Michael E. Haglund, OSB No. 772030
email: mhaglund@hk-law.com
Shenoa L. Payne
email: spayne@hk-law.com
HAGLUND KELLEY LLP
200 SW Market Street, Suite 1777
Portland, Oregon 97201
Phone: (503) 225-0777
Facsimile: (503) 225-1257

Attorneys for Plaintiff

UNITED STATES DISTRICT COURT

DISTRICT OF OREGON

PORTLAND DIVISION

MATS JARLSTROM, an individual, Plaintiff, v. **CITY OF BEAVERTON**, an Oregon municipal corporation, Defendant.	Case No.: 3:14-cv-00783-AC **DECLARATION OF MATS JARLSTROM**

I, Mats Jarlstrom, being sworn, say:

1. I am a resident of Beaverton, reside at 13520 S.W. Hart Road in the Hyland Hills neighborhood between Murray Boulevard and Hall Boulevard and make this declaration based upon my own personal knowledge.

2. I was born, raised and educated in Sweden with an equivalent of an American degree of a Bachelors in Science in Electrical Engineering or higher, which has given me excellent mathematical and scientific skills. I did my military service in the Swedish Air Force as an airplane-camera mechanic. I also worked in Sweden as an audio engineer in the research

Haglund Kelley LLP
200 SW Market Street, Suite 1777
Portland, OR 97201
Tel: (503) 225-0777 / Fax: (503) 225-1257
0000029574H073/ PL11

and development department for Luxor Electronics, a subcontractor for both Volvo and SAAB. Additionally, I was an engineering consultant designing powered loudspeakers for Audio-Pro in Sweden before moving to the United States in 1992. Here in the United States I am a legal resident but not a registered professional engineer. However, my skills as an expert in motional feedback of powered loudspeakers, which includes the knowledge of motion of an object (distance, velocity and acceleration) such as a moving loudspeaker cone and the electro-mechanical-acoustical relationships in this type of a system, enabled me to work as an expert witness in the United States District Court in the Western District of Washington on behalf of Audio Products International (Robert Carver v. Audio Products International). Currently I am self-employed and conduct research and development with electronics and acoustics to develop new test and measurement methods. I also currently contract with the United States Navy to maintain, upgrade and calibrate digital storage oscilloscopes for the United States Naval Air Warfare Division that are used in the testing and evaluation of military ordinance.

3. My family and I have lived in Beaverton for 19 years. I am a licensed Oregon driver. Most of my driving activity occurs within the City of Beaverton. I estimate that I am on Beaverton roads 10 or more times per week.

4. Within the City of Beaverton, much of my driving involves traveling on Murray Boulevard, Allen Boulevard, Hall Boulevard, Lombard Avenue, Denny Road and Tualatin Valley Highway. I regularly drive through Beaverton signalized intersections at Lombard and Allen, Hall and Allen, Murray and Allen and Tualatin Valley Highway and Murray. My driving activity is sometimes alone and other times involves my family which consists of my wife, son and daughter, either individually, all together or a combination.

:::

Haglund Kelley LLP
200 SW Market Street, Suite 1777
Portland, OR 97201
Tel: (503) 225-0777 / Fax: (503) 225-1257
0000029574H073/ PL11

5. Most of my activity as a pedestrian at signalized intersections occurs at the intersection of Murray Boulevard and Allen Boulevard. At that intersection location is a Safeway, which I shop at regularly, my bank which I use at least once a week, a Shari's and a McMenamin's which I eat at about once a month, and an accountant which I visit at least twice a year.

6. During the last year, I have devoted approximately one-third of my time to the study and analysis of traffic light timing at intersections in the City of Beaverton. This has involved monitoring and the taking of measurements at multiple intersections and an exhaustive analysis of the available literature regarding the engineering of traffic control devices and in particular the safety issues related to yellow signal timing in connection with traffic flow. Based upon my education and background, I believe that I am qualified to analyze the basic mathematics and physics related to a vehicle in motion and traffic flow to assess the potential for increased levels of collisions where yellow light intervals are shorter than required under the specifications in the Oregon Vehicle Code.

7. Attached as Exhibit 1 is a working Scientific Report, with its most current version dated September 9, 2014, that I authored on the subject of the Institute of Transportation Engineers (ITE) formula used in calculating traffic light change intervals.

8. My working scientific report presents simple tools to analyze and visualize the motion of a vehicle using basic mathematics and physics. The report also presents how the ITE formula's individual terms are related to a traffic intersection's geometrical dimensions together with conflicting traffic and a vehicle's critical stopping distance. It also explains the ITE formula calculations of the yellow and all-red phase times for the two different yellow light vehicle codes currently used in the United States – the *restrictive* and *permissive* yellow light laws.

Haglund Kelley LLP
200 SW Market Street, Suite 1777
Portland, OR 97201
Tel: (503) 225-0777 / Fax: (503) 225-1257
0000029574H073/ PL11

Furthermore, the report presents the details related to the ITE formula when a *yellow light violation* can occur based on the restrictive yellow law requiring that a driver "shall stop" facing the yellow light as per Or. Rev. Stat. 811.260(4).

9. Attached as Exhibit 2 to this Declaration is a study conducted and published in 2002 in the Journal of *Accident Analysis and Prevention* which I relied on in my study and analysis of traffic light timing. The study concludes that modifying traffic signal change intervals to values associate with the ITE recommended practice -- computing the length of the all-red or yellow clearance interval as a function of speed and width that *must be cleared* -- reduces the risk of crashes involving pedestrians and bicyclists and may reduce the overall risk of multiple-vehicle crashes, particularly those resulting in injuries. The study found that there was a significant 12% reduction in all reportable crashes involving injuries and a 37% reduction in crashes involving pedestrians and bicyclists for intersections that were re-timed to follow the ITE proposed practice compared to a control group of intersections.

10. Attached as Exhibit 3 to this Declaration is a Graph that compares a driver entering the example intersection attached as Exhibit A to my Complaint at 30 mph and a driver at 20 mph constant speed. The velocity versus time and distance graph show the ITE formula terms plotted along with current traffic light phase times linked to the motion of vehicles. The line marked "car critical stopping distance" (the line between the Green Safe "STOP" area and the Yellow Unsafe "STOP" area) divides the line between when it is safe for the driver to stop at the point the yellow light illuminates and when it is unsafe to stop, meaning the driver must proceed through the intersection with caution.

:::

:::

Haglund Kelley LLP
200 SW Market Street, Suite 1777
Portland, OR 97201
Tel: (503) 225-0777 / Fax: (503) 225-1257
0000029574H073/ PL11

11. Oregon's Vehicle Code contains a *restrictive* yellow law at Or. Rev. Stat. 811.260(4), and provides that a driver "shall stop" facing the yellow light. However, as both Exhibit A from the complaint and Exhibit 3 attached to this declaration show, the example intersection's traffic light change interval seems to be timed to a combination of the two different yellow laws (*permissive* and *restrictive*). The example's yellow light's phase time currently only includes the ITE formula's stopping term which is used for the *permissive* yellow law. However the *permissive* yellow law *mandates* that the very important ITE formula's clearance term is included in an all-red phase time to protect the intersection from any interfering cross-traffic including pedestrians since a vehicle is *permitted* to enter the intersection during the *full yellow phase.* Thus, the driver can legally enter the intersection at the very end of the yellow phase as the examples show. For the *restrictive* yellow law the important clearance time is included in the yellow light so the all-red phase becomes *optional* which is what the example intersection's minimal all-red phase time indicates. The words "the driver facing the light *shall stop* " under Or. Rev. Stat. 811.260(4) is *restricting* the driver to use the *full length* of the yellow light and is thus only allowing the driver to enter the intersection during the ITE formula's safe stopping time, and the yellow light's *added clearance time* is thus *restricted* by the wording of the law. Hence, a yellow light violation occurs if a driver did not stop when faced with the yellow light and enters the intersection during the *added yellow clearance time* as the ITE formula's clearance term calculates. Currently the example intersection shows that the very important ITE formula's clearance term is neither included in the yellow phase time nor is it included in the *optional* all-red phase, which is the reason the pedestrian is at danger when the pedestrian is given a "walk" signal *before* the vehicle has cleared and exited the intersection and crosswalk.

:::

Haglund Kelley LLP
200 SW Market Street, Suite 1777
Portland, OR 97201
Tel: (503) 225-0777 / Fax: (503) 225-1257
0000029574H073/ PL11

12. The "critical stopping distance," which is directly related to the ITE formula's first two terms as presented in Exhibit 1, is the exact distance at which a driver has two choices based on three specified input variables at a level intersection (0% grade): (1) driver perception-reaction time, (2) vehicle approach speed, and (3) a safe and comfortable deceleration rate. The first choice is that he can comfortably and safely stop at the entry of the intersection. The second choice is that he can travel the critical distance at the constant speed to be able to reach the intersection's entry point without violating either a red (permissive yellow law) or a yellow (restrictive yellow law) light at which point the driver will have to proceed through the intersection with caution. If a driver is at any point beyond the speed dependent critical stopping distance facing the yellow light, the driver *cannot* stop safely, and must proceed through the intersection with caution. This is why it is critical that the yellow phase (restrictive yellow law) or the all-red phase (permissive yellow law) include enough time for the driver to drive through and clear the intersection *before* the light changes and any conflicting traffic is allowed access to the intersection. Exhibit 1 explains the two yellow laws and how to implement the ITE formula's clearance term and time in the yellow and all-red phase described above.

13. Exhibit 3 shows how the critical stopping distance works. The critical stopping distance at 30 mph (or 44 ft/s) is 140.8 feet (Exhibit 1 includes the formula to calculate the critical distance at other vehicle speeds). For example, if a driver traveling at 30 mph faces the yellow light one/tenth of a second before reaching the critical stopping distance or 4.4 feet farther away from the intersection, a driver is in the Safe "STOP" Area, and the driver must stop. If the driver were to continue without accelerating, the driver would reach the intersection and violate the red light (permissive yellow law). If a driver traveling at 30 mph and facing the yellow light one/tenth of a second closer to the intersection than the critical distance or 4.4 feet

Haglund Kelley LLP
200 SW Market Street, Suite 1777
Portland, OR 97201
Tel: (503) 225-0777 / Fax: (503) 225-1257

closer, then the driver is in the Unsafe "STOP" Area, which means the driver cannot stop comfortably and safely and must proceed through the intersection with caution.

14. To stop "safely" means that the driver is perceiving-reacting and decelerating at the given parameters used to calculate the yellow light and its critical distance. If the driver is required to stop faster or in less distance (as presented with the two unsafe emergency stopping distances based on maximum roadway friction in Exhibit A to my Complaint) the driver has to react faster and/or decelerate harder, thus it becomes unsafe. In addition, stopping safely does not mean that a driver should have to rely on the safety features of the vehicle such as anti-lock braking systems, electronic stability control, seatbelts or even airbags to stop. Thus, the "nonemergency" deceleration rate defined by ITE is what is deemed safe and any higher rate is deemed unsafe.

15. As demonstrated in Exhibit 3, for vehicles that are in the Unsafe "STOP" Area when the yellow light illuminates and cannot stop safely but must proceed through the intersection with caution, yellow light durations must be long enough to allow the driver to reach and clear the "intersection exit" (78 feet), which is also the intersection's far side crosswalk and the path of the conflicting pedestrian in Exhibit A, *before the light turns red.* This is also what Or. Rev. Stat. 811.260(4) is describing: "If a driver cannot stop in safety, the driver may drive cautiously through the intersection." If a driver cannot stop safely, and must drive cautiously through the intersection, he cannot "accelerate" or violate the speed limit in order to reach the exit at 78 feet and fully clear the intersection.

16. However, the slower the driver goes, the longer it takes to clear the intersection. This effect is a product of the ITE formula itself presented in Exhibit 1. The ITE formula's first two terms calculates the yellow phase for the time it takes to travel the critical distance at

Haglund Kelley LLP
200 SW Market Street, Suite 1777
Portland, OR 97201
Tel: (503) 225-0777 / Fax: (503) 225-1257

constant speed and the ITE formula's deceleration term has the vehicle speed (velocity, V) in the numerator so the time it takes to travel the critical stopping distance is thus linearly decreasing with decreasing vehicle speed. The ITE formula's clearance term, which is calculating the time it takes to travel the intersection's width to the widest interference point, includes the vehicle speed (velocity, V) in the denominator. Having the velocity (V) variable in the denominator will have an opposite effect for the time it takes to clear the intersection – decreasing vehicle speed equals *increased* time to travel through the intersection.

17. An example of this effect is demonstrated in Exhibit 3. If a driver first faces the yellow light within the critical distance and must cautiously travel through the intersection, it takes more time for a slower driver than a faster driver to clear the intersection. The "critical stopping distance" for the 20 mph speed is 72.4 feet but the slower speed will add .9 seconds to the time it takes to reach the intersection's 78 feet clearance width. If a driver is driving 15 mph instead of 30 mph, it can add an additional 1.8 seconds to clear the intersection.

18. The danger from failing to exit the intersection before the light turns red is demonstrated in Exhibit A to my Complaint and Exhibit 3 to this Declaration. At 30 mph, the light turns red roughly at the same point the vehicle *enters* the intersection. The vehicle will take another roughly 1.8 seconds to reach the exit and another .5 to fully exit the intersection with a typical vehicle length (all the while the light is currently red). The pedestrian signal turns to "walk" when the car is .5 seconds into the intersection (assuming no timing errors in the programmed *optional* restrictive yellow law all-red phase). A pedestrian has a reaction time of less than 1.0 seconds to react to the "walk" signal before entering the intersection, and will likely enter the intersection before 1.5 seconds, roughly the same time the vehicle is .3 seconds away from reaching the exit of the intersection and, therefore, the pedestrian. Even if the driver was

Haglund Kelley LLP
200 SW Market Street, Suite 1777
Portland, OR 97201
Tel: (503) 225-0777 / Fax: (503) 225-1257

being "cautious" and *expected* the pedestrian to enter the crosswalk, the driver could not react to the pedestrian's presence in less than 1.0 seconds.[1] In addition to reacting, the driver could not physically stop, as the driver would travel 44 feet in the 1.0 seconds it takes to react, and it would take a total of 94 feet for an emergency stop on dry pavement, or 130 feet for an emergency stop on wet pavement. At the time the driver saw the pedestrian, the driver would be 13.2 feet away from the pedestrian. Therefore, even a "cautious" driver simply cannot avoid hitting a pedestrian under this scenario without other tactics, such as swerving.

19. At 20 mph, the light currently turns red after the driver has been in the intersection for approximately 0.7 seconds and a distance of 21.5 feet. It will take an additional 1.9 seconds for the vehicle to reach the intersection's exit and the light will currently be red during that time. The pedestrian signal turns to "walk" after the vehicle has been in the intersection for about 1.2 seconds, and the pedestrian will be entering the crosswalk within 2.2 seconds. Here, the driver will have only .5 seconds to react (.2 seconds more than for the 30 mph driver) and the pedestrian will have traveled farther into the roadway. If the driver is being cautious and expects the pedestrian to enter the crosswalk, the driver can *react* in 1.0 seconds, but the driver cannot both react *and conduct an emergency stop* in less than 1.0 seconds. An emergency stop at 20 mph takes 51.6 feet and 2.5 seconds, considering dry pavement, and 62.7 feet and 3.3 seconds considering wet pavement. At the time the 20 mph driver saw the pedestrian, the driver would be 14.7 feet away from the pedestrian.

:::

---

[1] Driver perception and reaction time according to ITE is typically 1.0 seconds for a low complexity expected event and 2.5 seconds for an unexpected event.

Haglund Kelley LLP
200 SW Market Street, Suite 1777
Portland, OR 97201
Tel: (503) 225-0777 / Fax: (503) 225-1257

20. A driver would have to drive as slow as 12.5 miles per hour to be able to emergency stop for the pedestrian stepping into the roadway if we assume dry pavement, 1.0 seconds perception-reaction time for both the driver and pedestrian, pedestrian moving at 4 ft/s and no timing errors in the currently programmed 0.5 seconds *optional* all-red phase time. An increased unexpected reaction time of 2.5 seconds will reduce the speed to 9.1 mph for the driver who is able to emergency stop for the pedestrian. Driving 12.5 miles per hour in a 30 mph speed zone obviously creates additional safety hazards. In a high-density traffic pattern, driving under half the speed limit is likely to induce a rear-end collision -- a prominent type of accident in traffic today. Driving 12.5 miles per hour is not safe, "cautious" or prudent and is also counterproductive for the overall traffic flow, one of the main reasons in addition to safety that traffic lights are used.

21. This is also true if a driver merely "decelerates" once he or she enters the intersection. If a driver is approaching the intersection at 30 mph constant speed and he faces the yellow light just within the "critical stopping distance" and the driver then slows down to be "cautious" before *entering* the intersection, the yellow phase time calculated by the ITE formula will neither allow this driver enough time to reach and enter the intersection on a legal yellow light which means the driver is violating a red light (*permissive* yellow law) or a yellow light (*restrictive* yellow law) nor allow the driver the time needed to travel through and exit the intersection. The reason is that a driver decelerating will not be covering the same distance as a vehicle that keeps traveling at the constant 30 mph speed as the ITE formula inherently is designed. Therefore, the decelerating driver will enter the intersection too late and thus violate the traffic signal and thereby cause more danger because the vehicle is in the intersection longer after the light has transitioned and will with higher probability interfere with any cross-traffic

Haglund Kelley LLP
200 SW Market Street, Suite 1777
Portland, OR 97201
Tel: (503) 225-0777 / Fax: (503) 225-1257

given a green light or a "walk" signal.

22. By studying the ITE formula, using mathematics and the laws of physics for a vehicle in motion traveling through an intersection, we can determine what driving "cautiously" through the intersection actually means. Here, "cautiously" must mean that a driver is prohibited from unsafely accelerating and violating the speed limit through the intersection in order to beat the red light -- *i.e.*, maintaining constant speed. If "cautious" meant that the driver was supposed to slow down, the driver would actually make the situation more dangerous. That is, driving slower does not prevent the danger to the pedestrian, it actually increases the danger.

23. Not only is the pedestrian in danger in the two driver speed examples above, the driver and drivers of other vehicles are also in danger. Because short yellow light durations do not allow the two drivers in the 30 mph and the slower 20 mph vehicle to drive through and clear the intersection *before* giving the pedestrian a "walk" signal, those drivers are likely to engage in other actions to avoid colliding with the pedestrian. A driver who is not able to emergency stop might make an evasive action just before hitting the pedestrian, or even after, due to the impact or shock. This evasive action can put the driver in the wrong lane, crash into another third party vehicle, or force a third party into oncoming traffic.

24. Exhibit A attached to my Complaint and Exhibit 3 to this Declaration do not account for the variation in the types of vehicles or the length of these vehicles traveling through the intersections. (Bicyclists, children and elderly are also not shown which all require extra time to stop or traverse an intersection). Other vehicles such as long trucks, public and school buses, or vehicles with trailers typically use air brakes which require extra reaction delay time before the brakes engage. The current yellow light phase timing only allows standard vehicles using hydraulic brakes to stop safely at 30 mph. Vehicles using air brakes, even assuming that these

Haglund Kelley LLP
200 SW Market Street, Suite 1777
Portland, OR 97201
Tel: (503) 225-0777 / Fax: (503) 225-1257

vehicles are able to stop with the typical ITE "nonemergency" deceleration rate, need both longer deceleration and intersection clearing times. If the design of the yellow-light phase does not adequately take into account these types of vehicles, these vehicles will need to drive slower to avoid the dilemma zone created by the too short yellow light which will in turn reduce the overall traffic flow and the danger is even more acute.

25. Attached as Exhibit 4 to this Declaration is a drawing showing two Graphs (the top graph shows velocity versus time *and* distance, the bottom graph shows velocity versus distance). The graphs combine all the relationships set forth by the ITE formula's individual terms with input variables related to a traffic light's change interval and the motion of a 30 mph vehicle traveling through the to-scale example intersection used in Exhibit A of the Complaint. The colored areas represent the green, yellow and red traffic light phases. The yellow area shows the time required for the yellow light phase for different *design speeds* or *posted speed limits* based on the ITE formula if it would follow Or. Rev. Stat. 811.260(4). For example, as demonstrated in this Exhibit 4, the eastbound S.W. Allen Blvd approach has a posted speed limit of 30 mph. For a vehicle following the *design speed* of 30 mph, total yellow phase time needs to be 5.5 seconds *minimum* to allow the vehicle to (1) travel the critical stopping distance, (2) traverse the intersection's clearance width and (3) travel one typical vehicle length. Proper application of the ITE formula's clearance term per Or. Rev. Stat. 811.260(4) into the yellow light as shown in Exhibit 4 would allow drivers who cannot stop safely to travel through and clear the intersection *before* allowing the pedestrian to enter into the vehicle's path. Doing so will greatly reduce the danger to the pedestrian, the driver, and drivers of other vehicles in the vicinity. This is the true purpose of the ITE formula and the use of a traffic control device in an intersection – maximize traffic safety and traffic flow.

Haglund Kelley LLP
200 SW Market Street, Suite 1777
Portland, OR 97201
Tel: (503) 225-0777 / Fax: (503) 225-1257
0000029574H073/ PL11

I declare under penalty of perjury that the foregoing is true and correct to the best of my knowledge.

DATED this 10th day of September, 2014.

Mats Jarlstrom

Haglund Kelley LLP
200 SW Market Street, Suite 1777
Portland, OR 97201
Tel: (503) 225-0777 / Fax: (503) 225-1257

Pamela Vanderheiden

m:	info@ord.uscourts.gov
.it:	Wednesday, September 10, 2014 1:27 PM
To:	nobody@ord.uscourts.gov
Subject:	Activity in Case 3:14-cv-00783-AC Jarlstrom v. City of Beaverton Declaration

This is an automatic e-mail message generated by the CM/ECF system. Please DO NOT RESPOND to this e-mail because the mail box is unattended.
*****NOTE TO PUBLIC ACCESS USERS*** Judicial Conference of the United States policy permits attorneys of record and parties in a case (including pro se litigants) to receive one free electronic copy of all documents filed electronically, if receipt is required by law or directed by the filer. PACER access fees apply to all other users. To avoid later charges, download a copy of each document during this first viewing. However, if the referenced document is a transcript, the free copy and 30 page limit do not apply.**

U.S. District Court

District of Oregon

Notice of Electronic Filing

The following transaction was entered by Haglund, Michael on 9/10/2014 at 1:27 PM PDT and filed on 9/10/2014

se Name: Jarlstrom v. City of Beaverton
ase Number: 3:14-cv-00783-AC
Filer: Mats Jarlstrom
Document Number: 34

Docket Text:
Declaration of Shenoa Payne . Filed by Mats Jarlstrom. (Related document(s): Objection[32].) (Attachments: # (1) Exhibit A) (Haglund, Michael)

3:14-cv-00783-AC Notice has been electronically mailed to:

Gerald L. Warren gwarren@geraldwarrenlaw.com, lkinman@geraldwarrenlaw.com

Michael E. Haglund mhaglund@hk-law.com, atodd@hk-law.com, kelley@hk-law.com, pvanderheiden@hk-law.com, spayne@hk-law.com, sscott@hk-law.com

Shenoa L. Payne spayne@hk-law.com, llaplante@hk-law.com

3:14-cv-00783-AC Notice will not be electronically mailed to:

The following document(s) are associated with this transaction:

ocument description: Main Document
Original filename: Not Available

Electronic document Stamp:
[STAMP ordStamp_ID=875559790 [Date=9/10/2014] [FileNumber=4870564-0] [
[illegible]74928d9bc42d405fd46f459baa67b79e92446ae621b64e649991d5583dadbd631414
[illegible]72c49a8f096e01a8b373f0f596b43429a05ce4e058ebd8b04a7c658]]
Document description: Exhibit A
Original filename: Not Available
Electronic document Stamp:
[STAMP ordStamp_ID=875559790 [Date=9/10/2014] [FileNumber=4870564-1] [
430e1ed20554bb3cf8349dc244487a4882f929e159a3cc55be458cf53a8b7665954d33
5476fd924ffc56691389f11199a74e9f8444e5f6a2a717023120584eb1]]

Michael E. Haglund, OSB No. 772030
email: mhaglund@hk-law.com
Shenoa L. Payne
email: spayne@hk-law.com
HAGLUND KELLEY LLP
200 SW Market Street, Suite 1777
Portland, Oregon 97201
Phone: (503) 225-0777
Facsimile: (503) 225-1257

Attorneys for Plaintiff

UNITED STATES DISTRICT COURT

DISTRICT OF OREGON

PORTLAND DIVISION

MATS JARLSTROM, an individual,

Plaintiff,

v.

CITY OF BEAVERTON, an Oregon municipal corporation,

Defendant.

Case No.: 3:14-cv-00783-AC

DECLARATION OF SHENOA L. PAYNE

I, Shenoa L. Payne, being sworn, say:

1. I am one of the attorneys for plaintiff in this case and make this declaration based on my personal knowledge.

2. Attached as Exhibit A is a true copy of the Transcript of the Proceedings before Judge Acosta on Defendant's Motion to Dismiss and Plaintiff's Motion for Leave to File First Amended Complaint, dated August 25, 2014.

I declare under penalty of perjury that the foregoing is true and correct to the best of my knowledge.

DATED this 10th day of September, 2014.

/s/ Shenoa L. Payne
Shenoa L. Payne

Haglund Kelley LLP
200 SW Market Street, Suite 1777
Portland, OR 97201
Tel: (503) 225-0777 / Fax: (503) 225-1257
0000029548H073 PL12

CERTIFICATE OF SERVICE

I hereby certify that on the 10th day of September, 2014, I served the foregoing **DECLARATION OF SHENOA L. PAYNE,** on the following:

Gerald L. Warren
Law office of Gerald Warren
901 Capitol Street, NE
Salem OR 97301
Attorney for Defendant

by the following indicated method(s):

☐ by **mail** with the United States Post Office at Portland, Oregon in a sealed first-class postage prepaid envelope.

☐ by **email**.

☐ by **hand delivery**.

☐ by overnight mail.

☐ by **facsimile**.

☒ by the court's Cm/ECF system.

/s/ Shenoa L. Payne
Shenoa L. Payne, OSB No. 084392

Haglund Kelley LLP
200 SW Market Street, Suite 1777
Portland, OR 97201
Tel: (503) 225-0777 / Fax: (503) 225-1257

Scientific Report

AN INVESTIGATION OF THE ITE FORMULA AND ITS USE

$$CP = \left[t + \frac{V}{2a + 2Gg} \right] + \frac{W + L}{V}$$

Abstract

This working report is a study of the universally adopted ITE formula which calculates a traffic light's change interval. Its sole purpose is to provide safe passage through an intersection for a wide range of vehicle types and pedestrians with high traffic flow. However, due to misinformation and misunderstandings (both presented and found in the manuals [5] referenced in this report) and lack of knowledge of the ITE formula's intendant use with the many different State's vehicles codes, safety is compromised. Proper understanding of the basic laws of physics is needed and the Professional Engineers (PE) that are applying the ITE formula to set the timing of an intersection's traffic lights are *required by law* to understand and apply the science to provide public safety.

This report is presenting the details of how the ITE formula's terms are used to calculate the yellow and all-red phase times for vehicles traveling through an intersection with conflicting traffic and especially how to apply the formula's clearance term with the two yellow laws; the *permissive* and *restrictive* yellow laws. The report includes the needed tools to investigate and illustrate a vehicle in motion. Great effort has been taken to simplify the involved mathematics and physics. All the kinematic formulas are derived from the basic definition of the average *velocity* and *acceleration*.

The investigation shows the inherent design of the formula and that the *critical stopping distance* is the source of its design. Given by a vehicle's speed, a driver's reaction time and a safe deceleration rate; the critical stopping distance is the *only point* referenced to an intersection's entry where a driver can *either stop* safely before entering *or go* the critical distance to reach the intersection's entry point on a *legal* yellow. However, the design of the formula is not allowing the driver to slow down within the critical stopping distance and *enter* the intersection. Thus the formula is designed to ONLY accommodate a vehicle stopping before entering or traveling through an intersection at constant or accelerated speed. The next report will cover the yellow phase time required for turns; a time which is greater than calculated by the ITE formula due to a vehicle is slowing down *within* the *critical stopping distance* when perform a turning maneuver.

Author

Mats Järlström
mats@jarlstrom.com
503-671-0312
Beaverton, Oregon, USA

Revision: 14 • September 9, 2014

Table of contents

This report is dedicated to Marianne Järlström and David Hodge.

1. The ITE formula

The Institute of Transportation Engineers' ITE formula was developed by Denos Gazis from GM Research Labs, Robert Herman and Alexei Maradudin and presented in 1959 in the paper *"The Problem of the Amber Signal Light in Traffic Flow"* [1]. Today the formula is used worldwide to calculate traffic light phase times such as the yellow change and all-red clearance intervals. Here is one example of this formula [1 2 3 4 5]:

$$CP = \left[t + \frac{V}{2a + 2Gg} \right] + \frac{W + L}{V} \qquad (1.1)$$

Where:

- CP = Change Period, total combined driver perception and reaction, vehicle stopping and clearance times, result expressed in seconds, (s).
- t = Perception and reaction time of the driver, typically 1.0 seconds for an expected event, (s).
- V = Speed of the approaching vehicle, expressed in feet per second, (ft/s).
- a = Comfortable deceleration rate of the vehicle, typically 10 feet per second squared, (ft/s^2).
- W = Width of the intersection at widest conflict point, expressed in feet, (ft).
- L = Length of vehicle, typically 20 feet, (ft).
- G = Acceleration due to gravity, 32.2 feet per second squared, (ft/s^2).
- g = Grade of the intersection approach, in percent (%) divided by 100, downhill is negative grade and uphill is positive grade.

1.1 The ITE formula's three terms

By studying the ITE formula (1.1) and the individual input variables, we can determine that it consists of three terms and all terms appear to specify or calculate time in seconds as follows:

1. Perception and reaction time of the driver $= t$ (1.2)
2. Deceleration time of the vehicle $= \frac{V}{2a + 2Gg}$ (1.3)
3. Intersection and vehicle clearance time $= \frac{W + L}{V}$ (1.4)

Describing the ITE formula (1.1) and its terms, the equation is simplified as follows:

$$CP = \left[t + \frac{V}{2a + 2Gg} \right] + \frac{W + L}{V}$$

or

$$\textit{Change Period} = \left[\textit{Perception Reaction Time} + \textit{Deceleration Time} \right] + \textit{Intersection \& Vehicle Clearance Time}$$

or

$$\textit{Change Period} = \left[\textit{Total Stopping Time} \right] + \textit{Clearance Time}$$

2. The usage of the ITE formula terms

This section explains how the three ITE formula terms are currently used [2] to implement the timing of traffic lights with different State's vehicle codes [5] presented in APPENDIX A.

2.1 The yellow phase

The driver perception and reaction time (1.2) and the deceleration time (1.3) terms are typically combined to calculate a traffic light's yellow phase time which is also the total stopping time of the ITE formula. This total stopping time is also directly linked to the *"one safe stopping distance"* or Gazis' *"critical stopping distance"* which will be further investigated later in this report.

2.2 The all-red phase

The remaining term, the intersection and vehicle clearance time (1.4), is commonly used to calculate traffic light all-red phase times. The all-red phase is a clearance time when all traffic lights are red and no vehicles are allowed to enter the intersection from any of its approaches. The all-red phase time allow vehicles that are still in the intersection to exit before conflicting traffic, including pedestrians that are given a green light to enter. The clearance term adds an important safety time to avoid traffic accidents.

2.3 The permissive yellow law

The *permissive yellow light law* is when a State's vehicle code only *warns* that a change of the traffic light from yellow to red is imminent and is thereby *permitting* a driver to enter the intersection during the *full* yellow phase. For this law, the all-red phase is mandatory since a vehicle can legally enter the intersection at the very end of the yellow phase and thus needs time to drive through and exit the intersection during the protection of the all-red phase. A violation occurs if the driver enters the intersection on a red traffic light signal.

2.4 The restrictive yellow law

There is also a *restrictive yellow light law* where a driver facing a yellow light *"shall stop"* and not enter the intersection unless the driver *"cannot stop in safety"*. A driver cannot stop in safety if the driver is closer to the intersection than *"one safe stopping distance"* or the *"critical stopping distance"*.

Some State's restrictive yellow light vehicle codes also add instructions for a driver's optional behavior when facing the yellow light such as *"if a driver cannot stop in safety, the driver may cautiously drive through the intersection"*. Here, the *"drive through the intersection"* is the ITE formula's clearance term (1.4) which for a *restrictive yellow light law* is added to the traffic light's yellow phase time. In addition, the word *"cautiously"* is instructing the driver not to accelerate to reach and clear the intersection's exit. Any unsafe acceleration would also violate the speed limit if the driver approached the intersection at the speed limit. For the *restrictive yellow light law* the all-red phase is *optional* since the clearance time is already included in the yellow phase time.

2.4.1 Restrictive law yellow traffic light violation

A jurisdiction having the restrictive yellow light vehicle code can cite a driver running a yellow light because the yellow phase time *includes the clearance term* (1.4) and is therefore longer than just the ITE formula's total stopping time. The words *"shall stop"* used by the restrictive yellow law is specifically added to prohibit or restrict the driver to use the *added* clearance time to enter the intersection. Thus a citation can be issued if the driver enters the intersection during the *added* yellow clearance time. (See also the marked "Violation Area" in figure 1).

2.5 Summary of the ITE formula and the two yellow traffic light laws
To summarize the ITE formula's terms and their usage with the *permissive* and the *restrictive yellow light laws* we have:

The Permissive Yellow Law
Where the driver is *permitted* to enter the intersection during the *full* yellow phase.

$$Yellow\ Phase\ Time = t + \frac{V}{2a + 2Gg} \qquad All - Red\ Phase\ Time = \frac{W + L}{V}$$

"Total Stopping" *"Clearance"*

The Restrictive Yellow Law
Where the *"driver shall stop facing the light"* due to the clearance time is added to the yellow phase.

$$Yellow\ Phase\ Time = t + \frac{V}{2a + 2Gg} + \frac{W + L}{V} \qquad All - Red\ Phase\ Time = Optional$$

"Total Stopping + Clearance"

The below figure 1 illustrates the ITE formula terms and the two yellow traffic light laws in a scaled intersection showing relative traffic light phase times for a constant velocity vehicle. The timing graphs of the traffic lights also show how the all-red phase relates to the conflicting traffic signal and when a traffic light violation occurs with the two different laws:

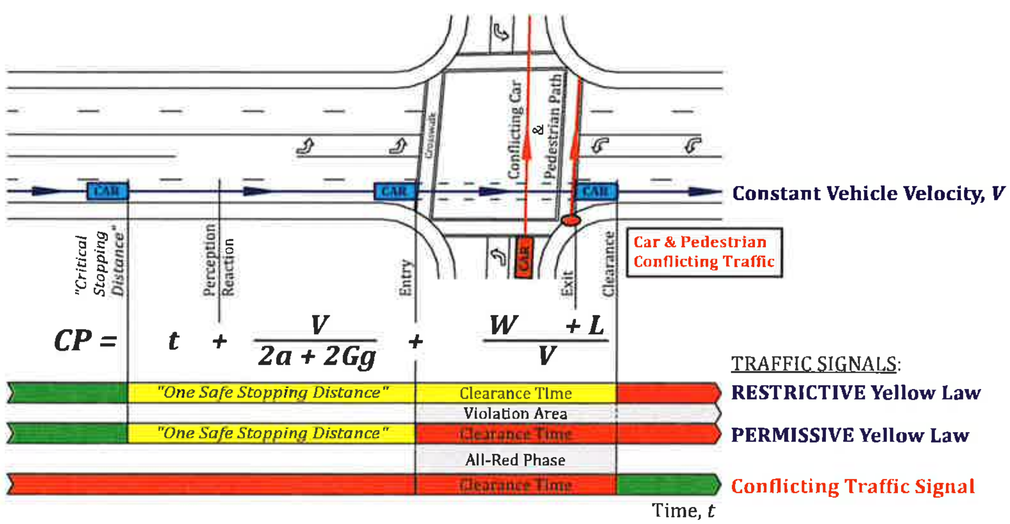


Fig. 1 - The ITE Formula Relative a Traffic Light Intersection and the Two Yellow Light Laws

3. Perception and reaction time

Driver perception and reaction time [6] [7] is a time where no changes are taking place to a vehicle's motion. This is due to it takes a driver some time to perceive and react to, for example a traffic signal changing from green to yellow and to make a decision whether he or she should make any changes such as stop or go. The time it takes can be broken down into three categories depending on what type of event the driver is reacting to or is making. Three low complexity type of events and some typical perception and reaction times used by ITE with examples are as follows:

1. Unexpected external event: 2.5 seconds - A deer entering the roadway.
2. Expected external event: 1.0 seconds - A changing traffic light or traffic control device.
3. Planned internal event *: 0.0 seconds - A driver is making a lane change or a turn.

* Event introduced by author.

Note: A traffic light is considered an expected event but an incorrectly timed traffic light intersection can cause unexpected events such as pedestrian or vehicle interferences. In addition, different vehicle braking systems such as tractor-trailer, school and public bus air brakes will add an extra reaction time delay of 0.5 seconds or more [8].

4. Stopping and clearance time

By studying the stopping and clearance terms of the ITE formula, we see the following input variables; vehicle length, vehicle speed and vehicle deceleration, plus intersection grade and intersection clearance width. Distance, velocity and acceleration can be presented in graph form to help us visualize and investigate the true physical nature of the ITE formula. The next step is to introduce visual tools such as vehicle motion graphs.

Note: Since this is working report, next version will included more detailed studies of the individual input variables of ITE formula in this section. Appendix B and C are included at this time which present some of this information:

Appendix B is presenting the effects of different stopping distances based on maximum roadway friction (emergency stopping) [6] [7] and air brake delays needed by trucks, public and school busses [8].

Appendix C is presenting a collection of maximum decelerations rates for different vehicle types and also their "cargo" which includes bus passengers and the related stopping distances.

5. Kinematics – The geometry of a vehicle in motion

The goal is to investigate the ITE formula and how it relates to a vehicle's motion in time and space by using basic mathematics and also present its motion using visual graphing tools.

5.1 Vehicle motion and the mathematics

A vehicle has three tight-coupled variables of motion; distance (*d*), velocity (*V*) and acceleration (*a*). The below flow diagram in figure 2 illustrates these states of motion and how they are linked through mathematical calculus functions which are called differentiation and integration. Differentiation is looking at a plotted curve's slope and integration is looking at the area under a plotted curve. However, this document is going to present a simplified method to use "calculus" to analyze the ITE formula by avoiding advanced mathematics on curves.

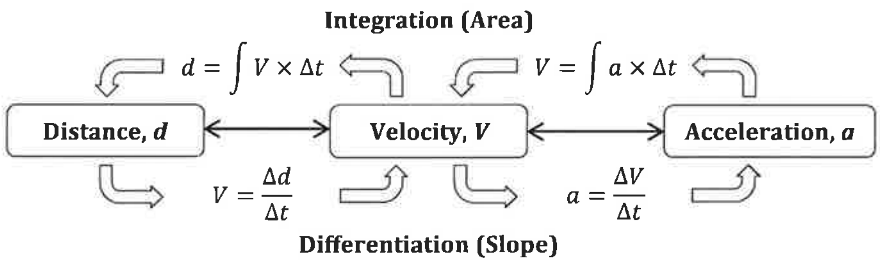


Fig. 2 - Flow Diagram of Motion over Time and their Mathematical Relationships

Figure 2 presents that the three variables of motion are closely connected through mathematics. We can mathematically convert, for example, acceleration to velocity by integrating acceleration over elapsed time (Δt), (the symbol "Δ" represents "change"). We can also convert distance over time to velocity by using differentiation. Using words, we can also describe differentiation and how it relates to a driver of a vehicle: The vehicle's velocity is the first derivative of the distance. Stepping on the accelerator or the brake, we experience a second derivative - acceleration or deceleration.

5.2 Motion input variables

We are familiar with both distance and velocity since most vehicles are equipped with both an odometer for distance and a speedometer for speed. Typically we have no standard "meter" installed in our cars to measure acceleration, even though "g-meters" are popular as an accessory for performance car enthusiasts.

In the United States, vehicle odometers measure distance in miles and the speedometers measure velocity in miles per hour (mph). As a driver, we continuously monitor the instantaneous vehicle speed (*V*), if not, we might get a speeding citation.

5.3 Constant deceleration or acceleration

The ITE formula is using vehicle velocity (*V*) as one important input variable. The formula is also including a *constant* deceleration rate (*a*) defined with a typical value of 10 ft/s^2. This *constant* deceleration rate (*a*) is telling us how fast a vehicle is slowing or is able to slow down or stop. One important factor to understand is that the ITE formula's average deceleration rate is a *constant rate or value over time* and can easily be plotted in a graph.

5.4 Constant acceleration graphing options

Let us look at the graphing options based on an average *constant acceleration* (a) and see how the closely related velocity (V) and distance (d) are visually presented versus time.

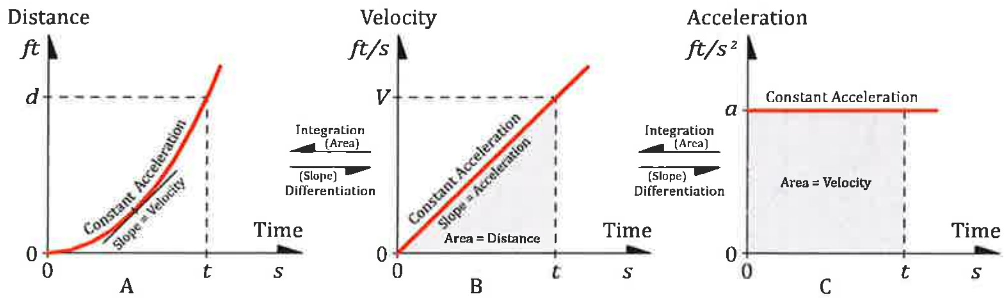


Fig. 3 - Graphing Options for Motion with Constant Acceleration

Figure 3 shows how the average constant acceleration (a) is plotted using the three variables of motion versus time. Studying the above graphs in figure 3 A, B and C we see:

A. Distance (d) versus time (t) graph shows constant acceleration (a) plotted as a curve.

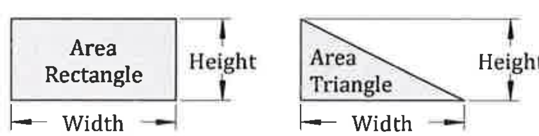
B. Velocity (V) versus time (t) graph presents the constant acceleration (a) as a straight line raising over time.

C. Acceleration (a) versus time (t) graph represents the constant acceleration (a) as a straight horizontal line.

We can also see in figure 3 that some areas under the plotted lines are shaped as triangles or rectangles. We also know that we can mathematically transform, for example, acceleration to velocity or velocity to distance using the calculus function called integration. Integration is the same as computing the area under a plotted curve. By carefully choosing a graphing method that will avoid curves and only uses straight lines we can simplify the mathematics for the "integration" or area calculations to basic geometry area calculations of rectangles and triangles:

$$\text{Area of a rectangle} = \text{Height} \times \text{Width}$$

$$\text{Area of a triangle} = \frac{\text{Height} \times \text{Width}}{2}$$



For example in figure 3C, velocity (V) is the integration of acceleration (a). Thus, integration is the area under the plotted line in the acceleration versus time graph which is equal to the "height" constant acceleration (a) times the "width" elapsed time (Δt).

5.5 The benefits of the velocity versus time graph

From the three graphing options we can see that by choosing a velocity (V) versus time (t) graph we get these key benefits:

1. The constant acceleration (a) defined by the ITE average deceleration rate, is velocity (V) plotted as a straight line in a velocity versus time graph.

2. Single integration which is the area under the plotted line of the velocity versus time graph will calculate traveled distance (Δd) during the elapsed time (Δt).
3. The integration of the velocity versus time plot becomes simple since the graph only have straight lines and we can use basic mathematics such as area and geometry calculations of rectangular and triangular shapes. Thus avoiding using advanced calculus functions or mathematics on curves.
4. Velocity or vehicle speed is the instantaneous measurement we as drivers are most familiar with.

Before we graph the ITE formula itself we can start to look at simple vehicle motion profiles using this graphing method and see with examples how vehicle velocity or speed versus time relate to distance and acceleration and their corresponding mathematical formulas.

6. First motion example: A vehicle traveling with a constant velocity

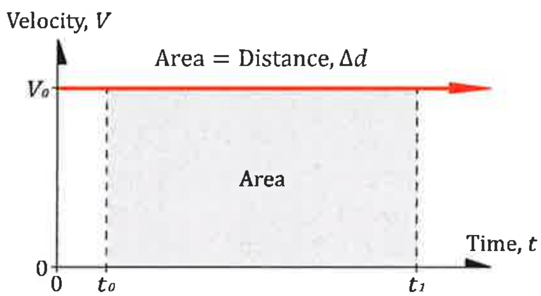


Fig. 4 - Constant Velocity

Variables:

$V_0 = Velocity$

$\Delta d = Distance$

$\Delta t = Elapsed\ Time$

$\Delta t = t_1 - t_0$

Formulas:

$V_0 = \frac{\Delta d}{\Delta t}$

$\Delta d = \Delta t V_o$

$\Delta t = \frac{\Delta d}{V_0}$

Figure 4 shows a velocity versus time graph of a vehicle traveling at a constant speed V_0 from time t_0 to time t_1. The constant speed is represented as a straight horizontal line over time. Speed or velocity is defined as distance traveled over elapsed time as we also see in the units we use for speed such as miles per hour (mph).

Based on the definition of average velocity we have:

$$Average\ velocity, V_0 = \frac{Distance, \Delta d}{Elapsed\ time, \Delta t} \quad (6.1)$$

Rearranging above equation (6.1) we also get:

$$Distance, \Delta d = \Delta t V_o \quad (6.2)$$

And:

$$Elapsed\ time, \Delta t = \frac{\Delta d}{V_0} \quad (6.3)$$

We can also see that the area under the graph is the height (velocity, V_0) multiplied with the width (elapsed time, $\Delta t = t_1 - t_0$). This area under the graph is the same as the traveled distance (Δd) of the vehicle as shown in equation (6.2). This visual understanding that the area under the plotted line in a velocity versus time graph equals distance will be very useful when we start to look at more complex motion profiles with changing vehicle speeds over time. This change of velocity over time is also referred to as acceleration or deceleration.

7. Second motion example: A vehicle traveling with a constant acceleration

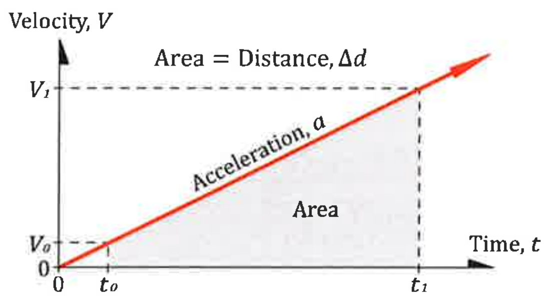


Fig. 5 - Constant Acceleration

Variables:	Formulas:
$a = Acceleration$	$a = \frac{V_1 - V_0}{\Delta t}$
$V_0 = Velocity\ at\ t_0$	$\Delta t = \frac{V_1 - V_0}{a}$
$V_1 = Velocity\ at\ t_1$	$V_1 = V_0 + a\Delta t$
$\Delta d = Distance$	$\Delta d = \Delta t\left(\frac{V_1 + V_0}{2}\right)$
$\Delta t = Elapsed\ Time$	$\Delta d = \frac{V_1^2 - V_0^2}{2a}$
$\Delta t = t_1 - t_0$	

Figure 5 shows a velocity versus time graph of a vehicle accelerating at a constant rate (a) from a standstill. At time t_0 the vehicle has reached a speed V_0 and at time t_1 the vehicle has reached speed V_1. The average acceleration (a) of the vehicle is defined as change in velocity ($V_1 - V_0$) over elapsed time ($\Delta t = t_1 - t_0$).

The definition of average acceleration is:

$$Average\ acceleration, a = \frac{Change\ in\ Velocity, V_1 - V_0}{Elapsed\ time, \Delta t} \tag{7.1}$$

When the vehicle speed is increasing over time, as presented in figure 5, the term $V_1 - V_0$ in formula (7.1) becomes positive and we have positive acceleration. If the vehicle speed is decreasing over time the term $V_1 - V_0$ becomes negative and we get negative acceleration. Negative acceleration is also called deceleration and occurs when the vehicle is slowing down or stopping.

Rearranging above equation (7.1) we also get:

$$Elapsed\ time, \Delta t = \frac{V_1 - V_0}{a} \tag{7.2}$$

And:

$$Velocity, V_1 = V_0 + a\Delta t \tag{7.3}$$

Note: As figure 5 shows, V_1 represents end velocity and V_0 initial velocity.

In figure 5, the area under the graph, which is also the distance the vehicle is traveling during the elapsed time ($\Delta t = t_1 - t_0$), is not as easy to calculate as with the previous constant velocity vehicle example. To solve the problem we will look at the two speed values at time t_0 and t_1 and calculate the average velocity. The average velocity is simple the sum of V_1+V_0 divided by 2. The area under the curve is then the average "height" or velocity times the elapsed time "width".

The formula for the traveled distance (Δd) during the elapsed time (Δt) is then:

$$Distance, \Delta d = \Delta t \left(\frac{V_1+V_0}{2}\right) \qquad (7.4)$$

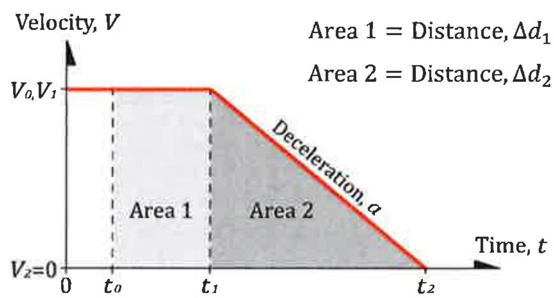
If we do not know the time (Δt) we can combine the above distance formula (7.4) with the formula for elapsed time (7.2) as shown here:

Take (7.2) $\Delta t = \frac{V_1-V_0}{a}$ and combine with (7.4) $\Delta d = \Delta t \left(\frac{V_1+V_0}{2}\right)$ which gives:

$$Distance, \Delta d = \frac{V_1^2 - V_0^2}{2a} \qquad (7.5)$$

Hint: Use the conjugate rule $(a + b)(a - b) = a^2 - b^2$ to combine the above formulas.

8. Third motion example: A vehicle traveling with a stopping motion



Area 1 = Distance, Δd_1

Area 2 = Distance, Δd_2

Fig. 6 - Constant Velocity and Deceleration

Area 1 formulas:

$$Time, \Delta t_1 = (t_1 - t_0) = \frac{\Delta d_1}{V_0}$$

$$Distance, \Delta d_1 = \Delta t_1 V_0$$

Area 2 formulas:

$$Time, \Delta t_2 = (t_2 - t_1) = \frac{V_1}{a}$$

$$Distance, \Delta d_2 = \Delta t_2 \left(\frac{V_1}{2}\right)$$

$$Distance, \Delta d_2 = \frac{{V_1}^2}{2a}$$

Figure 6 shows a vehicle traveling with an initial constant velocity (V_0) up until time t_1. The velocity (V_1) at time t_1 is still V_0 so we have $V_0 = V_1$. From t_1 the vehicle is decelerating at a constant rate (a) to a complete stop at time t_2. If we also introduce an initial time t_0 which is an added time before the vehicle is decelerating we see that this is a vehicle motion profile that is taking the shape of the first two terms of the ITE formula (1.1) – driver perception and reaction time ($t_1 - t_0$) plus vehicle stopping time ($t_2 - t_1$).

8.1 Total traveled distance calculations

The ITE formula's first term is the driver perception and reaction time. In figure 6 we can set the elapsed time (Δt_1) between time t_0 to t_1 to be the driver perception and reaction time value. Area 1 is then the distance the vehicle would travel during this perception and reaction time. We can use the first motion example and use its information with formula (6.2) since between time t_0 to t_1 both motion example vehicles are traveling at a constant velocity. The area 1 and distance (Δd_1) traveled during the perception and reaction time ($\Delta t_1 = t_1 - t_0$) is then:

$$\Delta d_1 = (t_1 - t_0)V_o \quad or \quad \Delta d_1 = \Delta t_1 V_o \tag{8.1}$$

From time t_1 to t_2, figure 6 is showing a vehicle's motion to slow down to a complete stop. At time t_1 the vehicle's speed is V_1 and it starts to decelerate with an average negative acceleration (a) until it has come to a complete stop at time t_2. Area 2 is the distance (Δd_2) the vehicle is traveling during the stopping or deceleration to come to a complete stop.

To calculate area 2 which is the distance (Δd_2) in figure 6 we can use the same methods and formulas as in the second motion example where the vehicle change velocity over time. In this example, the vehicle is decelerating to a complete stop so at time t_2 the velocity is zero ($V_2=0$). Therefore, the two distance formulas (7.4) and (7.5) then become:

$$Area\ 2 = \Delta d_2 = (t_2 - t_1)\left(\frac{V_2+V_1}{2}\right) \qquad or \qquad Area\ 2 = \Delta d_2 = \frac{V_2^2 - V_1^2}{2a}$$

Set $V_2=0$ (since vehicle stopped completely) and we get:

$$\Delta d_2 = (t_2 - t_1)\frac{V_1}{2} \qquad or \qquad \Delta d_2 = \frac{-V_1^2}{2a}$$

Since (a) is deceleration or negative acceleration, we change the sign of (a) to get:

$$\Delta d_2 = (t_2 - t_1)\frac{V_1}{2} \qquad or \qquad \Delta d_2 = \frac{V_1^2}{2a}$$

The total traveled distance (Δd) in figure 6 from time t_0 to time t_2 is then:

$$\Delta d = \Delta d_1 + \Delta d_2 \qquad \text{and set} \qquad V = V_0 = V_1$$

$$\Delta d = (t_1 - t_0)V + (t_2 - t_1)\frac{V}{2} \qquad \text{or} \qquad \Delta d = (t_1 - t_0)V + \frac{V^2}{2a}$$

If we compare the ITE formula with the two above distance equations we see that the equation including the deceleration term (a) is the best choice due to this variable is part of the ITE formula as one of the specified input values. We can also simplify the formula by using the variable (t) for the driver perception and reaction time instead of the elapsed time ($\Delta t_1 = t_1 - t_0$). The total stopping distance formula for this motion example than becomes:

$$Total\ Stopping\ Distance, \Delta d = tV + \frac{V^2}{2a} \tag{8.2}$$

The above distance formula (8.2) is also the ITE *"one safe stopping distance"* or the *"critical stopping distance"* if the vehicle is stopping on a level approach grade ($g=0$), traveling at a constant approach speed (V), setting the driver perception and reaction time to (t) and the road conditions and vehicle brakes will allow a deceleration rate (a).

8.2 Stopping time calculations

Let us now take a look at the time it takes for the vehicle to decelerate from time t_1 to t_2 in figure 6. In the second motion example we studied acceleration and we used the definition of the average acceleration to derive the elapsed time formula (7.2) again seen here:

$$\Delta t = \frac{V_1 - V_0}{a}$$

In the current example we are using different references to the initial velocity and the end velocity. We can rewrite formula (7.2) to match this example's area 2 as follows:

$$\Delta t_2 = t_2 - t_1 = \frac{V_2 - V_1}{a}$$

We already set $V_2=0$ in this example since the vehicle has completely stopped at time t_2. We also know that the average acceleration (a) is negative since the vehicle is decelerating. Setting $V_2=0$ and changing the sign of variable (a) to represent deceleration instead of acceleration we get:

$$\Delta t_2 = t_2 - t_1 = \frac{V_1}{a} \qquad (8.3)$$

The above formula (8.3) calculates the stopping time of the vehicle in figure 6 which is decelerating at rate of (a) to a complete stop from an initial velocity of (V_1).

8.3 Total stopping time calculations

By adding the driver perception-reaction time (t) (Area 1, $\Delta t_1= t_1-t_0$ in figure 6) to formula (8.3) we get the total stopping time Δt from time t_0 to time t_2. Thus, this formula would calculate the time it takes for a vehicle to travel *"one safe stopping distance"* or the *"critical stopping distance"* as per equation (8.2). Adding the perception-reaction time (t) to formula (8.3) we get:

$$Total\ Stopping\ Time, \Delta t = (t_2 - t_0) = t + \frac{V}{a} \qquad (8.4)$$

8.4 Comparison to the ITE formula

Let us now compare equation (8.3) for the vehicle's stopping or deceleration time in figure 6 with the ITE formula's second term (1.3) which is calculating the vehicle's deceleration time used for yellow traffic light change intervals.

Derived deceleration time formula (8.3):

$$\Delta t_2 = t_2 - t_1 = \frac{V_1}{a}$$

Set $V_1=V$ (vehicle approach speed) and we get

$$\frac{V}{a}$$

ITE formula deceleration time term (1.3):

$$\frac{V}{2a + 2Gg}$$

If grade is level, set $g=0$ and we get

$$\frac{V}{2a}$$

The above comparison show that the derived stopping time formula (8.3) is NOT matching the ITE formula's deceleration term (1.3) and the time it takes to decelerate to zero from an initial speed (V) for a given deceleration (a).

8.5 Why the difference?

The ITE formula's deceleration term (1.3) show an extra *"2"* in its denominator compared to formula (8.3) which is effectively doubling the deceleration rate (a) or dividing the vehicle's approach speed (V) by 2. Fact is, the ITE expression will reduce the calculated stopping time by a factor of two. We need to investigate why this *"2"* is added and also what effects it has to the timing of a traffic light's change interval related to a vehicle's motion.

It is now time to use all the derived formulas and the visual graphing tools by calculating an actual example using the typical input values recommended by the US Federal Highway Administration and the international Institute of Transportation Engineers.

9. ITE formula example using typical input values

For this example we will calculate the yellow traffic light's stopping time in a *permissive* State (no clearance time added to the yellow phase) for a 30 mph approach speed at a level intersection. The ITE formula and the input values are as follows:

$$Yellow\ Phase\ Time = t + \frac{V}{2a + 2Gg} \tag{9.1}$$

Where:

- t = Perception and reaction time of the driver, typically 1.0 seconds for an expected event, (s).
- V = Speed of the approaching vehicle, expressed in feet per second, (ft/s).
- a = Comfortable deceleration rate of the vehicle, typically 10 feet per second squared, (ft/s^2).
- G = Acceleration due to gravity, 32.2 feet per second squared, (ft/s^2).
- g = Grade of the intersection approach, in percent (%) divided by 100, downhill is negative grade and uphill is positive grade.

9.1 Speed unit conversion

First we need to convert the 30 mph vehicle approach speed to ft/s so we work with the correct units. To do this conversion we look at the unit mph which is miles per hour. We know that one mile is 5280 feet. We also know that one hour is sixty minutes and one minute is sixty seconds so we can setup the mph to ft/s conversion like this:

$$1\ mph = 1\frac{miles}{hour} = \frac{5280\ feet}{60\ minutes} = \frac{5280\ feet}{60 \times 60\ seconds} = \frac{5280\ ft}{3600\ s} = 1.466667\ ft/s$$

The example has an approach speed of 30 mph and if we apply the mph to ft/s conversion constant we get:

$$V = 1.466667\ \frac{ft/s}{mph} \times 30\ mph = 44\ ft/s$$

9.2 Calculation of the yellow phase time

Next, we can add the input values to the ITE formula for the example calculation:

$$Yellow\ Phase\ Time = t + \frac{V}{2a + 2Gg} = 1.0\ s + \frac{44\ ft/s}{2 \times 10\ ft/s^2} = 1.0\ s + 2.2\ s = 3.2\ s$$

Note: The term *"2Gg"* becomes zero since this example has a level approach grade *(g=0)*.

Let us now plot the example in a velocity versus time graph using the typical ITE formula input values and also visually present the above calculated traffic light's yellow phase time of 3.2 seconds referenced to the vehicle's motion profile.

9.3 Preparing to graph the example

To plot the example we should first investigate the data to set the velocity and time scales appropriately. Here is an initial list of the key events or data points to plot:

- Vehicle approach speed, *V=44 ft/s (30 mph)*
- Driver perception-reaction time, *t=1.0 s*
- Vehicle deceleration rate, *a=10 ft/*s^2
- Yellow phase time=*3.2 s*

9.4 Calculation of total stopping time

The previous list present a maximum velocity of 44 ft/s and a maximum ITE yellow phase time of 3.2 seconds. Let us investigate the vehicle's stopping time, Δt based on the approach speed (V) and deceleration (a) using information and the derived formula (8.3) from the third motion example. Adding the example values we get:

$$Vehicle\ Stopping\ Time, \Delta t = \frac{V}{a} = \frac{44\ ft/s}{10\ ft/s^2} = 4.4\ s$$

If we can also calculate the total stopping time using formula (8.4) which includes the 1.0 seconds driver perception-reaction time (t) and we have:

$$Total\ Vehicle\ Stopping\ Time, \Delta t = t + \frac{V}{a} = 1.0\ s + \frac{44\ ft/s}{10\ ft/s^2} = 5.4\ s$$

Based on this we see that the horizontal time scale should be a minimum of 5.4 seconds.

9.5 Verification of the ITE deceleration rate

We can also check that the ITE deceleration rate, *a=10 ft/*s^2 is correct by using the formula for the definition of acceleration (7.1). Set vehicle stopping time, $\Delta t=4.4\ s$, vehicle approach speed, $V_0=44$ *ft/s* and $V_1=0$ since the vehicle comes to a complete stop in formula (7.1):

$$Average\ acceleration, a = \frac{Change\ in\ Velocity, V_1 - V_0}{Elapsed\ time, \Delta t}$$

Add values plus change acceleration to deceleration (change sign of V_0 and set $V_1=0$) and we get:

$$a = \frac{V_1 - V_0}{\Delta t} = \frac{44\ ft/s}{4.4\ s} = 10\ ft/s^2$$

The above result shows that the stopping time, $\Delta t=4.4\ s$ and the ITE deceleration rate, *a=10 ft/*s^2 are verified correctly at *44 ft/s* (*30 mph*) vehicle speed.

9.6 Calculation of the total stopping distance

Let us also calculate the example vehicle's total stopping distance which is also including the distance the vehicle is traveling during the driver perception-reaction time. Here we can use the *"one safe stopping distance"* or the *"critical stopping distance"* formula (8.2) which was derived in the third motion example.

The formula and adding the example values we get:

$$\Delta d = tV + \frac{V^2}{2a} = 1.0\,s \times 44\,ft/s + \frac{(44\,ft/s)^2}{2 \times 10\,ft/s^2} = 44\,ft + 96.8\,ft = 140.8\,ft$$

The calculated *"critical stopping distance"* of 140.8 feet is the distance it takes for a vehicle to stop if it is traveling at 30 mph and the driver takes one second to react and respond to a change of a traffic control device based on the comfortable or nonemergency ITE deceleration rate of 10 ft/s².

We now have all information needed to plot the example with values.

9.7 Graph of the ITE formula example

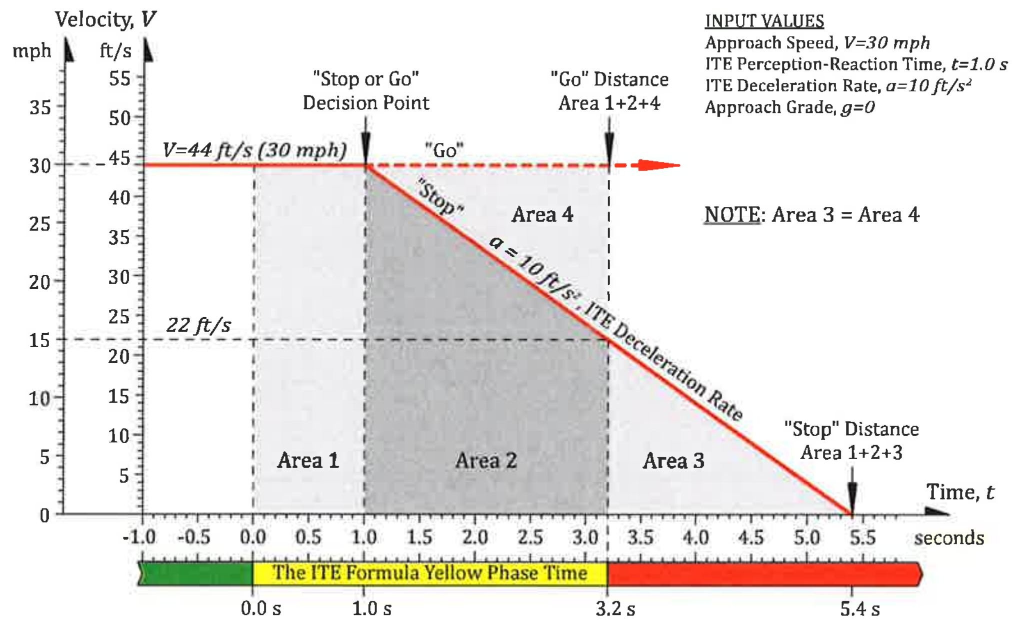


Fig. 7 - ITE Formula Example - 30 MPH Vehicle Motion and The Yellow Phase

9.8 Graph area-distance calculations

Figure 7	Average Velocity, V (Height)		Elapsed Time, Δt (Width)		Distance, Δd (Area)
Area 1:	$44\,ft/s$	×	*1.0 s*	=	$\Delta d_1 = 44.0\,ft$
Area 2:	$\frac{44\,ft/s + 22\,ft/s}{2} = 33\,ft/s$	×	2.2 s	=	$\Delta d_2 = 72.6\,ft$
Area 3:	$\frac{22\,ft/s + 0\,ft/s}{2} = 11\,ft/s$	×	2.2 s	=	$\Delta d_3 = 24.2\,ft$
Area 4:	$\frac{0\,ft/s + 22\,ft/s}{2} = 11\,ft/s$	×	2.2 s	=	$\Delta d_4 = 24.2\,ft$

Summary of calculated distance results from figure 7

Driver perception-reaction distance:	(Area 1)	$\Delta d_1 = 44.0\,ft$
Vehicle "Stop" distance:	(Area 2+3)	$\Delta d_2 + \Delta d_3 = 96.8\,ft$
Total "Stop" distance:	(Area 1+2+3)	$\Delta d_1 + \Delta d_2 + \Delta d_3 = 140.8\,ft$
Total "Go" distance:	(Area 1+2+4)	$\Delta d_1 + \Delta d_2 + \Delta d_4 = 140.8\,ft$

9.9 Driver decisions and optional behavior
Figure 7 shows a vehicle traveling at a speed of 30 mph or 44 ft/s. At time 0.0 seconds the driver sees a change of a traffic control device - a traffic signal is changing from green to yellow.

The driver takes 1.0 seconds to perceive and react to the traffic light's phase change. During the driver perception and reaction time of 1.0 seconds the vehicle is traveling 44 ft (Area 1). After this time the driver shall have decided to either "stop" or "go" as follows:

- **"Stop" decision**
  At 1.0 seconds the driver decides to stop and the vehicle is decelerating at the typical rate of 10 ft/s^2. It takes 4.4 seconds to decelerate to a complete stop and during the deceleration the vehicle is traveling 96.8 ft (Area 2 and 3 in figure 7). The total time and distance traveled (including the distance the vehicle traveled during the 1 second driver perception-reaction time) is 5.4 seconds and 140.8 feet. This total "Stop" distance traveled is equivalent to adding Area 1, 2 and 3 in figure 7.

- **"Go" decision**
  At 1.0 seconds the driver decides to make no changes and continues at the constant vehicle speed of 30 mph or 44 ft/s. During the yellow light's total phase time of 3.2 seconds the vehicle will travel a distance defined in the first motion example using formula (5.2):

  $$\Delta d = \Delta t V_o = 3.2\ s \times 44\ ft/s = 140.8\ ft$$

  The total "Go" distance of 140.8 feet is equivalent to adding Area 1, 2 and 4 found in figure 7. We can see that this constant velocity traveled distance during the yellow light phase time is the same as for the driver and vehicle that decided to stop and its total stopping distance.

Using the understanding that the areas under the plotted lines in figure 7 are equal to the distance traveled, we have:

Area 1+2+3 = Area 1+2+4, since Area 3 = Area 4

9.10 The ITE formula example's conclusions
By studying the example we can see that the "Go" vehicle will travel the same distance during the ITE formula's yellow phase time as the "Stop" vehicle will travel to a complete stop. However, the "Stop" vehicle will take 5.4 seconds to complete its traveled distance versus 3.2 seconds for the "Go" vehicle.

We can now draw the conclusion that the ITE formula for the yellow light's total stopping time is actually NOT based on time – the formula is based on *equal distance traveled* for a "Stop" or a "Go" vehicle up to a specific point – the intersection's entry point. This understanding explains the added

"2" in the denominator of the ITE formula's deceleration term (1.3) since the formula itself violates the basic laws of physics.

Yet, the ITE formula is calculating the traffic light's yellow phase stopping TIME for a permissive State in the example and we find that the *"one safe stopping distance"* or the *"critical stopping distance"* is therefore the most important formula to understand for the example is as follows:

- If a driver traveling at 30 mph faces a yellow light when he is closer than *"one safe stopping distance"* to the entry of the intersection he must "Go" and continue at the same constant speed without slowing down reaching the intersection's entry. If the driver is slowing down he might not be able to reach the entry during the time allocated by the ITE formula's calculated yellow phase time and will thus violate the red light.
- If a driver traveling at 30 mph faces a yellow light when he is farther away than *"one safe stopping distance"* to the entry of the intersection he "shall stop" and the driver is able to stop comfortably and safely based on the input variables for the ITE formula.

Finally, based on the understanding that the ITE formula is not calculating actual deceleration time per the basic laws of physics, we see that the decelerating "Stop" vehicle is still moving at 15 mph which is half the approach speed when the yellow light's phase time ends and it is taking another 2.2 seconds to come to a complete stop.

The traffic light's phase change to red and the extra time is not a problem for the stopping vehicle since it still has 24.2 feet (Area 3) to reach the full *"one safe stopping distance"* or the intersection's entry point. Thus the stopping vehicle will not enter the intersection on a red light. However, what happens, when for instance, a vehicle is within the *"critical stopping distance"* and is slowing down to make a right hand turn? Let us investigate.

10. Fourth motion example: A vehicle making a right hand turn

To be continued...

11. References

1. *"The Problem of The Amber Signal Light in Traffic Flow"*, (Denos Gazis, Robert Herman and Alexei Maradudin), Nov. 1959: http://jarlstrom.com/PDF/The_Problem_Of_The_Amber_Signal_Light_In_Traffic_Flow.pdf

2. *"Traffic Signal Timing Manual"*, (US Department of Transportation, Federal Highway Administration & Institute of Transportation Engineers ITE), June 2008, (Page 119 safe stopping distances, permissive/restrictive yellow laws & ITE formula; pages 137- 138): http://ops.fhwa.dot.gov/publications/fhwahop08024/fhwa_hop_08_024.pdf

3. *"Traffic Signal Timing Manual"*, (Institute of Transportation Engineers, ITE), 2009, (Pages 5, 12 & 13): http://jarlstrom.com/PDF/Traffic_Signal_Timing_Manual_ITE_2009_p5_12_13.pdf

4. *"Making Intersections Safer: A Toolbox of Engineering Countermeasures to Reduce Red-Light Running"*, (Federal Highway Administration & Institute of Transportation Engineers ITE), 2003, (ITE formula, document page 33, Chapter 3, Yellow Change Interval): http://safety.fhwa.dot.gov/intersection/resources/fhwasa09027/resources/Making%20Intersections%20Safer%20-%20A%20Toolbox%20of%20Engineering%20Count.pdf

5. *"NCHRP Report 731; Guidelines for Timing Yellow and All-Red Intervals at Signalized Intersections"*, (National Cooperative Highway Research Program), 2012, (See Chapter 6, page 44: "Should Yellow Change and Red Clearance Interval Timing Practices Vary Based on State Vehicle Code?" and differences between States page 64: "Appendix C"): http://onlinepubs.trb.org/onlinepubs/nchrp/nchrp_rpt_731.pdf

6. *"Stopping Sight Distance and Decision Sight Distance"*, (Transportation Research Institute Oregon State University for ODOT), Feb. 1997: http://www.oregon.gov/ODOT/HWY/ACCESSMGT/docs/stopdist.pdf

7. *"Stopping Sight Distance Discussion Paper #1"*, (Oregon State University, Robert Layton, Karen Dixon), April 2012: http://cce.oregonstate.edu/sites/cce.oregonstate.edu/files/12-2-stopping-sight-distance.pdf

8. *"2014-2015 Oregon Commercial Driver Manual"*, (Oregon Department of Transportation, ODOT & DMV), 2014, (Section 5: Air Brakes): http://www.odot.state.or.us/forms/dmv/36.pdf

12. Appendix A - Definition of the Yellow Traffic Signal for Vehicles by State

Source [5]: NCHRP Report 731 "Appendix C"

State	Definition	Steady Yellow Signal Vehicle Code
Alabama	Permissive	Vehicular traffic facing a steady circular yellow or yellow arrow signal is thereby *warned* that the related green movement is being terminated or that a red indication will be exhibited immediately thereafter.
Alaska	Permissive	*No specific information available, assume Uniform Vehicle Code as default.*
Arizona	Permissive	Vehicular traffic facing a steady yellow signal is *warned* by the signal that the related green movement is being terminated or that a red indication will be exhibited immediately thereafter when vehicular traffic shall not enter the intersection.
Arizona	Permissive	Vehicular traffic facing the signal is *warned* that the red or "STOP" signal will be exhibited immediately thereafter, and vehicular traffic shall not enter the intersection when the red or "STOP" signal is exhibited.
California	Permissive	A driver facing a steady circular yellow or yellow arrow signal is, by that signal, *warned* that the related green movement is ending or that a red indication will be shown immediately thereafter.
Colorado	Permissive	Vehicular traffic facing a steady circular yellow or yellow arrow signal is thereby *warned* that the related green movement is being terminated or that a red indication will be exhibited immediately thereafter.
Connecticut	*Permissive (Corrected by author)*	Vehicular traffic facing a steady yellow signal is thereby *warned* that the related green movement is being terminated or that a *red indication will be exhibited immediately thereafter, when vehicular traffic shall stop* before entering the intersection unless so close to the intersection that a stop cannot be made in safety.
Delaware	Permissive	Vehicular traffic facing the circular yellow signal is thereby *warned* that a red signal for the previously permitted movement will be exhibited immediately thereafter.
Florida	Permissive	Vehicular traffic facing a steady yellow signal is thereby *warned* that the related green movement is being terminated or that a red indication will be exhibited immediately thereafter when vehicular traffic shall not enter the intersection.
Georgia	Permissive	Traffic, except pedestrians, facing a steady CIRCULAR YELLOW or YELLOW ARROW signal is thereby *warned* that the related green movement is being terminated or that a red indication will be exhibited immediately thereafter when vehicular traffic shall not enter the intersection.
Hawaii	Permissive	Vehicular traffic facing a steady yellow signal is thereby *warned* that the related green movement is being terminated or that a red indication will be exhibited immediately thereafter when vehicular traffic shall not enter the intersection.
Idaho	Permissive	A driver facing a steady circular yellow or yellow arrow signal is being *warned* that the related green movement is ending, or that a red indication will be shown immediately after it.
Illinois	Permissive	Vehicular traffic facing a steady circular yellow or yellow arrow signal is thereby *warned* that the related green movement is being terminated or that a red indication will be exhibited immediately thereafter.

Indiana	Permissive	Vehicular traffic facing a steady circular yellow or yellow arrow signal is *warned* that the related green movement is being terminated and that a red indication will be exhibited immediately thereafter.
Iowa	***Restrictive***	A "steady circular yellow" or "steady yellow arrow" light means vehicular traffic is warned that the related green movement is being terminated and vehicular traffic shall no longer proceed into the intersection and ***shall stop***. If the stop cannot be made in safety, a vehicle may be driven cautiously through the intersection.
Kansas	Permissive	Vehicular traffic facing a steady circular yellow or yellow arrow signal is thereby *warned* that the related green movement is being terminated or that a red indication will be exhibited immediately thereafter when vehicular traffic shall not enter the intersection.
Kentucky	Permissive	Vehicular traffic facing a steady yellow signal is thereby *warned* that the related green movement is being terminated or that a red indication will be exhibited immediately thereafter when vehicular traffic shall not enter the intersection.
Louisiana	Permissive (Corrected by author)	Vehicular traffic facing a steady yellow signal alone is thereby *warned* that the related green signal is being terminated or that a red signal will be exhibited immediately thereafter and such vehicular traffic shall not enter or be crossing the intersection when the red signal is exhibited.
Maine	Permissive	If steady and circular or an arrow, means the operator must take *warning* that a green light is being terminated or a red light will be exhibited immediately
Maryland	Permissive	Vehicular traffic facing a steady yellow signal is *warned* that the related green movement is ending or that a red signal, which will prohibit vehicular traffic from entering the intersection, will be shown immediately after the yellow signal
Massachusetts	Permissive	*No specific information available, assume Uniform Vehicle Code as default.*
Michigan	***Restrictive***	If the signal exhibits a steady yellow indication, vehicular traffic facing the signal *shall stop* before entering the nearest crosswalk at the intersection or at a limit line when marked, but if the stop cannot be made in safety, a vehicle may be driven cautiously through the intersection.
Minnesota	Permissive	Vehicular traffic facing a circular yellow signal is thereby *warned* that the related green movement is being terminated or that a red indication will be exhibited immediately thereafter when vehicular traffic shall not enter the intersection, except for the continued movement allowed by any green arrow indication simultaneously exhibited.
Mississippi	***Restrictive***	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.

Missouri	Permissive	Vehicular traffic facing a steady yellow signal is thereby *warned* that the related green movement is being terminated or that a red indication will be exhibited immediately thereafter when vehicular traffic shall not enter the intersection.
Montana	Permissive	Vehicular traffic facing a steady circular yellow or yellow arrow signal is *warned* that the traffic movement permitted by the related green signal is being terminated or that a red signal will be exhibited immediately thereafter. Vehicular traffic may not enter the intersection when the red signal is exhibited after the yellow signal.
Nebraska	***Restrictive***	Vehicular traffic facing a steady yellow indication is thereby warned that the related green movement is being terminated or that a red indication will be exhibited immediately thereafter when vehicular traffic shall not enter the intersection, and upon display of a steady yellow indication, vehicular traffic *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.
Nevada	Permissive	Vehicular traffic facing the signal is thereby *warned* that the related green movement is being terminated or that a steady red indication will be exhibited immediately thereafter, and such vehicular traffic must not enter the intersection when the red signal is exhibited.
New Hampshire	Permissive	Vehicular traffic facing a steady circular yellow or yellow arrow signal is thereby *warned* that the related green movement is being terminated or that a red indication will be exhibited immediately thereafter when vehicular traffic shall not enter the intersection.
New Jersey	***Restrictive***	Amber, or yellow, when shown alone following green means *traffic to stop* before entering the intersection or nearest crosswalk, unless when the amber appears the vehicle or street car is so close to the intersection that with suitable brakes it cannot be stopped in safety. A distance of 50 feet from the intersection is considered a safe stopping distance for a speed of 20 miles per hour, and vehicles and street cars if within that distance when the amber appears alone, and which cannot be stopped with safety, may proceed across the intersection or make a right or left turn unless the turning movement is specifically limited.
New Mexico	Permissive	Vehicular traffic facing the signal is *warned* that the red signal will be exhibited immediately thereafter and the vehicular traffic shall not enter the intersection when the red signal is exhibited except to turn as hereinafter provided.
New York	Permissive	Traffic, except pedestrians, facing a steady circular yellow signal may enter the intersection; however, said traffic is thereby *warned* that the related green movement is being terminated or that a red indication will be exhibited immediately thereafter.

North Carolina	Permissive	When a traffic signal is emitting a steady yellow circular light on a traffic signal controlling traffic approaching an intersection or a steady yellow arrow light on a traffic signal controlling traffic turning at an intersection, vehicles facing the yellow light are *warned* that the related green light is being terminated or a red light will be immediately forthcoming.
North Dakota	Permissive	Vehicular traffic facing a steady circular yellow or yellow arrow indication is thereby *warned* that the related green movement is being terminated or that a red indication will be exhibited immediately thereafter when vehicular traffic may not enter the intersection.
Ohio	Permissive	Vehicular traffic, streetcars, and trackless trolleys facing a steady circular yellow or yellow arrow signal are thereby *warned* that the related green movement is being terminated or that a red indication will be exhibited immediately thereafter when vehicular traffic, streetcars, and trackless trolleys shall not enter the intersection.
Oklahoma	Permissive	Vehicular traffic facing a steady circular yellow or yellow arrow signal is thereby *warned* that the related green movement is being terminated or that a red indication will be exhibited immediately thereafter.
Oregon	***Restrictive***	A driver facing a steady circular yellow signal light is thereby warned that the related right-of- way is being terminated and that a red or flashing red light will be shown immediately. A driver facing the light *shall stop* at a clearly marked stop line, but if none, shall stop before entering the marked crosswalk on the near side of the intersection, or if there is no marked crosswalk, then before entering the intersection. If a driver cannot stop in safety, the driver may drive cautiously through the intersection.
Pennsylvania	Permissive	Vehicular traffic facing a steady yellow signal is thereby *warned* that the related green indication is being terminated or that a red indication will be exhibited immediately thereafter.
Rhode Island	Permissive	Vehicular traffic facing the signal is *warned* by it that the red or "stop" signal will be exhibited immediately afterwards, and the vehicular traffic shall not enter or be crossing the intersection when the red or "stop" signal is exhibited.
South Carolina	Permissive	Vehicular traffic facing a steady circular yellow or yellow arrow signal is thereby *warned* that the related green movement is being terminated or that a red indication will be exhibited immediately thereafter.
South Dakota	Permissive	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 the intersection when the red or "stop" signal is exhibited.

Tennessee	Permissive (Corrected by author)	Vehicular traffic facing the signal is *warned* that the red or "Stop" signal will be exhibited immediately thereafter and that vehicular traffic shall not enter or cross the intersection when the red or "Stop" signal is exhibited.
Texas	Permissive	An operator of a vehicle facing a steady yellow signal is *warned* by that signal that: (1) movement authorized by a green signal is being terminated; or (2) a red signal is to be given.
Utah	Permissive	The operator of a vehicle facing a steady circular yellow or yellow arrow signal is *warned* that the allowable movement related to a green signal is being terminated.
Vermont	Permissive	Vehicular traffic facing a steady yellow signal is thereby *warned* that the related green signal is being terminated or that a red signal will be exhibited immediately thereafter, when vehicular traffic shall not enter the intersection.
Virginia	***Restrictive***	Steady amber indicates that a change is about to be made in the direction of the moving of traffic. When the amber signal is shown, traffic which has not already entered the intersection, including the crosswalks, *shall stop* if it is not reasonably safe to continue, but traffic which has already entered the intersection shall continue to move until the intersection has been cleared. The amber signal is a warning that the steady red signal is imminent.
Washington	Permissive	Vehicle operators facing a steady circular yellow or yellow arrow signal are thereby *warned* that the related green movement is being terminated or that a red indication will be exhibited immediately thereafter when vehicular traffic shall not enter the intersection. Vehicle operators shall stop for pedestrians who are lawfully within the intersection control area as required by *RCW 46.61.235(1)*.
West Virginia	Permissive (Corrected by author)	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.
Wisconsin	***Restrictive***	When shown with or following the green, traffic facing a yellow signal *shall stop* before entering the intersection unless so close to it that a stop may not be made in safety.
Wyoming	Permissive	Vehicular traffic facing a steady circular yellow or yellow arrow signal is thereby *warned* that the related green movement is being terminated or that a red indication will be exhibited immediately thereafter.

13. Appendix B - Emergency Stopping Distances and Time Calculations (Rev. 10)

Note: Distances marked in **RED** violate the 30 mph critical stopping distance of 141 feet.

COMMON INPUT DATA	Value	
Perception/Reaction Time, t_{pr} (s):	1.0	(t=1.0 seconds for Emergency Stopping or ITE, Expected Event).
Air Brake Delay, t_b (s):	0.5	(t_b=0.5+ seconds air brake delay - tractor-trailers, school and public buses)
Grade, g (%):	0.0	(g is negative for down grade and positive for up hill).

30 MPH NOMINAL DESIGN ITE, Car Critical Stopping Distance Nonemergency Deceleration Rate

Design Speed, V (mph):	20	25	30	35	40	45	50	55
AASHTO Coefficient of Friction, f:	0.31	0.31	0.31	0.31	0.31	0.31	0.31	0.31
Deceleration Rate, a (ft/s^2):	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00
Critical Stopping Distance, d_c (ft):	72.3	103.8	140.7	182.9	230.5	283.5	341.8	405.5
Total Stopping Time, T (s):	3.9	4.7	5.4	6.1	6.9	7.6	8.3	9.1

Car - DRY Pavement

Design Speed, V (mph):	20	25	30	35	40	45	50	55
AASHTO Coefficient of Friction, f:	0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.60
Deceleration Rate, a (ft/s^2):	19.32	19.32	19.32	19.32	19.32	19.32	19.32	19.32
Emergency Stopping Distance, d (ft):	51.6	71.5	94.1	119.5	147.7	178.7	212.4	248.9
Total Stopping Time, T (s):	2.5	2.9	3.3	3.7	4.0	4.4	4.8	5.2

Car - WET Pavement

Design Speed, V (mph):	20	25	30	35	40	45	50	55
AASHTO Coefficient of Friction, f:	0.40	0.38	0.35	0.34	0.32	0.31	0.30	0.30
Deceleration Rate, a (ft/s^2):	12.88	12.24	11.27	10.88	10.30	9.98	9.66	9.66
Emergency Stopping Distance, d (ft):	62.7	91.6	129.8	172.3	225.5	283.9	*351.3*	417.0
Total Stopping Time, T (s):	3.3	4.0	4.9	5.7	6.7	7.6	8.6	9.4

30 MPH NOMINAL DESIGN ITE, Truck/Bus WITH airbrake delay Nonemergency Deceleration Rate

Design Speed, V (mph):	20	25	30	35	40	45	50	55
AASHTO Coefficient of Friction, f:	0.31	0.31	0.31	0.31	0.31	0.31	0.31	0.31
Deceleration Rate, a (ft/s^2):	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00
Critical Stopping Distance, d_c (ft):	87.0	122.2	162.7	208.7	259.9	316.6	378.6	446.0
Total Stopping Time, T (s):	4.4	5.2	5.9	6.6	7.4	8.1	8.8	9.6

Truck/Bus, NO air brake delay - DRY Pavement

Design Speed, V (mph):	20	25	30	35	40	45	50	55
AASHTO Coefficient of Friction, f:	0.46	0.46	0.46	0.46	0.46	0.46	0.46	0.46
Deceleration Rate, a (ft/s^2):	14.80	14.80	14.80	14.80	14.80	14.80	14.80	14.80
Emergency Stopping Distance, d (ft):	58.4	82.1	109.4	140.3	174.9	213.0	254.9	300.3
Total Stopping Time, T (s):	3.0	3.5	4.0	4.5	5.0	5.5	6.0	6.5

Truck, Truck/Bus, NO air brake delay - WET Pavement

Design Speed, V (mph):	20	25	30	35	40	45	50	55
AASHTO Coefficient of Friction, f:	0.25	0.23	0.21	0.20	0.19	0.18	0.18	0.17
Deceleration Rate, a (ft/s^2):	8.05	7.37	6.83	6.41	6.12	5.86	5.64	5.51
Emergency Stopping Distance, d (ft):	82.7	127.7	185.6	256.6	339.5	437.0	549.7	670.5
Total Stopping Time, T (s):	4.7	6.0	7.5	9.0	10.6	12.3	14.0	15.7

Truck/Bus WITH air brake delay - DRY Pavement

Design Speed, V (mph):	20	25	30	35	40	45	50	55
AASHTO Coefficient of Friction, f:	0.46	0.46	0.46	0.46	0.46	0.46	0.46	0.46
Deceleration Rate, a (ft/s^2):	14.80	14.80	14.80	14.80	14.80	14.80	14.80	14.80
Emergency Stopping Distance, d (ft):	73.1	100.5	131.4	166.0	204.3	246.1	291.6	340.7
Total Stopping Time, T (s):	3.5	4.0	4.5	5.0	5.5	6.0	6.5	7.0

Truck, Truck/Bus WITH air brake delay - WET Pavement

Design Speed, V (mph):	20	25	30	35	40	45	50	55
AASHTO Coefficient of Friction, f:	0.25	0.23	0.21	0.20	0.19	0.18	0.18	0.17
Deceleration Rate, a (ft/s^2):	8.05	7.37	6.83	6.41	6.12	5.86	5.64	5.51
Emergency Stopping Distance, d (ft):	97.4	146.1	207.7	282.4	368.9	470.1	586.4	710.9
Total Stopping Time, T (s):	5.2	6.5	8.0	9.5	11.1	12.8	14.5	16.2

Intersection Comparison Data: East & westbound SW Allen at SW Lombard 30 mph, 141 ft critical stopping distance.

References

Air brake delay and stopping distances:
ODOT Commercial Driver Manual: http://www.odot.state.or.us/forms/dmv/36.pdf
Stopping distances:
ODOT/OSU February 1997: http://www.oregon.gov/ODOT/HWY/ACCESSMGT/docs/stopdist.pdf
ODOT/OSU April 2012: http://cce.oregonstate.edu/sites/cce.oregonstate.edu/files/12-2-stopping-sight-distance.pdf

Note: Both OSU reports show an typographical error in Table 3B (97 report) and 5A (2012 report) for wet pavement emergency stopping at 50 mph. (Correct value: 351 vs typo. error: 357 feet)

14. Appendix C - Deceleration Rates and Stopping Distances Comparison (Rev. 5)

Note: Distances marked in **RED** violate the 30 mph critical stopping distance of 141 feet.

(No Air Brake Delay Added)	Maximum Deceleration, *a*				Vehicle Speed, *V*	
Federal and State Standards	ft/s²	g	mph/s	(*t*=1.0 s, grade=0%)	25 mph	30 mph
ITE & ODOT "Comfortable Rate":	10.00	0.31	6.82	→ Stopping Distance, ft:	103.8	140.7
ODOT/OSU Emergency Stopping	ft/s²	g	mph/s	(*t*=1.0 s, grade=0%)	25 mph	30 mph
Car Dry Pavement:	19.32	0.60	13.17	→ Stopping Distance, ft:	71.5	94.1
Car Wet Pavement 25 mph:	12.24	0.35	7.68	→ Stopping Distance, ft:	91.6	-
Car Wet Pavement 30 mph:	11.27	0.35	7.68	→ Stopping Distance, ft:	-	129.8
Car Wet Pavement 35 mph:	10.88	0.34	7.42	→ Stopping Distance, ft:	-	-
Truck/Bus Dry Pavement:	14.80	0.46	10.09	→ Stopping Distance, ft:	82.1	109.4
Truck/Bus Wet Pavement 25 mph:	7.37	0.23	5.02	→ Stopping Distance, ft:	127.8	-
Truck/Bus Wet Pavement 30 mph:	6.83	0.21	4.66	→ Stopping Distance, ft:	-	185.5
Truck/Bus Wet Pavement 35 mph:	6.41	0.20	4.37	→ Stopping Distance, ft:	-	-

0.5 s Air Brake Delay Added	Maximum Deceleration, *a*				Vehicle Speed, *V*	
ODOT/OSU Emergency Stopping	ft/s²	g	mph/s	(*t*=1.5 s, grade=0%)	25 mph	30 mph
Truck/Bus Dry Pavement:	14.80	0.46	10.09	→ Stopping Distance, ft:	100.5	131.4
Truck/Bus Wet Pavement 25 mph:	7.37	0.23	5.02	→ Stopping Distance, ft:	146.1	-
Truck/Bus Wet Pavement 30 mph:	6.83	0.21	4.66	→ Stopping Distance, ft:	-	207.6
Truck/Bus Wet Pavement 35 mph:	6.41	0.20	4.37	→ Stopping Distance, ft:	-	-
Bus Passenger Standing	ft/s²	g	mph/s	(*t*=1.5 s, grade=0%)	25 mph	30 mph
Maximum Unsupported:	2.25	0.07	1.54	→ Stopping Distance, ft:	353.3	495.5
Loss of Equilibrium:	5.47	0.17	3.73	→ Stopping Distance, ft:	177.8	242.7
Using Handhold:	6.43	0.20	4.39	→ Stopping Distance, ft:	159.5	216.4
Using Vertical Stanchion:	8.69	0.27	5.92	→ Stopping Distance, ft:	132.3	177.3
Bus Passenger Seated	ft/s²	g	mph/s	(*t*=1.5 s, grade=0%)	25 mph	30 mph
Very Uncomfortable:	7.08	0.22	4.83	→ Stopping Distance, ft:	149.9	202.6
Dislodged Untilted Seat:	15.12	0.47	10.31	→ Stopping Distance, ft:	99.5	130.0
Dislodged Tilted Seat:	16.73	0.52	11.41	→ Stopping Distance, ft:	95.2	123.9

NOTE: SW Allen Blvd at SW Lombard Ave, Beaverton Oregon
Design values: *V*=30mph, *a*=10 ft/s2, *t*=1.0 s and *g*=0% → 141 feet critical stopping distance (ITE).
(Distances marked in RED violate the 30 mph critical stopping distance of 141 feet at SW Allen Blvd)

References

ODOT and OSU, Emergency stopping distances for wet and dry road conditions:
February 1997: http://www.oregon.gov/ODOT/HWY/ACCESSMGT/docs/stopdist.pdf
April 2012: http://cce.oregonstate.edu/sites/cce.oregonstate.edu/files/12-2-stopping-sight-distance.pdf
Air brake delay and stopping distances:
ODOT Commercial Driver Manual: http://www.odot.state.or.us/forms/dmv/36.pdf
Standing and seated bus passenger maximum deceleration rates:
http://ntl.bts.gov/lib/33000/33300/33313/33313.pdf
http://ntl.bts.gov/lib/33000/33300/33340/33340.pdf

PERGAMON

Accident Analysis and Prevention 34 (2002) 215–220

ACCIDENT ANALYSIS & PREVENTION

www.elsevier.com/locate/aap

Changes in crash risk following re-timing of traffic signal change intervals

Richard A. Retting *, Janella F. Chapline, Allan F. Williams

Insurance Institute for Highway Safety, 1005 North Glebe Road, Arlington, VA 22201-4751, USA

Received 3 October 1999; received in revised form 11 December 2000; accepted 4 January 2001

Abstract

More than 1 million motor vehicle crashes occur annually at signalized intersections in the USA. The principal method used to prevent crashes associated with routine changes in signal indications is employment of a traffic signal change interval — a brief yellow and all-red period that follows the green indication. No universal practice exists for selecting the duration of change intervals, and little is known about the influence of the duration of the change interval on crash risk. The purpose of this study was to estimate potential crash effects of modifying the duration of traffic signal change intervals to conform with values associated with a proposed recommended practice published by the Institute of Transportation Engineers. A sample of 122 intersections was identified and randomly assigned to experimental and control groups. Of 51 eligible experimental sites, 40 (78%) needed signal timing changes. For the 3-year period following implementation of signal timing changes, there was an 8% reduction in reportable crashes at experimental sites relative to those occurring at control sites ($P = 0.08$). For injury crashes, a 12% reduction at experimental sites relative to those occurring at control sites was found ($P = 0.03$). Pedestrian and bicycle crashes at experimental sites decreased 37% ($P = 0.03$) relative to controls. Given these results and the relatively low cost of re-timing traffic signals, modifying the duration of traffic signal change intervals to conform with values associated with the Institute of Transportation Engineers' proposed recommended practice should be strongly considered by transportation agencies to reduce the frequency of urban motor vehicle crashes.

Keywords: Traffic signal re-timing; Motor vehicle crashes; Red light running

1. Introduction

USA traffic engineers rely heavily on traffic signals to control and separate conflicting traffic movements at busy intersections. However, safe signal operation requires a high degree of voluntary driver compliance, and many drivers do not comply with red lights (Porter and England, 2000). When drivers disregard red lights there is a risk of collisions between intersecting vehicles, as well as to other road users, including pedestrians and bicyclists. On a national basis, red light running contributes to substantial numbers of motor vehicle crashes and injuries. Drivers who run red lights are responsible for an estimated 260 000 crashes each year, of which approximately 750 are fatal (Retting et al., 1999a). The number of fatal motor vehicle crashes at traffic signals increased 18% between 1992 and 1998, far outpacing the 5% rise in all other fatal crashes (US Department of Transportation, 1993, 1999). Motorists are more likely to be injured in crashes involving red light running than in other types of crashes, according to analyses of police-reported crashes from four urban communities; occupant injuries occurred in 45% of the red light running crashes studied, compared with 30% for all other crashes in the same communities (Retting et al., 1995).

The principal method used to prevent crashes associated with routine changes in signal indications is the use of a so-called change interval, which consists of a steady yellow signal warning of an imminent change in the right-of-way, and at many intersections is followed by an all-red phase during which traffic approaching the intersection is required to stop and conflicting traffic is delayed from entering the intersection. No universal practice exists for selecting the duration of

* Tel.: +1-703-2471500; fax: +1-703-2471678.
E-mail address: rretting@iihs.org (R.A. Retting).

0001-4575/02/$ - see front matter
PII: S0001-4575(01)00016-1

change intervals or for determining whether to use an all-red phase. The *Manual on Uniform Traffic Control Devices* (US Department of Transportation, 1988) indicates that yellow change intervals normally range from 3 to 6 s, with longer intervals generally appropriate where traffic speeds are higher. The Institute of Transportation Engineers (1985) *Proposed Recommended Practice for Determining Vehicle Change Intervals* computes yellow interval timing as a function of approach speed and grade, along with assumed values for perception–reaction time, deceleration rate, and acceleration due to gravity. The Institute of Transportation Engineers (1999) *Traffic Engineering Handbook* states that the decision to use an all-red clearance interval is determined by intersection geometry, collision experience, pedestrian activity, approach speeds, local practices, and engineering judgment. The Institute of Transportation Engineers proposed recommended practice computes the length of the all-red interval, when used, as a function of approach speed and width of the intersecting roadway that must be cleared.

Prior research indicates that the duration of signal change intervals can affect the chance of red light running and potential intersection conflicts, which in turn may influence the risk of motor vehicle crashes. For example, Zador et al. (1985) reported that deficient change interval timing — particularly short yellow signals — increased the proportion of drivers who entered intersections and did not clear them during the clearance interval. Retting and Greene (1997) reported that red light running and potential right-angle vehicle conflicts were reduced at urban intersections when yellow and/or all-red signal timings were modified to values computed using the Institute of Transportation Engineers (ITE) proposed recommended practice. In a cross-sectional study, Stein (1986) reported that intersections with inadequate change interval timing relative to the ITE proposed recommended practice had higher crash rates than intersections with adequate timing.

Although these and similar studies indicate potential safety benefits of modifying the duration of signal change intervals, there is no direct evidence that such changes reduce the risk of motor vehicle crashes. The purpose of this study was to estimate potential crash effects of modifying the duration of traffic signal change intervals to conform with values associated with the ITE proposed recommended practice.

2. Methods

The study was conducted using standard four-leg signalized intersections located on roads under the jurisdiction of the New York State Department of Transportation (NYSDOT) in Nassau and Suffolk counties. Intersections were considered ineligible if the traffic signals had been recently installed, or if during the study period there was any major road construction that would remove signals from operation or substantially alter traffic flow for a prolonged period of time. A total of 122 intersections were identified for inclusion in the study. Half were randomly chosen to have their signals re-timed, and half had no changes made to their signal timing. Traffic engineering technicians visited the experimental sites to obtain geometric measurements and to sample traffic speeds for use in computing the duration of yellow and all-red change intervals. This information was not collected for control sites as they were not visited. Of the 61 experimental sites, ten were eliminated from the study due to possible errors in implementing timing changes, most often related to confusion over similarly named intersections. Also, five control sites were eliminated prior to examining the data based on post-randomization determination of inappropriate intersection configuration.

Based on the ITE proposed recommended practice for determining change intervals, the duration of the yellow signal is computed as follows:

$$y = t + v/(2a + 2Gg),$$

where y is the length of the yellow interval, to the nearest 0.1 s; t is the driver perception/reaction time, recommended as 1.0 s; v is the velocity of approaching vehicle, in ft./s; a is the deceleration rate, recommended as 10 ft./s^2; G is the acceleration due to gravity, 32 ft./s^2; and g is the grade of approach, in percent divided by 100 (downhill is negative).

The duration of the all-red clearance interval is determined by one of the following formulas:

$$r = (w + L)/v, \quad (1)$$

$$r = P/v, \quad (2)$$

or

$$r = (P + L)/v, \quad (3)$$

where r is the length of the red clearance interval, to the nearest 0.1 s; w is the width of the intersection measured from the near-side stop line to the far edge of the conflicting traffic lane; P is the width of the intersection measured from the near-side stop line to the far side of the farthest conflicting pedestrian crosswalk; L is the length of vehicle, recommended as 20 ft.; and v is the velocity of approaching vehicle, in ft./s

The recommended application of the red interval formulas is to use Eq. (1) where there is no pedestrian traffic, the longer of Eq. (1) or Eq. (2) where there is 'the probability' of pedestrian crossings, and Eq. (3) where there is significant pedestrian traffic or the crosswalk is protected by pedestrian signals. At the request of NYSDOT, Eq. (3) was applied to all experimental intersections. Application of the ITE formulas indicated that 40 of the 51 experimental sites required increases in the duration of change interval timing (Appendix A). The final data set consisted of these 40 experimental sites and 56 control sites.

Baseline and change interval timings based on ITE proposed recommended practice for experimental sites are provided in the appendix. During the baseline period, for the experimental sites yellow signal timings ranged from 3 to 4 s, with most set at 4 s, and all-red timings ranged from 2 to 3 s, with most set at 2 s. Computed yellow timings ranged from 2.6 to 5.4 s, and computed all-red timings ranged from 1.1 to 6.5 s. NYSDOT implemented the recommended tim12 ing intervals during October 1994. At some intersections, small deviations from recommended timings were made (i.e. where computations yielded values below the minimum allowed by NYSDOT). Independent field inspections were conducted to verify the timing changes.

Computerized crash data files were obtained from NYSDOT for experimental and control intersections for the period October 1991 through October 1997. Crash analyses were limited to 'reportable crashes,' defined by NYSDOT as those that involved injuries or a minimum of $1000 property damage. Although the data files include some, typically minor, crashes not required by New York law to be reported, detailed information concerning these 'nonreportable' crashes was not available, and the crashes were excluded. Approximately 60% of the crashes were reportable. The FREQ procedure of the SAS computer software (SAS Institute, 1990) was used to compute odds ratios (OR) and P-values. The odds ratios provide a comparison between experimental and control sites for postintervention crashes adjusted for the number of preintervention crashes.

3. Results

The total numbers of reportable crashes for the study period (including before and after timing changes) were 1985 for the experimental sites and 2621 for the control sites. Overall, 5% fewer reportable crashes were recorded during the 36-month postintervention study period compared with the 36-month preintervention period (Table 1). Though not statistically significant, an 8% reduction (OR = 0.92, $P = 0.08$) in all reportable crashes at experimental sites was found relative to those occurring at control sites. Table 1 also shows results for multiple-vehicle crashes combined, rear-end crashes, right-angle crashes, and crashes involving pedestrians and bicyclists. Experimental sites were 5% less likely than control sites to report multiple-vehicle crashes postintervention, although this change was not significant ($P = 0.20$). No significant changes were observed postintervention at experimental sites relative to control sites for right-angle or rear-end collisions. However, the 37% reduction in crashes involving pedestrians and bicyclists at experimental sites relative to control sites was significant ($P = 0.03$). As a quality control measure, pedestrian/bicyclist crash data for the control sites were examined to ensure that increases in the numbers of crashes were not confined to a small number of sites and were not the result of a data entry error. Analysis indicated that increases in pedestrian/bicyclist crashes at the control sites were widespread across the sample.

Table 2 lists results for analyses of injury crashes. Seventy-six percent of reportable crashes involved injuries. Overall, there was a significant 12% reduction ($P = 0.03$) in all reportable crashes involving injuries at experimental sites relative to those occurring at control sites. Experimental sites were 9% less likely than control sites to report multiple-vehicle injury crashes postintervention ($P = 0.10$). Again, a 37% reduction in crashes involving pedestrians and bicyclists at

Table 1
Number of crashes and odds ratios[a]

Crash type	Control		Experimental		OR	P
	Preintervention	Postintervention	Preintervention	Postintervention		
All reportable	1323	1298	1044	941	0.92	0.08
All multiple-vehicle	1241	1182	968	875	0.95	0.20
Rear-end	292	262	221	223	1.12	0.18
Right-angle	141	122	142	118	0.96	0.41
Pedestrian/bicyclist	62	94	59	56	0.63	0.03

[a] Preintervention and postintervention study periods were both 36 months, P-values are one-tailed.

Table 2
Number of injury crashes and odds ratios[a]

Crash type	Control		Experimental		OR	P
	Preintervention	Postintervention	Preintervention	Postintervention		
All reportable	1007	989	803	695	0.88	0.03
All multiple-vehicle	932	878	733	630	0.91	0.10
Rear-end	243	210	181	169	1.08	0.29
Right-angle	112	92	116	101	1.06	0.38
Pedestrian/bicyclist	62	94	59	56	0.63	0.03

[a] Preintervention and postintervention study periods were both 36 months; P-values are one-tailed.

experimental sites relative to control sites was significant ($P = 0.03$). Significant changes in crash risk were not observed for right-angle or rear-end injury crashes.

4. Discussion

Results from this study suggest that modifying traffic signal change intervals to values associated with the ITE proposed recommended practice reduces the risk of crashes involving pedestrians and bicyclists and may reduce the overall risk of multiple-vehicle crashes, particularly those resulting in injuries. The finding that 40 out of 51 experimental sites needed signal timing changes to conform with the ITE proposed recommended practice suggests the overall number of intersections that can benefit from signal timing changes is very large.

Although right-angle collisions generally are a specific target of signal change interval improvements, such crashes did not decline significantly at the experimental sites relative to the control sites postintervention. One reason may be that most timing changes in this study were relatively modest and, therefore, may not have been large enough to prevent right-angle crashes, which may occur several seconds after onset of the red signal. And unintentional running of red lights caused by inattention or other driver failures may occur long after the light has turned red, and, therefore, resulting crashes would not be reduced by this countermeasure. Also, crash type information provided by the NYSDOT computerized crash data files is rather vague and often does not provide adequate details for documenting more specific crash circumstances. Pedestrian crashes may be more affected by relatively small changes in the duration of signal change interval timing because of the tendency of many pedestrians to enter into the intersection immediately after onset of a green light or walk signal, thus potentially placing themselves in the path of drivers who are late clearing the intersection. For example, a study of real-world pedestrian behavior at signalized intersections reported that pedestrians began crossing, on average, within 1 s of the walk light illumination (Fugger et al., 2000). In discussing this finding, the authors state that it may be necessary to provide a clearance interval to protect pedestrians from drivers who enter on yellow or red signals, but they do not address the amount of clearance time needed.

Given the overall injury results, the large proportion of intersections in need of re-timing to conform with the ITE proposed recommended practice, and the relatively low cost of re-timing traffic signals, modifying the duration of traffic signal change intervals to conform with values associated with the ITE proposed recommended practice should be strongly considered by transportation agencies to reduce the frequency of urban motor vehicle injury crashes.

This study has limitations. The crash analysis did not account for numerous intersection-specific variables such as geometry, traffic volume, number of signal phases, and total cycle length, which could be factors in the relationship between the duration of the change interval and crash risk. Also, even though sites were randomly assigned to be experimental or control, they were not stratified or matched to control for influential factors such as geographic location, intersection design, and operational characteristics, and some experimental and control sites had to be dropped. Finally, long-term effects on crash risk are not known and may differ from those observed in the 3-year experimental period.

In addition to providing adequate signal change interval timing, the risk of crashes at traffic signals can be reduced through changes in signals, enhancing enforcement against red light running, and replacing signals with alternative forms of traffic control. For example, signal visibility can be improved by increasing the size of the signal display (typically from 8 to 12 in. lenses), installing brighter signals, installing additional signal heads, and repositioning the location of signal heads. Such efforts have been shown to reduce crashes and automobile insurance claims (Polanis, 1992; Feber et al., 2000). Red light cameras have been shown to substantially reduce red light violations, and this type of enforcement is supported by the majority of urban motorists (Retting et al., 1999b,c).

Two alternatives to traffic signal control that can reduce crash risk are roundabouts and multiway stop control. Persaud et al. (2002) reported that conversion of 24 US intersections from stop signs and signal control to roundabouts reduced total motor vehicle crashes by 39% and injury crashes by 76%. Following conversion of 199 urban intersections from traffic signal to multiway stop sign control, Persaud et al. (1997) reported a reduction in crashes of approximately 24%, with larger reductions found for injury crashes.

Acknowledgements

The authors acknowledge assistance provided by Jack Knoll, Donald Terry, Robert Limoges, and Tom Oelerich of the New York State Department of Transportation, Joseph Pecora and Edwin Hilbrandt of the Nassau County Department of Public Works, and Claire Segawa and Jessica Williams of the Insurance Institute for Highway Safety. This work was supported by the Insurance Institute for Highway Safety.

Appendix A

See Table A1 (overleaf).

References

Feber, D.J., Feldmeier, J.M., Crocker, K.J., 2000. The AAA Michigan Road Improvement Demonstration Program: an analysis of the effectiveness of using safety enhancements to help reduce societal and insurance costs. In: Proceeding of the Transportation Research Board 79th Annual Meeting. Transportation Research Board, Washington, DC (CD ROM).

Fugger, T.F., Randles, B.C., Stein, A.C., Whiting, W.C., Gallagher, B., 2000. Analysis of pedestrian gait and perception–reaction at signal controlled crosswalk intersections. Transportation Research Record 1705, 20–25.

Institute of Transportation Engineers, 1985. Proposed Recommended Practice for Determining Vehicle Change Intervals. Washington, DC.

Institute of Transportation Engineers, 1999. Traffic Engineering Handbook, 5th edn. Washington, DC.

Persaud, B.N., Hauer, E.J., Retting, R.A., Vallurupalli, R., Mucsi, K., 1997. Crash reductions related to traffic signal removal in Philadelphia. Accident Analysis and Prevention 29, 803–810.

Persaud, B.N., Retting, R.A., Garder, P.E., Lord, D., 2002. Observational before–after study of the safety effects of U.S. roundabout conversions using the empirical Bayer method. Transportation Research Record (in press).

Polanis, S.F., 1992. Reducing traffic accidents through traffic engineering. Transportation Quarterly 46, 235–242.

Porter, B.E., England, K.J., 2000. Predicting red-light running behavior: a traffic safety study in three urban settings. Journal of Safety Research 31, 1–8.

Retting, R.A., Greene, M.A., 1997. Influence of traffic signal timing on red light running and potential vehicle conflicts at urban intersections. Transportation Research Record 1595, 1–7.

Retting, R.A., Williams, A.F., Preusser, D.F., Weinstein, H.B., 1995. Classifying urban crashes for countermeasure development. Accident Analysis and Prevention 27, 283–294.

Retting, R.A., Ulmer, R.G., Williams, A.F., 1999a. Prevalence and characteristics of red light running crashes in the United States. Accident Analysis and Prevention 31, 687–694.

Retting, R.A., Williams, A.F., Farmer, C.M., Feldman, A.F., 1999b. Evaluation of red light camera enforcement in Oxnard, California. Accident Analysis and Prevention 31, 169–174.

Retting, R.A., Williams, A.F., Farmer, C.M., Feldman, A.F., 1999c. Evaluation of red light camera enforcement in Fairfax, Virginia. ITE Journal 69, 30–34.

SAS Institute, 1990. SAS/STAT User's Guide, ver. 6, 4th edn.. SAS Institute Inc., Cary, NC.

Stein, H., 1986. Traffic signal change intervals: policies, practices, and safety. Transportation Quarterly 40, 433–445.

US Department of Transportation, 1988. Manual on Uniform Traffic Control Devices. Washington, DC.

US Department of Transportation, 1993. Traffic safety facts 1992. Washington, DC.

US Department of Transportation, 1999. Traffic safety facts 1998. Washington, DC.

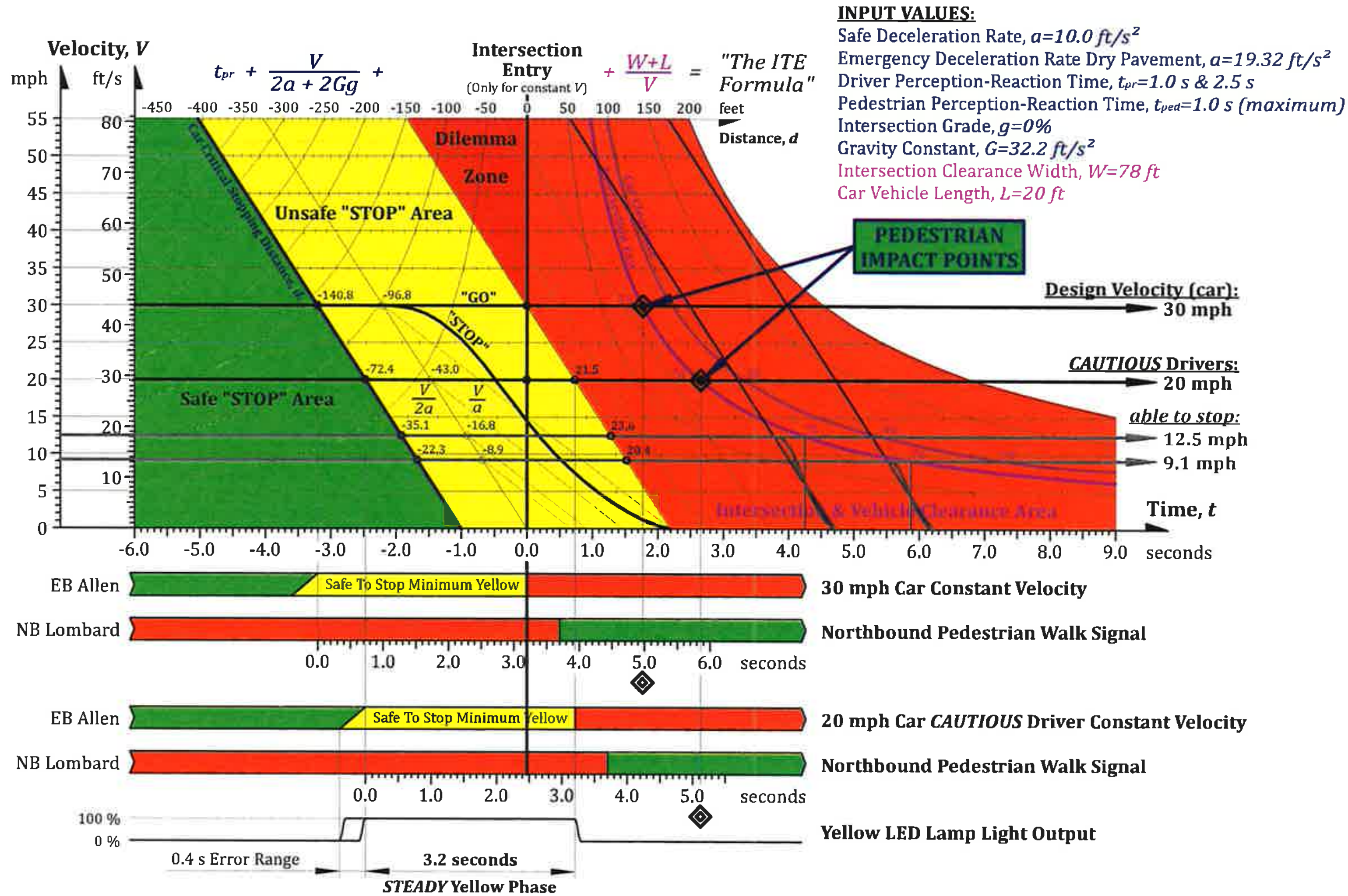
Zador, P.L., Stein, H.S., Shapiro, S., Tarnoff, P.J., 1985. Effect of signal timing on traffic flow and crashes at signalized intersections. Transportation Research Record 1010, 1–8.

Table A1
Baseline and computed change interval timings for 40 experimental intersections

Site no.	Direction[a]	Baseline signal timing			Institute of Transportation Engineers signal timing			Site no.	Direction[a]	Baseline signal timing			Institute of Transportation Engineers signal timing		
		Yellow	Red	Total	Yellow	Red	Total			Yellow	Red	Total	Yellow	Red	Total
62	NB/SB	4	2	6	3.9	3.1	7.0	85	NB/SB	4	2	6	3.4	3.5	6.9
62	EB/WB	4	2	6	4.8	1.9	6.6	85	EB/WB	4	2	6	4.8	1.5	6.3
64	NB/SB	3	2	5	3.8	4.6	8.4	86	NB/SB	4	2	6	3.3	4.6	7.9
64	EB/WB	4	2	6	4.7	1.9	6.6	86	EB/WB	4	2	6	4.9	1.3	6.2
66	NB/SB	4	2	6	3.5	3.3	6.8	87	NB/SB	4	2	6	3.2	4.6	7.8
66	EB/WB	4	2	6	4.9	1.4	6.3	87	EB/WB	4	2	6	4.8	1.6	6.4
67	NB/SB	4	2	6	4.7	1.9	6.5	88	NB/SB	4	3	7	3.0	5.7	8.7
67	EB/WB	4	3	7	4.7	1.9	6.6	88	EB/WB	4	2	6	4.8	1.4	6.2
68	NB/SB	4	3	7	4.5	2.3	6.8	89	NB/SB	4	2	6	3.4	4.2	7.6
68	EB/WB	4	3	7	5.0	3.2	8.2	89	EB/WB	4	2	6	4.8	1.7	6.5
69	NB/SB	4	3	7	3.1	4.7	7.8	90	NB	4	2	6	2.6	5.6	8.2
69	EB/WB	4	3	7	5.4	1.1	6.5	90	EB/WB	4	2	6	4.9	1.3	6.2
70	NB	4	2	6	2.9	3.1	6.0	91	NB/SB	4	2	6	3.8	2.3	6.1
70	EB/WB	4	2	6	3.8	1.5	5.3	91	EB/WB	4	2	6	4.7	1.7	6.4
71	SB	4	2	6	3.0	3.0	5.9	92	NB/SB	3.5	2	5.5	3.9	2.7	6.7
71	EB/WB	4	2	6	3.1	2.3	5.4	92	EB/WB	4	2	6	4.7	2.0	6.7
72	NB/SB	4	2	6	2.9	3.4	6.3	97	NB/SB	4	2	6	3.3	4.4	7.7
72	EB/WB	4	2	6	3.1	2.4	5.5	97	EB/WB	4	2	6	4.7	1.6	6.3
74	NB/SB	4	2	6	2.9	3.4	6.3	98	NB/SB	4	3	7	4.0	1.9	5.9
74	EB/WB	4	2	6	4.2	1.7	5.9	98	EB/WB	4	2	6	3.8	4.6	8.4
75	NB/SB	4	3	7	3.8	3.5	7.3	100	NB/SB	4	2	6	4.4	2.4	6.8
75	EB/WB	4	2	6	4.9	1.9	6.8	100	EB/WB	4	2	6	3.4	3.8	7.3
76	NB/SB	4	2	6	3.9	3.6	7.6	101	NB/SB	4	2	6	4.5	1.6	6.1
76	EB/WB	4	2	6	4.2	2.4	6.7	101	EB/WB	4	2	6	3.6	3.8	7.4
77	NB/SB	4	2	6	2.8	5.0	7.7	102	NB/SB	4	3	7	4.8	2.8	7.6
77	EB/WB	4	3	7	4.4	2.3	6.7	102	EB/WB	4	2	6	3.1	2.9	6.0
78	NB/SB	4	2	6	3.2	3.3	6.5	104	NB/SB	4	2	6	5.3	1.5	6.9
78	EB/WB	4	2	6	4.3	1.7	6.0	104	EB/WB	4	2	6	2.8	6.2	9.0
79	NB/SB	4	2	6	2.8	5.9	8.7	105	NB/SB	4	2	6	5.4	1.6	7.0
79	EB/WB	4	2	6	4.4	1.6	6.0	105	EB/WB	3	2	5	3.8	3.9	7.7
80	NB/SB	4	2	6	3.7	4.6	8.3	109	NB/SB	4	2	6	3.7	2.9	6.6
80	EB/WB	4	2	6	5.1	1.5	6.6	109	EB/WB	4	2	6	4.5	1.9	6.3
81	NB/SB	4	2	6	2.7	6.5	9.1	110	NB/SB	4	2	6	4.4	1.8	6.2
81	EB/WB	4	2	6	4.2	2.4	6.6	110	EB/WB	3.5	2	5.5	3.0	4.0	7.0
82	NB/SB	4	2	6	3.6	3.4	6.9	111	NB/SB	4	2	6	4.3	1.7	6.1
82	EB/WB	4	2	6	4.5	1.6	6.1	111	EB/WB	3.5	2	5.5	3.5	2.8	6.3
83	NB/SB	3	2	5	3.1	4.5	7.7	112	NB/SB	4	2	6	4.2	1.8	6.1
83	EB/WB	4	2	6	4.5	1.4	5.8	112	EB/WB	3.5	2	5.5	2.8	4.5	7.3
84	NB/SB	4	2	6	3.3	4.9	8.2	113	NB/SB	4	2	6	4.5	1.8	6.3
84	EB/WB	4	2	6	4.7	1.8	6.5	113	EB/WB	3.5	2	5.5	3.5	3.5	7.0

[a] Direction of travel: EB, eastbound; NB, northbound; SB, southbound; WB, westbound.

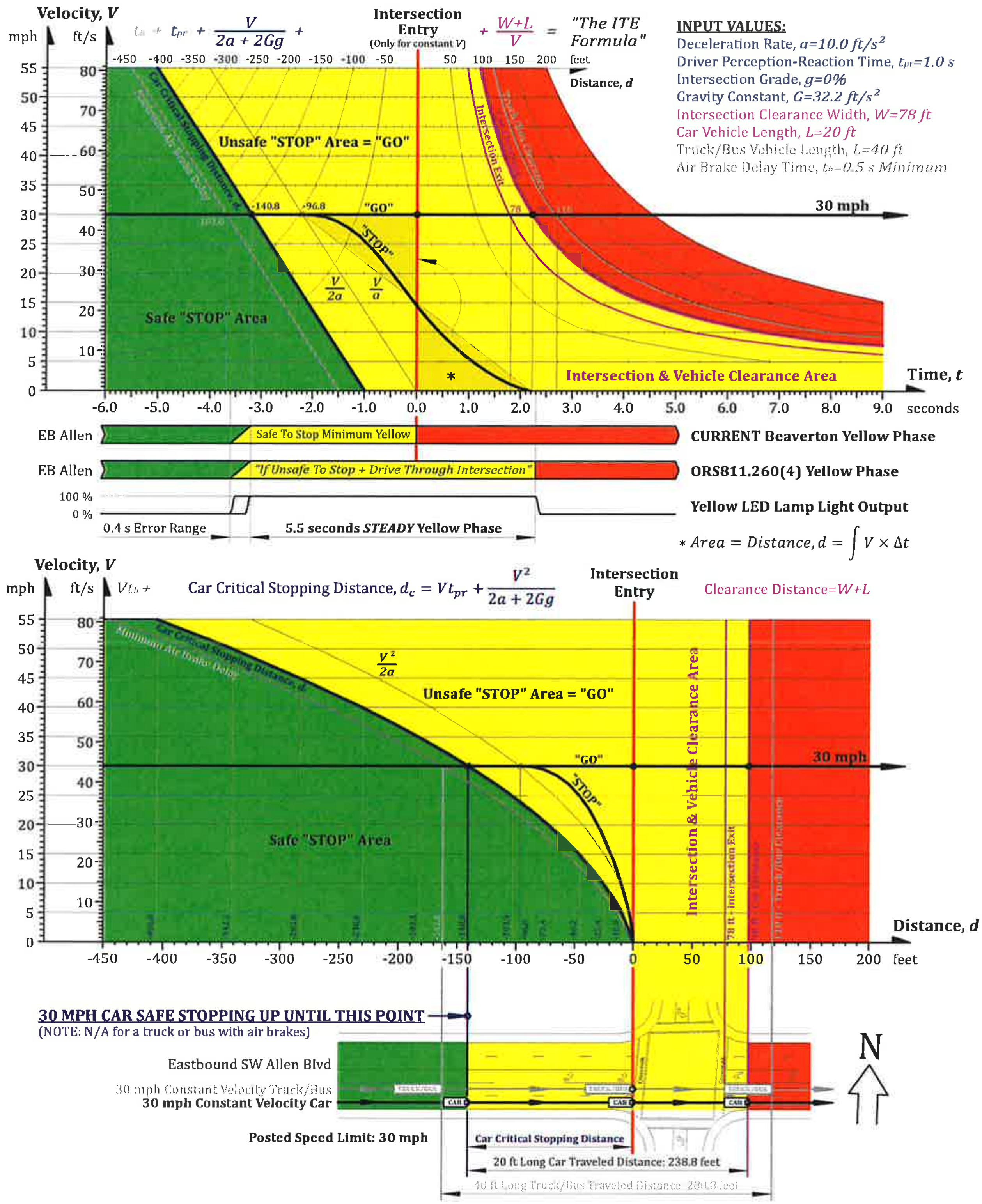
Ex. 2
Page 6 of 6



Shown Examples: CURRENT Yellow Timing for 9.1, 12.5, 20 and 30 MPH Eastbound SW Allen Blvd. at SW Lombard Ave. Beaverton, Oregon

Complaint "Exhibit A" Velocity vs. Time & Distance Yellow Traffic Light Vehicle Motion Graph

Mats Järlström • mats@jarlstrom.com • 503-671-0312 • Beaverton, Oregon, USA • September 9, 2014 • Rev. A



Shown Example: 30 MPH Eastbound SW Allen Blvd. at SW Lombard Ave. Beaverton, Oregon

ORS811.260(4) Velocity vs. Time & Distance Yellow Traffic Light Graphs

Mats Järlström • mats@jarlstrom.com • 503-671-0312 • Beaverton, Oregon, USA • September 9, 2014 • Rev. A

CERTIFICATE OF SERVICE

I hereby certify that on the 10th day of September, 2014, I served the foregoing **DECLARATION OF MATS JARLSTROM,** on the following:

Gerald L. Warren
Law office of Gerald Warren
901 Capitol Street, NE
Salem OR 97301

Attorney for Defendant

by the following indicated method(s):

☐ by **mail** with the United States Post Office at Portland, Oregon in a sealed first-class postage prepaid envelope.

☐ by **email**.

☐ by **hand delivery**.

☐ by overnight mail.

☐ by **facsimile**.

☒ by the court"s Cm/ECF system.

/s/ Michael E. Haglund
Michael E. Haglund, OSB No. 772030

Haglund Kelley LLP
200 SW Market Street, Suite 1777
Portland, OR 97201
Tel: (503) 225-0777 / Fax: (503) 225-1257

Pamela Vanderheiden

m:	info@ord.uscourts.gov
nt:	Wednesday, September 10, 2014 1:26 PM
To:	nobody@ord.uscourts.gov
Subject:	Activity in Case 3:14-cv-00783-AC Jarlstrom v. City of Beaverton Declaration

This is an automatic e-mail message generated by the CM/ECF system. Please DO NOT RESPOND to this e-mail because the mail box is unattended.
*****NOTE TO PUBLIC ACCESS USERS*** Judicial Conference of the United States policy permits attorneys of record and parties in a case (including pro se litigants) to receive one free electronic copy of all documents filed electronically, if receipt is required by law or directed by the filer. PACER access fees apply to all other users. To avoid later charges, download a copy of each document during this first viewing. However, if the referenced document is a transcript, the free copy and 30 page limit do not apply.**

U.S. District Court

District of Oregon

Notice of Electronic Filing

The following transaction was entered by Haglund, Michael on 9/10/2014 at 1:25 PM PDT and filed on 9/10/2014

se Name:	Jarlstrom v. City of Beaverton
ase Number:	3:14-cv-00783-AC
Filer:	Mats Jarlstrom
Document Number:	33

Docket Text:
Declaration of Mats Jarlstrom . Filed by Mats Jarlstrom. (Related document(s): Objection[32].) (Attachments: # (1) Exhibit) (Haglund, Michael)

3:14-cv-00783-AC Notice has been electronically mailed to:

Gerald L. Warren gwarren@geraldwarrenlaw.com, lkinman@geraldwarrenlaw.com

Michael E. Haglund mhaglund@hk-law.com, atodd@hk-law.com, kelley@hk-law.com, pvanderheiden@hk-law.com, spayne@hk-law.com, sscott@hk-law.com

Shenoa L. Payne spayne@hk-law.com, llaplante@hk-law.com

3:14-cv-00783-AC Notice will not be electronically mailed to:

The following document(s) are associated with this transaction:

Document description: Main Document
Original filename: Not Available

Electronic document Stamp:
[STAMP ordStamp_ID=875559790 [Date=9/10/2014] [FileNumber=4870561-0] [
[illegible]febe5f73d155ffa216efb7c2fa4ee9bb3382d45192ee048d7b79bff9f7ab22dbd9cc
[illegible]4f3f835670ae080562cd3d65f89688efec9177ed9655b2b55997106]]
Document description: Exhibit
Original filename: Not Available
Electronic document Stamp:
[STAMP ordStamp_ID=875559790 [Date=9/10/2014] [FileNumber=4870561-1] [
179f0a3f0dff0fcae4abbcb766310680a7bc0e5eff6bc525a409abefbcf7934cbf22bf
b2a6546ab54eb1a24f27c82398d5013b48729096262220eca9fcdf23c7]]