Helping Autonomous Vehicles at Signalized Intersections

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Abstract. The conventional way of operating vehicles is being revolutionized. In the coming years, driverless "self-driving" vehicles will be traveling on roadways alongside human-driven vehicles.

Self-driving vehicles are currently at several stages of development. This development could range from a stage where the driver completely controls the vehicle at all times to a stage where the vehicle itself controls all the operations from the start to stop.

Human error accounts for the majority of vehicle collisions. Therefore, driverless vehicles could have great potential for improving safety, mobility and air quality at a signalized intersection.

With self-driving vehicles, human behaviour does not play any role when the vehicle makes decisions to stop or perform a turning manoeuvre. On the other hand, signal timing parameters (e.g. duration of green, amber and red clearance times) are calculated taking into consideration human perception and reaction time. Will the existing methods of calculating signal timing parameters suffice for the needs of self-driving vehicles? Should there be consultation and/or collaboration between road authorities and the manufacturers of self-driving vehicles?

In this paper the signal timing parameters will be reviewed taking into consideration both human-driven vehicles and self-driving vehicles, in the interest of safety and efficiency at signalized intersections.

SCOPE

This paper assesses the signal timing parameters taking into consideration the safety of all levels of vehicle automation.

As per the National Highway Traffic Safety Administration (NHTSA) classification, these are, Level 0 "No Automation", Level 1 "Function-Specific Automation", Level 2 "Combined Function Automation", Level 3 "Limited Self-driving Automation", and Level 4 "Full Self-driving Automation".

The definitions below cover the complete range of vehicle automation levels:

● ***Level 0 – No-Automation:*** *The driver is in complete and sole control of the primary vehicle controls (brake, steering, throttle, and motive power) at all times, and is solely responsible for monitoring the roadway and for safe operation of all vehicle controls. Vehicles that have certain driver support/convenience systems but do not have control authority over steering, braking, or throttle would still be considered "level 0" vehicles. Examples include systems that provide only warnings (e.g., forward collision warning, lane departure warning, blind spot monitoring) as well as systems providing automated secondary controls such as wipers, headlights, turn signals, hazard lights, etc. Although a vehicle with V2V warning technology alone would be at this level,* *that technology could significantly augment, and could be necessary to fully implement, many of the technologies described below, and is capable of providing warnings in several scenarios where sensors and cameras cannot (e.g., vehicles approaching each other at intersections).* (5)

● ***Level 1 – Function-specific Automation:*** *Automation at this level involves one or more specific control functions; if multiple functions are automated, they operate independently from each other. The driver has overall control, and is solely responsible for safe operation, but can choose to cede limited authority over a primary control (as in adaptive cruise control), the vehicle can automatically assume limited authority over a primary control (as in electronic stability control), or the automated system can provide added control to aid the driver in certain normal driving or crash-imminent situations (e.g., dynamic brake support in emergencies). The vehicle may have multiple capabilities combining individual driver support and crash avoidance technologies, but does not replace driver vigilance and does not assume driving responsibility from the driver. The vehicle's automated system may assist or augment the driver in operating one of the primary controls – either steering or braking/throttle controls (but not both). As a result, there is no combination of vehicle control systems working in unison that enables the driver to be disengaged from physically operating the vehicle by having his or her hands off the steering wheel AND feet off the pedals at the same time. Examples of function-specific automation systems include: cruise control, automatic braking, and lane keeping.* (5)

● ***Level 2 - Combined Function Automation:*** *This level involves automation of at least two primary control functions designed to work in unison to relieve the driver of control of those functions. Vehicles at this level of automation can utilize shared authority when the driver cedes active primary control in certain limited driving situations. The driver is still responsible for monitoring the roadway and safe operation and is expected to be available for control at all times and on short notice. The system can relinquish control with no advance warning and the driver must be ready to control the vehicle safely. An example of combined functions enabling a Level 2 system is adaptive cruise control in combination with lane centering. The major distinction between level 1 and level 2 is that, at level 2 in the specific operating conditions for which the system is designed, an automated operating mode is enabled such that the driver is disengaged from physically operating the vehicle by having his or her hands off the steering wheel AND foot off pedal at the same time.* (5)

● ***Level 3 - Limited Self-Driving Automation:*** *Vehicles at this level of automation enable the driver to cede full control of all safety-critical functions under certain traffic or environmental conditions and in those conditions to rely heavily on the vehicle to monitor for changes in those conditions requiring transition back to driver control. The driver is expected to be available for occasional control, but with sufficiently comfortable transition time. The vehicle is designed to ensure safe operation during the automated driving mode. An example would be an automated or self-driving car that can determine when the system is no longer able to support automation, such as from an oncoming construction area, and then signals to the driver to reengage in the driving task, providing the driver with an appropriate amount of transition time to safely regain manual control. The major distinction between level 2 and level 3 is that at level 3, the vehicle is designed so that the driver is not expected to constantly monitor the roadway while driving.* (5)

● ***Level 4 - Full Self-Driving Automation (Level 4):*** The vehicle is designed to perform all safety-critical driving functions and monitor roadway conditions for an entire trip. Such a design anticipates that the driver1 will provide destination or navigation input, but is not expected to be available for control at any time during the trip. This includes both occupied and unoccupied vehicles. By design, safe operation rests solely on the automated vehicle system. (5)

In the rest of this paper the vehicle level 0 will be named “conventional vehicles”, and the vehicle levels 3 and 4 will be named the “AV”.

In this paper the following is assumed:

-The AV is adaptive and capable of adjusting itself momentarily to inclement weather conditions (i.e. snow, rain, fog) and roadway conditions (e.g. wet pavements, work zones).

-The AV on-board computer is programmed so that the AV abides with traffic laws (i.e. not to exceed posted speed limit, follow the rules of traffic signal indications, and stop at STOP signs etc.).

-The AV is capable of responding to traffic control signal indication changes in a split second. However, this response time can be calibrated by the manufacturers of the AV to resemble the human perception-reaction time.

INTRODUCTION

The transition from conventional vehicles to the AV may last for decades. In the interim, various levels of vehicle automation will traverse the roadways simultaneously.
This paper will focus on assessing the suitability of existing methods of calculating signal timing parameters to suit the needs of conventional vehicles and the AV.

The AV could reduce congestion on highways where capacity expansion projects are not feasible. The AV could change the concept of vehicle ownership. As a result, the number of commuting vehicles could drop. This will reduce emissions related to vehicles and improve air quality.

Driving in autonomous mode allows the operator to use his/her time for other useful tasks such as reading, working remotely.

The use of the AV could reduce the number and severity of vehicle collisions. The AV could offer mobility to elderly and disabled people. In rural areas, the AV could complement public transit.

Based on transportation surveys, it is estimated that the average car is parked up to 95 percent of the time, which requires designating large areas solely for parking. On the other hand, the AV will be able to drop passengers and move to serve others with no need for a parking space. As a result, the AV will allow more efficient use of land use in our cities.

Driver performance at signalized intersections

Driver performance is influenced by many psychological, environmental, and vehicle design factors. This paper will focus on the following factors:

1) Driver perception and reaction time.

   Driver perception-reaction time used for calculating the yellow change interval is 1 second minimum (8). Under specific conditions (typically isolated rural or high-speed locations with posted speed 80 km/h or higher), road authorities may choose to employ a longer perception-reaction time (6).

2) Factors such as driver age, fatigue, or alcohol consumption.

   Driver age, fatigue and the various forms of distracted driving do not apply to the AV. The algorithms ruling the AV on board computer allow the AV to drive conservatively at or below the posted speed limit and follow the traffic laws with all decisions made in a nominal time.

3) Design speed
   a. Typically, road authorities use the 85^{th} percentile speed for calculating the yellow change interval, the passage time and the location of the long distance loop detectors.
   b. The posted speed limit is established by law or regulation. It is not an accurate estimate of the 85^{th} percentile speed.
   c. The 85^{th} percentile speed, in the absence of field measurement, is approximately 11 km/h above the posted speed limit for through traffic vehicles, and approximately 8 km/h below the posted speed limit for left-turning vehicles (8).

4) The intersection geometric design has an impact on the visibility of signal indications, the stopping sight distance and the signal timing design.

It is important to consider the factors above when calculating the traffic control signal parameters. Otherwise, the traffic control signal will operate improper timing resulting in unsafe conditions (collisions), low LOS, wasted commuter times and increases in fuel consumption.

The basic timing parameters used to develop signal timing plans for a standard eight-phase intersection

The following parameters are typically programmed for each phase in the traffic signal controller (NEMA & 170 specifications):

1) Minimum Green Time
2) Passage time (Vehicle Extension Time)
3) Maximum green Time
4) Yellow change interval
5) Red clearance interval
6) Pedestrian Timing Intervals (walk interval, pedestrian clearance interval)

For coordinated systems, in addition to the above, the important parameters are: cycle length, phase split, and offsets.

The following section identifies any concerns - and recommended solutions - related to the current methods of determining signal timing parameters.

SIGNAL TIMING PARAMETERS

1) MINIMUM GREEN

The minimum green parameter represents the least amount of time that a green signal indication is displayed when a signal phase is activated (2).

Drivers do not expect an immediate termination of a signal display that has just started. Therefore, a minimum interval time is used in order to avoid violating driver expectations.

With the volume-density mode of operation, an “added initial” feature could be used with actuated phases to increase the minimum green time to account for the vehicles stored between the long distance detector and the stop line at the onset of green.

The added initial feature increases the minimum as necessary based on the vehicles that arrived while the signal is not green. Without the “added initial” feature, the minimum green would have to be set high to clear all stored vehicles.

A start-up time of up to 4 seconds is usually considered when calculating the effective green time for a phase.

The current method of calculating the duration of the minimum green time should be adequate for both conventional vehicles and AVs.

Recommendation 1:

The AV start-up time should be a programmable feature. If it is too short, there could be a conflict between the AV entering the intersection at the onset of green and a conventional vehicle clearing the intersection from a previous phase. Therefore, a delay time should be programmed to the start-up time of the AV. The duration of the delay time should be automatically adjustable based on local driving conditions and driver behaviour.

2) PASSAGE TIME (also referred to as vehicle extension or unit extension)

The passage time is the maximum amount of time one vehicle actuation can extend the green interval while green is displayed (2).

Passage time values are typically based on detection zone length, detection zone location (relative to the stop line), number of lanes served by the phase, and vehicle speed (2).

On high speed approaches, the duration of the passage time and the location of associated detection zone(s) must be determined in a manner to allow the controller to terminate the phase while vehicles still have enough time to stop.

A proper location of the detection zone is at the beginning of the "decision zone". The limits of the decision zone are approximately defined between 5.5 seconds and 2.5 seconds of travel time from the stop line (1).

When a driver sees the onset of yellow, he/she has to decide whether the vehicle is too close to stop safely or too far to clear the intersection before the onset of red. This leads to a period of indecision during which the vehicle keeps moving (Figure 1).

To help drivers at high speed approaches, one or more detectors could be placed upstream of the stop line starting at the beginning of the decision zone.

The passage time value and the position of the associated detector(s) are calculated based on the approach speed (typically the 85th percentile speed). The passage time value should be adequate to prevent a phase from terminating before a vehicle clears the decision zone.

Recommendation 2:

At the onset of the yellow indication, the AV should be able to decide almost instantaneously whether it should stop or go. If the AV starts deceleration in order to stop and a conventional vehicle is following too closely, or a following conventional vehicle is accelerating assuming it can clear the intersection, then the AV is exposed to a rear-end collision. A possible solution to this scenario is to program a delay time to the AV response time, so the AV performs as well as a skilled defensive driver.

Also, at high speed approaches, advance detection methods may be utilized where all vehicles within a defined area and within identified min & max speed values are captured. The new detection methods (e.g. radar based) are capable of dynamic estimates of the arrival of each vehicle and providing individualized protection for each vehicle approaching the intersection.

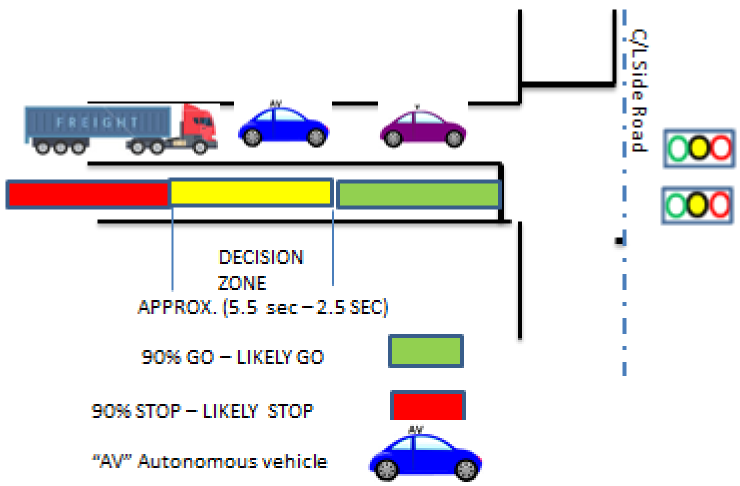

Figure-1 The AV & conventional vehicles at the onset of yellow

3) MAXIMUM GREEN

The maximum green time parameter defines the maximum amount of time that a green signal indication can be displayed in the presence of a conflicting demand. Typical maximum green values for left-turn phases range is 15 -30 sec; for through phases serving minor roads 20 – 40 seconds; for through phases serving major road 30 – 60 seconds (2).

The Maximum green time is applicable to actuated phases. Its duration is calculated using capacity analysis methods. It should be adequate to reduce the number of times a phase maxes out. At isolated intersections, the maximum green should be long enough to clear the expected traffic volume and short enough to reduce the delay to other traffic movements.

<u>Recommendation 3:</u>

The AV travel speed is equal to or below the posted speed limit while conventional vehicles usually travel at a speed equal to or higher than the posted speed limit; this could result in large gaps and could cause the phase to terminate (gap out) early. The traffic controller should be programmed to provide reasonable passage times based on field measurements.

Also, when conducting capacity analyses, the saturation flow rates (reciprocal measurement of time headway) should be based on the average time headway of both conventional vehicles and the AV.

4) YELLOW CHANGE INTERVAL

The yellow change interval is intended to alert a driver to the impending presentation of a red indication (2).

It is the first interval following the green right-of-way interval. It is a clearance interval to warn approaching traffic to clear the intersection before conflicting traffic receives a green indication (6).

Under the permissive yellow law, the yellow change interval has two purposes:

a) It permits approaching vehicles that can come to a comfortable stop to stop.
b) It permits approaching vehicles that are either within the intersection or too close to the stop line to clear the intersection.

The ITE kinematic equation is the recommended and commonly used method for calculating the yellow change interval (8).

$Y = T + V / (2 (a + G g))$ ……………………………………. (1)

Where:

Y = length of the yellow change interval (sec)

T = perception – reaction time, generally assumed as 1 second

$V = 85^{th}$ percentile approach speed (km/h)

‘a = average deceleration rate, generally assumed (11 km/h/s)

‘g = approach grade (percentage divided by 100, negative for downgrade)

G = acceleration due to gravity (35.3 km/h/s)

The AV reaction time is a split second, and it travels at a speed equal to or below the posted speed limit. Therefore, if the duration of the yellow interval is sufficient for conventional vehicles, it will be sufficient for the AV as well (Figure 2).

Recommendation 4:

If the duration of the installed yellow change interval is less than the calculated value from equation 1, the AV might not be able to stop comfortably at the stop line or it might cross the stop line on red. Road authorities should ensure that the installed yellow change interval is adequate.

Also, an instant reaction of the AV to the onset of the yellow signal indication could result in a rear-end collision if a conventional vehicle is following too closely. A possible solution to this scenario is to calibrate the AV reaction time (adjustable delay time) to the onset of the yellow signal indication based on roadway conditions.

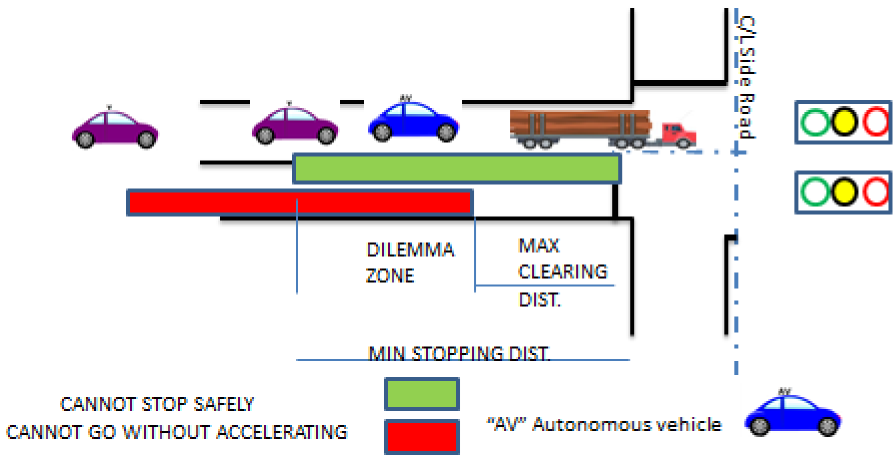

Figure – 2 The AV & conventional vehicles in the dilemma zone

5) RED CLEARANCE INTERVAL

The red clearance interval can be used to allow a brief time to elapse after the yellow indication, during which the signal heads associated with the ending phase and all conflicting phases display a red indication (2).

The red clearance is a safety related parameter. The following equation is recommended for calculating the red clearance interval (8):

$R = 3.6 (W + L) / V$ …………………………………… (2)

Where,

R = Red clearance interval (seconds)

W = Intersection width (m)

L = Vehicle length, generally assumed to be 6 m

V = 85^{th} percentile approach speed (km/h)

Recommendation 5:

To avoid a conflict between the AV clearing the intersection and a conventional vehicle entering the intersection at the onset of green, the use of the posted speed limit is recommended instead of the 85^{th} percentile speed when calculating the red clearance interval.

6) PEDESTRIAN TIMING INTERVALS

The “walk” interval is intended to give pedestrians adequate time to perceive the walk indication and depart the curb before the pedestrian clear interval begins (2).

The “pedestrian clear” interval is intended to provide time for pedestrians who depart the curb during the “walk” indication to reach the opposite curb (2).

Recommendation 6:

The programming of the AV should consider the behaviour of errant pedestrians, who might start crossing the road during the pedestrian clearance interval or while facing a Don`t Walk signal display.

7) TIMING PARAMETERS FOR COORDINATED SYSTEMS

There is a unique set of coordination parameters including cycle length, phase splits, phase sequence and offsets.

The “cycle length” under coordinated operation is the time elapsed between the endings of two sequential presentations of a coordinated phase green interval (2).

Under coordinated operation, each non-coordinated phase is provided a “split” time. The “split” time represents the sum of the green, yellow change, and red clearance intervals for the phase (2).

The “offset” entered in the traffic controller represents the time that the reference phase begins (or ends) relative to the system master time zero. The reference phase is specified to be one of the two coordinated phases (e.g. phases 2 & 6) (2).

Recommendation 7:

In coordinated systems, the relative offsets are calculated by dividing each roadway link length by the design speed for the link. The design speed is usually the actual or desired travel speed (85^{th} percentile speed). If the AV is travelling at a speed below the design speed, it will travel outside the progression green band and encounter more stops and delays. Therefore, the development of signal coordination plans should take into consideration the prevailing travel speeds for conventional vehicles as well as the AV.

CONCLUSION AND RECOMMENDATIONS

This paper provides an assessment of signal timing parameters with respect to safety and efficiency at signalized intersections. Although the focus of this paper is on the AV, there are other advancements in the auto industry, such as Connected Vehicles (CVs) that complement the AV technology. Both AV and CV technologies work hand in hand to enhance safety, mobility and air quality.

The assessment leads to the following recommendations:

-The current methods of calculating the minimum and maximum green time parameters are acceptable for both conventional vehicles and the AV.

-The programming of the on-board computers shall consider deploying adjustable delay times based on local driving conditions (provincial, territorial, and municipal) and driver behaviour.

-The calculation of the passage time parameter and associated detection zones based on a fixed approach speed is problematic. It does not serve the needs of the AV on high speed roadways. At high speed roadways, the use of advanced detection methods (e.g. wide area detection utilizing radar based technology) will better serve conventional vehicles as well as the AV.

-The duration of the yellow change interval should be calculated according to the ITE’s kinematic equation. A shorter duration of the yellow change interval will adversely impact the safety of both conventional vehicles and the AV.

-The red clearance time should be calculated using the posted speed limit instead of the 85^{th} percentile speed.

- If the AV travelling speed is below the design speed, it will disrupt the progression of traffic flow because it will be travelling outside the progression band. It is necessary to coordinate the green time at closely spaced signalized intersections, taking into consideration the prevailing travel speeds of both conventional vehicles and the AV.

To help the AVs at signalized intersections, there should be collaboration between road authorities and the manufacturers of the AVs. Some of the responsibilities are highlighted below:

Responsibility of road authorities

Road authorities shall:

Review and take appropriate action to update signalized intersections, signals hardware, detection methods, and signal timing aspects.

Review any updates to the roadway design standards, regulations, and by-laws.

Discuss with the provincial and local police any issues related to the enforcement of laws for the operation of the AVs side by side with conventional vehicles.

Consult with the auto manufacturers any concerns about the AVs performance.

Responsibility of the AV manufacturers

The AV manufacturers shall:

Maintain state of the art software for the on-board computers operating the AV, continuously developing/adding applications to enhance the safety and mobility of the AV.

Consider adding CV technology in all new vehicles. The more vehicles equipped with CV technology the safer and better mobility.

Ensure the algorithms ruling the on-board computer in the AV are programmed to react to traffic control devices and local traffic laws as a skilled defensive driver would.

Equip the AVs with effective security systems to protect the AV against cyber-attacks and risks resulting from potential gaps in the operating system.

Provide advice and support to road authorities and respond to their concerns.

Inform road authorities of any infrastructure limitations (e.g. visibility of signal indications, signs and pavement markings) to enhance the performance and safety of the AV.

Responsibility of the media

The success of the AV paradigm relies on public acceptance. The public should be educated about the AV as a future mode of mobility.

DISCLAIMER

The contents of this paper reflect the views of the author.

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