's equation to work, drivers need to know a critical piece of information. A critical piece that drivers don't know. Drivers need to know the location of a point on the road called the *decision point*. It is a point on the road closest to the intersection where you can still apply your brakes and stop safely. Our knowledge of this point is required by the equation. That knowledge in tandem with the DOT properly setting the yellow duration, would then provide drivers with the necessary information to always make right decisions.

But by omitting half the information, your DOT creates a *dilemma zone*, a zone of indecision where upon seeing the light turn yellow, you don't know whether to stop or go. The Department of Transportation is fully aware of their problem child. They have offered many papers on how to reduce the accidents the dilemma zone creates. But for some strange reason, the DOT hasn't thought of painting a big line at the decision point, nor has the DOT thought to increase the yellow duration to the time it takes for a car to stop. The latter solution would remove the decision point altogether because a driver could always brake without penalty. Anyway, *the dilemma zone is the engineering defect which births and feeds red light camera companies.*

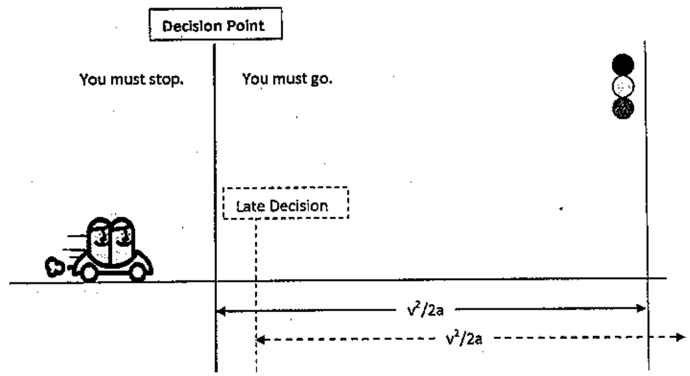
Every time we approach an intersection when the light turns yellow, we guess where the decision point is. The standard has always required that it not be a guess, but we have been guessing for decades. We had been getting by with guessing because police officers don't sit at intersections 24 hours a day, nor do they hand out tickets to those who run red lights by a fraction of a second. We do not get by anymore. Red light cameras leave no room for guessing but engineers still force us to guess. Red light cameras raise the bar of enforcement, but engineering practice has never risen to meet the bar. Cities and red light camera companies exploit the discrepancy. Cities punish the wrong party.

t_p?

Where is the decision point? The decision point is located at the safe braking distance on the approach to the intersection. The safe braking distance is $v^2/2a$ where v = speed limit and a = deceleration of a car.

If we arrive at this **unmarked point** on the road at the **exact time the light turns yellow**, we can decide to stop or go and either ~~decision is safe. If we~~ decide to go, we will arrive at the intersection just as the light turns from yellow to red. If we decide to stop, we will stop at the intersection and the light will have already been red for several seconds.

we perceive



Though this sounds reasonable, consider . . .

1. If we make a decision to stop too late, say just 2 feet after we pass the unmarked decision point, we will run a red light. We will stop 2 feet into the intersection because we still need that $v^2/2a$ distance to stop. I am only stating laws of physics. The light is already red because the yellow light had already turned red **long ago.** **ITE's yellow interval is half the length of time needed to stop.**

   A late decision usually does not prevent us from stopping on time. We compensate by braking harder. However the later we decide, the harder it is to stop. There is also the problem of cars behind us. The harder we brake, the greater the likelihood they will rear-end us. Stopping hard is problematic. We may run the red light because we were really too close to the intersection to begin with. We may run

the red light because braking hard would have caused the car behind us to hit us. Either case we skid into the intersection ***on a red.***

2. If we are farther away from the intersection than the decision point when the light turns yellow, and we guess to go, then we enter the intersection **on a red** light while going the speed limit.

   When we see a yellow light, ITE's equation **biases** us to **go.** To go is logically our best option because we already know it is **impossible to stop within the yellow interval.**

   Many times we are sincerely not sure what to do. In those cases we prefer acceleration because we want to be safe. We will chance a red light in favor of being safe. We speed up to make sure we clear the intersection before cross traffic gets a green. We also accelerate because we know that we cannot stop our car within the time the light is yellow. When acceleration is not enough, we will enter the intersection **on a red.**

It is true that we do often guess right. But also it is true we guess wrong. **Because the very nature of the equation presents us a guess**, the probability is > 0 that we will guess wrong at some point—perhaps a handful of times each year. We will approach the intersection in just such a way that it is not clear what we should do. Since the equation biases us to beat-the-light, we will most likely go. It is a statistical certainty that we will run the red light at some point. Your DOT knows that is exactly what their dilemma zone does. Your town knows that too, and so they have set up red light cameras to profit from the statistical certainty.

There are solutions.

1. To prevent people from running red lights, all we have to do is set the yellow interval to the stopping time. Make "yellow light means brake" the premise. If we do this simple thing, the light turning to yellow conveys a clear and simple meaning: By seeing the light turn yellow, we can now brake without penalty and our safety is guaranteed.

   No longer do we have to wage the debate, "Should I go or should I stop?" We can stop.

   Stopping on time may not always be possible, but at least we will glide thru the intersection ***on a yellow.*** There will be no cross traffic because their light is still red. We are safe. Because we can stop comfortably, we don't have to worry about rear-enders. Cars behind us will not be surprised by a comfortable stop. We don't have to panic at red light camera intersections. We don't have to slam on the brakes to avoid a citation. We can rest in the fact that if we decide to try to stop, our try will not be penalized.

2. To prevent people from running red lights, keep ITE's equation but mark the road at the safe braking distance from the intersection. The marker could be a painted line which drivers could see, or perhaps small ruts in the road which drivers could hear. One could also invent a detector for inside the car which reads an emitter from the intersection. When the detector and emitter sense the car at the decision point, the emitter could beep.

   Solution 2 has problems though. Solution 2 takes away a driver's focus from the intersection. Solution 2 does not work for cars within the safe braking distance travelling under the speed limit when the light turns yellow. For such cars, stopping or going will still be a guess. So Solution 1 is better. Solution 1 works all the time in any circumstance.

Traffic Flow Preempts Safety

What was ITE thinking when they came up with their equation? How do professional engineers justify their equation? Why is the premise "Yellow light Means Go" as opposed to "Yellow Light Means Brake?" Ask an engineer and he will tell you:

1. Because if we made the yellow light interval longer, we would increase traffic congestion. [More yellow means less green, and less green means fewer cars going through the intersection.]

2. If we make the yellow light the stopping time, that'll give people who do not stop too much time. They will treat the yellow as a green.

   [What the engineer does not realize, is that people already treat the yellow as a green—because ITE's equation forces them to do it! Yellow means Go!]

The story from traffic engineers is always the same. Engineers emphasize the need for cars to go over the need for cars to stop. ITE's yellow light equation is just one example. There are others:

1. Shorten left turn arrow yellows to 3.0 seconds as if all cars are going 20 mph--because most cars are in line waiting to turn left. But that's a big problem for cars that approach the intersection when there is no line waiting at the light. These cars approach at the speed limit. Did the laws of momentum suddenly change for objects in the left lane? Do you see a 20 mph speed limit sign in the left lane of a 45 mph road?

2. Purposefully design an intersection forcing cars to run red lights. ITE actually recommends this. See page 412 in the Traffic Engineer

Handbook, 6th edition, 4th paragraph from the bottom. ITE says that is okay for people to run red lights so long as DOTs provide enough all-red time so that the car can get across the intersection before cross-traffic gets a green. ITE doesn't think of the legal ramifications of making people run red lights. ITE doesn't think of what happens to safety when they turn the all-red interval into a yellow. ITE forgets the purpose of the all-red interval.

The Erroneous Yellow Light Equation

The equation Departments of Transportation use to set the length of the yellow light is

[redacted]

$t_p + \frac{V_c}{2a + 64.4g} = t_p + \frac{V_c}{2(a + 6g)}$

The equation expresses mathematically the premise that "yellow light means go." The premise comes from the paper *Determining Vehicle Signal Change and Clearance Intervals*, Washington D.C., ITE 1994:

> "This formula for determining the length of the yellow change interval provides enough yellow time for a vehicle to travel, at its initial speed, over the distance it would take to stop at a comfortable average deceleration before entering the intersection."

Note that cars entering into the intersection are the ones that determine the yellow light interval. **Cars that go, not brake, determine how long the yellow light lasts. Yellow means go.** ?

The premise, "Yellow means go" is an error in physics. The correct premise is "Yellow light means brake." Even a child knows this. States like Arizona have advertising campaigns that promote "Yellow Light Means Brake." Well, surprise! Your DOT never learned correct physics. Your DOT has never connected the dots. 1. Red lights mean stop. 2. Yellow lights exist only to serve red lights. 3. Therefore, yellow lights mean stop. The traffic engineer really has a hard time with this. To accept the syllogism means he has to acknowledge his 45 year old sin and repent from it.

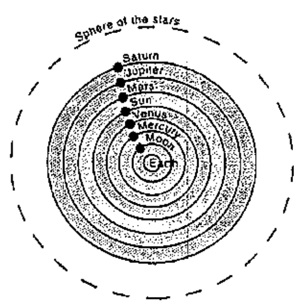
What is an Error in Physics?

I only explain what a physics error is because I have found that most traffic engineers do not know what a physics error is or recognize its tell-tale bad signs. While engineers have taken physics courses, they do not seem to remember the kind of thinking that goes into creating those equations. Traffic engineers claim that "the math is right." But the math is right only when the premise upon which the math rests is right.

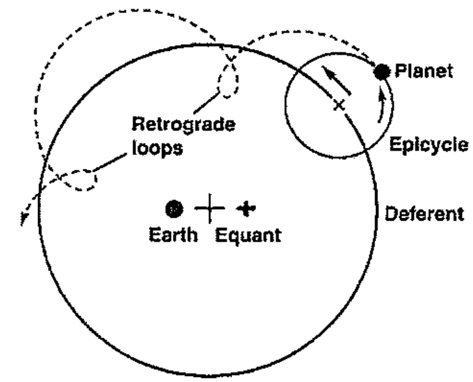
From history, I illustrate a different bad physics premise. This one is from the ancient Greek astronomer Ptolemy.

The Earth-Centric Universe

Ptolemy's premise was that the Earth was at the center of the Universe. ITE's premise is like Ptolemy's premise. Though well-intended, and it sort of works, it is still wrong:

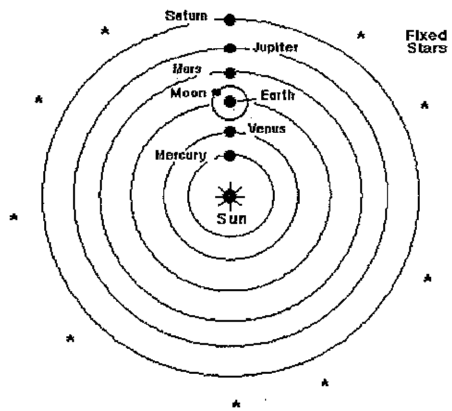


By using his model, Ptolemy could predict the motion of the planets. His predictions only worked to a point, because his math only worked to a point. His math couldn't explain planetary retrograde motion. Because the math had problems, Ptolemy understood that his premise was off. So Ptolemy kludged his up premise. Instead of making the planets travel in perfect circles, he had them travel in Spirograph paths:



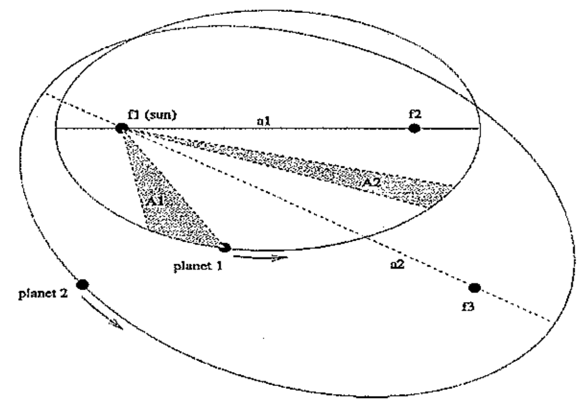
Each planet now danced in its own "epicycle" along its circular orbit. Ptolemy liked this better because it explained the observed motions of the planets better. The epicycle model held for centuries.

After 16 centuries, the astronomer Copernicus measured that Ptolemy's math didn't describe actual observations. Ptolemy's math worked great for Ptolemy's premise, but reality exposed problems in Ptolemy's math. By implication, that problem in the math meant a problem in the premise. Copernicus questioned the Earth-Centric Universe. So in order to make the math fit reality, Copernicus dissed Ptolemy's premise and proposed that the Sun, not the Earth, is at the center of the Solar System:



Copernicus' premise made things much better. By putting the Sun at the center, Copernicus could both explain the retrograde motion of the planets and describe the motions of the planets by using the equation of perfect circles.

As you know, Copernicus' math didn't quite hit the nail on the head either. A century later, Kepler changed Copernicus's premise from circular orbits to elliptical orbits. The math of the ellipse, not the circle, perfectly predicts the planetary motions. To this day we use Kepler's premise and math equations:



Back to red light cameras and yellow light equations.

Traffic engineers always claim the math behind the yellow light equation is right. But reality says otherwise. Measurements taken by the red light cameras observe that every one in every city consistently runs red lights. That kind of observation means one of two things:

1. That either every one in every city is a bad driver, each one carelessly running red lights, or more likely . . .

2. The yellow light equation, which governs people running red lights, has a problem.

The reasons why 1 is false are:

- No one purposes to run red lights. Most people are not suicidal. No one looks at a red light and says, "Oh, I am going to intentionally run that light for the fun of it."

- One cannot believe that the population of an entire city consists of all bad drivers. The red light cameras have measured that 120,000 people in Cary are red light runners. That's everybody in town.

Thousands of cars running red lights is the tell-tale sign of a bad premise in action. These cars run red lights because the math of ITE's yellow light equation forces upon drivers a false reality which no one can obey.

Accepting ITE's Premise

If you accept ITE's premise, "yellow light means go," then you believe

1. That stopping and going, even though your life depends on it, should be a guess.
2. That it is okay for people to cause accidents because the equation offers no event which the driver can use to guarantee his safety.
3. That it is okay for the yellow light interval to be half that required to stop your car, despite that inducing a bias to go instead of stop.
4. That it is okay for the yellow light interval to be half that required to stop your car, despite that causing rear-end collisions.
5. That drivers who beat-the-light intentionally want to run red lights.
6. That it is okay to be penalized for braking when seeing a light turn yellow.
7. That it is okay to encourage full-speed T-Bone crashes.
8. That red light camera programs are a great way to make money, since the equation induces a guess and a bias which stack the deck in favor of the red light camera company.
9. That everyone in the Town of Cary is a felon because the Town of Cary has issued 120,000 tickets—equal to the population of Cary.
10. That it is okay to disregard places like Georgia who found that adding 1 second to all ITE's yellow light intervals reduced the red light runners by 80%. That forced the red light camera companies to pull out. [By increasing the yellow interval by 1 second, Georgia gets closer to the value Newton's Laws of Motion dictates. If Georgia increases the yellow time to what Newton's Law requires for stopping cars, Georgia will see their 80% decrease go to 99.9%.]

Accepting the Correct Premise

If you accept the correct premise, "yellow light means brake," then you believe

1. That traffic control devices should have a clear and simple meaning.
2. That seeing a light turn yellow should guarantee your safety.
3. That you should never get penalized for braking.
4. That cars never have to rear-end you.
5. That skidding into the intersection on a yellow is better than on a red.
6. That running full speed into cross-traffic never has to happen.
7. That red light camera programs should never exist, for the only people running red lights would be the occasional drunk, and there's no profit in that.

North Carolina Law

ITE's equation appears in section 5, page 19 of the NCDOT Intelligent Transportation and Signal Systems Unit *Design Manual*. It is Std 5.2.2, Sheet 4 of 4. The *Design Manual* cites the Institute of Traffic Engineers (ITE) *Traffic Engineering Handbook* (2008, 6th edition, p. 412) as the source of the equation.

Cary Town Charter App 2.8, N. C. Session Law 2004-141, old Cary Town Charter 8.15 (prior to 2/2011) and N. C. Session Law 2001-286 state that the duration of the straight-thru yellow interval must equal or exceed the yellow interval from this equation. Many of North Carolina's yellow intervals *do not equal or exceed* the yellow intervals from this equation. Those red light cameras, by City Charter and State Law, are explicitly illegal.

The Town of Cary ignores this yellow light equation when it shorts its independently phased left turn yellows. The Town of Cary opts to use a different NCDOT "standard," a standard which allows Cary to give a 45 mph car the braking distance of a 20 mph car. That is the length of a Greyhound bus. Good luck stopping within that distance. In this case, the NCDOT standard is arbitrary and capricious. It is illegal. It cannot be enforced because it explicitly opposes Newton's Laws of Motion—the highest laws in the universe.

Many yellow intervals do abide by ITE's equation. But then they either fall short 2 to 3 seconds as required by the good physics of yellow means brake, or Cary fails to mark the safe braking distance line as required by the equation.

ITE's equation distorts reality. When you plug the yellow times from ITE's equation back into the Newton's Laws of Motion, you in effect compute the real stopping distances. These are the distances ITE's equation gives if you try to stop within the yellow interval. These are the distances which you attempt to stop in when you are past the unmarked decision point. These distances fall short of every safe stopping distance standard in the world.

Braking Distances When You Think Yellow Means Stop

Speed Limit	NCDOT Minimum Safe Braking Distance	Length of Time the Signal is Yellow	Yellow Time Braking Distance
	This equation $S_{b\,safe} = v^2/2a$ is correct. It comes from Newton's Laws. The NCDOT fixes $a = 11.2\ ft/s^2$. NCDOT gets 11.2 ft/s² from AASHTO's *A Policy on Geometric Design of Highway and Streets*, *2004*, p. 111-112.		The equation $S_b = at^2/2$ determines distance travelled when you know the deceleration constant and time spent stopping. This equation comes from Newton's Laws of Motion. If you think "Yellow Means Brake", this column is the distance you have to come to a stop. In other words, you can never slam on your brakes upon seeing the light turn yellow and expect to stop by the time the light turns to red.
	$S_{b\text{-}safe} = v^2/2a$	$t = v/2a$	$S_{b\text{-}unsafe} = at^2/2$
55 mph = 80.7 ft/s	290 ft	3.6 s	72.6 ft
45 mph = 66 ft/s	194 ft	2.9 s	48.6 ft
35 mph = 51.3 ft/s	117 ft	2.3 s	29.4 ft
25 mph = 36.7 ft/s	60.0 ft	1.6 s	15.0 ft
15 mph = 22 ft/s	21.6 ft	0.9 s	5.4 ft

Derivation of the Yellow Light Equation

The Instigator

After I got flashed by a red light camera, I discovered that my intersection's (Cary Towne Blvd. at Convention) yellow light interval did not meet the minimum required by the ITE's equation. It turned out that the NCDOT had increased the speed limit on my road from 35 mph to 45 mph but never bothered to increase the yellow interval accordingly. The speed limit is now 45 mph, but the NCDOT had set yellow light interval for a 35 mph road. 6 months after Cary convicted me, on March 19, 2011 they increased the yellow light interval to that for a 45 mph road. Red light runners decreased by 80%. Cary did not refund anyone's money. From this one light, Cary illegally stole $427,950 according to their own Charter.

The same thing happened to Susan Sharma at a different intersection. She ran the red light at High House Road at Prestonwood in September 2006. That intersection's yellow light was also shorter than the minimum requirement. Cary convicted her anyway. One month later Cary increased the yellow light interval to that mandated by their Charter. Cary did not admit the problem. Cary did not refund her money. Cary stole $ 299,350.00 from this light.

To this day, Cary refuses to admit it.

Grail Quest

The legality of the red light cameras is built upon the validity of ITE's equation. Even though I already knew *my* red light camera was illegal, I still wanted to understand the equation. For me to complain about a yellow light interval without understanding the principles the NCDOT uses to set them would mean my potential embarrassment in front of the judge. I wanted to make sure I could understand and derive the equation before pleading the case.

I searched the internet for a derivation of ITE's equation but found none. I found the North Carolina Statutes, the Town of Cary Ordinances, the NCDOT Signals Manuals, the ITE Handbook and the Manual for Uniform Traffic Control Devices, but I could not find the derivation of the yellow light interval. Engineering books have that equation in them. But not one ever shows the derivation. Every book adopts ITE's equation without inspection.

I have a B.S. in physics from the University of Arizona. I figured I should be able to put that education to use. So with pencil in hand, I derived an equation. The problem is only a classical mechanics problem. Any freshman physics student could do it. But the equation I derived was not ITE's equation.

Did I make a mistake? No I didn't. It turns out I could not derive ITE's equation because ITE's equation cannot be derived. That's because ITE's equation is wrong. The equation controls the motion of cars, but *in itself it is not an equation of motion*. To an engineer, the words in italics register nothing. But those words spell doom and gloom to a physicist. Those words mean that ITE's equation does not describe reality. Only equations of motion describe the reality of moving objects. ITE's equation is not an equation of motion; therefore, ITE's equation does not describe the real world. One cannot just impose such equations upon Mother Nature and expect Mother Nature to obey.

In order to derive ITE's equation, I would have had to miraculously repeat ITE's false premise. This explains why no book shows a derivation. Everyone just transferred the equation into their own book. The equation is a fantasy, someone's wishful thinking.

Stopping Distance Equation

The way I discovered how ITE arrived at their fantasy equation was an accident. I stumbled upon the stopping distance equation. The stopping distance has that extra "2" in the denominator just like the ITE's yellow interval equation. The stopping distance does come from Newton's Laws of Motion. It includes the amount of distance a car travels during the perception interval and the amount of time a car takes to brake. Here's the equation, and it is correct:

$$S = t_p v_o + v_o^2/2(a_b + 32.2g)$$

The stopping distance equation has two parts.

1. $S_p = t_p v_0$ = perception distance

2. $S_b = v_0^2/2(a_b + 32.2g)$ = braking distance

Traffic engineers first ask the question: *What distance does the car travel from when the driver first sees the light turn yellow to where the driver comes to a stop at the intersection?* This first question is a consequence of the bad premise. Traffic engineers are interested in the distance it takes a car to stop, not how long it takes a car to stop. Traffic engineers are not interesting in how long it takes a car to stop, but rather for a car to proceed through this braking distance. Yellow light means go. The bad premise at work.

Stopping Distance Derivation

Here's the derivation of the stopping distance equation. Traffic engineers get this equation right. It is important for you to know that they do get this right and that it is based on Newton's Laws of Motion. For when DOTs choose to set yellow intervals shorter than this equation, they are in affect violating the immutable Laws of Motion, forcing cars to run red lights. This includes yellows intervals for left turn lanes, for the Laws of Motion apply to all places in the universe including left turn lanes.

One first must see how to derive the stopping distance equation in order to see how the ITE modifies it to arrive at their unsafe yellow interval:

The distance a car travels when the driver first sees the yellow light:

3. $S = x_p + d_s$

4. $S = t_p v_o + d_s$

Where

S = total distance car travels from when the driver observes a green light that just turned yellow to when the car comes to a stop

$x_p = t_p v_o$ = distance car travels during the perception time

d_s = distance car travels while braking

t_p = the perception time = the number of seconds it takes the driver to observe and to initiate a response to a green light that just turned yellow

v_o = speed limit

First solve d_s.

Using the equations of motion:

5. $v = dx/dt$
6. $v = v_o + at$
7. $S = x_p + \int v\, dt$
8. $S = x_p + \int (v_o + at)\, dt$
9. $S = t_p v_o + v_o t_a + a t_a^2/2$ — When a is a constant
10. $d_s = v_o t_a + a t_a^2/2$
11. $t_a = (v_f - v_o)/a$ — From 6, solve for t
12. $t_a = -v_o/a$ since $v_f = 0$ — The final speed is 0 mph.
13. $d_s = v_o(-v_o/a) + a(-v_o/a)^2/2$ — Substitute 12 into 10.
14. $d_s = -v_o^2/a + v_o^2/(2a)$
15. $d_s = -v_o^2/2a$

a = acceleration of the car (negative value is deceleration)
v_f = final velocity (0 = stopped)
v_o = initial velocity (the speed limit)
t_a = time it takes car to go from initial to final velocity

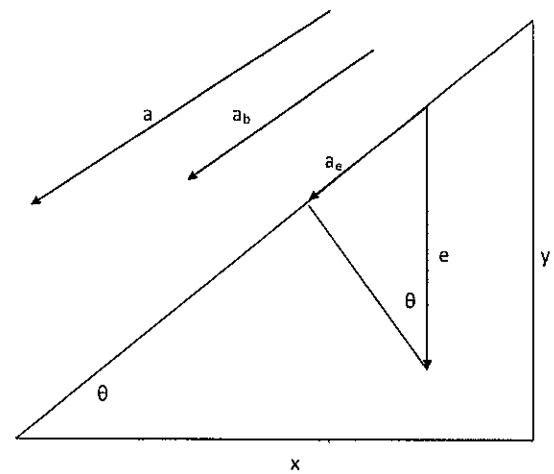
Plug d_s from equation 15 into equation 4.

16. $S = t_p v_o - v_o^2/2a$

Let the acceleration now be a declaration. Set a = -a.

17. $S = v_o t_p + v_o^2/2a$
18. $S = v_o(t_p + v_o/2a)$

What contribution does the grade of the road add to the car's acceleration? What is the acceleration, a_e, to the car caused by earth's gravitational acceleration?



19. $a = a_b + a_e$

Where

a_b = deceleration of the car due to the application of car's brakes
a_e = acceleration of the car due to force of gravity due to grade of road

ITE makes an assumption about a_b. Only a physicist would catch it. ITE assumes that on a level road, that the brakes of any vehicle can apply a force $\mathbf{F_b}$ resulting in a constant deceleration a_b. That means that no matter the mass of the vehicle, be it a Toyota Corolla or an 18-wheeler, the vehicle can always decelerate at a_b. That is why I can draw the above diagram using acceleration vectors instead of force vectors, the latter which a physicist would normally expect.

20. g = grade of road = rise over run = y / x

21. $g = y/x = \tan\theta$

22. $\theta = \tan^{-1} g$

23. $\sin\theta = a_e/e$

24. $a_e = e\sin\theta$

25. $a_e = e\sin(\tan^{-1} g)$

Using the small angle approximations, for small values of θ:

26. $\theta \approx \sin\theta$

27. $\theta \approx \tan\theta$

From equation 21 and equation 27:

28. $g \approx \theta$

From equation 26, substitute $\sin\theta$ for g in equation 24:

29. $a_e = eg$

For small grades:

30. $S = v_o(t_p + v_o/2(a_b + a_e))$
31. $S = v_o(t_p + v_o/2(a_b + eg))$
32. $S = v_o(t_p + v_o/2(a_b + 32.2g))$

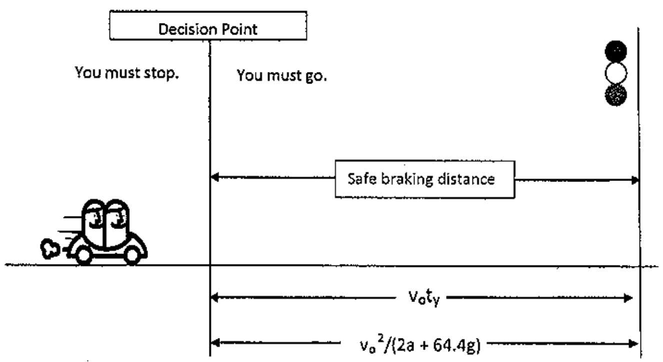
Because earth's gravitational acceleration is $e = 32.2\ ft/s^2$

$$S = v_o(t_p + v_o/2(a_b + 32.2g))$$

is the *correct* formula for the distance from where the driver first sees the light turn yellow to where the driver comes to a stop at the intersection.

While the distance equation is right, the way the NCDOT and ITE computed how much time it takes for the driver to travel that distance is wrong. Instead of using a car that stops to traverse the stopping distance, they use a car that proceeds.

The False Premise at Work



The creators of the ITE's equation (eq. 35) use the safe braking distance point on the road before the intersection in order to determine how long the yellow light must be. But instead of using the amount of time it takes a car a stop to set the yellow time, ITE takes the amount of time it takes a car *that is not going to stop* to determine the yellow time.

The left side of equation 33 is the distance a car travels which does not brake. The right side of equation 33 is the distance a car travels if he does stop.

33. $v_o t_y = v_o^2/(2a + 64.4g)$

where t_y = yellow time for a car going the speed limit to traverse the braking distance.

34. $t_y = v_o/(2a + 64.4g)$

It is easy to get confused here. Any physicist knows that $v_o^2/(2a + 64.4g)$ implies a time to stop. But t_y is not that time. Let me explain.

In equation 33, equating the distance a car travels which does not brake to the distance a car travels when he stops, sets up the time it will take the car which does not brake to traverse the braking distance. That time is the unknown variable. It is the yellow time.

The math of equation 34 expresses the time it takes for a car that does not stop, to traverse the safe braking distance.

This seems like an oxymoron. It is not an oxymoron. It is just the expression of a bad premise. It is very odd. What is being sacrificed here?

When you compute the yellow time this way, only at the distance $v_o^2/(2a + 64.4g)$ before the intersection, if the yellow turns yellow right at the point where the driver crosses that distance, can a driver decide either to stop or go and not run a red light. If the driver is farther than that distance, then the driver must stop. If the driver is closer than that distance, then the driver must go.

3

At the distance $v_o^2/(2a + 64.4g)$ before the intersection, if the driver decides to go, t_y seconds later he will enter the intersection at the instant the light turns red.

At the distance $v_o^2/(2a + 64.4g)$ before the intersection, if the driver decides to stop, he is going to travel $v_o^2/(2a + 64.4g)$. When he comes to a stop, he will be stopped exactly at the intersection. The time it will take him to stop is $v_o/(a + 32.2g)$. This time is twice as much as the yellow time. Though it will take twice as long for him to stop, he will be able to stop before the intersection because all he is going to travel is $v_o^2/(2a + 64.4g)$. It is just that half the time the driver is coming to stop, the light will be red. The driver needs not only the yellow time to stop, but also the red time.

Which brings us to ITE yellow light equation:

35. Yellow Interval = $t_p + v_o/(2a + 64.4g)$

35 is the equation, albeit incorrect, one finds in ITE's Traffic Engineering Handbook and the NCDOT Design Manual:

[redacted]

Impractical and Dangerous

While the math exactly represents the false premise, one cannot apply the math without jeopardizing everyone's lives. The problems of this equation are:

A. It is impractical because you do not know the location of $v_o^2/(2a + 64.4g)$. It's guess work. The traffic engineer just created the dilemma zone.
B. You have no option which guarantees your safety.
C. Safe braking is not always an option. You can get penalized for it.
D. If you think you have passed $v_o^2/(2a + 64.4g)$, but really you haven't and you decide to go, you will run a red light.
    a. You will run over a pedestrian.
    b. You will have a full-speed t-bone crash.
    c. You will get a red light camera ticket.
    d. You will get a ticket the old fashioned way—by a cop.
E. If you are inside $v_o^2/(2a + 64.4g)$, and you decide to stop, you no longer have the safe braking distance to stop.
    a. You will skid through the intersection **on a red**.
    b. Your head will go through the windshield.
    c. You will run over a pedestrian.
    d. You will have a low-speed T-bone crash.
    e. You will be rear-ended.
    f. You will get a red light camera ticket *for trying to stop*.
    g. You will get a ticket the old fashioned way—by a cop.

The Correct Yellow Light Interval Equation

Here's the correct derivation of the yellow light interval. This derivation is based on the correct premise that yellow light means brake, which means that yellow interval = stopping time.

36. $v_f = v_o + at$

37. $0 = v_o + at$ $\qquad v_f = 0$ because the final speed is a full stop

38. $v_o = -at$

39. Redefine a as a deceleration: $a = -a$.

40. $t = v_o/a$ = time it takes to come to a stop from the speed limit v_o

41. Yellow Light Interval = $t_p + v_o/(a_b + a_e)$

t_p = perception time
v = final velocity (0 = stopped)
v_o = initial velocity (the speed limit)
a_b = deceleration of car due to force of car's brakes
a_e = deceleration of car due to force of earth's gravity
e = acceleration of earth's gravity = 32.2 ft/s^2

From equation 41 and equation 25:

42. The correct yellow interval for all values of grade is:

$$\text{Yellow Interval} = t_p + v_o/[a_b + e\sin(\tan^{-1} g)]$$

From equations 41, 26 and 27,

43. The correct yellow interval for small values of grade

$$\text{Yellow Interval} = t_p + v_0/(a_b + eg)$$

Failures Even In the Correct Equation

The observant physicist will see a major limitation of all the yellow interval equations I have so far presented. All these equations apply only to dry roads. The equations are invalid when the road is slippery.

Rain or ice reduces the coefficient of friction of the road surface, which increases the safe braking distance, which increases the yellow light time. There is a formal mathematical expression for equation 42 which includes the coefficient of friction, but I do not present it here.

When it rains outside and you get a red light camera ticket, you can legally say, "Your yellow light duration doesn't account for when the road is slippery. It only accounts for dry conditions. You cannot judge my driving based on a red light camera that bases it decision on an equation that does not work in the rain. I am not God. I cannot stop the rain." See how far that gets. But that is exactly the case. As long as yellow light interval controller technology does not compensate for the realities of Nature, the judgment of an in-situ policeman remains necessary.

Just note that red light cameras enforce the law to the mathematical preciseness of the yellow light equation, whether or not the math represents reality. The equation also has physical demands which the traffic engineer must meet, one of which he currently never meets. The engineer currently does not mark the road at the safe braking distance, which creates the dilemma zone. Red light camera companies exploit the engineering failures. Cities shift the blame to the driver.

Conclusion

Equation 42 is what should appear in the *NCDOT Intelligent Transportation and Signal Systems Unit Design Manual* and in the *Institute of Traffic Engineers Traffic Engineering Handbook*. There is no need for equation 43, because there is no need for small angle approximations in the age of calculators.

(The small angle approximation is satisfactory for grades between -10 and 10. But for grades outside those bounds, the small angle approximation gives less time than it needs to for inclines, and more than it needs to for declines.)

As for the red light cameras, keep them. The red light cameras are the devices which caught the DOT with their pants down and the Town of Cary with their hands in the cookie jar. The cameras are independent monitoring devices. They are precision quality control instruments. What the Town of Cary did not expect and does not admit, is that the cameras caught the biggest offender of the law, and the biggest menace to public safety--the Institute of Traffic Engineers and the North Carolina Department of Transportation.

Once the towns set their yellow intervals to what physics demands, there won't be enough income from the program to sustain the program. There simply won't be enough people running red lights.

The Correct Yellow Intervals and Distances

Speed Limit (mph) v_0	Yellow Interval (s) $1.5 + v_0/a$	Braking Distance (ft) $v_0^2/2a = ½at_b^2$	Perception Distance (ft) $1.5v_0$	Stopping Distance (ft) $1.5v_0 + v_0^2/2a$
65	10.0	405.7	143	548.7
55	8.7	290.5	121	411.5
45	7.4	194.5	99	293.5
35	6.1	117.6	77	194.6
25	4.8	60.0	55	115.0
15	3.5	21.6	33	54.6

Where 1.5 s = perception time and a = 11.2 ft/s^2 as set by the standards of the NCDOT and AASHTO. These are the values for a level road. You will find the very same braking distances in AASHTO's *A Policy on Geometric Design of Highways and Streets*, 2004, p. 112. AASHTO perception and stopping distances are even more conservative than the ones listed above. AASHTO uses 2.5s for a perception time as opposed to NCDOT's 1.5s. AASHTO says 1.5s is good for an expected event, but on average, people need 1.0s more to react to an unexpected event.

As you see from this table, the math works. Note $t_b = v_0/a$ = braking time. The yellow intervals now accurately reflect the braking distances.

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I own a software company and a music company, Talus Software and Talus Music, in North Carolina. My clients and employers have included NASA, The Lunar and Planetary Laboratory, ICAgen, Inc., General Electric, Engineering Technologies Intl, S & H Machine and Engineering, and believe it or not, the North Carolina Department of Transportation. I *know* those guys.

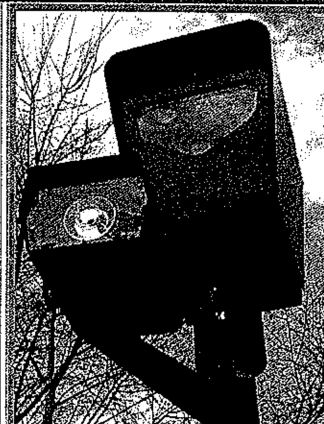
I graduated in 1983 from the University of Arizona with a bachelor of science in physics, minor in astronomy.

Enhanced and Verified By:

William T. Lynch, PhD Physics

2011

Isaac Newton vs. Red Light Cameras



The Dilemma Zone
Defect Caused By Traffic Engineers
Creator of Red Light Camera Companies

Brian Ceccarelli
redlightrobber.com
6/3/2011

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Dilemma Zone Defined

The Federal Highway Administration (FHWA)

> The area in which it may be difficult for a driver to decide whether to stop or proceed through the intersection at the onset of the yellow signal indication. It is also referred to as the "option zone" or the "zone of indecision."[1]

The Institute of Traffic Engineers (ITE)

> The dilemma zone is a space between two points on an approach to a signalized intersection, generally defined as beginning at a point where approaching drivers—when shown a yellow display—will stop at the stop line of the intersection and ending where drivers—again, when shown a yellow display—will proceed through the intersection before the red indication is displayed. Between these two points, drivers are in a dilemma as to whether to stop or proceed. Some will decide to stop and others continue on. An abrupt stop may cause a rear-end crash and failing to stop may cause a right-angle crash.[2]

Dilemma Zone -- an Engineering Defect

Most DOTs and organizations like the National Motorist Association know that traffic engineers must set the yellow light interval to that computed by ITE's equation. Most DOTs in the world use ITE's equation as their formal spec. But what they don't know is that this same ITE equation, not only requires that traffic engineers set the yellow light interval correctly, *but also requires that traffic engineers disclose the safe braking distance line to the driver*.

A correctly set yellow light interval works only when engineers implement it in tandem with full disclosure of the safe braking distance. This tandem requirement comes directly from Newton's Laws of Motion, Newton's Laws of Motion being embedded in ITE's equation. Traffic engineers need to paint a line on the approach to every signalized intersection indicating the location of the safe braking distance. The need to do this is just as important as the need to set the yellow interval correctly.

Without disclosure of the safe braking distance line, the engineer forces the driver, upon seeing a light turn yellow, to guess whether to stop or to proceed. This guess creates the "zone of indecision"—the dilemma zone.

Yellow Light Defined

Prerequisite: Place a *line* at the safe braking distance from the intersection.

1. When the driver sees the light turn yellow and he has not yet crossed the *line,* he must stop. The light will be red by the time the driver gets to the intersection. If he goes, then he will run a red light and possibly cause a T-bone collision.

2. If the driver has already crossed the line when light turns yellow, the driver must go. The light will still be yellow when the driver gets to the intersection. If the driver tries to stop, he may cause a rear-end collision.

3. If the driver is on the *line* when the light turns yellow, the driver must stop. The yellow will turn red the instant the driver gets to the intersection. If the driver goes, he will run the red light but he will traverse the intersection within the all-red interval. He will be safe.

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.[3]

Definition by Words

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

Definition by Math[4]

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

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

Where:

t_p = perception time in seconds
v = speed limit in ft/s
a = safe deceleration of car in ft/s^2
G = Acceleration due to Earth's gravity (32.2 ft/s^2)
g = grade of the road in %/100, downhill is negative grade

Safe Braking Distance—Expression of Newton's Law of Motion

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

To see a formal math derivation of the safe braking distance equation from Newton's Laws of Motion, see *Derivation of the Yellow Light Equation*, Red Light Robber, http://redlightrobber.com/red/links_pdf/Derivation.pdf.

Yellow Light Equation – Not Totally Arbitrary

This spec incorporates the immutable Newton's Laws of Motion. Half of the spec computes the yellow time. The other half computes the safe braking distance. The safe braking distance derivation is an exact expression of a higher law that governs the universe. It is as important to the formula as the yellow time itself. But traffic engineers choose to implement only the yellow time half, not the safe braking distance half. By your DOT not implementing the full spec, your DOT violates the higher law and establishes conditions that force drivers to run red lights.

In order for drivers to obey the spec, the driver needs for traffic engineers to disclose the exact location of the safe braking distance:

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

Which in tandem requires traffic engineers to set the yellow light interval to:

$$Y = t_p + \frac{S_b}{v}$$

Setting Y but not disclosing S_b is like requiring a cook to bake bread for 20 minutes but not telling the cook at what temperate to cook it. The repercussions of badly cooked bread are raw dough or burnt crust. The repercussions of badly cooked intersections are rampant red light running, rear-enders and T-bone crashes.

The Name "The Yellow Light Interval Equation" – One Possible Name

The name "The Yellow Light Interval Equation" can be redubbed the "The Safe Braking Distance Line Equation":

$$S_b = v(Y - t_p)$$

where the traffic engineer paints a line at S_b from the intersection. It is equally valid. Traffic engineers did not consider refactoring the polynomial. Actually the real problem with traffic engineers (and this is a truthful statement not a sarcastic one) is that traffic engineers do not know physics.

Physics is the science of expressing reality in terms of math. It is reality to math. Not math to reality. ITE's equation demonstrates the latter: capricious math forced upon Nature, and thus rejected. A physicist sees ITE's equation and says, "Aside from ITE's equation never working because it is not an equation of motion, ITE's equation still demands me to set the yellow light interval to Y and tell the driver the location of the safe braking distance S_b. But even when I do all that, that equation still creates a dilemma zone for cars travelling slower than the speed limit inside the safe braking region when the light turns to yellow. The equation will always cause problems."

A traffic engineer sees ITE's equation and says, "I will set the yellow light interval to Y only for straight-thru lanes. I'll use a different standard, the MUTCD 3 second minimum, for left turn lanes. I'll give those left-turning cars 3 seconds even when the straight-thru cars get 4.5 seconds. Law of Momentum? What's that? Safe braking distance line? What 's that? By the way, there is this awful dilemma zone which has been causing red light running, crashes and deaths

for decades. We don't know what causes all this, but look at all our efforts to curtail its effects."

In total frustration of seeing cars running red lights and crashing, town councils and sheriffs follow up with, "We'll put up some red light cameras. Those will make Newton's Laws of Motion go away."

Yellow Duration Shortened - Repercussions

When the traffic engineer does this,

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

he sets the yellow interval to a length less than the equation requires, and in so doing violates Newton's Laws of Motion. Since t_p and v are constants, the traffic engineer cuts into the safe braking distance. The driver no longer has enough distance within which to stop his car. The driver must go through the intersection. The traffic engineer forces drivers to run red lights.

Everyone has heard of cities shortening the yellow light durations, but few understand how reprehensible that is. There is a tremendous penalty for the engineer's crime of violating the immutable Laws of the Universe. Mother Nature does not take too kindly to being violated. By looking at the red light camera data, you will see that shortening Y even so much as a mere ½ second, more than quadruples the number of red light runners. Just a ½ second mistake puts millions of people in harm's way.

Many people accuse cities of intentionally shortening yellow lights. While I am sure some cities do so once seeing all the money a short yellow pulls in, I believe that most cities initially are not aware of their preexisting short yellows. At first cities are only aware that they have problems at certain intersections—that certain intersections have far more accidents and have more people running red lights. Cities place their cameras at these intersections.

It seems to never cross a city's mind that problem intersections are caused by engineers. Cities rather believe that thousands of drivers spontaneously get a suicide complex at their problem intersections, willfully run its red light, and then by the time they get to the next intersection, gain their sanity again. By accusing drivers of behavior disorders, cities enact the solution of enforcement. Sheriffs get behind this idea because the only thing they know is enforcement. Cities install cameras to penalize drivers. Cities penalize in an attempt to affect positive change in the drivers' behavior.

But once the red light camera data comes in, cities find that driver behavior hasn't changed. People are still running reds as usual. Cities do not understand that the problem must lay elsewhere. Given the traffic signal plans for those problem intersections, one immediately discovers that these problem intersections have specific and rather obvious engineering defects. The disparity of red light running statistics from one intersection to the next makes it obvious. At the top of the failure list is a yellow shorter than Newton's Laws. Next on the list is the dilemma zone. The dilemma zone is on every list.

Once the cameras are up and collecting the money, as my colleague Barnet Fagel the Ticket Doctor puts it, the cameras become like cocaine. The income is addictive. Cities will not take the cameras down. Cities will not even use the camera data to help their engineers because helping their engineers would mean less revenue. On top of that, many cities like Cary have a tiered contract with their symbiotic traffic camera company. The more tickets Cary issues, the higher percentage of money Cary keeps. It profits Cary to keep DOT engineers in the dark.

Omission of Safe Braking Distance Line -- Repercussions

I bet until now you never heard about the safe braking distance line. After all none of us has ever seen one. Am I fussing about nothing? We all seem to have been getting along just fine without such a line these past decades.

Or have we?

Why do people run red lights? Why do accidents happen? Even though most people never witness crashes, crashes do happen and at a rate of several dozen at each intersection each year. Why are crashes so frequent and why at every intersection?

It is the outcome of the presence of the dilemma zone.

Even when traffic engineers set the yellow correctly, there is still a tremendous amount of people running red lights.

If you believe your Town Council, a Town Council that supports red light cameras, then you believe everyone in the city, and I mean *everyone*, intentionally runs reds lights. You believe that everyone in the city drives like the Dukes of Hazzard. You believe that every soccer mom and church pastor drives a 69 Dodge Charger named General Lee, and is being chased by Sheriff Roscoe P. Coltrane.

I have told you that violating the Laws of Motion causes reprehensible consequences. I have told you that a yellow ½ second shorter than that required by the Laws of Motion more than quadruples the number of the people running reds. Well. *Quadruples from what?* It quadruples from the number of people running red lights due to the dilemma zone.

Even when DOTs set yellows to the ITE spec, there is still a steady stream of cars running red lights. By not providing the safe braking distance line, the traffic engineer violates Newton's Laws of Motion and again forces drivers to run reds. A short yellow and a dilemma zone is a case of worse on top of bad. Remove the short yellow, one removes the worse, but the bad is still there. And the bad is very bad.

By omitting the safe braking distance line, the traffic engineer forces you to guess. How good a guesser are you? The farther away from the intersection you are, the easier it is to know you must stop. The closer to the intersection you are, the easier it is to know you must go. But somewhere in the middle, you really don't know whether you have the distance to stop or the time to go. This is the dilemma.

Imagine you are driving into Cary, North Carolina. It is early Spring. The pear trees are spiked with white flowers, the scent of freshly blooming dogwoods waft in the air. You are exiting off Highway 1 onto the Cary Parkway. You turn west onto Cary Parkway. You approach High Meadows Drive.

Reality strikes. You see the photo-enforced sign. There's a camera there. The pressure is on.

Do you know far back 194.5 ft is from the intersection's stop line?

The light turns yellow. You are 195.0 ft from the intersection. You are not sure whether to go or stop. You guess to go. Oops! Wrong guess. You were really 6 inches farther from the intersection than the DOT's secret safe braking distance line when the light turned yellow. You ran the light by 1/10th of a second. Ticket for you.

This scenario, this single scenario, guarantees those red light camera companies a steady income. 99.9999% of all red light running on properly yellow-timed intersections are fraction of a second violations. All these puny little violations are the result of a guess forced upon you by the traffic engineer, because the traffic engineer failed to disclose the safe braking distance as required by Newton's Laws of Motion.

Some people may not guess as well as you. They may decide to go even from farther back, perhaps even from 217.8 ft—which is what they could do if Cary was a city in California. In that case, by the time they get to the intersection, not

@ speed limit

only would the light be red but also cross traffic would have a green light. Oops! T-Bone crash.

Some people are old. An old granny might be overly cautious. She is 100 ft from the intersection when the light turns yellow. Like most people, she believes the yellow light means brake. But she is within the safe braking distance and should go. But being the granny she is, she slams on the brakes. Oops! Rear-end crash. The duration of the yellow interval is half the time it takes for a car to stop. No one can stop their car within the time the light is yellow. Granny doesn't know that. Hardly anybody knows that.

The fraction of a second violation, the rear-ender and the T-bone crash: they are all products of the dilemma zone.

Solutions

To remove the dilemma zone; a.k.a., zone of indecision, remove the decision. Instead of forcing drivers to guess what they have to do, just tell them what they have to do.

There are two ways to remove the decision. There's the best way, and there's a compromise.

Best Way

Instead of ITE's equation, use the following equation:

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

Now Y is the time it takes you to perceive the light change and brake to a stop.

If DOTs set the yellow light interval to this solution, drivers *always* have the option to brake. Drivers no longer have to guess between two opposing actions. Graceful braking is always a possibility. Even when the driver is too close to the intersection, the worse he can do is gracefully slow down and glide through the intersection on a yellow.

This solution covers all possibilities. This solution covers the case where the driver is within the safe braking distance, but going slower than the speed limit. If the light turns yellow, he can still gracefully brake and never get penalized.

This solution is the easiest to implement. DOTs only have to increase the yellow light durations by 1 – 3 seconds depending on the speed limit. DOTs don't have to get out a can of paint.

After the DOT implements this solution, then DMVs must education drivers on what a yellow light means. This time DMVs could actually explain what a yellow light means.

The biggest complaint from traffic engineers about this solution is that drivers have too much yellow. Traffic engineers believe that drivers will just treat the yellow light as if it means go. My rebuttal is, "Even now that is what your yellow means."

The reason why this solution is the best solution, and I would add *the only solution,* is because the solution is an equation of motion. As opposed to ITE's equation which tries to impose reality, this equation actually describes reality.

Compromise

The compromise is the solution I have been mentioning from the beginning. Make DOTs paint a line at the safe braking distance. This implies that DOTs keep ITE's equation.

The painted line works when cars are travelling at the speed limit on the entire approach to the intersection.

There are a couple of show stoppers to this solution:

1. Painting a crucial line on the road on the approach to the intersection may distract a driver's attention away from the intersection.
2. Crucial lines on the road are not easily visible in bad weather or at night. Watching for a light only is much easier and much more reliable.
3. Lines eventually wear off.
4. This solution does not address the case when a driver is travelling slower than the speed limit within the safe braking distance when the light turns yellow. This situation still requires the driver to guess whether to stop or go. Therefore this solution does not make the dilemma zone go away.
5. The possibility of two opposing actions (stop or go) still exists.

Conclusion

Not in their wildest dreams do people ever consider that their DOT, the organization responsible for vehicular *motion* in the State, does not understand the Laws of Motion. But the raw data from the red light cameras show exactly that. That data points a solid finger at the physics incompetence of DOTs.

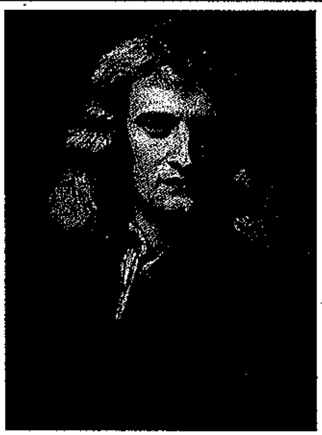
Cities need desperately to trust their own Department of Transportation. It is awful that they cannot. It is psychologically more comforting and definitely more lucrative for cities to point a finger at drivers rather than face this inconvenient truth. But it is now time to wake up. You can actually thank the red light camera companies for revealing the truth, albeit underhandedly.

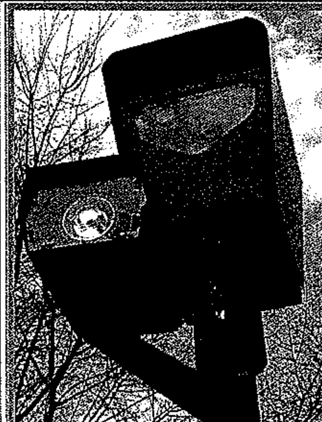
If we remove all the engineering defects, we should see perhaps one red light runner per intersection per month. That's right, 1 perhaps 2 per month.

Right now we see hundreds of runners per month. Sometimes thousands. Are we to be satisfied when we get the numbers down from 1000 to 50 runners per month? To 30? How about 20? Is this a game of the *Price is Right* where lower numbers are acceptable and higher numbers are not? The only acceptable number of cars running a red light is 0. 0 is acceptable. Anything else is not. We are talking about human beings, not jelly beans. We are playing Russian roulette, not rummy. Engineers must stop systemically loading the guns. Short yellow light = 2 bullets. Dilemma zone = 1 bullet. The occasional drunk driver is bad enough.

2011

Isaac Newton vs. Red Light Cameras





Short Yellow and Turns
Exposing the Traffic Engineer's Mistakes

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6/24/2011

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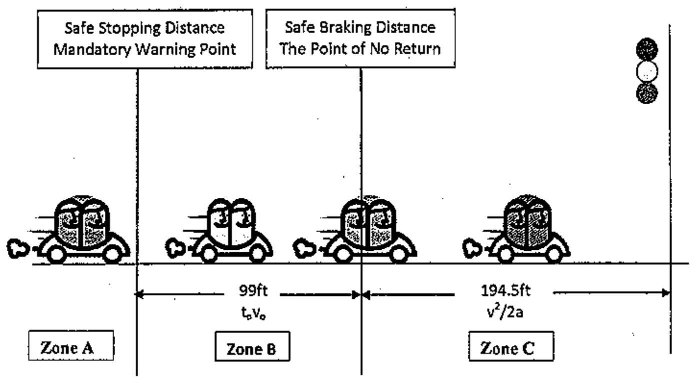
Yellow Light Defined

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, 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. 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 slows down. But the very act of slowing down eats 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 this turning driver as 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. This paper contains a mathematical proof of this statement.

There is also the problem of the dilemma zone. This paper does not cover the dilemma zone. It deserves its own paper.[7]

really kinematics

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[9] which computes the location of the segment for you.

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

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

Definition by Math[2]

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

2. $Y = t_p + \frac{v}{2a+2Gg}$

Where:

t_p = perception time in seconds
v = speed limit in ft/s
a = safe deceleration of car in ft/s^2
G = Acceleration due to Earth's gravity (32.2 ft/s^2)
g = grade of the road in %/100, downhill is negative grade small θ

Safe Braking Distance—Expression of Newton's Law of Motion[5]

3. $S_b = \frac{v^2}{2a+2Gg}$

$v_f^2 - v_i^2 = 2a\Delta x$

$\Delta x = \frac{v^2}{2a}$

$a = a_d + G\sin\theta$

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. $Y = t_p + \frac{S_b}{v}$
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. $S_b = \frac{v^2}{2a}$
10. $S_b = \frac{66^2}{2(11.2)}$
11. $S_b = 194.5$ 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. $Y = t_p + \frac{v}{2a}$

13. $\frac{v}{2a} = Y - t_p$

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. $S_s = vt_p + v \frac{v}{2a+2Gg}$
26. $S_s = 33.6 * 1.5 + \frac{33.6^2}{2\ 11.2}$ = 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. $S_b = 194.5$ ft

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

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

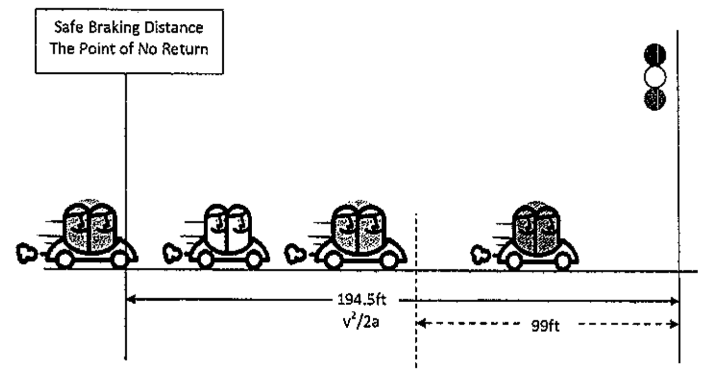
The safe braking distance equation (eq. 3), unlike Cary's other equations, is not arbitrary. One must use this equation without compromise. The safe braking distance equation part of the Yellow Light Equation is derived from Newton's Second Law of Motion. Everyone has no choice but to obey it.

Which Cars Does Cary Force to Run Red Lights?

Cary forces left-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 left-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.[3]

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

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

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

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

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

   d. $d_e = 86.4$ ft

?

given that time to slow

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*.[8] 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?

For unjustifiable reasons.

1. 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.[4,5]

2. There are technical writer errors in the NCDOT specs which imply to traffic engineers all over North Carolina that left-turn movement speeds within the intersection measured for all-red clearance intervals can be used for yellow interval approach speeds.

3. There is the MUTCD spec 4D.12 stating that 3.0 seconds is the minimum yellow time. Red light camera companies encourage legislators to put this MUTCD statement directly into the laws. Many traffic engineers take this out of context by applying it to *all* yellows.

   For an analogy of misuse, the USDA states that the minimum temperature to cook meat is 145°F. Steaks need 145°F. Ground beef needs 160°F. Chicken needs 165°F. The minimum temperature is 145°F.

   Chicken is on the menu and Cary's traffic engineers have set the oven to 145°F. Cary gives everyone botulism.

   Yellow time must increase with speed limit. This is a basic fact of Nature.

   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 bump up the yellow interval to 3.0 seconds. This increase engages for speed limits less than 22.9 mph on a level road; for example, in school zones.

4. In the end, one thing is certain. Traffic engineers do not know basic physics.

The General Case

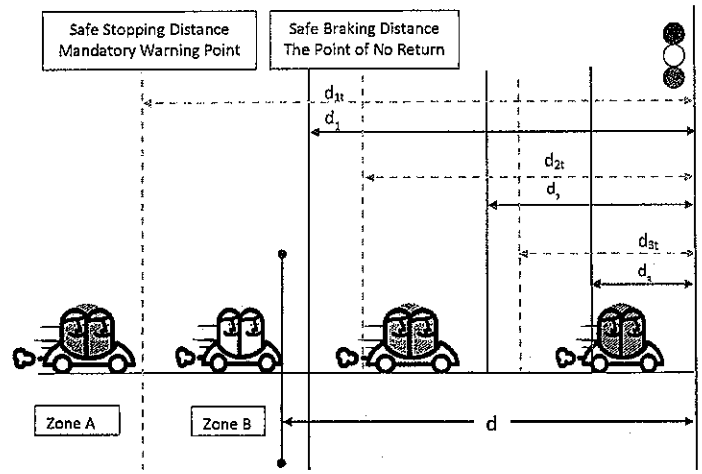


Table 1 – Short Yellows Force Drivers to Run Red Lights

#	Formula	Meaning
30	$d_{1t} = vt_p + \frac{v^2}{2a}$	A green light must turn yellow at distance d_{1t} or farther for a driver to stop. d_{1t} is called the safe stopping distance. d_{1t} is the distance from intersection to the safe stopping distance. 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.

©consta

31	$d_1 = \frac{v^2}{2\alpha}$	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. d_1 is called the safe braking distance. d_1 is a derivation of distance travelled according to Newton's Second Law of Motion.[5] This equation does not allow any compromises.
32	$d_{2t} = vt_p + v(T - t_p)$	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[15], in other words, Cary does not short the yellow, then: $d_{1t} = d_{2t}$
33	$d_2 = v(T - t_p)$	d_2 is the maximum distance a driver can travel during the yellow light after he perceived the light turning from green yellow.
34 	$d_{1t} \leq d \leq d_{2t}$	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.

@ const a   *@ const v*   *OK*

Table 2 - Turning Forces Drivers to Run Red Lights

#	Formula	Meaning
35	$d_{3t} = vt_p + v(T - t_p)$	d_{3t} is the maximum distance a driver can travel during the yellow light. v is his average speed.
36	$d_3 = v(T - t_p)$	d_3 is the distance a driver travels during the yellow light after he perceived the light turning from green yellow. 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.
37	$v_e \leq v$	The driver's speed when he enters the intersection. For legal purposes, entry speed must be <= speed limit.
38	$v = \frac{v + v_e}{2}$	Average speed from v decelerating to v_e
39	$v_{e-min} = v - a(T - t_p)$	v_{e-min} is the minimum speed which with a driver can enter the intersection.
40 	$v_e < v_{e-min}$	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.

not const. a during this time   *while braking*   *car has when turns light red*

290   *d1t*   *d2t*   *< 290 ft t yellow < 3.6 s*

41	$d_{1t} \le d \le d_{3t}$	At the time the light changes from green to yellow, the Town of Cary will force all drivers at distance d from the intersection to run a red light.

Table 3 - Deceleration

#	Formula	Meaning
42	$\alpha = a + G \sin(\tan^{-1} g)$	For any grade g
43	$\alpha = a + Gg$	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_{3t}	Distance a driver travels during the yellow light
d_3	Distance a driver travels during the yellow light after he perceived the light turning from green yellow
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].
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.

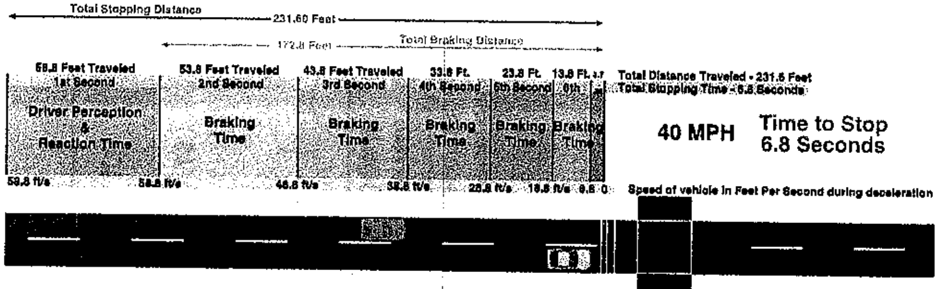
34 does not compensate for wet/icy (coef. of friction)

ENGINEERING VS. REALITY - Are We Fooling Ourselves?

Institute of Transportation Engineers formula for calculating vehicle stopping Distance

$$S = Vt + \frac{V^2}{2a} = 58.8 + \frac{58.8 \times 58.8}{2 \times 10\ Ft/S} = 58.8 + \frac{3457.44}{20} = 58.8 + \quad = 231.6$$

S = Stopping Distance in Feet
V = Vehicle Speed, Feet Per Second, 40mph = 58.8 feet per second
t = Perception-Reaction Time
a = Deceleration Rate, 10 feet per second per second



Institute of Transportation Engineers formula for calculating vehicle stopping Time

$$Y = Vt + \frac{V}{2a} = 58.8 + \frac{58.8}{20} = 1 + \quad = 3.94$$

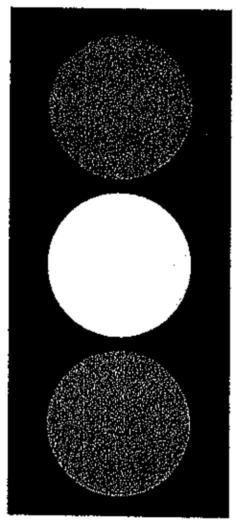
ITE Time to Stop 4 Seconds

2.8 Seconds Too Short

100 ft — 200 ft — 300 ft — 360 ft (scale 1 block = 5 ft.)

POINTS TO PONDER:

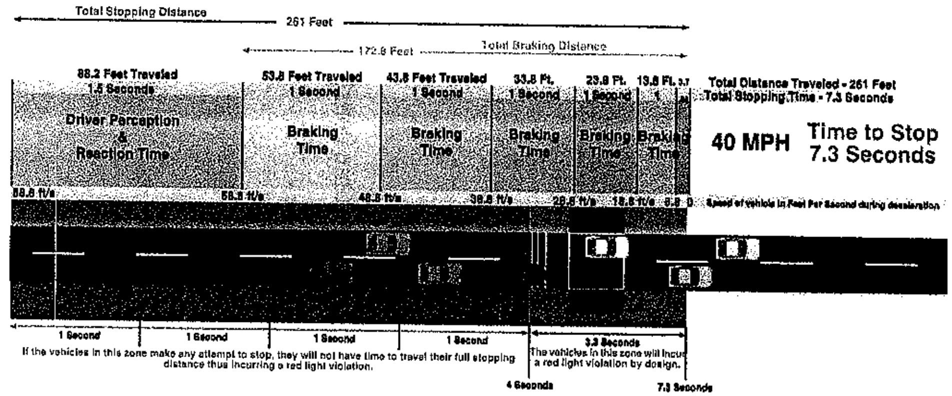
1. Normal range of yellow light timing is 3 to 6 seconds.
2. At speeds above 30 MPH, even 6 seconds total clearance time **may not be enough to stop.**
3. Most violations of the yellow change interval DO NOT result in crashes, due to "lost time" of 3 seconds per phase.
4. **Longer** change intervals are called for with **higher** approach speeds, **regardless of the posted speed limit,** therefore there is **no such thing** as merely **"meeting standards"** with yellow light timing.
5. Yellow intervals over 6 seconds may lead to increases in rear end crashes in some situations.
6. Photo enforcement can lead to **increases in crashes due** to inordinate **driver focus** on what the signal is doing, at the **expense of everything else!**



This chart represents the true reality on the street. Traffic engineers know that 1.5 seconds is the absolute minimum perception and reaction time drivers need to be safe. The National Safety Council recommends 2.5 seconds (.75 reaction & 1.5 perception) ITE recommended deceleration rate of 10 feet per second requires 172.8 feet of stopping distance on dry pavement at 40 mph which takes 5.8 seconds to complete. Therefore the correct formula for determining yellow light duration is:

$$y = T + \frac{V}{A} = 1.5 + \frac{58.8}{10} = 1.5 + 5.8 = 7.3 \text{ seconds}$$

y = Yellow Time in Seconds
V = Vehicle Speed, Feet Per Second, 40mph = 58.8 feet per second
t = 1.5 Seconds Perception-Reaction Time
a = Deceleration Rate, 10 feet per second per second



GETTING BACK TO REALITY

1. **Credibility with the public** is the key to effective traffic control.
2. ITE and the engineering community should consider current driver population, vehicle mix, and distractions when **setting standards** for **yellow light timing.**
3. **Longer yellows** can be an **effective countermeasure** to red light crashes, particularly right angle crashes.
4. Combination of Yellow plus All Red interval can keep **yellows from becoming too long.**
5. Photo enforcement should **not be considered a substitute** for good traffic engineering practice.
6. **Other countermeasures** such as better signal visibility using back plates, better intersection definition with striping, and fewer distractions such as unnecessary signing, could **reduce crashes without the need for photo enforcement.**

William L. Triay
Mayors Military Advisory Committee
City of New Orleans

Steven C. Strength, PE, PTOE
New Orleans Regional Who Dat Coalition

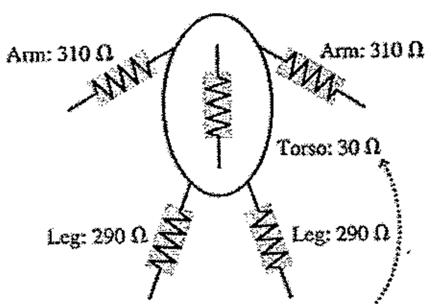
4. (18) A typical medical defibrillator has a capacitance of 32 μF and is charged to 4000 V. The capacitor is discharged across the torso of a person (see the resistance model below).

a) Calculate the time constant for the discharge of the capacitor through the torso.

b) Will the capacitor be fully discharged after a time equal to one time constant? Show your reasoning.

c) A rescuer is administering CPR during the defibrillation. The rescuer accidentally experiences a potential difference of 500 V (DC) between one hand and a foot. Assume that the rescuer has bare and wet hands and feet, with skin resistance of only 200 Ω at the hand and also at the foot. How much current will flow through the rescuer, and is this likely to be dangerous to the rescuer?

FIGURE 26.12 Resistance model of the body.



When current traverses the torso between any two points (arm to arm, arm to leg, leg to leg) this adds a resistance of 30 Ω.

TABLE 26.1 Physiological effects of currents passing through the body

Physiological effect	AC current (rms) (mA)	DC current (mA)
Threshold of sensation	1	3
Paralysis of respiratory muscles	15	60
Heart fibrillation, likely fatal	> 100	> 500

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- engineer
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en·gi·neer·ing *noun* \-ˈnir-iŋ\

Definition of ENGINEERING Like

1 : the activities or function of an engineer

2 **a** : the application of science and mathematics by which the properties of matter and the sources of energy in nature are made useful to people

b : the design and manufacture of complex products <software *engineering*>

3 : calculated manipulation or direction (as of behavior) <social *engineering*> — compare GENETIC ENGINEERING

See engineering defined for English-language learners »
See engineering defined for kids »

Examples of ENGINEERING

This control panel is a good example of smart *engineering*.

First Known Use of ENGINEERING

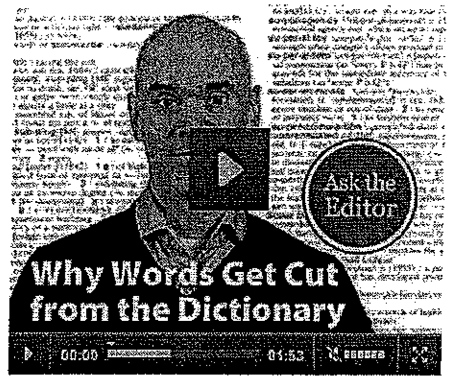
1720

Rhymes with ENGINEERING

fictioneering, mountaineering, power steering

engineering *noun* *(Concise Encyclopedia)*

Professional art of applying science to the optimum conversion of the resources of nature to the uses of humankind. Engineering is based principally on physics, chemistry, and mathematics and their extensions into MATERIALS SCIENCE, solid and fluid MECHANICS, THERMODYNAMICS, transfer and rate processes, and systems analysis. A great body of special knowledge is associated with engineering; preparation for professional practice involves extensive training in the



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application of that knowledge. Engineers employ two types of natural resources, materials and ENERGY. Materials acquire uses that reflect their properties: their strength, ease of fabrication, lightness, or durability; their ability to insulate or conduct; and their chemical, electrical, or acoustical properties. Important sources of energy include fossil fuels (coal, petroleum, gas), wind, sunlight, falling water, and nuclear fission. *See also* AEROSPACE ENGINEERING, CIVIL ENGINEERING, CHEMICAL ENGINEERING. GENETIC ENGINEERING, MECHANICAL ENGINEERING, MILITARY ENGINEERING.

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>
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> You're right; engineering is strategy, and natural selection is trial and error with no mind behind it. I have no idea what debate I was referring to. Sorry bro.
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Definition of engineering

Word of the Day

perfunctory
Definition: (adjective) unenthusiastic, routine, or mechanical.
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< engineer   engird >

en·gi·neer·ing (ĕn'jə-nîr'ĭng) KEY

NOUN:

1.
   a. The application of scientific and mathematical principles to practical ends such as the design, manufacture, and operation of efficient and economical structures, machines, processes, and systems.
   b. The profession of or the work performed by an engineer.
2. Skillful maneuvering or direction: *geopolitical engineering; social engineering.*

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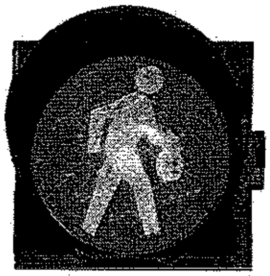


Misapplied Physics in the International Standards that Set Yellow Light Durations Forces Drivers to Run Red Lights

Brian Ceccarelli, Joseph Shovlin

The international standards that traffic engineers use to set yellow light durations are in opposition to the laws of motion. Misapplied physics creates systematic errors at signalized traffic intersections guaranteeing a steady stream of drivers running red lights. These errors are exploited by red light camera companies and governments. The systematic errors also induce thousands of vehicle crashes each year.

Many times we have approached an intersection when the light turns yellow and we did not know whether to stop or go. Sometimes we have accelerated to beat the light and other times we have slammed on the brakes in order to stop. Other times we have entered the intersection just a fraction of a second after the light turned red. Often we travel down the left turn lane and commit ourselves to enter the intersection, only to have the light turn to yellow and then to red before we could execute the turn.

These situations occur commonly to all drivers. We experience them many times a year. Over the decades we have grown accustomed and desensitized to such situations. The authors of this paper would not have given them a second thought had it not been for the fact that we are commuting in Cary, North Carolina, a town that operates red light cameras. Had not one of these cameras flashed one of the authors, you would not have this paper to read. These common red light running scenarios, though technically illegal, are the forced behavioral outcomes of systematic errors of the Institute of Transportation Engineers' (ITE) Yellow Change Interval Formula.

stopping distance w/ initial speed V_0

$\Delta X = t_p V_0 + \frac{V_0^2}{2a}$

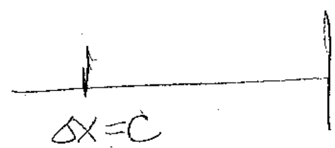
The ITE Yellow Change Interval Formula

Equation 1a is the Formula as it appears in ITE's *Traffic Engineering Handbook*[1] and *Traffic Signal Timing Manual*[2]. This Formula and its equivalents (1b, 1c) appear in traffic signal specifications for almost every jurisdiction in the world.

Equations 1. ITE Yellow Change Interval Formula

a	$Y = t_p + \left[\frac{v}{2a + 2Gg}\right]$
b	$Y = t_p + \frac{1}{2}\left[\frac{v}{a + Gg}\right]$
c	$Y = t_p + \frac{1}{2} t_b$

≠ time to traverse stopping distance at V_0



Variable	Description
Y	yellow light duration
t_p	perception/reaction time constant
v	vehicle's approach speed. The approach speed is not necessarily the speed limit.
a	safe deceleration constant of vehicle ITE's value = 10 ft/s^2 AASHTO's value[3] = 11.2 ft/s^2
G	Earth's gravitation acceleration constant
g	grade of the road in %/100. Downhill is negative grade.
a + Gg	effective deceleration of car
t_b	braking time. The time required by the vehicle to decelerate from **v** to a stop.

~1/3 G

irrelevant also irrelevant

The Formula is not an equation of motion. The 2 in the denominator (1b, 1c) is the disqualifying factor. Had the formula been $Y = t_p + v/(a + Gg)$, then the formula would be an equation of motion. But that is not what we see. The Formula says $v/\mathbf{2}(a + Gg)$. That means the yellow light lasts *half* the time it takes for a driver to stop. Because traffic engineers have been using this Formula for decades, what is the Formula's intent? And because the Formula is not an equation of motion, how does the Formula affect drivers today?

The intent

Look at the Formula this way:

Eq 2. The Formula is Derived From Braking Distance

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

$$\textbf{Yellow Duration} = \textbf{Perception Time} + \frac{\textbf{[Safe Braking Distance]}}{\textbf{Approach Speed}}$$

In equation 2, the yellow light duration equals the time it takes for the driver to perceive and decide what to do when the light turns yellow, plus the time it takes for the driver to traverse the safe braking distance at the approach speed. "Traversing the braking distance but not braking" sounds like mixing apples and oranges. It is. But recall that the Formula is not an equation of motion.

no

For now regard the approach speed as the speed limit. We will take up the issue of approach speed versus speed limit later.

Let us define the *critical distance*. In equation 3, traffic engineers define the critical distance as the safe braking distance plus the distance the driver travels during the time that he perceives and reacts to the signal change to yellow[4].

Eq 3. The Critical Distance

$$c = v\,t_p + \left[\frac{v^2}{2(a + Gg)}\right]$$

We are now ready to define the intent of the Formula. If the driver is farther from the intersection than the critical distance c when the light turns yellow, then he must stop. By embedding the braking distance into the yellow signal time, the Formula gives a faraway driver enough distance to stop safely and legally. If the driver is closer to the intersection than c, then the driver does not have enough distance to stop safely. The driver must proceed and enter the intersection. The Formula gives the proceeding driver enough time to enter the intersection before the light turns red *with the precondition that the driver approaches the intersection at a speed* $\geq v$.

Forcing drivers to run red lights

The application of the Formula fails to properly apply physics in two respects.

1. The Formula never provides enough time for a driver to decelerate *and* enter the intersection. For an equation to accommodate deceleration, an equation must obey the equation of motion $a = \Delta v / \Delta t$. The Formula does not. The Formula shorts the required deceleration time by half. Therefore for any driver who must slow down anywhere within the critical distance before entering the intersection, the Formula creates a type I dilemma zone[5]. A type I dilemma zone is a region on the road where if the driver is in it when the light turns yellow, the driver can neither stop safely nor proceed safely without running a red light.

   Traffic engineers create type I dilemma zones at every intersection because every intersection must handle one or more of the following types of drivers:

   a. Turning drivers. U, left and right turning drivers need to slow down to execute a turn.

b. Drivers going straight who must slow down for traffic waiting at the next nearby intersection beyond the immediate intersection. This situation is typical of busy downtown streets where intersections are close together.
c. Drivers going straight who must slow down for the stop sign or signal light at the next intersection beyond the immediate intersection.
d. Drivers who tap their brakes to avoid colliding with vehicles entering or exiting business entrances or side streets close to the intersection.
e. Drivers going straight who slow down to avoid colliding with an opposing left turning driver playing chicken.
f. Drivers going straight who slow down for any objects in front of them.
g. Drivers who slow down for bumps in the road.
h. Drivers who slow down for potholes in the road.
i. Drivers who slow down to go over railroad tracks.
j. Defensive drivers. Drivers who slow down just to be cautious. No matter how defensive drivers are, they cannot escape dilemma zones[6]. In fact the more cautious the driver, the more the Formula forces the driver to run a red light.

2. The Formula assumes that all drivers know the precise location of the critical distance. If the driver guesses incorrectly by so much as an inch, deciding to go rather than stop, then the Formula will force him to run a red light. To compensate for a possible wrong guess, the driver often accelerates or slams on the brakes. The Formula is responsible for each behavior because the Formula does not provide the driver with a margin of error. In an instant the mandate to stop turns into the mandate to go. Because the Formula only provides half the time to stop, the driver is better off accelerating. Traffic engineers even expect drivers to accelerate[7]. The region on the road where a driver must guess whether to stop or go is called a type II dilemma zone[8]. A type II dilemma zone is different than a type I zone. Whereas a type I zone is a region on the road where the only outcome is running a red light, a type II zone is a region on the road where a viable solution exists, but the reasonably perceptive driver does not know what it is. Type II zones are also called indecision zones.

not really

?

Engineers make the Formula fail further by . . .

1. Plugging the wrong numbers into the Formula. For example the speed limit is 45 mph but the engineer accidentally plugs in 35 mph. In Cary, North Carolina, one of the authors and 8500 other drivers got flashed by a red light camera at an intersection whose yellow signal had this kind of mistake[9]. Also engineers

routinely plug in 0% for the grade when the road goes downhill. 12,000 Cary drivers were flashed by a red light camera at this type of intersection[8].

2. Plugging in an approach speed which is less than the speed limit. This effectively forbids drivers from travelling at the speed limit. Drivers are entrapped by the speed limit sign. An approach speed set less than the posted speed limit shortens the braking distance below the minimum required by a driver travelling at the legal speed. The legally moving driver can no longer stop safely. Instead he must run the red light. Every protected left turn signal in Cary is like this, contributing to over 100,000 drivers running red lights[9].

can stop — can't stop — must go at V_0

The size and location of type I dilemma zones is a function of approach speed, perception time, deceleration, grade, minimum intersection entry speed and actual yellow time[10]. On a level 45 mph road using the ITE standards, the dilemma zone in the left lane extends from 284 feet (critical distance) to 178 feet from the intersection. Any driver who in this zone travelling at the approach speed at the onset of yellow, who will enter the intersection at 31 mph or less, will be forced to run a red light[11].

this is unclear – see my calcs

History of the Formula

The Formula was invented in 1959 by Denos Gazis, et. al. of GM Research Labs. Equation 4a is in Gazis' paper *The Problem of the Amber Signal Light in Traffic Flow*[12]. Equation 4b expresses the same meaning as 4a.

Eq 4. Gazis' 1959 Formula

A	$t_{min} = t_p + \left[\frac{v_0}{2a}\right] + \frac{w+L}{v_0}$
B	$t \geq t_p + \left[\frac{v_0}{2a}\right] + \frac{w+L}{v_0}$

Variable	Description
t_{min}	minimum yellow duration

t_p	perception/reaction time
v_o	maximum allowable speed at the critical distance
a	safe deceleration of vehicle
w	Width of the intersection
L	length of the longest vehicle

Gazis explicitly designed the Formula to handle only one traffic situation. The Formula only handles the straight-thru movement driver who can proceed unimpeded to and thru the intersection at the maximum allowable speed[13]. That is the context of the Formula and that is as far as it goes. Gazis knew that his Formula was not a magic pill. Gazis knew that it did not provide adequate time for vehicles that slow down before entering an intersection. He knew it neither worked for turning movements nor for vehicles at two close-by intersections[14]. He also knew that treating the Formula as an equality did not give the driver a margin of error. That is why Gazis expressed his Formula as an inequality.

- Today's traffic engineers misapply the Formula to every traffic situation.
- Today's traffic engineers misapply the Formula as an equality.

The third term $(w + L)/v_0$ in equation 4 is the amount of time it takes for a vehicle to travel across and clear the intersection at the maximum allowable speed. Today the third term is called the all-red clearance interval. It is the amount of time that drivers on all approaches see a red light. In Gazis' day, the all-red clearance time had to be added to the yellow light duration because the traffic signal hardware could not simultaneously display red on all approaches. This limitation is still true today for many traffic signals. Whether or not the traffic signal can show all-red, traffic engineers systematically take the third term out of context by setting v_0 to the maximum allowable speed instead of the speed of the slowest vehicle as it traverses the intersection. The slowest vehicle is usually the left-turning vehicle.

The 1959 Formula did not compensate for the acceleration due to gravity for vehicles on a hill. In 1982 ITE remedied that shortfall by including Gg in its *Manual of Traffic Signal Design*. The expression Gg is a small angle approximation. The approximation does not significantly affect the yellow time until grades exceed ± 10%. Not all jurisdictions use the version of the Formula with the Gg. Surprisingly California does not[15] and California includes San Francisco.

Approach speed

ITE instructs the engineer to plug in the *approach speed* for v into the Formula. Approach speed is a term specific to traffic engineering. Traffic engineers have a nebulous definition of approach speed. In the context of intersections, the approach speed is the speed with which a vehicle approaches an intersection.

Physicists are aware, however, that the definition of v in the Formula is not nebulous but exact. Approach speed v must be v_0, the *initial* velocity of the vehicle at the critical distance from the intersection. That is the physical meaning of v in the basic equation of motion *stopping distance* = $v^2/2a$.

But in 1965 ITE miscopied the original Formula into the *Traffic Engineering Handbook*[16]. v_0 became v. ITE forgot the naught.

Eq 5. ITE Traffic Engineering Handbook, 1965

$$Y = t_p + \frac{1}{2}\left[\frac{v}{a}\right] + \frac{w+L}{v}$$

The miscopy has led traffic engineers to believe they could define v arbitrarily. Since 1994 ITE has been instructing traffic engineers to set v for turn lanes to the *average* velocity of the speed limit and the vehicle's intersection entry speed[17]. This practice is why yellow durations for left turn lanes are now 3.0 seconds while yellow durations for straight-thru lanes are 4.5 seconds. The practice also causes red light camera citations to spike when Cary decreases left turn yellow durations from 4.0 to 3.0 seconds[18].

Speed limit

Approach speed is not necessarily the speed limit. Let us define speed limit.

Speed limit has a different meaning to the traffic engineer than to the judge, police officer and driver. To the traffic engineer, the speed limit is that speed which separates the bottom 85% from the top 15% of freely flowing vehicle speeds[19]. This method is called the 85th percentile rule. This method implies that the speed limit actually changes during the day and for different stretches of road. The 85th percentile speed during peak hours is less than that at midnight. The 85th percentile speed on a level part of the road is less than that going down a hill on the same road. The speed that engineers customarily post is the one they measured for a level road at peak-hour traffic. Engineers also round the posted speed to the nearest 5 mph.

Engineers purpose to set their speed limits by accommodating human behavior not by imposing iniquitous values. But because traffic engineers are restricted to handle wide variations of geography and human activity with a single blob of paint on a lonesome sign, the engineer's speed limit and what police and cameras think of as the speed limit are often at odds. As vehicles come down off a hill, a 35 mph sign at the bottom of a hill may be appropriate for the next section of road, but the 85th percentile speed of freely-flowing traffic at the speed limit sign may be 50 mph. The incompatibility spells opportunity for the assiduous police officer and the speed camera company.

While engineers are limited to express one speed limit for a road that requires many, engineers are not so limited when expressing the speed for setting yellow light durations. Engineers are mandated by their specifications to measure the approach speed independently from posted speed, compute the yellow duration from the approach speed, and set the traffic signal hardware to the result[20]. The approach speed must not be less than the posted speed limit lest it takes away the driver's legal right to travel at the speed limit. (Using an approach speed less than the speed limit disables a driver from stopping safely from the speed limit.)

Perception time and deceleration

The variance in measurements of perception time and deceleration contribute to dilemma zones as well. Values for these constants are very subjective and subject to much debate. Table 1 gives you an idea of averages used by different standards.

Table 1. The "Constants" Perception Time and Deceleration

	t_p	a
ITE	1 second	10 ft/s2
AASHTO	2.5+ seconds	11.2 ft/s2
Gazis/Original	1.14 seconds	10.7 ft/s2

The American Association of State Highway and Traffic Officials (AASHTO) wrote an interesting chapter in *A Policy on Geometric Design of Highways and Streets* about driver reaction times[21]. AASHTO's conclusion is that "a brake reaction time of 2.5 s is considered adequate for conditions that are more complex than the simple conditions used in laboratory and road tests, but is not adequate for the most complex conditions encountered in actual driving".

Yet no jurisdiction uses AASHTO's recommendation. North Carolina uses 1.5 seconds. Oregon uses 1.7 seconds. Most others use ITE's 1.0 second.

Deceleration is also subjective. Comfortable deceleration means values around ⅓ G. Gazis' deceleration is ⅓ G. However Gazis said that ⅓ G is "feasible but is a fairly high deceleration not desirable in normal driving."[22] In this case Gazis' and AASTHO's values are less desirable than ITE's.

Note that the Formula does not consider commercial vehicles with air brakes. Air brakes do not engage all at once like passenger car brakes. Once the driver's foot presses the brake pedal, it takes about 0.5 seconds for the air pressure to build up so that the brakes can achieve a steady deceleration[23]. A traffic engineer desiring to cover the needs of all vehicles would add a brake lag time to the Formula but no engineer does this.

It is sobering to understand the traffic engineer's mentality. In the world of traffic engineering, the goals of traffic safety often compete with the goals of traffic flow. When push comes to shove, flow usually wins out. In the case of yellow light durations, the more the signal cycle spends in yellow phases, the less the signal cycle can devote to green phases. The more yellow, the less green. The less green, the less flow. Less flow is bad so engineers use values to cover the *majority* of drivers and vehicles, not values that cover *all* drivers and vehicles. So with willful intent and prior knowledge, engineers design their signals knowing they will cause drivers and vehicles on wrong side of the percentiles to run red lights. ITE explicitly recommends the practice of forcing drivers to run red lights. ITE instructs engineers to cap yellow durations to 5 seconds even when their own formula suggests they should be longer. ITE hopes that the all-red interval will allow the resulting red light runners to get to the other side of the intersection uninjured[24].

Gazis categorized red light runners into deliberate violators and non-violators[25]. Non-violators are red light runners entrapped by common ordinary and expected dilemma zone having to run the red up to 4.5 seconds into the red. Deliberate violators traverse the intersection in the middle of a red phase. Red light cameras and overzealous police officers do not discern the difference.

Consequences of the Formula

Yellow lights which are short by a fraction of a second relative to the Formula forced 400% more drivers to run red lights in Cary. Figure 1 is a graph[26] of the number of red light camera citations versus time at the eastbound approach on Cary Town Blvd. at Convention Drive. In March 2010, the Town of Cary fixed its incorrect assumptions about this intersection and increased the signal's straight-thru yellow duration from 4.0 seconds to the Formula's 4.5 seconds. The number of red light runners decreased by about 75%. The Town of Cary had cut short this yellow since 1984. Cary placed a red light camera at this intersection in 2004. It was the first camera Cary installed. Cary has kept all the money it received even during the high period.

Fig 1.

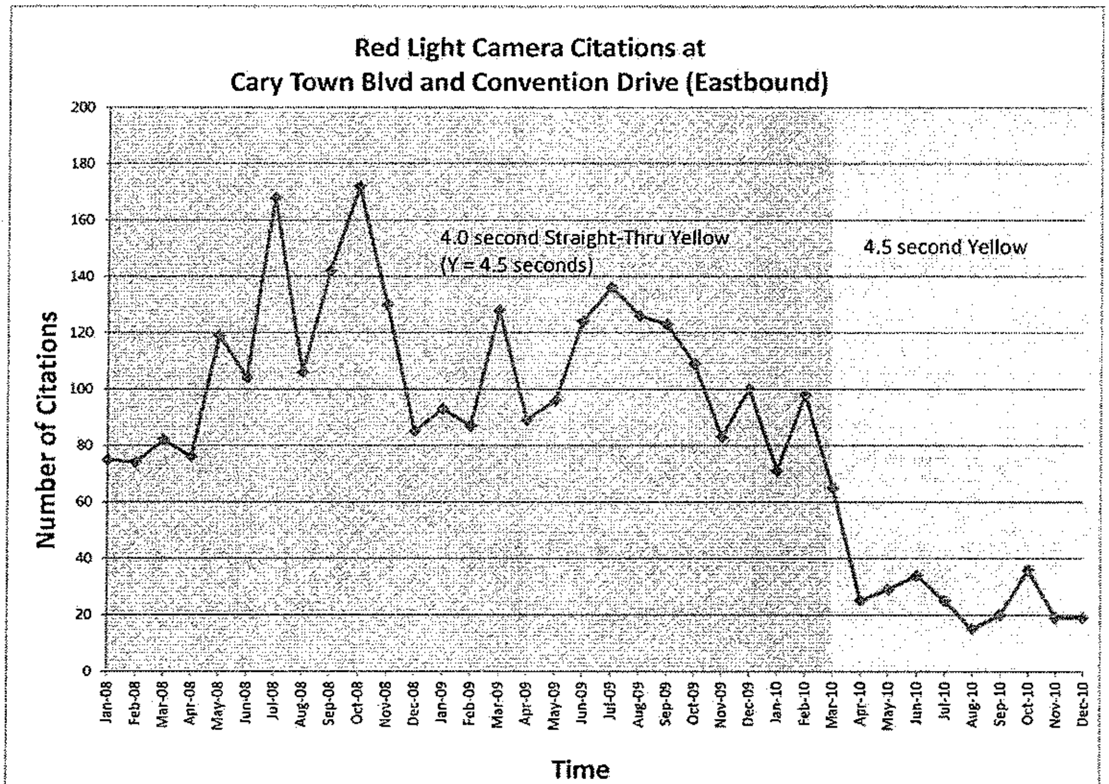
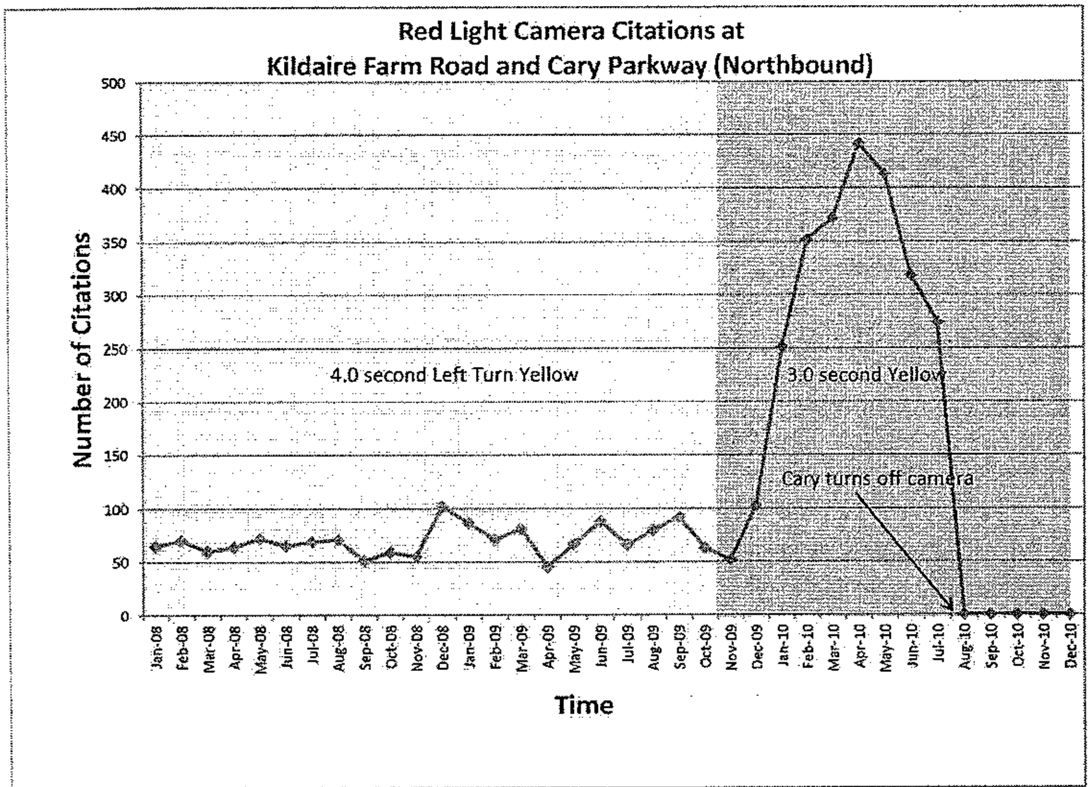


Figure 2 is a graph[26] of the number of red light camera citations on the northbound approach of Kildaire Farms Road at Cary Parkway. In January 2010, the Town of Cary decreased the left turn yellow duration from an already inadequate 4.0 seconds to 3.0 seconds using the 1994 ITE specification as justification. The Formula time for straight-thru movement for this road is 4.5 seconds. The already high volume of red light runners increased about 600%. The Town of Cary turned off the camera by the end of August 2010. The Town of Cary kept all the money it received even during the high period.

Fig 2.



Drivers running red lights during the low periods are not necessarily violators either. By simply applying the usual federal standards, the Town of Cary subjects all drivers at all times to type I and type II dilemma zones. Reduction in the red light running rate only indicates a reduction in the sizes of the dilemma zones, not their absence. At Cary Town Blvd. and Convention, the low period red light runners are most likely type II dilemma zone victims because there is a low volume of turning traffic at this intersection. At Kildaire Farms Road and Cary Parkway, there always has been a type I dilemma zone in the left turn lane because 4.0 seconds undercuts the laws of motion. Both intersections have a type II dilemma zone for straight-thru traffic, and a type I dilemma zone for anyone who must slow down before entering the intersection.

The Town of Cary currently operates 17 red light cameras. Cary has installed these cameras on the approaches of intersections that have the most numerous and longest type I dilemma zones. There is no exception. These locations are where Cary and the red light camera company can reap the most money.

Solution

The solution[27] is equation 6. Equation 6 handles most cases. It gives drivers the distance to stop. It gives drivers the time to proceed at the approach speed. It gives drivers the time to slow down in order to execute a turn. It gives drivers the time required to decelerate and enter an intersection which means that drivers can tap the brakes to avoid hitting obstacles in front of them. In the Driver's Manual, the DMV can now replace the meaning of the yellow light from "yellow means that the signal is about to turn red, stop if you think best, go if you think best, but we may make you run a red light anyway," to the instruction "a driver always has the option to brake without running a red light."

that $\frac{1}{2}$ again

Equation 6 still does not handle weather conditions. The technology does not yet exist to sense and transmit contributions by the weather to the vehicle's motion. The solution does not accommodate the force of the contribution by wind, or the contribution by water on the coefficient of friction between the road and tires.

Eq 6. The Solution

$$Y = t_p + \frac{v_0}{a + G\sin(\tan^{-1} g)}$$

Variable	Description
Y	duration of yellow light
t_p	perception + reaction + air-brake time
v_0	velocity of vehicle measured at $v_0^2/2[a + G\sin(\tan^{-1}(g))]$ from the

	intersection $v_0 \geq$ posted speed limit
a	safe deceleration The value assumes that all vehicles from motorcycles to 18-wheelers have brakes which can exert a force to decelerate the vehicle at the decelerate rate of ***a***.
G	Earth's gravitational constant
g	grade of road (rise over run, negative values are downhill)
$G\sin(\tan^{-1}(g))$	precise expression for the contribution of Earth's gravity towards a vehicle's deceleration on a hill of grade g. When $g < 0.10$, $Gg \approx G\sin(\tan^{-1}(g))$.

Authors

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Joseph Shovlin is a research scientist at Cree Labs in Research Triangle Park, North Carolina. Dr. Shovlin received his Ph.D. in physics in 1990 from Ohio University.

References

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

[2] Institute of Transportation Engineers, *Traffic Signal Timing Manual*, Publication TB-020, 2009, **5-12** (2009).

[3] American Association of State Highway and Transportation Officials, *A Policy on Geometric Design of Highways and Streets*, **111** (2004).

[4] Gazis, Herman, and Maradudin, GM Research Labs The Problem of the Amber Signal Light in Traffic Flow, Institute for Operations Research and the Management Sciences, Vol 8, No. 1, **114** (1960).

[5] Tom Urbanik and Peter Koonce, *The Dilemma with Dilemma Zones*, Proceedings, ITE District 6 Annual Meeting, **1** (2007).

[6] Gazis, Herman, and Maradudin, **124**.

[7] Gazis, Herman, and Maradudin, **118**.

[8] Tom Urbanik and Peter Koonce, **1**.

[9] Town of Cary, *Cary Citation Spreadsheet*, website http://redlightrobber.com (August 10, 2012).

[10] Brian Ceccarelli, *Short Yellow and Turns, Exposing the Traffic Engineer's Mistakes*, website http://redlightrobber.com, **25 - 28**, (May 14, 2012).

[11] Brian Ceccarelli, *Short Yellow and Turns Spreadsheet*, website http://redlightrobber.com, (August 10, 2012).

[12] Gazis, Herman, and Maradudin, Equation 9. **118**.

[13] Gazis, Herman, and Maradudin, **113**.

[14] Gazis, Herman, and Maradudin, **129**.

[15] California Department of Transportation, *California MUTCD*, Table 4D-102(CA) **936** (2012).

[16] Institute of Traffic Engineers, *Traffic Engineering Handbook*, 3rd Edition, Institute of Traffic Engineers, Washington DC, **101** (1965).

[17] Institute of Transportation Engineers, *Determining Vehicle Signal Change and Clearance* Intervals, Publication IT-073, **4** (1994).

[18] Town of Cary, Brian Ceccarelli, Cary Citations Spreadsheet, website http://redlightrobber.com (August 10, 2012).

[19] Institute of Transportation Engineers, *Traffic Engineering Handbook*, 6th Edition, Publication TB-010B, **101** (2010).

[20] North Carolina Department of Transportation, *Traffic Management & Signal Systems Unit Design Manual*, **Standard 5.2.2, Sheet 4 of 4** (2009).

[21] American Association of State Highway and Transportation Officials, *A Policy on Geometric Design of Highways and Streets*, **110, 111** (2004).

[22] Gazis, Herman, and Maradudin, **118**.

[23] Fawzi P. Bayan, et. al, *Brake Timing Measurements for a Tractor-Semitrailer Under Emergency Braking*, Publication 2009-01-2918, Scientific Expert Analysis Limited, **5** (2009).

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

[25] Gazis, Herman, and Maradudin, **131**.

[26] Town of Cary, Brian Ceccarelli, Graphs of Cary Camera Data, website http://redlightrobber.com (August 10, 2012).

[27] Brian Ceccarelli, *Derivation of the Yellow Light Interval Equation*, http://redlightrobber.com (August 10, 2012).

Revised

September 5, 2012 – Draft 22

avg ~~speed~~ velocity $V = \frac{x}{t}$ ← final ~~speed~~ velocity ← initial ~~speed~~ velocity

avg acceleration $a = \frac{V_f - V_0}{t}$

$$\frac{V_0 + V_f}{2} = \frac{x}{t}$$

$$(V_0 + V_f) = \frac{2x}{t}$$

$$V_0 - V_f = at$$

$$(V_0 + V_f)(V_0 - V_f) = 2ax$$

deceleration ~~$a = \frac{V_0 - V_f}{t}$~~ ~~$a = \frac{V_f - V_0}{t}$~~

$V_f < V_0$

decelerating to a stop: $a = \frac{V_0 - 0}{t} = \frac{V_0}{t}$

how far car travels in decelerating

$$V_0^2 - V_f^2 = 2ax$$

decelerate to stop

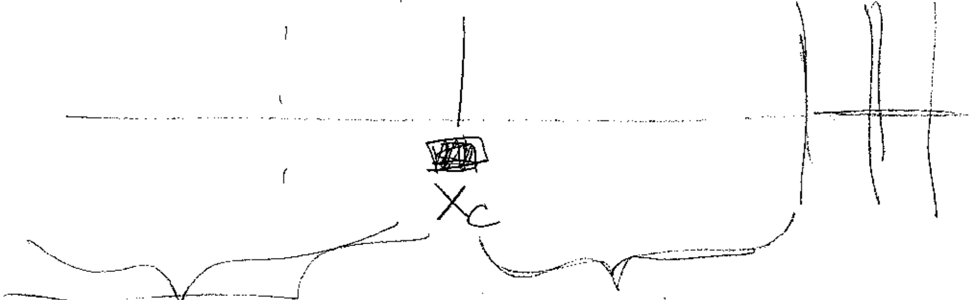
$$V_0^2 = 2ax \rightarrow x = \frac{V_0^2}{2a}$$

total distance to stop safely with reaction time t_p

$$x = V_0 t_p + \frac{V_0^2}{2a}$$

V_0 = velocity when light changes ←

for car going at ~~speed limit~~ ~~approach speed~~ design speed when light changes ($V_0 = V_{\text{design speed}}$) $x = x_c$



can stop safely

can't stop safely – must continue

yellow light interval must be long enough for this to happen

assume continued travel at V_0: $t = \frac{x_c}{V_0}$

if driver slows, will take longer than this

~~A speed~~ car traveling at greater than design speed has "stop safely" pushed back by a lot (v^2) – region where can't stop + can't clear

STATE OF NORTH CAROLINA

COUNTY OF WAKE

IN THE GENERAL COURT OF JUSTICE
SUPERIOR COURT DIVISION
10-CVS-019930

BRIAN CECCARELLI, individually and as class representative,

Plaintiffs,

v.

TOWN OF CARY

Defendant.

AFFIDAVIT OF ELIZABETH GEORGE

ELIZABETH GEORGE, being first duly sworn, deposes and says:

1. I have personal knowledge of the facts hereinafter stated and am competent to testify as a sworn witness to the matters contained herein. I am over the age of 18 years.

2. I received a Ph.D. in Physics in 1993 from the University of Wisconsin – Madison.

3. I am currently employed by Wittenberg University as an Associate Professor and Chair of the Physics Department and have been with the university since 1998.

4. My Curriculum Vitae, including a list of publications, is attached to this Affidavit as Exhibit "A."

5. Based on my education and training in physics, I am qualified to testify regarding the dilemma zones created by the yellow light duration formula used by traffic engineers.

6. My conclusions are based on basic principles that I teach in my physics courses.

7. a) When a traffic light changes from green to yellow, a vehicle traveling at a given speed requires a certain distance to stop safely. If the vehicle is closer to the intersection than this critical distance, the driver cannot safely stop short of the intersection and has to continue through the intersection instead of stopping. When the yellow light duration is too short for a vehicle traveling at this speed to clear the intersection before the light turns red, a Type I dilemma zone is created, in which a driver cannot stop safely, but also cannot get through the intersection before the light turns red without speeding up. When the yellow light duration is set to the ITE yellow light change interval based on a design speed lower than the speed limit, Type I dilemma zones are created for vehicles traveling between the design speed and the speed limit. Drivers in a dilemma zone do not have enough room to stop safely, and also do not have enough time to clear the intersection before the light turns red without speeding.

   The eastbound Cary Towne Blvd. and Convention Drive intersection under the 1991 signal plan is an intersection with such a dilemma zone. With a yellow light duration of 4.0 seconds and a speed limit of 45 mph, a driver needs to be at least 293 feet from the intersection to perceive that the light has turned yellow and stop safely. Drivers closer than this distance must continue through the intersection, but at 45 mph a driver can travel only 264 feet in the 4.0 seconds that the light is yellow. (Standard NCDOT values for perception time and deceleration rate have been used in this calculation.) Thus, drivers traveling at the speed limit between 264 and 293 feet from the intersection at the instant the light turns yellow can neither stop safely nor reach the intersection at the speed limit before the light turns red. If drivers are required to completely clear the intersection before the light turns red, the dilemma zone is even larger.

b) When the yellow light duration in a turn lane is set to the ITE yellow light change interval based on the speed limit for vehicles traveling straight through, a similar Type I dilemma zone is created. Drivers in this zone are too close to the intersection to stop safely, but because they have to slow down below the speed limit in order to turn safely, the yellow light interval is not long enough to allow drivers to clear the intersection while making a turn before the light turns red.

Such a dilemma zone exists at the northbound Cary Parkway and Kildaire Farms intersection with the yellow light duration set to 3.0 seconds in the left turn lane. Drivers approaching at the speed limit of 45 mph who are closer than 293 feet from the intersection at the instant the light turns yellow cannot stop safely and must continue through the intersection, but even if they do not need to slow to make the turn they can travel only 198 ft at the speed limit before the light turns red. Slowing to make the turn makes the distance that can be traveled in 3.0 seconds even shorter than 198 feet, so there is a very large dilemma zone for drivers who plan to turn left at this intersection. Even for drivers who have already slowed to 30 mph when the light turns yellow there is still a dilemma zone in the region between 132 and 152 feet from the intersection.

This the ____ day of November, 2011.

____
Elizabeth George

STATE OF OHIO
COUNTY OF _____
Sworn to and subscribed before
me this ___ day of November, 2011.

____
Notary Public
My Commission Expires:________________

Cary Town Blvd + Convention Drive

@ 45 mph (66 ft/s)

$t = t_p + \frac{V_o}{2a} = 4.45\,s$ to clear at 45 mph

from ~~stop~~ $x_c = 293$ ft

in ~~at~~ 4.0 s, at 45 mph travel 264 ft

so if traveling at speed limit between 264 + 293 ft
can't stop, can't clear w/o speeding

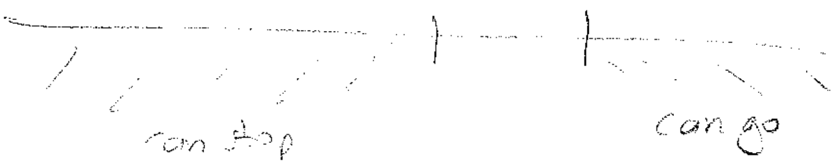
---

30 mph = 44 ft/s

in 3.0 s, w/ $t_p = 1.5$ s
1.5 s left for travel = ~~66 ft~~

} can only go through from closer than 132 ft

~~braking~~ stopping distance $1.5(44) + \frac{44^2}{2(11.2)} = 152$ ft



20 mph = 29 ft/s   travel = 88 ft
stop = 81 ft

OK - just barely

engineering practice is properly based on laws of physics that describe how objects actually behave

avg speed $V = \frac{\Delta x}{\Delta t} = \frac{d}{t}$

avg acceleration $a = \frac{\Delta V}{\Delta t} = \frac{V_f - V_0}{t}$

deceleration $a = \frac{V_0 - V_f}{t}$ to stop, $a = \frac{V_0}{t}$

$a = 11.2$ ft/sec^2
$t_p = 1.5$ s

through: posted speed limit

to apply formula
"design speed" = initial speed at time light turns

drivers who are too close to stop safely must continue,
and at the critical distance they can't slow down at all
(must travel w/ avg velocity = design speed)
↳ L-turn?

: t_p

THE PROBLEM OF THE AMBER SIGNAL LIGHT IN TRAFFIC FLOW

Denos Gazis, Robert Herman, and Alexei Maradudin†

Research Laboratories, General Motors Corporation, Warren, Michigan

(Received November 27, 1959)

A theoretical analysis and observations of the behavior of motorists confronted by an amber signal light are presented. A discussion is given of the following problem: when confronted with an improperly timed amber light phase a motorist may find himself, at the moment the amber phase commences, in the predicament of being too close to the intersection to stop safely or comfortably and yet too far from it to pass completely through the intersection before the red signal commences. The influence on this problem of the speed of approach to the intersection is analyzed. Criteria are presented for the design of amber signal light phases through whose use such 'dilemma zones' can be avoided, in the interest of over-all safety at intersections.

WE LIVE in a difficult and increasingly complex world where man-made systems, man-made laws and human behavior are not always compatible. This paper deals with a problem peculiar to our present civilization, for which a satisfactory solution based on existing information and analysis is not available. The problem in question is that of the amber signal light in traffic flow.

Undoubtedly everyone has observed at some time or other the occurrence of a driver crossing an intersection partly during the red phase of the signal cycle. There are few of us who have not frequently been faced with such a decision-making situation when the amber signal light first appears, namely, whether to stop too quickly (and perhaps come to rest partly within the intersection) or to chance going through the intersection, possibly during the red light phase. In view of this situation we were led to consider the following problem: can criteria presently employed in setting the duration of the amber signal light at intersections lead to a situation wherein a motorist driving along a road within the legal speed limit finds himself, when the green signal turns to amber, in the predicament of being too close to the intersection to stop safely and comfortably and yet too far from it to pass through, before the signal changes to red, without exceeding the speed limit? From experience we feel that a problem exists, and we ask if it is feasible to construct a signal light system such that the characteristics of a driver and his car, the geometry

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of the road and intersection, and the law are all compatible with one another.

Some thought has already been devoted to this question[1,2] but it is our opinion that the problem at hand does not appear to have been thought through deeply enough as a problem in operations research nor does it appear to have been supported adequately by published observational and experimental data. It is our intention in this paper to contribute toward the understanding of this situation. First, we derive and discuss some simple relations between car speed, driver decision and reaction time, the parameters of the road and intersection, and the duration of the amber signal light. The results of measurements of the duration of amber signal lights, driver decision plus reaction time, and other parameters entering into the theoretical discussion are next presented. Finally, we discuss the experimental results in the light of theory and the traffic codes of cities and towns throughout the country.

We are well aware that there may be practical difficulties involved in incorporating the results and conclusions of an analysis such as ours into the practical planning of traffic systems, and we do not consider such problems here. It is our hope, rather, that in pointing out the existence and nature of the amber-signal-light problem we may stimulate others to pursue it further and make certain that the driver is confronted with a solvable decision problem. We are, of course, also motivated by the desire to contribute effectively toward the improvement of over-all driver safety and, in this case specifically, safety at intersections.

ANALYTICAL CONSIDERATIONS

We consider the traffic situation depicted in Fig. 1, in which a car traveling at a constant speed v_0 toward an intersection is at a distance x from the intersection when the amber phase commences. The driver is then faced with two alternatives. He must either decelerate and bring his car to a stop before entering the intersection or go through the intersection, accelerating if necessary, and complete his crossing before the signal turns red. In these cases his acceleration or deceleration will begin at a time δ_1 or δ_2 after the initiation of the amber phase, respectively. These time intervals δ_i measure the reaction time-lag of the driver-car complex as well as the decision-making time of the driver.

In order to carry out a mathematical investigation of the problem we assume a constant acceleration a_1 in the case of crossing the intersection, or a constant deceleration a_2 in the case of stopping before entering the intersection. If, furthermore, the effective width of the intersection is denoted by w, the length of the car by L and the duration of the amber phase by τ, the following relations can be derived:

1. If the driver is to come to a complete stop before entering the intersection, we find that

$$(x-v_0\,\delta_2)\geqq v_0^2/2a_2. \qquad (1)$$

2. If the driver is to clear the intersection completely before the light turns red, we must have

$$(x+w+L-v_0\,\delta_1)\leqq v_0\,(\tau-\delta_1)+\tfrac{1}{2}\,a_1\,(\tau-\delta_1)^2. \qquad (2)$$

It is to be noted that the effective width, w, used in the preceding equation is meant to denote the approximate distance between a painted stopping line or a building line and a 'clearing line' whose position is necessarily somewhat indefinite because of the geometry of real intersections.

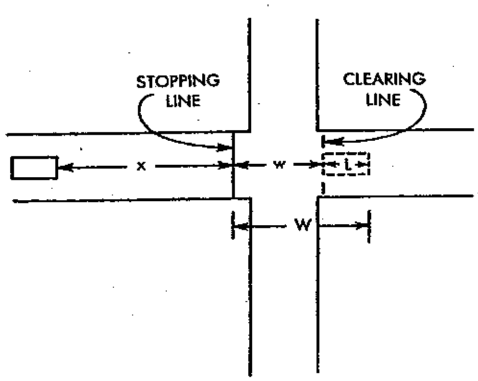

Fig. 1. Geometry of an intersection showing distances to be covered by a car of length L in the two alternative cases of going through and stopping before the intersection.

Equations (1) and (2) can be used for the discussion of the two alternatives and their ramifications. Thus, solving equation (1) for a_2 we obtain, assuming the equality sign,

$$a_2=\tfrac{1}{2}\,v_0^2/(x-v_0\,\delta_2). \qquad (3)$$

Equation (3) gives the (constant) deceleration needed in order to bring the car to a stop just before the intersection as a function of the distance of the car from the intersection at the initiation of the amber phase. We see that a_2 becomes infinite for $x=v_0\,\delta_2$, as it must. However, even for values of x greater than $v_0\,\delta_2$, the deceleration given by (3), while finite, may be so large as to be uncomfortable to the driver and his passengers, or may be unsafe under the prevailing road conditions, or even physically impossible. Therefore, assuming the existence of a maximum deceleration a_2^* by which the car can be brought to a stop before the intersection safely and comfortably, equation (1) defines a 'critical distance', namely,

$$x_c=v_0\,\delta_2+v_0^2/2a_2^*. \qquad (4)$$

If $x > x_c$ the car can be stopped before the intersection, but if $x < x_c$ it will be uncomfortable, unsafe, or impossible to stop. We note that this critical distance is independent of the duration of the amber phase, τ, and depends only on the characteristics of the driver-car complex. The required deceleration is plotted versus distance in Fig. 2.

Turning, now, to the second alternative, namely, going through the

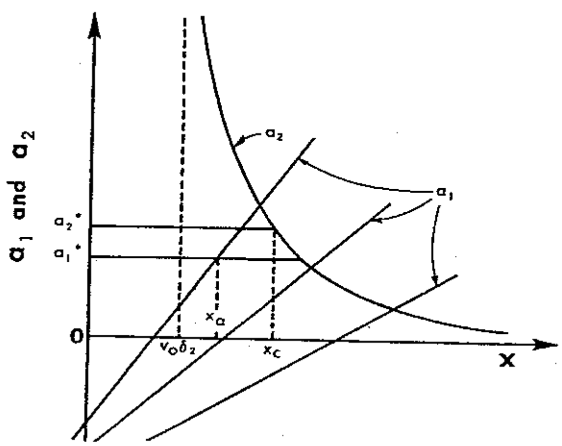

Fig. 2. Variation of the deceleration required in order to stop before the intersection, a_2, or the acceleration required to clear the intersection, a_1, versus the distance from the intersection, x. The x-intercept of the a_1 versus x lines defines a distance x_0 which is the maximum distance, apart from the width of the intersection and the length of car, which can be covered without acceleration during the amber phase.

intersection, we solve equation (2) for a_1, assuming the equality sign, and obtain

$$a_1 = 2\,x/(\tau-\delta_1)^2 + 2\,(w+L-v_0\,\tau)/(\tau-\delta_1)^2. \tag{5}$$

Equation (5) gives the (constant) acceleration needed in order that the car may clear the intersection just as the signal turns red, as a function of the distance x of the car from the intersection at the start of the amber phase. For various values of the parameters involved, equation (5) represents a family of straight lines in the x,a_1-plane with slope

$$da_1/dx = 2/(\tau-\delta_1)^2, \tag{6}$$

and intercept on the x-axis,

$$x_0 = v_0\tau - (w+L). \tag{7}$$

The quantity x_0 is the maximum distance the car can be from the intersection at the start of the amber phase and still clear the intersection without acceleration during the amber phase. The position of x_0 with respect to x_c, and the character of the line represented by equation (5), determine whether or not the duration of the amber phase has been adequately designed, taking into account the requirements of the law and the physical 'boundary conditions' of the problem. Thus, if $x_0 > x_c$, the driver,

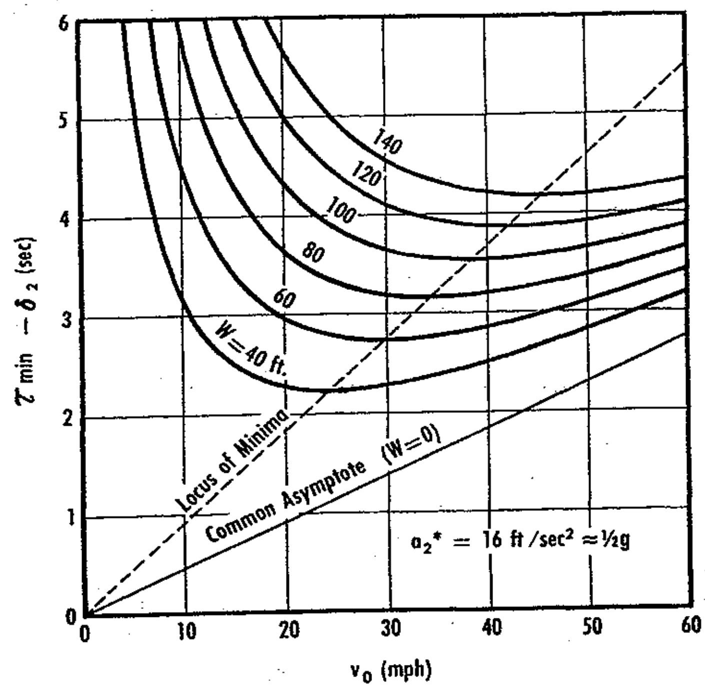

Fig. 3. Variation of the minimum amber-phase duration, τ_{min}, which is required in order that there be no dilemma zone, versus constant approach speed, v_0, for various intersection widths plus car length, W. (The constant deceleration is assumed to be 16 ft/sec^2.)

once past the critical distance x_c, can clear the intersection before the signal turns red. If, however, $x_0 < x_c$, a driver at a distance x from the intersection such that $x_0 < x < x_c$ will find himself in a very awkward position if the amber phase begins at that moment. He cannot stop safely and hence he has to attempt to go through the intersection. From Fig. 2 we see that he can achieve this only by accelerating. If, however, v_0 happens to be the maximum allowable speed, the driver will find himself in the following predicament. He can neither bring his car to a stop safely nor can he go through the intersection before the signal turns red without violating the speed limit.

There is an even worse possibility, which is realized for even shorter values of τ. This is the case where $x_0 < x_c$ and the slope da_1/dx is sufficiently large that the line represented by equation (5) intersects a line $a_1 = a_1^*$, where a_1^* is a maximum possible acceleration, at a point which has an abscissa x_a smaller than x_c. Then, for $x_a < x < x_c$, a driver cannot stop safely and he cannot clear the intersection before the initiation of the red light phase even if he is willing to utilize all the power resources of his car while violating the speed limit.

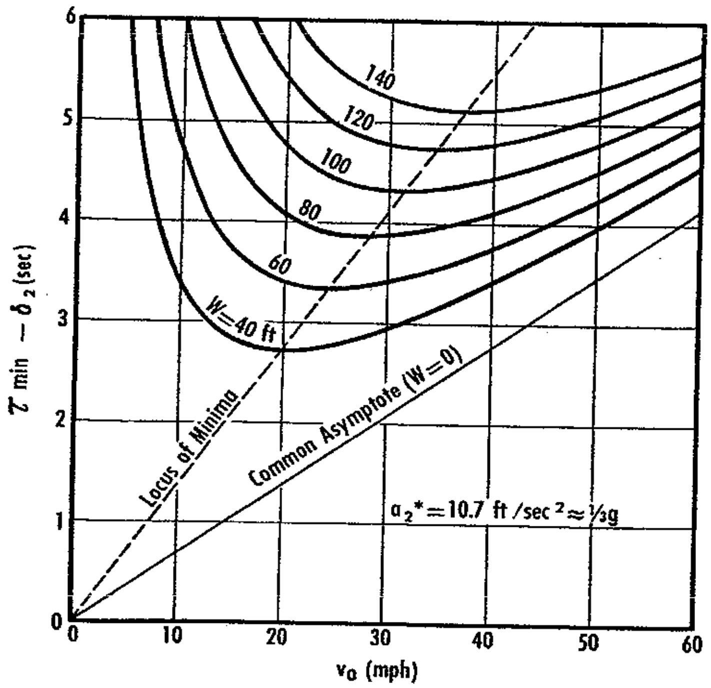

Fig. 4. Variation of the minimum amber-phase duration, τ_{min}, which is required in order that there be no dilemma zone, versus constant approach speed, v_0, for various intersection widths plus car length, W. (The constant deceleration is assumed to be 10.7 ft/sec^2.)

It may be pointed out that this maximum possible acceleration depends on the approach velocity v_0. It is well known that the higher the velocity of a car the lower its accelerating capability. Thus an average good car can have an acceleration of as much as ½ g starting from rest, but only about 0.08 g when traveling at 65 mi/hr.† (Note that g is the earth's gravitational acceleration.)

Let us now discuss the design of the duration of the amber phase. From the graphical representation of Fig. 2, we see that the minimum

† We are indebted to Mr. Joseph Bidwell for furnishing us with the experimental data on the accelerating capability of a car as a function of its speed.

TABLE I

COMPARISON OF OBSERVED AND CALCULATED AMBER-PHASE DURATIONS

Street	Cross street	Speed limit (mi/hr)	Approximate effective width of intersection	Duration of amber phase	Theoretical $\tau_{\min}$: eq. (5)[a]			
					$a_2^* = 10.7$ ft/sec^2		$a_2^* = 16$ ft/sec^2	
					$\delta_2 =$ 1.14 sec	$\delta_2 =$ 0.75 sec	$\delta_2 =$ 1.14 sec	$\delta_2 =$ 0.75 sec
South of Main	Catalpa	25	60	2.7[b]	4.91	4.52	4.33	3.94
North on Mound	Chicago	30	75	3.4	5.25	4.86	4.56	4.17
East on Chicago	Van Dyke	30	80	4.0	5.36	4.97	4.67	4.28
North on Woodward	Calvert	30	—	3.6	—	—	—	—
East on 11 Mile	Van Dyke	35	55	3.4	4.90	4.51	4.10	3.71
West on 14 Mile	Southfield	35	60	6.8	5.00	4.61	4.20	3.81
South on Woodward	9 Mile	35	80 to	4.5	5.39	5.00	4.59	4.20
			120		6.16	5.77	5.36	4.97
North on Woodward	Savannah	35	65	3.85	5.10	4.71	4.30	3.91
North on Mound	13 Mile	40	50	3.6	5.00	4.61	4.09	3.70
West on Chicago	Van Dyke	40	80	4.0	5.51	5.12	4.60	4.21
West on 8 Mile	Ryan	40	70	3.9	5.34	4.95	4.43	4.04
North on Van Dyke	12 Mile	40	80	4.1	5.51	5.12	4.60	4.21
East on 12 Mile	Van Dyke	45	65	4.0	5.44	5.05	4.41	4.02
North on Woodward	11 Mile	45	80	3.44	5.67	5.28	4.64	4.25
North on Woodward	Lincoln	45	75	3.75	5.59	5.20	4.56	4.17
South on Van Dyke	Chicago	50	70	3.8	5.74	5.35	4.60	4.21

(a) Two values of the time lag δ_2 were assumed. One of them is the observed average 1.14 sec and the other a lag of 0.75 sec frequency assumed as a minimum. A car length was taken as 15 ft to be conservative. Two values for the maximum deceleration a_2^* were assumed. One of them is equal to $\frac{1}{3}g$ which is feasible but is a fairly high deceleration not desirable in normal driving. The other one is equal to $\frac{1}{2}g$, which corresponds to a very hard stop. (Note that 0.6 g is about the absolute maximum deceleration under ideal conditions.)

(b) The amber phase here was measured at about 2.1 sec prior to a modification in the signal cycle. We have been informed of an even shorter amber phase of only about 1.5-sec duration at an intersection in California where an individual received a ticket for being in this intersection on the red signal.

amber-light duration, denoted by $\tau_{\min}$, which guarantees the safe execution of either one of the alternatives of stopping or going through the intersection without accelerating, corresponds to $x_0 = x_c$. Hence

$$\tau_{\min} = (x + w + L)/v_0, \tag{8}$$

and, using equation (4),

$$\tau_{\min} = \delta_2 + \tfrac{1}{2}\, v_0/a_2^* + (w+L)/v_0. \tag{9}$$

A simple numerical example will show the magnitude of the quantities involved. Assuming $v_0=45$ mi/hr$=66$ ft/sec, $a_2^*=0.5\ g\approx 16$ ft/sec^2, $\delta_2=1$ sec, $w=65$ ft, and $L=15$ ft, we find $x_c=202$ ft and $\tau_{min}=4.28$ sec.

It may be noted that the length of the car, L, is added to the effective width of the intersection, w, in order to determine the length of travel through the intersection. The length of the car contributes the quantity

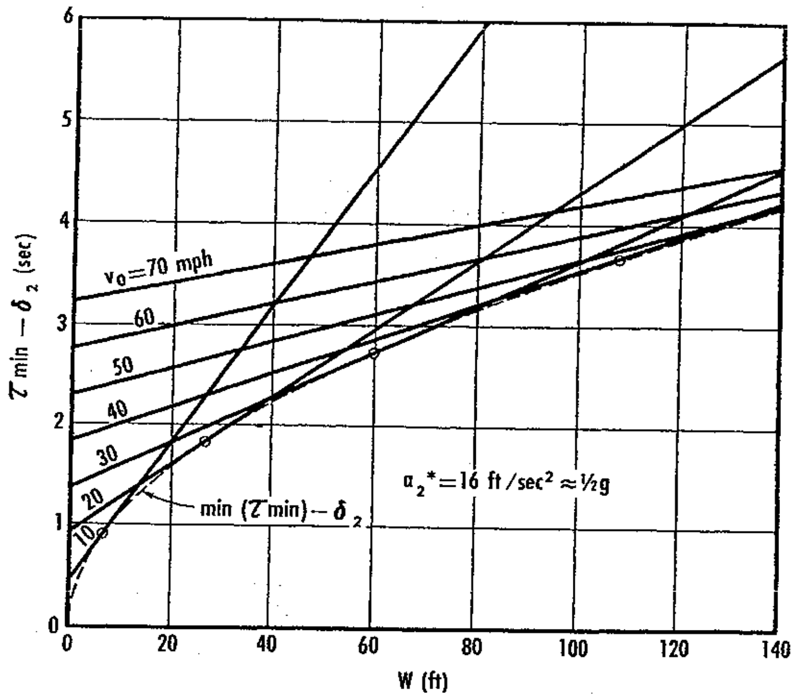

Fig. 5. Variation of the minimum amber-phase duration, τ_{min}, which is required in order that there be no dilemma zone, versus the intersection width plus car length, W, for various values of the constant approach speed, v_0. (The constant deceleration is assumed to be 16 ft/sec^2.)

L/v_0 in the computation of τ_{min}. This means that the required τ_{min} is substantially longer for vehicles such as long trucks, buses, or vehicles with trailers, even assuming that these vehicles can stop with the same maximum deceleration a_2^* as shorter ones. One may retort that traffic signals should not be designed for these 'unusual' cases. However, these unusual vehicles *are* allowed on the highways, and if the design of the amber phase does not take them into account then the questions raised in the introduction regarding the compatibility of law and physical characteristics become even more acute.

Returning now to the expression for τ_{min} given in equation (9), we use this result to plot $\tau_{\min}$ versus v_0 in Figs. 3 and 4 for various values of the parameter

$$W = w + L \tag{10}$$

and for two values of the maximum deceleration a_2^*, namely, $\frac{1}{2}\,g$ and $\frac{1}{3}\,g$. (For comments on the magnitude of these decelerations, see the first

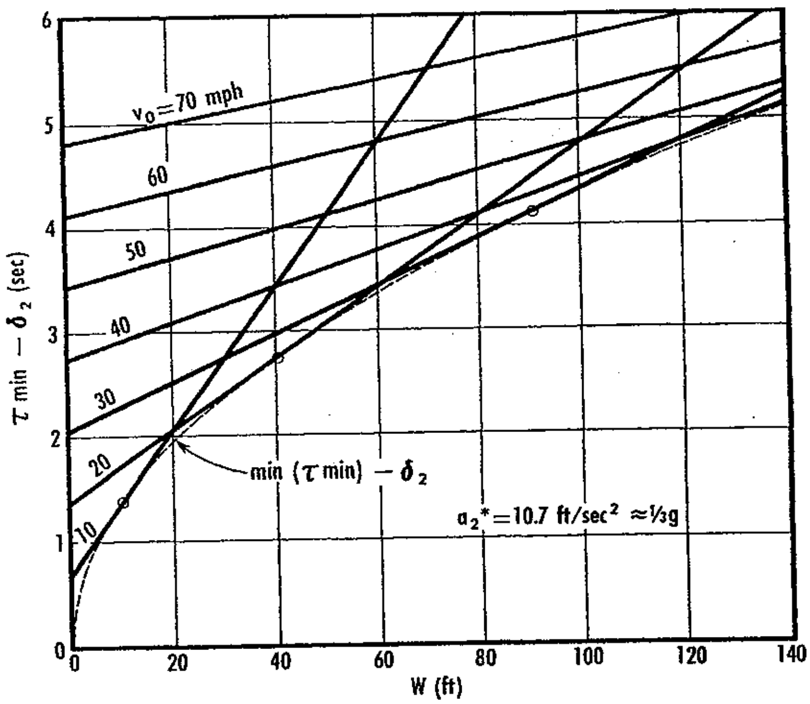

Fig. 6. Variation of the minimum amber-phase duration, $\tau_{\min}$, which is required in order that there be no dilemma zone, versus the intersection width plus car length, W, for various values of the constant approach speed, v_0. (The constant deceleration is assumed to be 10.7 ft/sec.)

footnote in Table I, as well as reference 2, p. 68.) The minima of the various curves correspond to values of the approach velocity v_0, assumed equal to the speed limit, which would minimize $\tau_{\min}$ for a given value of W. From equation (9) we have

$$\partial\tau_{\min}/\partial v_0 = 1/2a_2^* - W/v_0^2, \tag{11}$$

and $\partial\tau_{\min}/\partial v_0 = 0$ for

$$v_0 = \sqrt{2\,a_2^*\,W}. \tag{12}$$

Hence the absolute minimum length of the amber phase is given by

$$\min(\tau_{\min}) = \delta_2 + \sqrt{2\,W/a_2^*}. \tag{13}$$

Figures 5 and 6 contain plots of $(\tau_{\min}-\delta_2)$ versus W for different values of the approach velocity v_0, and for the same two values of a_2^* as in Figs. 3 and 4. Equation (9) yields a family of straight lines in the plane $(\tau_{\min}-\delta_2)$ versus W. The envelope of these lines corresponds to $\min(\tau_{\min})$ as given by equation (13).

The foregoing discussion is illustrated in Fig. 7, where each of the two shaded zones precludes one of the two alternatives of stopping or going through the intersection. Thus, a car at a distance from the intersection smaller than x_c cannot stop safely, whereas a car at a distance greater than x_0 cannot go through the intersection without accelerating before the light turns red.

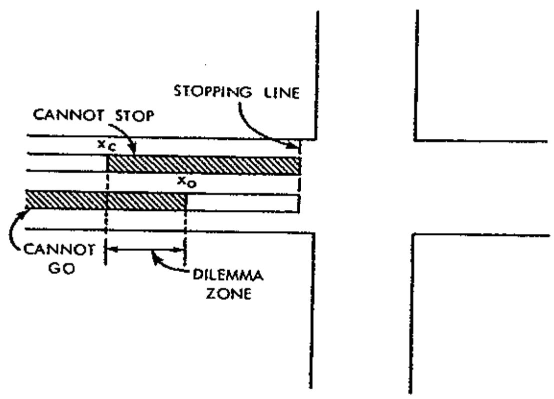

Fig. 7. Schematic diagram showing the 'dilemma zone' near an intersection.

As mentioned already, when $x_0<x_c$ the driver is in trouble if he finds himself in the region $x_0<x<x_c$, which in the sequel will be referred to as the 'dilemma zone.'

The preceding arguments have been established on the assumption that the approach speed of the motorist is equal to the speed limit so that he cannot accelerate to clear the intersection without exceeding the speed limit. It is possible, however, that even if the amber phase is improperly set so that a dilemma zone exists for an approach speed equal to the speed limit, a motorist may, under certain circumstances, avoid encountering such a dilemma zone if his approach speed is smaller than the speed limit. This is so because the critical distance, x_c, decreases rapidly as the approach speed decreases. On the other hand, if the driver is at a distance from the intersection slightly larger than this reduced x_c when the amber-light phase begins he may be able, under certain circumstances, to clear the intersection within this phase by accelerating until he has reached the speed limit and then proceeding through the intersection at this speed. An example of this case is illustrated in Fig. 10, which is discussed a little later.

If we assume that the driver's acceleration from v_0 to v_l (the speed

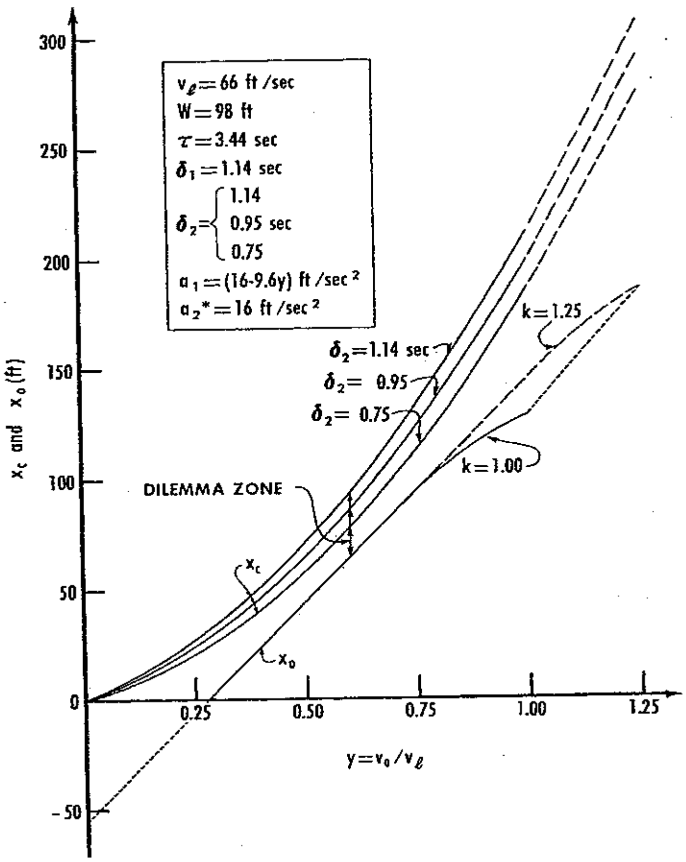

Fig. 8. Northbound on Woodward Avenue at 11 Mile Road. Variation of the critical distance, x_c, and the maximum distance which can be covered within the amber phase duration, x_0, versus the ratio of the approach speed to the speed limit, $y = v_0/v_l$. It is assumed that in crossing the intersection the car may accelerate up to a speed not in excess of kv_l.

limit) is constant and equal to a_1, the equation which replaces equation (2) is

$$x_0 = \begin{cases} v_0\,\delta_1 - W + (v_l^2 - v_0^2)/2a_1 + v_l\,[\tau - \delta_1 - (v_l - v_0)/a_1] \\ \qquad\qquad \text{for} \quad \tau \geqq \delta_1 + (v_l - v_0)/a_1, \\ v_0\,\delta_1 - W + v_0\,(\tau - \delta_1) + (\tfrac{1}{2}\,a_1)\,(\tau - \delta_1)^2 \\ \qquad\qquad \text{for} \quad \tau \leqq \delta_1 + (v_l - v_0)/a_1, \end{cases} \tag{14}$$

where W is given by (10) and x_0 is the distance of the car from the intersection at the moment the amber phase commences. It is assumed that the car just clears the intersection before the light turns red. Rewriting (14) to give x_0 as a function of $y=v_0/v_l$, where $0\leqq y\leqq 1$, we obtain

$$x_0=\begin{cases}-W+v_l\,\tau-v_l\,\delta_1\,(1-y)-(v_l^2/2a_1)(1-y)^2 \\ \qquad\qquad\qquad\qquad \text{for} \quad \tau\geqq\delta_1-(v_l/a_1)(1-y), \\ -W+\tfrac{1}{2}\,a_1(\tau-\delta_1)^2+v_l\,\tau y \qquad \text{for} \quad \tau\leqq\delta_1-(v_l/a_1)(1-y).\end{cases} \tag{15}$$

Equation (1) remains unchanged, so that

$$x_c=\delta_2\,v_l\,y+(v_l^2/2a_2^*)\,y^2. \tag{16}$$

For simplicity we assume that $\delta_1=\delta_2=$ 1.14 sec (*see* the following section), while $a_2^*=\tfrac{1}{2}\,g=16$ ft/sec^2. The (constant) acceleration a_1 is, however, a function of the car speed at the moment when the car begins to accelerate. An analytic expression for this speed dependence of a_1, which fits the experimental data adequately enough for our purposes is

$$a_1(v_0)=\begin{cases}(16-0.145\,v_0)\text{ ft/sec}^2 & \text{for} \quad 0\leqq v_0\leqq 110\text{ ft/sec}, \\ 0 & \text{for} \quad v_0 \quad >110\text{ ft/sec},\end{cases} \tag{17}$$

where v_0 is given in ft/sec. We assume, for simplicity, that a car traveling at an approach speed v_0 can maintain a constant acceleration a_1, as given by equation (17), for a length of time of the order of τ. It should be noted that there are marked differences in the dynamic characteristics of various cars with regard to acceleration. The preceding equation gives an acceleration which is on the high side and is applicable to the high-powered modern car. Low-powered cars develop considerably lower accelerations, particularly at high speeds. If one were to assume lower accelerations, the problem of the dilemma zone would be accentuated.

Using equations (15), (16), and (17), we have plotted x_0 and x_c as functions of y for three different intersections in Figs. 8, 9, and 10.

The curve for x_0 has a straight segment, corresponding to the second expression in (15), and a curved segment corresponding to the first expression. These two segments are tangent at the point y_t satisfying the equation

$$1-y_t-(\tau-\delta_1)(a_1/v_l)=0. \tag{18}$$

Hence, in view of (17), we have

$$y_t=[1-16\;(\tau-\delta_1)/v_l]/[1-0.145\;(\tau-\delta_1)], \tag{19}$$

where speeds are given in ft/sec and times in seconds.

From Fig. 7 we see that there is no dilemma zone if $x_0 > x_c$; of the situations depicted in Figs. 8–10 we see that in only one case, namely, that shown in Fig. 10, is there an absence of a dilemma zone, and this is so only for $0.15 < y < 0.57$. This means that at this particular intersection a car traveling at the speed limit of 65 mi/hr would encounter a dilemma zone of 106 ft, approximately six car-lengths, at a distance of 286 ft from the

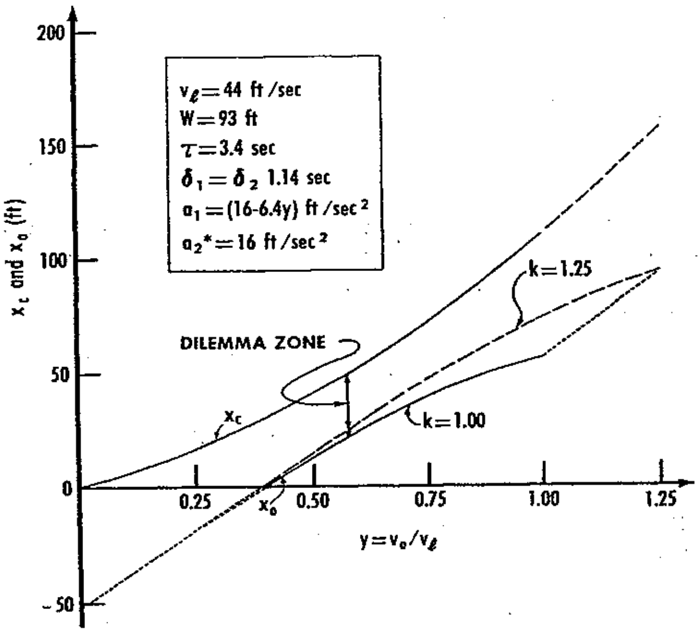

Fig. 9. Northbound on Mound Road at Chicago Road. Variation of the critical distance, x_c, and the maximum distance which can be covered within the amber-phase duration, x_0, versus the ratio of the approach speed to the speed limit, $y = v_0/v_l$. It is assumed that in crossing the intersection the car may accelerate up to a speed not in excess of kv_l.

intersection. On the other hand, if the speed of the car is 37 mi/hr or lower, no such zone exists. It need hardly be pointed out that under ordinary driving conditions a speed of 37 mi/hr on a highway with a 65 mi/hr-maximum is unrealistic, and quite possibly dangerous.

From the preceding discussion we ascertain that if one were to assume, for low-powered cars, accelerations lower than those given by (17), the values of x_0 would be reduced considerably and the dilemma zones increased in the entire range $0 \leqq y \leqq 1$.

Approaching an intersection at a speed lower than the speed limit is one facet of defensive driving. It is seen from the preceding discussion that this in itself is not always sufficient to obviate the dilemma-zone problem. Another facet of such defensive driving consists of the maneuver of coasting toward the signal light with one's foot readied on the brake. The advantage, in this case, which comes from shortening the reaction

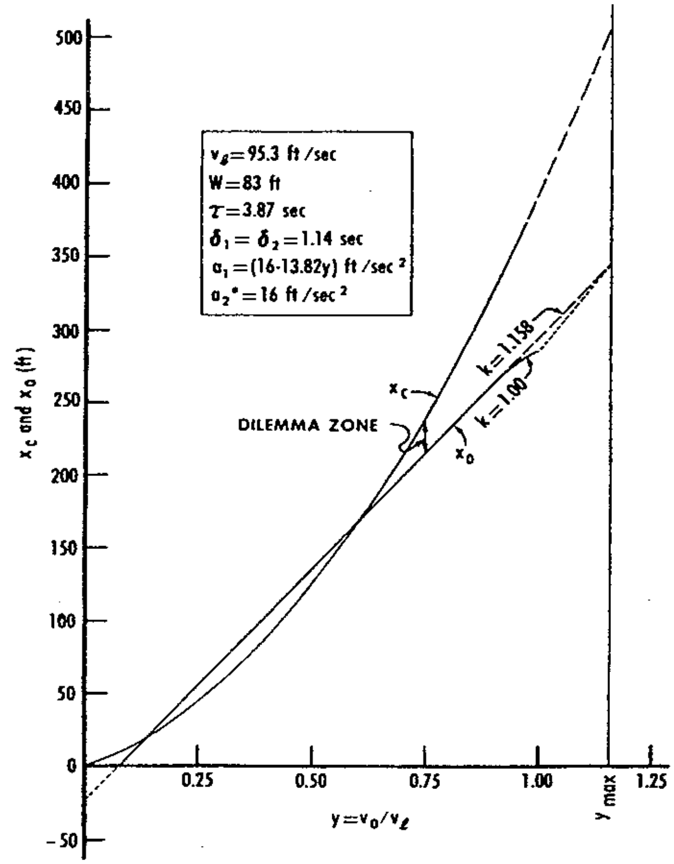

Fig. 10. Northbound on Stephenson Highway at 15 Mile Road. Variation of the critical distance, x_c, and the maximum distance which can be covered within the amber-phase duration, x_0, versus the ratio of the approach speed to the speed limit, $y = v_0/v_l$. It is assumed that in crossing the intersection the car may accelerate up to a speed not in excess of kv_l. The value of $k = 1.157$ corresponds to the maximum speed of 110 ft/sec according to equation (17).

time, is reflected in a decrease of the critical distance x_c. The improvement, which is by no means an absolute cure, can be seen from the curves plotted in Fig. 8 for two values of δ_2 other than the observed average. Such defensive driving, however, should be used with discrimination and great caution when approaching intersections in a high-density traffic pattern since it may induce a rear-end collision—a prominent type of accident in traffic today.

Many drivers take the attitude that there is nothing sacred about the speed limit! Suppose one, starting with an initial speed $v_0 = yv_l$, where v_l is again the official speed limit, accelerates to a final speed equal to or less than v_l' given by

$$v_l' = kv_l. \qquad (k > 1) \quad (20)$$

The analysis already carried out can be applied to this case on the assumption that the 'effective speed limit' is $v_l' = kv_l$ and the initial speed

$$v_0 = y'v_l' = (y/k)\, v_l'. \qquad (0 \leqq y' \leqq 1) \quad (21)$$

The x_c versus y curve obviously does not change. The ordinate of the x_0 versus y curve at $y' = 1$, i.e., at $y = k$, is

$$x_0^* = -W + v_l\, \tau k. \qquad (22)$$

In Figs. 8 and 9 we have plotted with dashed lines the curves of x_0 corresponding to 'effective speed limits' equal to 1.25 v_l (i.e., $k = 1.25$). Similarly in Fig. 10 we have plotted with a dashed line the curve of x_0 for $k = 1.158$. This value of k corresponds to an 'effective speed limit' equal to the assumed maximum possible speed of 110 ft/sec (75 mi/hr), according to equations (17). Again, these curves are made up of two segments, one straight and one curved, which are tangent at the point

$$y_t' = [k - 16\ (\tau - \delta_1)/v_l]/[1 - 0.145\ (\tau - \delta_1)]. \qquad (23)$$

The straight segment is an extension of the one already plotted on the basis of the second expression in (15), which is independent of the effective speed limit.

From these figures we see that even if the driver is willing to accelerate to speeds greatly in excess of the speed limit, he still cannot eliminate the dilemma zone.

With regard to the length of the dilemma zone, the following additional remark can be made on the basis of the preceding discussion. If a driver encounters a dilemma zone, the maximum possible distance of the rear bumper of his car from the clearing line of Fig. 1 at the moment the red phase commences is equal to the length of the dilemma zone. This maximum distance is realized if the driver is just past x_c when the amber phase commences. Now, if the indecision zone is greater than the effective width of the intersection plus the car length, W, the driver may even have to *enter* the intersection during the red phase. From Fig. 10 it is seen that this may happen, at the intersection under consideration, to a driver who approaches the intersection at the speed limit and does not want to exceed this limit, since in this case the dilemma zone of 106 ft is greater than $W=83$ ft.

OBSERVATIONS

IN ORDER TO compare the theoretical results of the preceding section with physical reality the following kinds of observations were carried out on

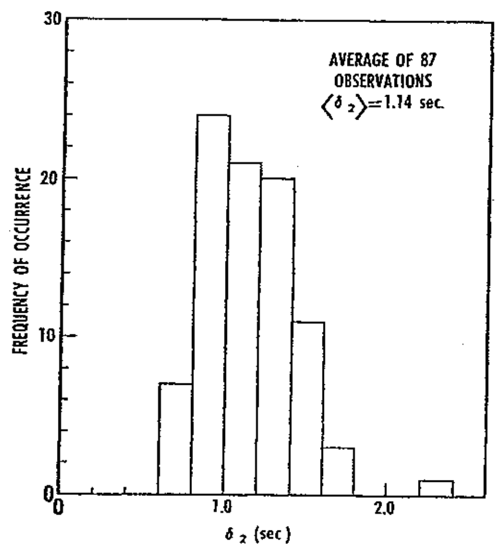

Fig. 11. Histogram showing the observed frequency of occurrence of various intervals of decision and reaction time in braking, δ_2, in a total of 87 measurements.

the manner in which people actually drive and the pattern in which amber signal light phases are in practice set:

1. Duration of amber-light phase.
2. Motorists' braking reaction time (including the decision time and the reaction time lag).
3. Average number of motorists per cycle who run through the red light.
4. The dimensions of the road and intersection together with the posted speed limit.
5. Traffic density.
6. The effective critical distance x_c.

Most of the observations were made at street intersections within about a fifteen-mile radius of the General Motors Technical Center. It was not our intention to make our data exhaustive, but we feel that enough measurements were made so that fairly definite conclusions based on them could be drawn.

We begin by presenting in Table I a sampling of the data obtained on amber-signal-light times, speed limits, and approximate intersection widths, at a number of intersections, together with theoretical values of the minimum amber-light phase, τ_{min}, calculated from equation (8) using two values of the maximum deceleration and two values of the braking reaction time.

TABLE II

OBSERVED AND CALCULATED CRITICAL DISTANCE, x_c

Street	Cross street	Speed limit	Effective x_c	Theoretical x_c ($a_2^*=0.5\ g$)
North on Woodward Avenue	Lincoln	45 mi/hr	165 ft	211 ft
West on 8 Mile Road	Ryan	40	145	174
North on Woodward Avenue	11 Mile Road	45	185	211

In measuring the drivers' braking reaction time, an observer was stationed near a given intersection at a distance somewhat greater than the estimated x_c. The observer would then arbitrarily choose a car in the interval between himself and the intersection and would measure the time

TABLE III

TRAFFIC FLOW AND PER CENT TRAFFIC-LIGHT VIOLATIONS

Street	Cross street	Number cars in intersection per cycle	Average number cars running through red signal per cycle	Per cent of cars running through red signal	Amber phase (sec)
North on Woodward Avenue	Lincoln	62.3	1.2	1.93	3.75
		53.8	0.8	1.49	3.73
West on 8 Mile Road	Ryan	42.1	0.7	1.66	3.9
North on Woodward Avenue	11 Mile Road	54.5	1.2	2.20	3.49
North on Woodward Avenue	Woodland	91.6	0.5	0.55	4.23
North on Woodward Avenue	Sylvan	95.1	0.1	0.11	4.69
North on Woodward Avenue	Webster	46.1	0.4	0.87	3.67

interval between the moment the amber signal came on and the moment when the red brake tail light flashed. The distribution of such delay times is plotted in Fig. 11 on the basis of 87 observations. The mean delay time was found to be 1.14 seconds.

The determination of an average effective x_c was carried out using the following criterion: it is the closest distance at which a car can be from the intersection, when the amber signal commences, and still be capable of stopping before entering the intersection. Measurements of this quantity were made at several intersections and the results are shown in Table II together with the theoretical values calculated from equations (4). The observed x_c was in general a little smaller than the theoretical x_c corresponding to the speed limit of the observed intersections. This was probably due to the fact that the traffic was moving, on the average, a little slower than the posted speed limit, since our observations were made during the heavy traffic of the rush hour.

Finally, we measured at a few intersections the average number of cars that ran through the red signal per signal light cycle during rush hour traffic (4:30–6:00 P.M.), together with the average number of cars that pass through the intersection per signal light cycle. These results are shown in Table III.

The preceding pertains to a single traffic light. Analogous results may be obtained for two closely spaced traffic lights, as in the case of crossing of a divided highway. However, this case is rather complicated and will not be discussed here. There are other variations to the problem of the dilemma zone such as the case of a vehicle approaching an intersection at slow speed with the intention of making a turn. This is a case of known practical difficulty and some information can be obtained from the present analysis with w taken equal to the distance traversed while turning.

Some additional data regarding the amber-light phase were obtained from three other cities, namely, Washington, D. C., Silver Spring, Maryland, and Los Angeles, California. On the average, the amber-light phases were slightly shorter in Los Angeles and slightly longer in the Washington, D. C., area, relative to those in the Detroit area. There are no significant differences, and the conclusions of this paper will apply in those areas also.

DISCUSSIONS AND CONCLUSIONS

THE *Uniform Vehicle Code* of the National Committee on Uniform Traffic Laws and Ordinances[3] gives the following definition for the purpose of the amber signal light:

> Vehicular traffic facing the signal is thereby warned that the red or 'Stop' signal will be exhibited immediately thereafter and such vehicular traffic shall not enter or be crossing the intersection when the red or 'Stop' signal is exhibited.

Most of the traffic ordinances throughout the United States that we have seen have followed this definition with slight variations such as the omission of the phrase "or be crossing (the intersection). . . ." Some ordinances make an attempt to provide an operational definition of the meaning of the amber signal with definite instructions to the driver on how to behave. A typical example of such an ordinance is the following:

Vehicular traffic facing the signal shall stop before entering the nearest crosswalk at the intersection, but if such stop cannot be made in safety, a vehicle may be driven cautiously through the intersection.

Both definitions, of course, assume that the signal has been designed properly so that the driver can behave as directed and in general can solve the decision problems he encounters. It is interesting to note that the *Manual on Uniform Traffic Control Devices for Streets and Highways*[4] makes the following statement:

Confusion has frequently arisen from the misuse of this yellow lens. When the length of yellow vehicle-clearance interval is correct, and the standard meaning above described† is generally observed, necessary functions of warning and clearing the intersection are performed by this interval.

This is a reasonable statement to which we, of course, subscribe. Our investigations show, however, that out of approximately 70 intersections studied, only one had an amber phase long enough to prevent an appreciable dilemma zone, i.e., a zone longer than about one car-length, if one assumes a 'comfortable' deceleration of $\frac{1}{3}\,g$ and a decision and reaction time-lag equal to our measured average of 1.14 sec. Even if one assumes the very large deceleration of $\frac{1}{2}\,g$ and a decision-reaction time lag of 0.75 sec, only four out of the 16 typical intersections of Table I yield a dilemma zone smaller than one car-length. Out of these four, one, namely the sixth zone in Table I, gives no dilemma zone at all and is the only such intersection observed in the area.

The fact that almost all the intersections have sizeable dilemma zones is reflected in the data of Table III, which indicate that at the intersections studied as many as two cars went through the red light per light cycle, with an average of close to one car per cycle. It is true that in none of the observed cases did there appear to be any distinct possibility of an accident. However, the fact remains that an average of eleven out of every thousand cars were very much in the middle of the intersection when the red signal started, in violation of the *Uniform Vehicle Code*. This leaves them open to the possibility of receiving a traffic citation from an assiduous police officer. We might mention here that we were rather surprised to discover a traffic ordinance that made no distinction whatsoever between the yellow and red lights. The instruction regarding both was that "Vehicular traffic facing the signal shall stop before entering the nearest crosswalk at the intersection," a requirement which is clearly impossible to obey under many circumstances. It is interesting to note that in a state-issued driver-instruction pamphlet we again find that the amber and red lights are inter-

† The standard meaning referred to is precisely that quoted above as due to the *Uniform Vehicle Code* of the National Committee on Uniform Traffic Laws and Ordinances.[4]

preted alike without regard to the operational problems considered here. The same pamphlet instructs the drivers to "... drive a reasonable speed which will allow me to stop when the amber light comes on." The analysis given in this paper clearly shows that even reduction of speed and defensive driving when approaching an intersection does not necessarily eliminate the dilemma zone problem if the amber phase is inadequate.

The problem of determining the proper duration of the amber phase of the light cycle is perhaps more difficult and complicated than may appear at first sight. In this connection we quote MATSON, SMITH, AND HURD:[1] "In urban areas where speeds are relatively low, yellow lights of about 3-sec duration are satisfactory at most locations. At rural, high-speed locations where stopping time may have a duration of 5 to 8 sec, road users tend to attempt to clear the intersection rather than stop. Five seconds is probably a practical maximum yellow duration in such location."

We are aware of the fact that traffic engineers are inclined to shorten the amber phase for various reasons. One of them, probably one of the most important ones, is their conviction, undoubtedly substantiated, that drivers are inclined to ignore a long amber phase and treat it as merely a continuation of the green phase. They believe that as many drivers, if not more, will go through the red light when the amber phase is too long, as will do so if it is too short. However, we believe that it is the duty of the traffic engineers and the drafters of traffic ordinances to present the average, honest, driver with a solvable decision problem. As it stands now, a driver who is in the middle of an intersection when the red light comes on may not be a deliberate violator, but may be the victim of an improperly designed light cycle. It is true that accidents are in general prevented because of some delay of approach of the cross traffic and also by the judicious use of overlapping red cycles. This fact, however, does not release the unwilling violator from the legal responsibility which may become alarming in the case of an accident. On the other hand, with an adequate amber phase it would be easier to separate the violators from the nonviolators, insofar as traffic is concerned.

We believe that a correct resolution of this problem may be found in one of the following alternatives:

1. Design the amber-light phase according to some realistic criteria in order to guarantee that a driver can always be in a position to obey the law.
2. If the amber-light phases are to be kept short relative to criteria such as determined herein, it may be desirable to state the vehicle code in such a way as to make it compatible with the driver, car, road, and signal characteristics.

In either case it would be very advisable to educate both the driving public and the law-enforcing agencies as to the exact operational definition of the amber light. Needless to say, the fewer the variations of traffic ordinances in this respect, from one locality to another, the fewer the chances of confusion. We wish to re-emphasize our hope that a well-thought-out and operationally sound traffic and enforcement system, together with the healthy driver attitudes of a properly educated public, will promote safer and more efficient driving conditions.

ACKNOWLEDGMENTS

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REFERENCES

1. T. M. Matson, W. S. Smith, and F. W. Hurd, *Traffic Engineering*, McGraw-Hill Book Company, Inc., 1955, p. 326.
2. *Traffic Engineering Handbook*, edited by Henry K. Evans, Institute of Traffic Engineers, New Haven, 1950.
3. *Uniform Vehicle Code*, National Committee on Uniform Traffic Laws and Ordinances, Washington, D. C., 1956, p. 100.
4. *Manual on Uniform Traffic Control Devices for Streets and Highways*, Public Roads Administration, Washington, D. C., 1948, p. 107; *see also* the 1954 Revisions to this Manual, p. 6.

Red Clearance Interval. The red clearance interval is an optional interval that follows a yellow change interval and precedes the next conflicting green interval. The red clearance interval is used to provide additional time following the yellow change interval before conflicting traffic is released.

MUTCD states that the red clearance interval should not exceed 6 sec.[18] The appropriate red time for the approach should be calculated using the following formula found in ITE's *Determining Vehicle Signal Change and Clearance Intervals*:[19]

$$R = (w+L)/v$$

where
R = all red interval (sec.)
w = width of stop line to far side no-conflict point (ft.)
v = design speed (ft./sec.)
L = length of vehicle (typically 20 ft.)

For exclusive turn movements, the value of w should be measured along the vehicle turn path from the stop line to the no-conflict point.

The decision to use a red clearance interval is determined by intersection geometrics, crash experience, pedestrian activity, approach speeds, local practices and engineering judgment.

6. Left Turns

Three operational modes are available when provisions for left turns are made in the phasing of a traffic control signal:

1. **Permissive (permitted) mode only**—in which drivers may turn left after yielding to conflicting traffic or pedestrians during the circular green indication, along with the parallel through movements. A separate left-turn lane is often provided but not required. No regulatory sign is required, but an informational sign may be used.

2. **Protected (exclusive) mode only**—during which left turns are permitted only when a left green arrow is displayed. There is no conflicting vehicular or pedestrian traffic. Typically, a separate left-turn lane is provided. If the left-turn movement occurs when the adjacent through movement is shown a circular red indication, a separate left-turn lane must be provided.

   A separate left-turn signal face must be used where the signal sequence does not provide for the simultaneous movement of the parallel through traffic. The change interval display may consist of either a yellow left arrow or a circular yellow. The yellow indication must match the green indication; that is, if the separate left-turn face provides a circular green, a circular yellow is provided. If the separate left-turn signal face provides a green left arrow, the yellow indication must be a left arrow. MUTCD requires that all green arrow indications must be followed by yellow arrow indications. The red interval may use a red arrow only if a yellow arrow indication is used. Otherwise, a circular red is required.

   When a separate signal face is used, it should be positioned in line with the turning movement approach. A left-turn signal sign (R10-10) is required unless the signal face consists of arrows only or unless it is properly hooded, shielded, or louvered to ensure that conflicting circular yellow or red indications are not readily visible to motorists in the through lanes.

3. **Protected/permissive (exclusive/permitted) mode**—a combination of both the protected and the permissive modes whereby left turns may be made during the green display as defined under the respective modes. Green and yellow arrow indications are required for this type of operation.

   The controller phasing for protected/permissive mode is the most complicated of the three modes in that it combines the other two modes. Four distinct controller-phasing schemes are commonly employed:

- lead-left turn with parallel, non-conflicting through traffic;
- simultaneous lead-left turns with no parallel through traffic;
- lag-left turn with parallel, non-conflicting through traffic; and
- simultaneous lag-left turns with no parallel through traffic.

a head start or the pedestrians can be held until the initial queue of vehicles has been served. However, such controller phasing may have a detrimental effect on vehicle flow and, if part of a system, on system capacity.

The goals of traffic safety and traffic capacity must be balanced when determining controller phasing for an intersection. The following section describes the various components of controller phasing. More in-depth discussion can be found in the *Manual of Traffic Signal Design* and *Signalized Intersections: Informational Guide*.[14,15]

Green Interval. Ideally, the length of the green display on each approach to an intersection will be sufficient—but not excessive—to serve all the vehicles and pedestrians queued during the red interval. Several PC-based computer programs are available to assist in determining the green interval timing.

For semi- or fully-actuated controllers, a minimum and maximum amount of green time must be determined and allocated for each phase and programmed into the controller. These values are derived from the analysis results of the timing software or other method of analysis used by the designer.

For pre-timed signal controllers, the length of the green display is based on engineering judgment. Traffic and pedestrian counts for a specific period of time are often used in determining the signal timing.

Yellow Change Interval. The purpose of the yellow change interval, which is required to be the first interval following every circular green or green arrow indication, is to warn approaching traffic of the termination of the related green interval or that a red signal indication will follow (see "Vehicle Detector Placement").

MUTCD states that yellow change intervals should have duration of 3 to 6 sec.[16] To determine the appropriate yellow time for the approach, this should be calculated using the Kinematic Model—Formula 1 found in ITE's *Determining Vehicle Signal Change and Clearance Intervals*:[17]

$$Y = t + [v/(2a+2Gg)]$$

where:
Y = yellow clearance interval (sec)
t = reaction time (typically 1 sec.)
v = design speed (ft./sec.)
a = deceleration rate (typically 10 ft./sec.^{2})
g = acceleration due to gravity (32.2 ft./sec.^{2})
G = grade of approach (percent/100, downhill is negative grade)

The equation shown above includes a reaction time, a deceleration element and an intersection clearing time. In view of the operational history of the yellow change interval and the assumptions used in the formula, applying the formula requires the exercise of engineering judgment.

Because a long yellow change interval may encourage drivers to use it as a part of the green interval, maximum care should be used when exceeding 5 sec. If the interval is too short, rear-end crashes may result. When the calculation for yellow change interval time indicates a time longer than 5 sec., a red clearance interval typically provides the additional time.

Some jurisdictions time the yellow change interval to enable a vehicle to clear the intersection before the onset of a conflicting green display. Other jurisdictions allow a conflicting green display to be shown before the intersection is cleared. Still others allow a conflicting green display to be shown after the vehicles have cleared the center line of the conflicting approach. Engineering judgment should be exercised in selecting the operation of the yellow change interval to ensure safe passage of vehicles in the intersection.

As can be seen from the formula above, slower speeds result in higher values of yellow clearance time. When calculating the needed time, consideration should be given to the values for the 15th-percentile speed, particularly at wider intersections.

The calculations for steep downgrades will yield values that some drivers may consider excessive. Simply reducing the interval times may create dangerous operating conditions. The engineer should consider lowering the approach speeds by reducing the speed limit or by the use of a warning beacon or other measures.

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03 **Except as provided in Paragraph 4, the pedestrian signal heads shall continue to display a steady UPRAISED HAND (symbolizing DONT WALK) signal indication when the pedestrian hybrid beacon faces are either dark or displaying flashing or steady CIRCULAR yellow signal indications. The pedestrian signal heads shall display a WALKING PERSON (symbolizing WALK) signal indication when the pedestrian hybrid beacon faces are displaying steady CIRCULAR RED signal indications. The pedestrian signal heads shall display a flashing UPRAISED HAND (symbolizing DONT WALK) signal indication when the pedestrian hybrid beacon faces are displaying alternating flashing CIRCULAR RED signal indications. Upon termination of the pedestrian clearance interval, the pedestrian signal heads shall revert to a steady UPRAISED HAND (symbolizing DONT WALK) signal indication.**

Option:

04 Where the pedestrian hybrid beacon is installed adjacent to a roundabout to facilitate crossings by pedestrians with visual disabilities and an engineering study determines that pedestrians without visual disabilities can be allowed to cross the roadway without actuating the pedestrian hybrid beacon, the pedestrian signal heads may be dark (not illuminated) when the pedestrian hybrid beacon faces are dark.

Guidance:

05 *The duration of the flashing yellow interval should be determined by engineering judgment.*

Standard:

06 **The duration of the steady yellow change interval shall be determined using engineering practices.**

Guidance:

07 *The steady yellow interval should have a minimum duration of 3 seconds and a maximum duration of 6 seconds (see Section 4D.26). The longer intervals should be reserved for use on approaches with higher speeds.*

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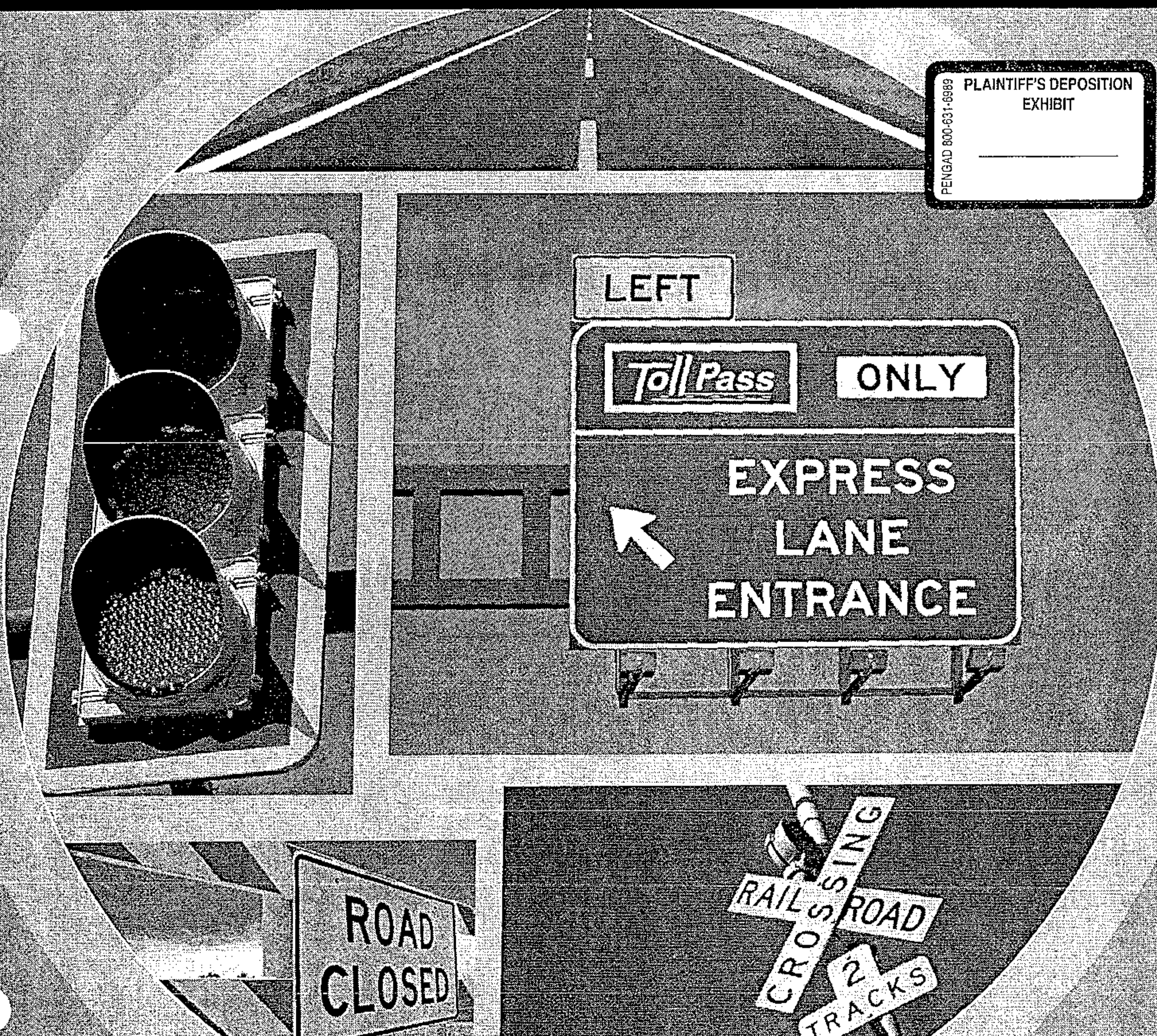

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