©2022 Published in 10th International Symposium on Innovative Technologies in Engineering and Science 21-23 October 2022 (ISITES2022 Bursa - Turkey)
https://doi.org/10.33793/acperpro.05.03.3561

Calculation of the delays of autonomous vehicles at signalized intersections using the Webster method

[1]Recep Bilal Sıkar, [2] Hakan Aslan
[1]Faculty of Engineering, Department of Civil Engineering Istanbul University – Cerrahpaşa, Istanbul – Turkey
[2] Faculty of Engineering, Department of Civil Engineering, Sakarya University, Sakarya – Turkey

Abstract

Traffic lights have an important role in the control of traffic flow as one of the key components at intersections. Delays occurring at signalized intersections significantly affect travel time Coordinating intersections is one of the most effective ways to achieve a steady flow of traffic. By means of illuminated and signal-coordinated intersections, the delay time, queue length, and travel time of vehicles moving on arterial roads may be significantly reduced. Autonomous vehicles developed within the scope of today's technology have now become a part of transportation systems. This paper evaluates the effectiveness of autonomous vehicle systems to minimize delays at intersections.

Keywords: Delay analysis, autonomous vehicle (AV), Webster method, artificial intelligence.

1. Introduction

It is one of the most effective methods for calculating delays at signalized intersections. Webster's method models delay by considering saturated streams. In this study, a signalized intersection was first modelled by Webster's method, and then the autonomous status of oncoming vehicles was investigated.

2. Literature

In the literature, the Webster method is described as the following;

‘The Webster method has since become a traditional technique to design signal timings for isolated intersections both in Australia and overseas’[1]
Webster's model [2], developed in 1958, the delay calculation procedure has stood the test of time as a fundamental method of analyzing traffic signals.
It is stated that the Webster method calculates the delay using the parameters introduced through the optimization of the cycle length.[3]
Liu, H., Rai, L., et all mentioned that in the Webster model, the total delay and the average delay of an intersection rely on the vehicle arrival rate and the intersection capacity.[4]

*Corresponding author: Address: Faculty of Engineering, Department of Civil Engineering Istanbul University-Cerrahpaşa, TURKEY. E-mail address: recep.sikar@iuc.edu.tr.

3. Methodology

3.1. Traffic Composition

Due to the difference in the types of vehicles that will use the signaling system and their effects on the capacity, the vehicles should be expressed in automobile equivalent units in the calculations. The following coefficients are used for the analysis scope of this paper.

Car:	1.00
Left Turning Car:	1.6
Right Turning Car:	1.0—1.4
Heavy Vehicle (Medium Scale):	1.5
Heavy Vehicle (Truck, Truck etc.):	2.3
Bus:	2.00
Motorcycle:	0.4
Bicycle:	0.2
Minibus, Pickup Truck:	1.3
Midibus:	1.5

If the intersection slope is more than 3.0%, the automobile equivalents might be taken higher values.

3.2. Saturated Flow

Saturated flow rate is the maximum hourly volume that can pass through an intersection with a given lane or group of lanes if that lane is solid green for one hour. In other words, the saturated flow is the maximum number of vehicles allowed to pass when the light turns red to green at a signalized intersection.

In the Webster Method saturation flow rates are computed using the following equations:

$$\boldsymbol{S = \frac{3600}{a}} \qquad \textbf{(1)}$$

a=volume/capacity ratio

The other formula for saturation flow rate:

$$\boldsymbol{S = \frac{3600}{h}} \qquad \textbf{(2)}$$

S=saturation flow rate (veh/h/lane)
h=average time headway in the platoon

Depending on the width of the lane entering the intersection, the saturated flow values can be given as follows.

Chart 1. Saturated flows for different lane widths

Lane width (m)	3	3.3	3.6	3.9	4.2	4.5	4.8	5.1
S: Saturated flow (vehicle/hour)	1850	1875	1900	1950	2075	2250	2475	2700

3.3. Webster Method

In this method optimum cycle time is determined through the formula given below bold

$$\boldsymbol{Copt = \frac{1.5 * L + 5}{1 - Y}}$$

L: total lost time during the period that can be taken as 5 seconds for each phase.
Y: It is the sum of the ratios of the maximum flow value (q) in each phase to the saturated (S) flow.

$$\boldsymbol{Y = y_1 + y_2 + \ldots\ldots + y_n = \frac{q_1}{s_1} + \frac{q_2}{s_2} + \ldots\ldots\ldots + \frac{q_n}{s_n}}$$

Cycle time: It is a complete cycle of the signal indicators.

The necessary formula for the calculation of the apparent green time (G) is;

$$\boldsymbol{G = \frac{y}{Y}(C_{opt} - L)}$$

G: Green time (sec) at each phase
y: q/s rates at each phase
Y: This is the sum of the q/s rates for the cycle. The q/s values have the highest value for each phase.

4. Applied example

For the analysis, a signal-controlled junction having four approaching traffic flow are considered and displayed below.

4.1. Definitions

When calculating, peak hours with the highest traffic flow values reflecting the busiest case should be taken into account. Therefore, the traffic flow data at the hours of the highest traffic flow were collected for the modelled intersection and analyzed. The data for 15-minute intervals during which the traffic flow is supposedly homogeneous were included in the calculations and the peak hour factors were obtained accordingly.

The following figure illustrates the phase system designed for the available traffic flows at the junction considered.

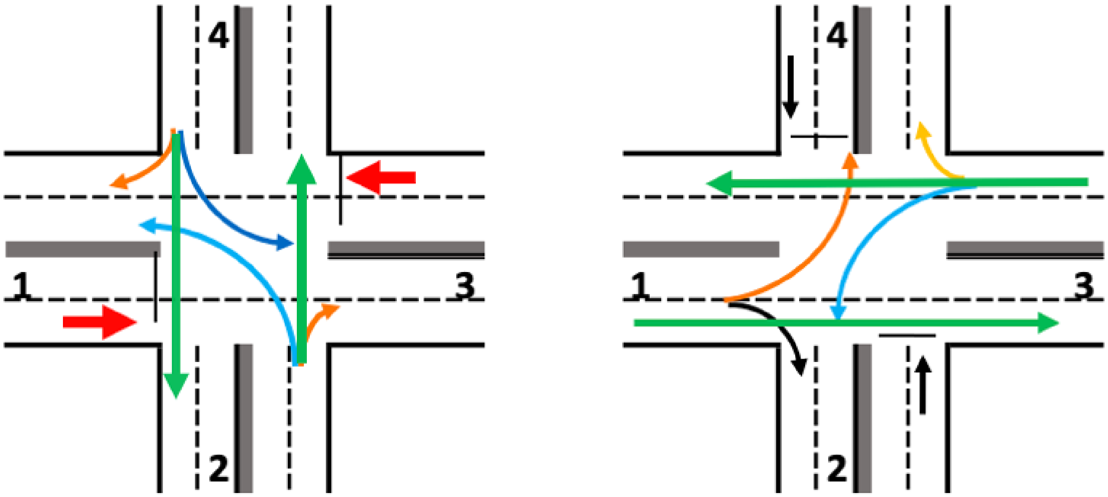


Figure 1. Phase diagrams

4.2. Calculation of Peak Hourly Volumes

Hourly traffic values for each flow in terms of car equivalency are given below.

Chart 2. Traffic flow values

Flow Direction	Hourly Traffic (veh/h)
1	479
2	281
3	408
4	433

In addition to hourly changes, traffic volumes may also show significant changes within an hour. In other words, there might be peak values in some short time intervals compared to other intervals within that specific one-hour period of counting. A transportation system should serve the value at the peak hour when the volume is the highest, as well as in the lower time zone with the maximum traffic volume, where the traffic is generally homogeneous. This leads the engineers to develop the peak hour volume (PHF) concept explained below.

$$PHF = \frac{V}{4 * V_{15}}$$

PHF: Peak hour factor
V: Hourly volume, vehicle/hour
V_{15}: maximum volume in 15-minute during peak hour, vehicles/hour

Chart 3. Peak hour flow values for each flow direction

Flow Direction	PHF
1	0.75
2	0.72
3	0.65
4	0.61

Yellow and lost times were taken as 4s and 5s for each phase, respectively.

Chart 4. PHF corrected traffic volume values for intersection flow directions

Flow Direction	Peak Hourly Volume (veh/h)	PHF	Adjusted Hourly Valume (veh/h)	% straight	% right	% left	% straight (commercial vehicle-minibus)	% right (commercial vehicle-minibus)	% left (commercial vehicle-minibus)	Saturated Flow (veh/h/lane)
1	479	0.75	639	65	3	32	18	19	17	1800
2	281	0.72	390	67	27	6	15	39	25	1800
3	408	0.65	628	59	15	26	12	2	43	1800
4	433	0.61	710	37	37	26	16	10	4	1800

Following, the design flow values obtained for all directions of automobile equivalency are illustrated in the following table.

Chart 5. Design flow values

Flow Direction	**Peak Hourly Volume in terms of Automobile Equivalency**	**PHF**	**Design Flow Value**	**q_i**	**Lane Saturation Flow Value**	**y_i**	
1	479	0,75	639	836	1800	0,23	Phase2
2	281	0,72	390	487	1800	0,14	Phase1
3	408	0,65	628	834	1800	0,23	Phase2
4	433	0,61	710	944	1800	0,26	Phase1

4.3. Delay Calculation

As one of the most important parameters to evaluate the performance of the intersections, delay values need to be calculated for different traffic volumes and geometric structures. For this reason, the delays were obtained for both normal traffic flow and those under autonomous flow conditions.
With the Webster model, the delay is formulated as in the equation 3 given below [5]:

$$d = \frac{c(1-\lambda)^2}{2(1-\lambda x)} + \frac{x^2}{2q(1-x)} - 0.65\left(\frac{c}{q^2}\right)^{\frac{1}{3}} * x^{(2+5\lambda)} \text{........................(3)}$$

where;
λ = green ratio,
x = degree of saturation
q = flow rate in each lane
c = cycle time
d = average delay per vehicle

The degree of saturation; is the ratio of the flow passing through an intersection lane to the maximum flow that can pass through that intersection (x = q / λ.s).

In Webster's model, the first term refers to uniform movement, while the second represents random movement. The last part, the correction term, represents 5% to 15% of the total delay. To obtain the formulation, the last term is multiplied by 0.9 (Webster, 1958).

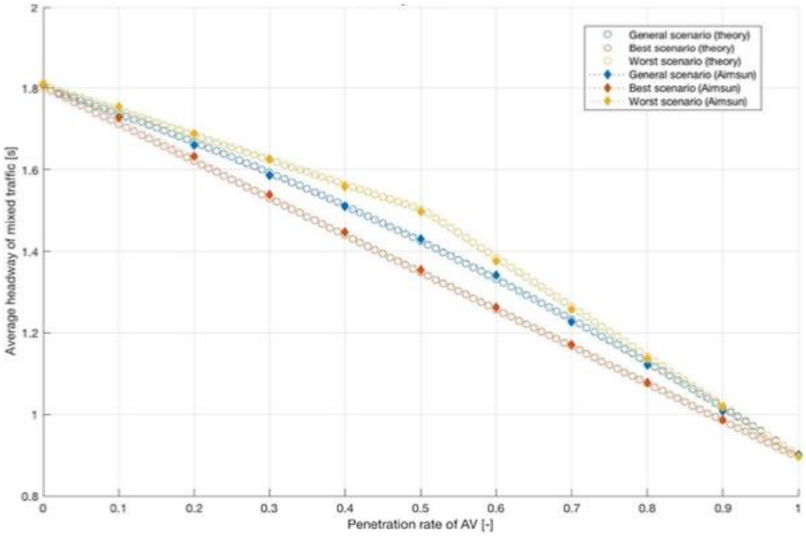
The final state of the statement is as follows;

$$d = 9/10\left(\frac{c(1-\lambda)^2}{2(1-\lambda x)} + \frac{x^2}{2q(1-x)}\right) \qquad (4)$$

5. Autonomous Vehicle Delay Analysis

As stated above, the delay calculation with the Webster method is to be calculated with the saturated flow value. At formula (2) saturated flow is associated with headway. Generally, a normal vehicle headway value is accepted as 2 sec.

Figure 2. The minimum, maximum, and expected value of headway in mixed traffic for different penetration rates for Autonomous Vehicles (AV).[6]



As stated in the article that ‘the filled diamonds depict the results of the microsimulation analysis. The circles are the theoretical headway. $h_{N\text{-}N} = 1.8$[s], $h_{AV\text{-}AV} = 0.9$[s], $h_{AV\text{-}N} = 1.8$[s], and $h_{N\text{-}AV} = 1.2$[s].’[6]

As can be seen in Figure 1, theoretical headway is accepted at 0.9s for delay analysis for the situation where the oncoming vehicles are autonomous. The delay analysis for the case of oncoming vehicles is found with the webster method, created by using the saturated flow value calculated according to the headway of the autonomous vehicles. The saturated current value should be adjusted according to the headway value of autonomous vehicles, so the h value in formula 2 is taken as 0.9. With this process, the saturation flow value is calculated for autonomous vehicles and the steps in the webster method are arranged according to this value and the delay value is found. (s=3600/0.9). In addition to the information presented it should be stated that the value of 3600 specified in formula 2 may change according to the road widths.

6. Results

For analysis purposes, different scenarios have been taken into consideration to evaluate and compare the effect of the methods on various traffic flows. For that purpose, hourly traffic volumes were increased by 10 percent, resulting in 5 different traffic volume values. The traffic volumes used for the analysis are listed below:

Chart 6. Traffic volumes

Direction 1 Volume (veh/h)	Direction 2 Volume (veh/h)	Direction 3 Volume (veh/h)	Direction 4 Volume (veh/h)
479	281	408	433
527	309	449	476
575	337	490	520
623	365	530	563
671	393	571	606

The delay values calculated for normal vehicles, that is the vehicles are freely able to move, by considering 5 different volume values are listed below:

Chart 7. Delay values for normal vehicles

Direction 1 Delay (s)	Direction 2 Delay (s)	Direction 3 Delay (s)	Direction 4 Delay (s)
9,04	6,856	9,03	8,03
10,02	7,44	10,01	8,89
11,25	8,1656	11,24	9,98
12,8	9,09	12,8	11,36
14,9	10,31	14,89	13,2

The delay values calculated for autonomous vehicles by considering 5 different volume values are listed below:

Chart 8. Delay values for autonomous vehicles

Direction 1 Delay (s)	Direction 2 Delay (s)	Direction 3 Delay (s)	Direction 4 Delay (s)
5,9	4,97	5,9	5,29
6,07	5,07	6,06	5,44
6,25	5,18	6,25	5,6
6,44	5,3	6,44	5,76
6,65	5,42	6,64	5,94

7. Discussion

As a result of the data obtained, the delay values corresponding to the traffic volume increasing by 10 percent for each direction were calculated separately for normal and autonomous vehicles.

Intermediate values were obtained by making predictions with machine learning algorithms. All the results are presented in Figures 3-10. The values indicated with red dots in the figures represent the delay values corresponding to the increasing traffic volume. The values indicated with blue lines are the regression values produced by machine learning algorithms. gives. Polynomial regression analysis was chosen as the most appropriate analysis method since the results obtained were distributed in the form of polynomials. As can be seen from Figures 3-10, increasing traffic volume for both normal vehicles and autonomous vehicles causes a polynomial increase in delays. In addition, as can be seen from the results of the delay analysis, it is observed that the use of autonomous vehicles significantly reduces the delays in the system.

Figure 3. Direction 1 traffic volume and delay for normal vehicles

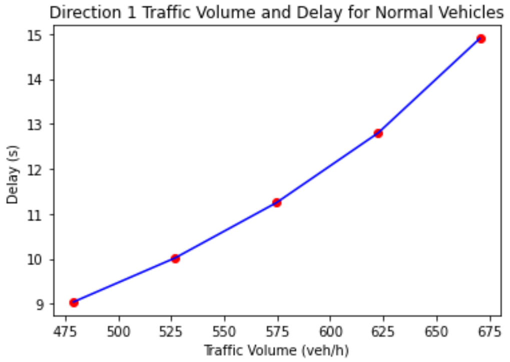


Figure 4. Direction 1 traffic volume and delay for autonomous vehicles

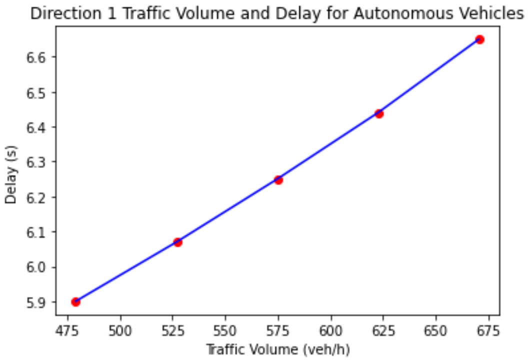


Figure 5. Direction 2 traffic volume and delay for normal vehicles

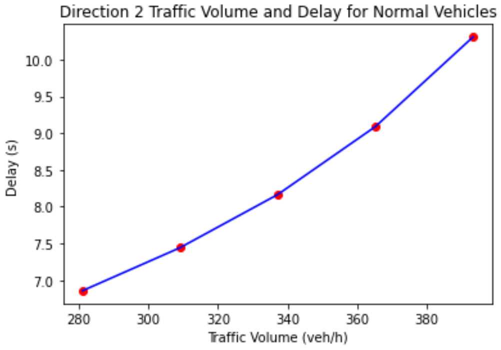


Figure 6. Direction 2 traffic volume and delay for autonomous vehicles

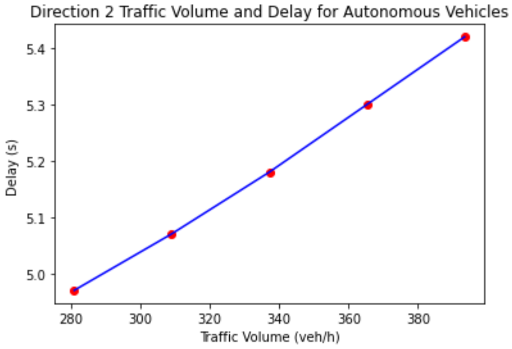


Figure 7. Direction 3 traffic volume and delay for normal vehicles

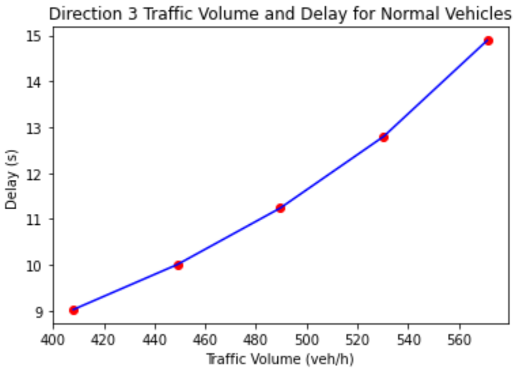


Figure 8. Direction 3 traffic volume and delay for autonomous vehicles

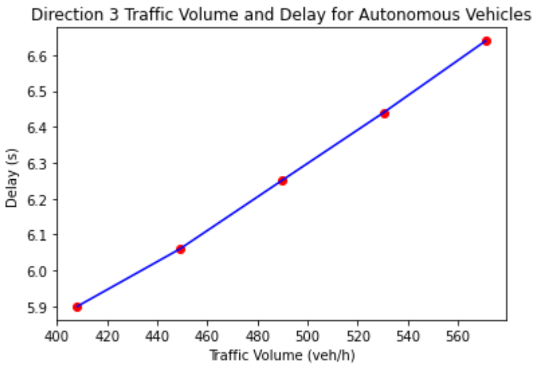


Figure 9. Direction 4 traffic volume and delay for normal vehicles

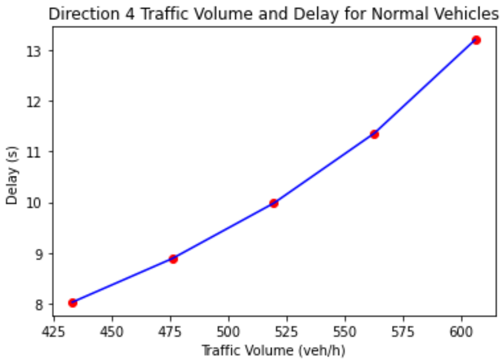
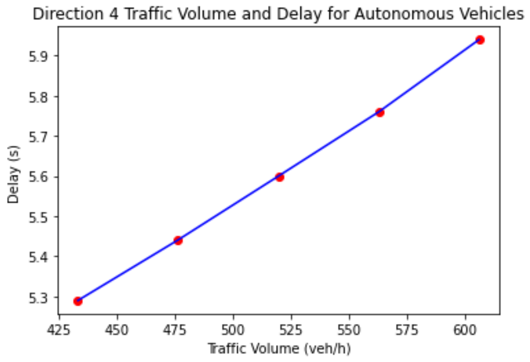


Figure 10. Direction 4 traffic volume and delay for autonomous vehicles



8. Conclusions

Delay is time lost for reasons other than the driver. It is used to determine capacity and measure operational performance at signalized intersections. Due to the development of technology, autonomous vehicles have started to be used in transportation. This situation has revealed the problem of taking autonomous vehicles into account in the calculation of vehicle delays at intersections. In this study, calculations are made on a sample intersection system by showing how to delay calculations made for normal vehicles and autonomous vehicles through the Webster method. For both cases, regression analysis is carried out by employing machine learning algorithms. The development of a specific algorithm for autonomous vehicles will be the next stage of this research.

References

[1] NIGARNJANAGOOL, S., & Hussein, D. I. A. (2005). Evaluation of a dynamic signal optimization control model using traffic simulation. IATSS research, 29(1), 22-30.

[2] Traffic Signal Settings, by F.V. Webster, Road Research Technical paper no. 39, Ministry of Transport, Her Majesty's Stationary Office, 1958.

[3] Li, Y., Wei, D. D., Mu, Z., Xiong, Z. H., Wang, Y. H., & Yin, W. S. (2015). Study of the time-collocation of the signal lamp at intersection. Mathematical modeling of engineering problems, 2(2), 5-10.

[4] Liu, H., Rai, L., Wang, J., & Ren, C. (2019). A new approach for real-time traffic delay estimation based on cooperative vehicle-infrastructure systems at the signal intersection. Arabian Journal for Science and Engineering, 44(3), 2613-2625.

[5] Cheng, D. & Messer, C. & Tian, Z. & Liu, J. Modification of Webster´s Minimum Delay Cycle Length Equation Based on HCM 2000. Paper Submitted to the Transportation Research Board for Presentation and Publication at the 2003 Annual Meeting in Washington. D.C. 2003.

[6] M. Ramezani, J. A. Machado, A. Skabardonis and N. Geroliminis, "Capacity and delay analysis of arterials with mixed autonomous and human-driven vehicles," 2017 5th IEEE International Conference on Models and Technologies for Intelligent Transportation Systems (MT-ITS), 2017, pp. 280-284, doi: 10.1109/MTITS.2017.8005680.