Review of Traffic Control Signal Timing Parameters for Autonomous Vehicles

Ousama Shebeeb, P. Eng.

Abstract. In the coming years, legislation may pass allowing autonomous / self-driving vehicles to travel on roadways side by side with human-driven vehicles.

Automated vehicles are still a developing technology. Developments 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 start to stop.

Human error accounts for the majority of vehicle collisions. Therefore, automated / driverless vehicles will have great potential for improving safety, mobility and air quality at signalized intersections if Vehicle-to-Vehicle (V2V) and Vehicle–to-Infrastructure (V2I) communications are established.

On the other hand, traffic control signal timing is designed to take into consideration driver perception and reaction time. But, with autonomous vehicles, human behaviour does not play any role when the vehicle makes a decision to stop or perform a turning manoeuvre. Also, to avoid liability in case of a collision, most likely autonomous vehicles will be programmed to comply with the posted speed limits on the roadway.

Will the existing methods of calculating signal timing parameters suffice for the needs of autonomous vehicles? Will there be a need to change the current methods of calculating signal timing?

In this paper a review is given of the signal timing parameters (e.g. duration of green, passage time, amber and red clearance times) taking into consideration the requirements of both human-driven vehicles and the autonomous / driverless 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”.

In the rest of this paper the vehicle level 0 will be named “conventional vehicles”, vehicle levels 1&2 will be named “vehicles” and vehicle levels 3&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 assess the suitability of existing methods of calculating signal timing parameters to suit the needs of all vehicle levels (NHTSA classification).

<u>The promise of the AV includes the following:</u>

The AV could help in mitigating traffic congestion problems 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.

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 could change the future of land use in our cities.

The following hardware is included in the AV:

Research on the web indicates that the AV hardware is relatively similar among manufacturers. However, it is the software operating the on-board computer that will make the difference.

Currently, the AV has a laser sensor on the top to capture a 360 degree image and millions of data points every second. Also, it has a camera mounted near the rear-view mirror to obtain images of traffic control signal indications, roadway signs and pavement markings. The images and data collected by the AV are processed by sophisticated software (e.g. Google software, Ford software…etc.).

The AV is also equipped with an ultrasonic sensor called the "positioning sensor" that works along with the GPS to calculate the AV mapping position.

In addition, it has four radar sensors, three sensors mounted in the front of the AV and one sensor mounted in the back.

Driver performance at signalized intersections

The following factors affect driver performance at signalized intersections:

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) Design speed
   a. Typically, road authorities use the 85th 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 85th percentile speed.
   c. The 85th 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).

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

4) There are other factors that affect driver performance 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.

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

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

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, splits, and offsets.

The following section identifies any concerns related to the current 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.

Concerns:

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”.

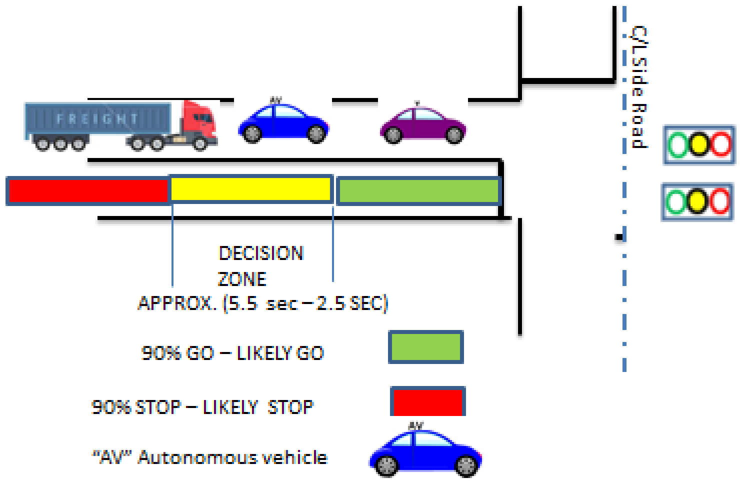

Figure-1 "the AV & conventional vehicles on a high speed approach at the onset of yellow"

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.

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.

Concerns:

At the onset of the yellow indication, the AV should be able to decide in a split second 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.

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.

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.

Concern:

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 signal timing in the controller should be programmed to provide reasonable passage times based on field measurements.

When conducting capacity analyses, the saturation flow rates (reciprocal measurement of time headway) should consider 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 = 85th 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 illustrates the dilemma zone when the yellow change interval is poorly designed.

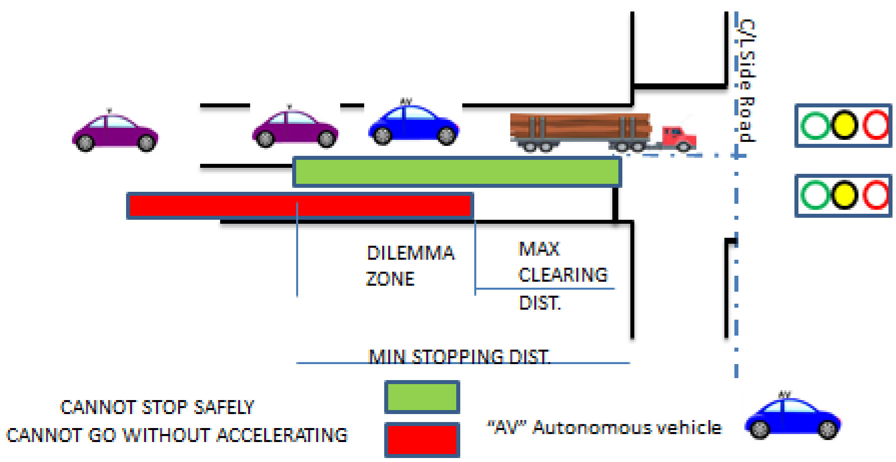

Figure – 2 “Dilemma zone boundaries”

Concerns:

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.

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)

Concerns:

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).

Concerns:

The programming of the AV shall 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, split values, offsets and sequence of phases.

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 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).

Concern:

In coordinated systems, the offsets are calculated by dividing each roadway link length by the design speed for the link. The design speed is usually the 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 a review of traffic control signal timing parameters from the perspective of safety and efficiency at signalized intersections for both conventional vehicles and the AV. The review leads to the following recommendations:

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

2. Adjustable delay times should be programmed to the start-up and reaction times of the AV. The duration of the delay times should be automatically adjustable based on the local driving conditions and driver behaviour.

3. 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. 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.

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

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

6. 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. 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.

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

DISCLAIMER

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

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Author information:

Ousama Shebeeb, P. Eng.

Traffic Signals Engineer

Traffic Office

Highway Standards Branch

Provincial Highways Management Division

Ontario Ministry of Transportation

Tel (905) 704-2221

Email: Ousama.shebeeb@ontario.ca