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 not know physics. They are playing with algebra without knowing its physical implications.

The "2" in the denominator disqualifies the formula as an equation of motion. That means trouble. (I'll describe what trouble later.) And so to bring my February 2010 Derivation paper rapidly to a close, I simply let my paper end with "*The formula is not an equation of motion*." A physicist understands the implications of that in 15 seconds. ITE, IIHS and VHB did not understand.

The Insurance Institute of Highway Safety (IIHS) reviewed by February 2010 *Derivation* paper. IIHS made the same mistakes as ITE and VHB. This is when I realized that *traffic engineers do not know the fundamental concepts of physics*. How can engineers get to be engineers without knowing the fundamentals? The very definition of engineering in Merriam-Webster's dictionary is "applied physics." Get the physics wrong and you get the engineering wrong.

And so I published a new version of the *Derivation of the Yellow Light Equation* in August 2010. This version did not start with the premise that the traffic engineers *meant* for the yellow interval to be equal to the time needed for a vehicle to stop. This version started out with the fact that traffic engineers *purposed* to use an equation which violates the laws of the universe. And since traffic engineers demonstrated that they do not know what makes physics physics, the new version began with a basic lesson on equations of motion. I described why equations of motion are called equations of motion and what happens when one tries to describe moving objects with equations which are not equations of motion.

In order to refute the engineer's defense, "But the math works", I responded, "The math works for the math, but not for the physical situation which the math is supposed to represent." I used Copernicus' model that planets orbit in circles around the Sun. While Copernicus' math for circles worked for circles, it didn't work for planets because planets do not travel in circles but rather in ellipses. The math works but the math does not apply to the physical reality of planets.

Also in the August 2010 edition of *Derivation*, I identified one of the formula's flaws: The formula makes drivers guess whether to stop or go. Traffic engineers know of this problem and label it the outcome of drivers being in an *indecision zone (aka, type II dilemma zone).* Engineers know about the problem and have a label for it, but do not realize that their own formula creates it. To engineers it is a mystery why the indecision zone exists. Engineers blame it on aberrant human behavior. To physicists it is obvious why the indecision zone exists: *the formula is not an equation of motion* and no amount of human behavior can adapt to an equation which is not an equation of motion.

After August 2010, it took me a whole year to identify the second problem. This problem was far worse than the first. The second problem is a set of nasty problems inflicted upon the driver, each problem a game of Russian roulette. I identified that *the formula forbids any driver to decelerate for any reason before entering the intersection.* The act of decelerating before entering the intersection exhausts the yellow time. According to the formula, drivers who are too close to stop safely must proceed to the intersection at the maximum allowable speed. <u>At the maximum allowable speed!</u> The formula does not apply to a driver who must decelerate under the maximum allowable speed while approaching an intersection showing a yellow light.

Therefore the formula forces many types of drivers to run red lights including these: Turning drivers, drivers at two close-by intersections, drivers at intersections near business entrances, drivers at intersections with railroad tracks and defensive drivers. Turning drivers have to slow down to execute a turn. Drivers approaching a yellow light at one intersection have to slow down for the red light at the next nearby signal. Defensive drivers slow down to make sure the coast is clear. Think of any situation where you have to slow down before entering the intersection. In such a situation, the formula will set you up to run a red light.

As for defensive drivers, Julie O'Conner an attorney in Phoenix who handles red light camera cases all over Arizona told me that over 80% of the red light camera tickets go to senior citizens. That is not because seniors are slower in reacting to yellow lights. Seniors simply slow down when they see a yellow light. The formula penalizes that kind of behavior.

Traffic engineers know about this problem as well. They label it *a type I dilemma zone.* Drivers who decelerate and enter the intersection suffer the same fate as drivers subjected to yellow interval shorter than the formula. They have no choice but to run a red light. A type I dilemma zone is a region on the road where if a driver is in it when the light turns yellow, the situation will force the driver to run a red light no matter what decision the driver makes. There is not enough distance to stop. There is not enough time to proceed legally without running a red light. *A type I dilemma zone is another result of the formula not being an equation of motion.*

What applies to indecision zones also applies to type I dilemma zones. Engineers know about the problem but do not realize that their own formula creates it.

B. VHB: "The equation is based on the work by Gazis . . . while minimizing the dilemma zone."

BC: VHB and Gazis admit the existence of the dilemma zone. Both confess that the formula causes problems which have to be "minimized." Gazis at least understood that the engineer is the party responsible for creating the dilemma zone which forces drivers to run red lights. Gazis called red light runners entrapped by a dilemma zone "non-violators."

I have no problem with Gazis. Gazis said that his own formula works only for the straight-movement driver who can proceed to the intersection unimpeded. Gazis explicitly said in his own paper that his formula does not work for turning drivers or drivers at two close-by intersections.

VHB, IIHS and every traffic engineer I have talked to never read Gazis' paper closely.   Yet even in the absence of Gazis' paper, VHB, IIHS and traffic engineers are without excuse. Every engineer must understand physics to know that the formula is not an equation of motion and because of that, the formula has unforgiveable consequences.   The requisites for equations of motion have been explicitly quantified since 1687.   Any college freshman physics student knows them.   Traffic engineers do not. Engineering by definition is applied physics.   Get the physics wrong and the engineer *malpractices* his profession. Let me put traffic engineers on notice.   You are committing malpractice. This malpractice has become the bread and butter of red light camera companies.

VHB: "The derivation of the equation . . . [in Gazis' paper] . . ."

BC: Gazis does not derive the equation.   Gazis' starting point for his derivation of the yellow light equation is $v^2/2a$, the braking distance.   Gazis does not show the derivation of the braking distance and Gazis does not include grade in his version of the formula.

C. VHB: "Millions of vehicles travel on our nation's roadways every day at signalized intersections with yellow interval based on the kinematic equation."

BC: VHB offers this as proof of the success of the formula. But the simultaneous existence of the continuous profitability of red light camera companies, 100,000 injuries per year and 1000 deaths on our nation's highways are the proof that formula is not a success but a rampant failure. While about 98% of drivers can make it through a signal cycle without running a red light, 2% cannot.   As opposed to VHB, IIHS and the consensus of traffic engineers, I do not call a game of Russian roulette a success.   The "kinematic equation" is not an equation of *motion* and therefore the word "kinematic" is fraudulent physics.

D. VHB: "The kinematic equation used to determine yellow change intervals is based on a sound application of equations of motion."

   BC: A false statement. One can say that the kinematic equation is based on equations of motion but not a sound application of equations of motion. The formula is by definition a misapplication of the laws of physics. By mixing the physical properties of two disparate objects (braking and non-braking cars) into one equation, the equation does not fully apply to either.

E. VHB quoting BC: "I searched the internet for a derivation [of the equation], but I found none . . . . Not even the engineering books bother to show a derivation. Every book and website take the equation for granted and assume it is correct."

   VHB: "The widely-accepted kinematic equation suggested for determining yellow change intervals first appeared in the third edition of the Traffic Engineering Handbook is based on formative work by Gazis, et al. Their derivation presented in the paper is the foundation for the kinematic equation method suggested by ITE for the past 45 years."

   BC: VHB doesn't want to admit they have never seen a full derivation besides mine. As for what VHB said, I already knew that.

   I still have the only full derivation on the internet. Still no book bothers to show a derivation of the entire formula. No publication other than my own shows in *full detail* where the entire formula comes from.

   Gazis' starting point is the braking distance. That is not where a physicist would begin and that is what originally through me off. A physicist sees the need to compute a time, not a distance. The first step Gazis took is off a cliff. Nonetheless in my paper I derive the braking distance from the laws of motion.

In 1982 ITE added the acceleration due to the Earth's gravity by grade term (Gg) to Gazis' formula. No publication shows where Gg comes from. I derived Gg and put that in my paper. It comes from an application of F = ma and a small angle approximation.

F. VHB quoting BC: "The creators of the official equation erroneously divided both sides of the braking distance equation by the speed limit."

   BC: I thought that and I still think that. It is true. Dividing both sides of the braking distance equation by the speed limit is an error. I thought that because my original thesis was that "Who in their right mind would set the yellow interval to the time it takes a driver to *go*?" Red means stop. Yellow only exists for red. Therefore yellow should mean stop, not go. Therefore you don't divide by the speed limit.

G. VHB quoting BC: "Apparently ITE's focus was on cars going through the intersection, not cars stopping at the intersection."

   VHB: Gazis does both.

   BC: Gazis does "stop". Gazis does "go the speed limit". Gazis does not do decelerate and enter. There are cases 1, 2 and 3. All are equally important. Gazis does 1 and 2 only. ITE applies Gazis to 3 but Gazis says one cannot apply the formula to 3.

   Gazis' formula comes with utopic preconditions and assumptions. Even Gazis admitted this right at the beginning of his paper. As for stopping, the formula gives the driver who is farther from the intersection than the critical distance the mandate to stop, assuming the driver knows within an inch where the critical distance is from the intersection. As for going, the formula gives the driver who is closer than the critical distance from the intersection the mandate to go, assuming the driver knows within an inch where the critical distance is from the intersection, and understands that he must proceed to the intersection at the speed limit unimpeded by other cars or objects, whether that is possible or not.

The formula does not handle drivers who must slow down before entering the intersection. Turning drivers, defensive drivers, drivers approaching intersections close to other intersections, drivers approaching intersections close to business entrances, drivers approaching intersections with potholes, drivers approaching intersections with railroad tracks, drivers slowing down for cars in front of them . . . all these people are victimized by the formula. The formula forces all these drivers to run red lights.

H. VHB: "In the state of North Carolina, yellow change intervals must be timed according to the traffic signal plan designed by the professional engineer. The designing engineer is not required to use the kinematic equation suggested by ITE and may determine the variables applied in the equation or the full change interval based on engineering judgment. . . . SL 2004-141

BC: Incorrect.

A signed and sealed plan must meet the requirements of the NCDOT's "Guidelines for the Preparation of Traffic Signal & Intelligent Transportation System Plans on Design-Build Projects," 2009, p. 3. One of the requirements in that Guide is adherence to the *NCDOT Intelligent Transportation and Signal Systems [ITSS] Unit Design Manual* (page 1). This ITSS Unit Design Manual contains Spec 5.2.2 which is the same kinematic equation as in the old NCDOT Design Manual referenced by SL 2001-286. Therefore a traffic engineer must adhere to the kinematic formula because it is in the Design Manual and both session laws directly or indirectly point to it.

And if the traffic engineer doesn't adhere to that kinematic formula and his signal plan sets a time lower than the kinematic formula, then he violates the laws of physics for what little physics the kinematic equation does cover. A yellow value set less than the kinematic formula disables the driver's ability to stop safely from the legally posted speed. The engineer entraps the driver with a speed limit sign.

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Institute of Transportation Engineers
1627 Eye Street, NW, Suite 600 | Washington, DC 20006 USA
Telephone: +1 202-785-0060 | Fax: +1 202-785-0609
ite_staff@ite.org

ITE Canon of Ethics

EAM

Response to Isaac Newton vs. Red Light Cameras: Derivation of Yellow Interval Equation

Prepared For:

Institute of Transportation Engineers

Prepared By:

Vanasse Hangen Brustlin, Inc.

Kimberly Eccles, P.E.

Hugh McGee, Ph.D., P.E.

Mindy Liu

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Executive Summary

The function of a traffic signal is to alternate the right-of-way among the various traffic movements. This function must be accomplished safely while minimizing the delay to vehicles and pedestrians and maximizing the capacity of the intersection. Vital to accomplishing these objectives is the yellow change interval. The steady yellow signal indication warns vehicle traffic that the related green movement is being terminated and that a red indication will be displayed immediately thereafter.

In many jurisdictions, the yellow change interval is followed by a red clearance interval. During this red clearance interval, the red signal indication is displayed to all traffic. It provides additional time, typically 1 to 3 seconds, before the conflicting traffic is given a green indication (or a 'walk' indication in the case of pedestrian traffic). This red clearance interval is provided as a safety measure to prevent angle crashes by allowing any vehicle that may have entered the intersection during the yellow interval to clear the intersection.

The *Manual on Uniform Traffic Control Devices (MUTCD)* is published by the Federal Highway Administration. It is the national standard for traffic control devices on any road open to public travel. The *MUTCD* is used to provide consistent application of traffic control devices. Section 4D.26 of the 2009 edition of the *MUTCD* addresses the yellow change interval. Under Standard' (a shall requirement) it states "The duration of the yellow change interval shall be determined using engineering practices." It provides Guidance (a should recommendation) that,in part states: "A yellow change interval should have a minimum duration of 3 seconds and a maximum duration of 6 seconds." Under Support (informational only statements) the following is stated: "engineering practices for determining the duration of the yellow change and red clearance intervals can be found in ITE's [Institute of Transportation Engineers] *Traffic Control Devices Handbook* and in ITE's *Manual of Traffic Signal Design."* Both of these ITE publications suggest applying a form of a kinematic equation for determining change intervals.

In February 2010, Brian Ceccarelli disseminated a report "Issac Newton vs. Red Light Cameras" disputing the calculation of the yellow change interval at traffic signals using the kinematic equation. This memorandum summarizes a response Mr. Ceccarelli's report.

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Mr. Ceccarelli's general thesis is that the yellow interval duration calculated using the kinematic equation supported by ITE is not long enough for vehicles to stop at the onset of yellow. 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. Mr. Ceccarelli also questions the grade variable applied in the kinematic equation and the duration of yellow change intervals in the state of North Carolina and other locations that use the kinematic equation.

To respond to Mr. Ceccarelli's report, the following is offered in support of applying the kinematic equation for determining yellow change intervals:

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- The kinematic equation suggested for determining yellow change intervals first appeared in the third edition of the ITE *Traffic Engineering Handbook*, published in 1965. The equation is based on work by Gazis, Herman, and Maradudin. The derivation of the equation considers both the vehicle that stops before the intersection and the vehicle that continues through the intersection, while minimizing the dilemma zone.
- The duration of the yellow change intervals is not the time to traverse the braking C stopping distance. The vehicle does not need to be stopped by the end of the yellow change interval. For the stopping vehicle, the important element is that the stopping distance is sufficient.
- The kinematic equation for determining yellow change intervals determines the minimum yellow change interval that considers the needs of both of the stopping vehicle and the vehicles that goes through the intersection.
- The modification for grade is based on the standard formula for stopping distance on a grade.
- In the state of North Carolina, yellow change intervals must be timed according to the traffic signal plan designed by the professional engineer. The designing engineer is not required to use the kinematic equation suggested by ITE and may determine the variables applied in the equation or the full change interval based on engineering judgment.

D Millions of vehicles travel on our nation's roadways every day at signalized intersections with yellow intervals based on the kinematic equation. They are able to do this without any unusual maneuvers. The kinematic equation used to determine yellow change intervals is based on a E sound application of equations of motion. The traffic engineering profession continues to confirm the assumed parameters used in the equation based on the best available research to ensure that intersections are timed to safely and effectively accommodate the nation's traffic.

Background

The function of a traffic signal is to alternate the right-of-way among the various traffic movements. This function must be accomplished safely while minimizing the delay to vehicles and pedestrians and maximizing the capacity of the intersection. Vital to accomplishing these objectives is the yellow change interval. The steady yellow signal indication warns vehicle traffic that the related green movement is being terminated and that a red indication will be displayed immediately thereafter. This yellow change interval normally has a duration of 3 to 6 seconds.

In many jurisdictions, the yellow change interval is followed by a red clearance interval. During this red clearance interval, the red signal indication is displayed to all traffic. It provides additional time, typically 1 to 3 seconds, before the conflicting traffic is given a green indication (or a 'walk' indication in the case of pedestrian traffic). This red clearance interval is provided as a safety measure to prevent angle crashes by allowing any vehicle that may have entered the intersection during the yellow interval to clear the intersection. The yellow interval and red clearance interval are often referred to collectively as the change period.

The *Manual on Uniform Traffic Control Devices (MUTCD)* is published by the Federal Highway Administration. It is accepted as the national standard for traffic control devices on any road open to public travel. The *MUTCD* is used to provide consistent application of traffic control devices. Section 4D.26 of the 2009 edition of the *MUTCD* addresses the yellow change interval through standards (a shall requirement), guidance (a recommendation but not required), and supporting information. As as a standard it states: "The duration of the yellow change interval shall be determined using engineering practices." It provides guidance that, "A yellow change interval should have a minimum duration of 3 seconds and a maximum duration of 6 seconds. The longer intervals should be reserved for use on approaches with higher speeds." It also supports that "engineering practices for determining the duration of the yellow change and red clearance intervals can be found in ITE's [Institute of Transportation Engineers]*Traffic Control Devices Handbook* and in ITE's *Manual of Traffic Signal Design* (see Section 1A.11)." Both of these ITE publications suggest applying a form of a kinematic equation for determining change intervals.

Several ITE publications include information on a kinematic equation that can be used to calculate change intervals. Agencies often refer to this equation as the "ITE Equation." The equation is based on the work of Gazis, Herman, and Maradudin. The calculated change interval allows time for the motorist upon seeing the yellow signal indication to decide whether to stop or enter the intersection. It allows time for motorists further away from the signal to decelerate comfortably and motorists closer to the signal to continue through to the far side of the intersection. Generally, the first two terms of this equation are used to calculate the yellow change interval, while the third term is used for calculation of the red clearance interval.

The most current edition of the *ITE Traffic Engineering Handbook, 6th Edition* provides Equation 1 and Equation 2 for calculating the yellow change and red clearance intervals, or change period:

$$Y = t + \frac{V}{2a + 2Gg} \qquad \text{[Equation 1]}$$

$$R = \frac{W + L}{V} \qquad \text{[Equation 2]}$$

Where:

- Y = yellow change interval, in seconds;
- t = perception-reaction time, nominally 1 second;
- a = deceleration rate, (ft/s^2, typical 10 ft/s^2)
- V = design speed, (ft/s);
- G = acceleration due to gravity, 32.2 ft/s^2;
- g = percent grade, positive for upgrade, negative for downgrade;
- R = red clearance interval, in seconds;
- W = width of intersection, curb to curb, in feet; and
- L = length of vehicle, typically 20 feet.

The history of the development of this equation is documented in *A History of the Yellow and All-Red Intervals for Traffic Signals*. This report, prepared for ITE, chronicles the history of the published guidelines and practices for determining the length of time for the display of the yellow change interval and the red clearance interval. As previously mentioned, this kinematic equation is based on the work of Gazis et al. and has been used in some form by the traffic engineering community for nearly 50 years.

Objective

In February 2010, Brian Ceccarelli disseminated a report "Issac Newton vs. Red Light Cameras" disputing the calculation of the yellow interval at traffic signals. Mr. Caccarelli believes that the kinematic equation used for determining yellow change intervals is in error and states that yellow change intervals in the state of North Carolina and other jurisdictions that apply the kinematic equation do not provide adequate change intervals. This memorandum summarizes a response to Mr. Ceccarelli's report. This memorandum first directly responds to Mr. Ceccarelli's general thesis. Second, it summarizes the derivation of the kinematic equation for determining yellow change intervals based on the work of Gazis et al. Third, it responds to specific statements made by Mr. Ceccarelli in his document.

Response to Ceccarelli's General Thesis

Mr. Ceccarelli's general thesis is that the yellow interval duration calculated using the ITE kinematic equation is not long enough for vehicles to stop at the onset of yellow. His thesis is that the yellow interval should be equal to the time needed for a braking vehicle to traverse the stopping distance. Mr. Ceccarelli has misunderstood the need of the stopping vehicle and the duration of the yellow interval. The duration of the yellow interval is not the time to traverse the stopping distance of a braking vehicle. For the stopping vehicle, the important element is not the amount of time that is needed to stop, but that there is sufficient distance in which to stop in

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advance of the stop bar at a comfortable deceleration. The calculated time of the yellow interval is used to determine that the vehicle has an adequate distance in which to stop. As the vehicle is stopping, the light may turn red. The signal indication at the time the vehicle comes to a complete stop has no bearing on the vehicle. This is explained in more detail in the next section of this memorandum.

Derivation of Kinematic Equation

The kinematic equation for determining change intervals is derived in the following manner, based on the work of Gazis et al.

At the onset of the yellow signal indication, a driver may decide to: a) decelerate and stop before the intersection, or b) continue through the intersection. Assuming that the stopping vehicles decelerate uniformly, the kinematic equations of motion apply to vehicles approaching the intersection. For this derivation, we assume two vehicles approaching an intersection (Figure 1):

- **Vehicle A** decelerates and stops before the intersection. Vehicle A is farther from the intersection and at a distance from the intersection where the vehicle is able to decelerate and stop but cannot continue through the intersection.
- **Vehicle B** continues through the intersection. Vehicle B is closer to the intersection and at a distance from the intersection where the vehicle is unable to decelerate and stop but able to continue through the intersection.

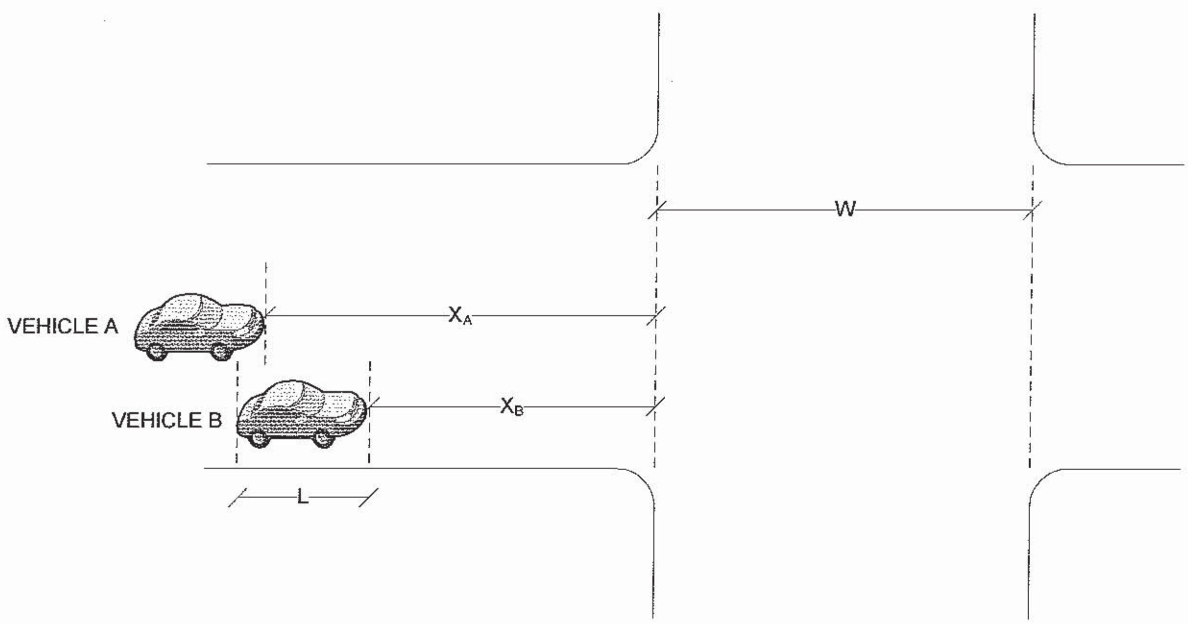

Figure 1

Vehicle A travels an initial speed, v_i, and decelerates at a constant rate of a to final speed, v_f. Applying a kinematic equation (Equation 3), the stopping distance, s, shown in Equation 4.

$$v_f^2 = v_i^2 + 2as \qquad \text{[Equation 3]}$$

Setting $v_f = 0\ mph$ and solving for s

$$0 = v_i^2 + 2as$$

$$s = \frac{V_i^2}{2a} \qquad \text{[Equation 4]}$$

Taking into account that the driver of Vehicle A has a perception-reaction time, δ, the minimum distance a vehicle must be from the intersection if they are to stop before the intersection is shown in Equation 5, where the first term is the stopping distance and the second term is the distance traveled while the driver perceives and reacts to the yellow signal indication.

$$X_A \geq \frac{V_i^2}{2a} + V_i\delta \qquad \text{[Equation 5]}$$

Since X_A is a minimum distance, all vehicles that are at a distance greater than X_A should be able to stop before the intersection, and all vehicles less than X_A should continue through the intersection, assuming they have the same deceleration rate and approach speed. Vehicles that continue through the intersection are represented by Vehicle B in Figure 1 and are at a distance, X_B, from the intersection. The "stop" and "go through" areas are shown in Figure 2. The minimum time, t_{min}, needed to travel at uniform velocity, V_i, the distance, X_B, to and through

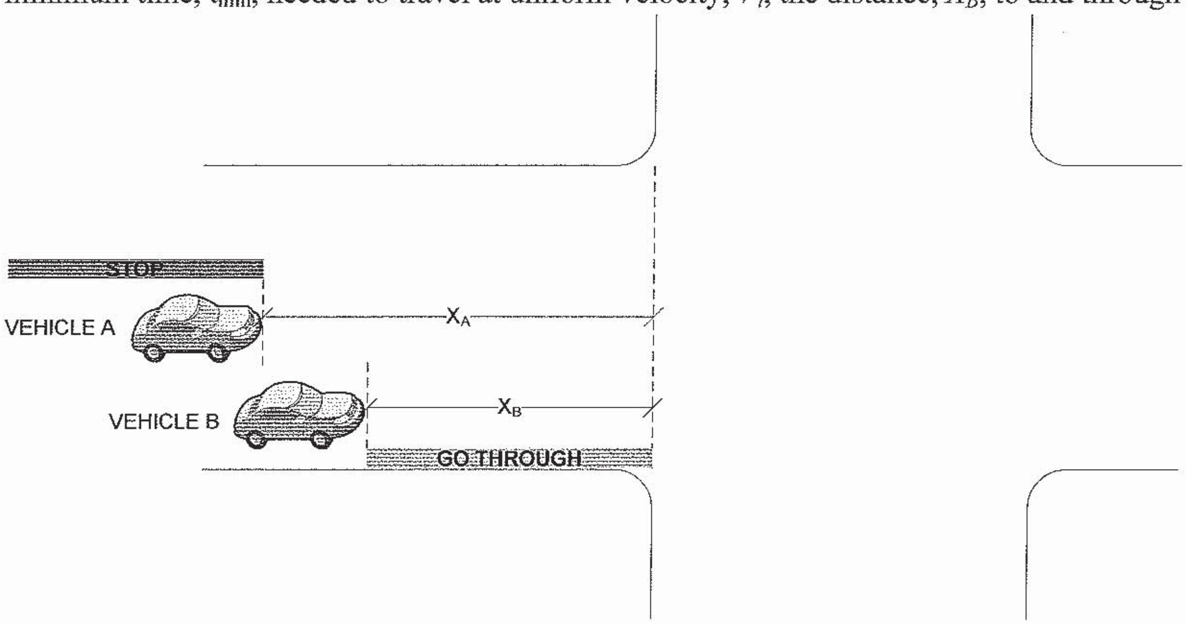

Figure 2

the intersection of width, W, for a vehicle with length, L, can be calculated as follows based on a kinematic equation (Equation 6):

$$t = \frac{d}{v} \qquad \text{[Equation 6]}$$

Where:

t = time
d = distance
v = speed

$$t_{min} = \frac{X_B + W + L}{V_i} \qquad \text{[Equation 7]}$$

The driver also has a perception-reaction time, but during that time, they are still traveling at speed, V_i, towards their goal of the far side of the intersection. Therefore, Equation 7 has only one term.

For all points closer than the distance X_A from the intersection, vehicles will continue through the intersection. The resulting minimum yellow interval needed so that no vehicles find themselves in the situation where they are too close to the intersection to stop safely (distances less than X_A from the intersection), but without enough time to get through the intersection safely is $\tau_{\min}$. In order to find that time, $\tau_{\min}$, we set X_B equal to X_A. If X_B is greater than X_A, a dilemma zone is created. Setting $X_A = X_B$, the resulting $\tau_{\min}$ is shown in Equation 8.

$$X_A = X_B$$

$$\frac{V_i^2}{2a} + V_i\delta = \tau_{\min} V_i - (W + L)$$

$$\tau_{\min} = \frac{V_i}{2a} + \delta + \frac{W + L}{V_i} \qquad \text{[Equation 8]}$$

Gazis et al. describes this time as the minimum yellow interval needed. Yellow change intervals less than this value will either necessitate that vehicles decelerate to a stop unsafely and uncomfortably or that vehicles are still in the intersection after the yellow interval ends.

The Gazis derivation did not consider the roadway grade along the approach to the intersection. If the grade is positive (uphill), the stopping distance will be shorter and if it is negative then a longer stopping distance will be needed. The ITE *Manual of Traffic Signal Design* introduces an additional parameter to accommodate the effects of approach grade. Based on the standard formula for stopping distance on a grade, a modified coefficient of friction is added to the first term in Equation 8. The yellow change interval becomes:

$$\tau_{\min} = \frac{V_i}{2a + 64.4g} + \delta + \frac{W + L}{V_i} \qquad \text{[Equation 9]}$$

Where:

g = percent of grade divided by 100 (positive for upgrade, negative for downgrade)

The *Manual of Traffic Signal Design* notes that for very steep downgrades, the equation results in excessively long yellow change intervals, which may be remedied by reducing the speed limit, and thus the approach speed, using warning signs, or other similar measures.

Response to Specific Statements

Mr. Ceccarelli's statements and corresponding responses are as follows:

Statement: *"I searched the internet for a derivation [of the equation], but I found none... Not even the engineering books bother to show a derivation. Every book and website take the equation for granted and assume it is correct."*

Response: The widely-accepted kinematic equation suggested for determining yellow change intervals first appeared in the third edition of the Institute of Transportation Engineers (ITE) *Traffic Engineering Handbook*, published in 1965. Prior to 1965, the ITE suggested determining the change interval based on the stopping distance and intersection width.

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The equation and procedure presented by ITE in the third edition of the *Traffic Engineering Handbook* is based on formative work by Gazis et al. Their paper is one of the first published studies on change intervals and presents a theoretical analysis and observational study of driver behavior in reaction to the yellow signal indication. The derivation presented in the paper is the foundation for the kinematic equation method suggested by ITE for the past 45 years. A simplified summary of this derivation has also been presented in this memorandum. For a thorough history of the determination of change intervals in the United States, refer to ITE's report, "A History of the Yellow and All-Red Intervals for Traffic Signals."

Statement: *"While the distance equation is right, the way the NCDOT and ITE computed how much time it takes for the driver to travel the distance is wrong."*

Response: Mr. Ceccarelli mistakenly assumes that the yellow change interval should be equal to the time needed for a braking vehicle to traverse the stopping distance. For the stopping vehicle, the important element is not the time needed to stop, but the stopping distance. For the vehicle that continues through the intersection, the important element is that there is sufficient time to clear the intersection (or in the case of permissive laws, for the vehicle to enter the intersection and then clear the intersection during red). The kinematic equation for determining yellow change intervals determines the minimum time that considers both vehicles. The

A

calculated change interval allows a driver to either stop or go through the intersection without accelerating. This minimum time is calculated by setting the critical distance for stopping equal to the maximum distance for clearing the intersection. In the theoretical case, this equation eliminates the dilemma zone (i.e., do you go or do you stop).

The yellow change interval, by definition, warns traffic of an impending change in the right-of-way. It allows drivers to decide to either stop or go through the intersection. The duration of the yellow change intervals is not the time to traverse the braking stopping distance. For Vehicle A in Figure 1, the important element is not the amount of time that is needed to stop, but that there is sufficient distance in which to stop. The vehicle does not need to be stopped by the end of the yellow change interval as long as they are able to comfortably stop before entering the intersection.

Statement: *"The creators of the official equation erroneously divided both sides of the braking distance equation by the speed limit (v_o)."*

G

Response: As shown in the derivation in Gazis et al. and in this memorandum, the kinematic equation considers the minimum distance from the intersection for the vehicle that stops (Vehicle A) and the maximum distance for the vehicle that goes through the intersection (Vehicle B). The equation does not determine the time required to traverse the braking stopping distance. Additionally, the speed variable typically represents the approach speed rather than the posted speed limit. The *Traffic Control Devices Handbook* refers to this speed as the 85th percentile approach speed, while the *Manual of Traffic Signal Design* suggests applying the approach speed.

Statement: *"Apparently ITE's focus was on cars going through the intersection, not cars stopping at the intersection."*

H

Response: The derivation by Gazis et al. and in this memorandum show that the kinematic equation considers the vehicle that stops (Vehicle A) and the vehicle that goes through the intersection (Vehicle B).

Statement: *"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."*

Response: The modification for grade is based on the standard formula for stopping distance on a grade. Grades are generally not larger than 3% on an approach and rarely is an approach grade 10%. This modification accommodates the effect of upgrades and downgrades on the rate of deceleration. The *Manual of Traffic Signal Design* notes that for very steep downgrades, the equation results in excessively long yellow change intervals, which may be remedied by reducing the speed limit, and thus the approach speed, using warning signs, or other similar measures.

Statement: *"...I had discovered that my intersection's yellow light interval did not meet the minimum required by the NCDOT's equation."*

Response: In the state of North Carolina, yellow change intervals must be timed according to the traffic signal plan designed by the professional engineer. The designing engineer is not required to use the kinematic equation suggested by ITE and may determine the variables applied in the equation or the full change interval based on engineering judgment. Session Law 2004-141, Section G.S. 160A-300.2(e) states:

> "The duration of the yellow light change interval at intersections where traffic control photographic systems are in use shall be no less than the yellow light change interval duration on the traffic signal plan of record signed and sealed by a licensed North Carolina Professional Engineer in accordance with Chapter 89C of the General Statutes, and shall be in full conformance with the requirements of the Manual on Uniform Traffic Control Devices."

The yellow change interval must also conform to the requirements in the Manual on Uniform Traffic Control Devices (MUTCD). Section 4D.26 of the 2009 edition of the MUTCD states the following standard, which is "a statement of required, mandatory, or specifically prohibitive practice regarding a traffic control device":

> "The duration of the yellow change interval shall be determined using engineering practices."

The MUTCD also provides the following guidance, which is "a statement of recommended, but not mandatory, practice in typical situations, with deviations allowed if engineering judgment of engineering study indicates the deviation is appropriate":

> "A yellow change interval should have a minimum duration of 3 seconds and a maximum duration of 6 seconds. The longer intervals should be reserved for use on approaches with higher speeds."

The following is provided as additional support, "an informational statement that does not convey any degree of mandate, recommendation, authorization, prohibition, or enforceable condition":

> "Engineering practices for determining the yellow change and red clearance intervals can be found in ITE's 'Traffic Control Devices Handbook' and in ITE's 'Manual of Traffic Signal Design' (see Section 1A.11)."

Summary

D

In summary, millions of vehicles travel on our nation's roadways every day at signalized intersections with yellow intervals based on the kinematic equation. They are able to do this without any unusual maneuvers. The kinematic equation used to determine yellow change intervals is based on a sound application of equations of motion. The kinematic equation is a flexible and defensible method for calculating change intervals with the aim of allowing vehicles to safely and comfortably stop before the intersection or go through the intersection. However, the profession continues to confirm the assumed parameters used in the equation based on the best available research to ensure that intersections are timed to safely and effectively accommodate the nation's traffic. ITE is currently working on a proposed recommended practice for determining change intervals, and a separate, on-going change interval study through the National Highway Cooperative Research Program (NCHRP) will present new field studies on change intervals.

Glossary of Terms

15^{th} Percentile Speed – The speed at which 15 percent of the vehicles in a sample are traveling at or below.

85^{th} Percentile Speed – The speed at which 85 percent of the vehicles in a sample are traveling at or below.

95^{th} Percentile Speed – The speed at which 95 percent of the vehicles in a sample are traveling at or below.

All-Red Interval or All-Red Clearance Interval – An optional interval following the yellow interval and preceding the next conflicting green interval during which all traffic at an intersection view a red signal indication and are not permitted in the intersection.

Amber Light – A term describing the yellow signal indication.

Amber Light Phase – The duration of the yellow signal indication.

Approach Grade – The slope of the roadway at the entrance, or approach, to an intersection.

Approach Speed – The velocity of a vehicle approaching an intersection.

Change Interval – Refers to the period of time between conflicting green signal indications, may consist of a yellow interval only or a yellow and all-red interval.

Change Period – Refers to the period of time between conflicting green signal indications, may consist of a yellow interval only or a yellow and all-red interval.

Conflicting Traffic Movements – Traffic movements that if allowed into the intersection at the same time would intersect paths.

Cycle – One complete sequence of all traffic signal indications.

Dilemma Zone – An area in advance of the signal where, if a yellow interval duration is not long enough, vehicles in this area at the onset of yellow can neither stop safely and comfortably before the intersection nor continue through the intersection without accelerating before the onset of the red signal indication.

Green Interval – A period of time indicating that vehicles have the right-of-way.

Green Signal Indication – The illumination of the green traffic signal lens during which traffic movements facing the lens are permitted.

Interval – the part of a signal cycle during which signal indications do not change.

Kinematic Equation – An equation based on the aspects of motion apart from considerations of mass and force.

Non-Dilemma Change and Clearance Interval – Duration of the yellow and possibly all-red interval(s) that does not create a dilemma zone for approaching motorists. That is, all vehicles, depending on their distance from the intersection at the onset of the yellow interval can either stop safety and comfortably before the intersection or continue through the intersection without accelerating before conflicting traffic is released.

Perception-Reaction Time – The time needed for a motorist to see the signal indication (perception) and then begin executing the appropriate response (reaction).

Permissive Yellow Law – Describes local laws that allow vehicles to enter the intersection throughout the entire yellow interval, and be in the intersection during the red indication as long as they entered the intersection during the yellow interval.

Phase – The entire sequence of green, yellow and red intervals in a cycle assigned to an independent traffic movement or combination of movements.

Phase-Change Interval – Refers to the period of time between conflicting green signal indications. May consist of a yellow interval only or a yellow and an all-red interval.

Red Clearance Interval -- An optional interval following the yellow interval and preceding the next conflicting green interval during which all traffic at an intersection view a red signal indication and are not permitted in the intersection; allows time for vehicles who entered the intersection during the yellow interval to exit, or clear, the intersection.

Red Signal Indication – The illumination of the red traffic signal lens during which traffic movements facing the lens are not permitted to enter the intersection.

Restrictive Yellow Law – Describes local laws that do not allow vehicles to be in the intersection during the red indication, even if the entered the intersection during the yellow interval.

Right-of-Way – The precedence of passage of a traffic movement into an intersection over other traffic movements at an intersection.

Signal Timing – The distribution of a length of time (cycle) between traffic movements including the allocation of green, yellow and red indications for each movement.

Signal Indication – The illumination of a traffic signal lens.

Signal Lens—that part of the signal section that redirects the light coming directly from the light source and its reflector, if any.

Speed Limit – The maximum (or minimum) travel speed on a street established by law, ordinance, or regulation.

Stop Line or Stop Bar – A pavement marking that denotes where traffic should stop in advance of an intersection.

Stopping Distance – The distance a vehicle travels while decelerating to a complete stop.

Traffic Movements – Describes both vehicles and pedestrians at an intersection grouped together by the direction they are traveling through the intersection.

Traffic Signal – A power-operated traffic control device by which traffic is warned or directed to take a specific action. Traffic is warned or directed by a series of green, yellow and red lens that illuminate.

Velocity – The speed and direction that a vehicle is traveling.

Warning Clearance Interval – A superseded term that refers to the yellow interval.

Warning Interval – A term that refers to the yellow interval.

Yellow Interval or Yellow Change Interval – The first interval following the green interval **during which the steady yellow signal indication is displayed.**

Yellow Clearance Interval – An outdated term to describe the yellow interval.

Yellow Signal Indication – The illumination of the yellow signal lens.

Yellow Warning Indication – A term that the yellow signal indication results.

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