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Evaluation of Emission-Based and Delay-Based Traffic Signal Controls at Isolated Intersections

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Abstract **-** Traffic congestion accounts for 25% of global green gas emissions and is exacerbated by increased vehicle usage, particularly in the Asia-Pacific region. Effective traffic signal control is essential for reducing congestion and air pollution, as poor control can worsen these problems. Traffic congestion at signalized intersections significantly causes delays and increased fuel consumption. This research aims to develop a method for calculating traffic signal timings that minimize emissions at isolated signalized intersections. The literature review reveals that different vehicle operating modes (idling, decelerating, accelerating, cruising) affect emission rates differently, and improved signal control can reduce emissions. It also highlights the limitations of Webster 1958 method, primarily focusing on minimizing delays. The proposed method calculates signal timings by considering the relationship between delay, the number of stops, and cycle length. Emissions are calculated based on the time vehicles spend in different operating modes. A case study at an intersection formed by two one-way streets compares the proposed method with Webster's method. The results show that the proposed method reduces NOx emissions and the number of stops per vehicle, although it increases the average delay per vehicle. The study concludes that methods focusing on minimizing delays yield different results from those focusing on minimizing emissions. Intersections with significantly different directional traffic volumes should prioritize emission reduction in signal timing design. Future research should develop methods considering the effects of hybrid electric vehicles on signal timing.

Keywords**:** emissions, traffic signal, delays, stops

1. Introduction

Traffic congestion at signalized intersections causes significant travel delays and increased fuel consumption. The Thailand Department of Highways manages the national highways, which include around 2,200 signalized intersections. Therefore, developing appropriate traffic signal timing designs is necessary to ensure safety and travel efficiency. Currently, urban traffic congestion is a substantial problem. According to [1], the transportation sector is responsible for 25% of global CO2 emissions, with road transport making up 75% of these emissions. In addition to greenhouse gas emissions, transportation contributes to traffic congestion, noise pollution, and road accidents. Rapid economic growth in the Asia-Pacific region over the past few decades has led to increased vehicle usage and ownership, particularly in urban centers. Cities in this region contribute 75% of the regional greenhouse gas emissions, a figure that is expected to rise due to rapid urban expansion.

In urban settings, traffic signals play a vital role in regulating traffic to ensure the safe passage of vehicles and pedestrians. Traffic congestion at intersections is a major source of air pollution. The severity of air pollution escalates with traffic congestion and frequent stop-and-go movements at intersections, where vehicles function in various modes, including idling, accelerating, decelerating, and cruising. As traffic volume increases, the importance of efficient signal control grows. Effective signal control can mitigate congestion, whereas poor signal control can exacerbate congestion and contribute to severe air pollution.

Travel demand is affected by various factors, including the time of day, day of the week, season, weather conditions, and unpredictable events such as accidents, special events, or construction activities. Cities globally have adopted traffic signal control systems that continuously adjust signal plans based on actual traffic conditions. Since 1958, when Webster [2] proposed a method for calculating signal timings, traffic researchers have developed numerous algorithms focused on minimizing overall delay (Minimum Delay Objective). However, studies by Ma and Nakamura [3], Coelho, Farias, and Rouphail [4] and [5], and Qian et al [6] have found that designing signal timings to minimize emissions (Minimum Emission

Objective) yields different results from those aimed at minimizing overall delay, particularly in terms of cycle length and phase split. Therefore, the objectives of this study are:

- To develop a method for calculating traffic signal timings that can reduce emissions from vehicles at isolated signalized intersections.
- To investigate effects of emission-based and delay-based signal timings on delays, stops, and emissions via traffic simulation experiments.

The rest of this paper includes a literature review, which covers literature on delay analysis and signal control at intersections. Next, the method for calculating traffic signal timings to emissions at isolated intersections are presented followed by a case study where the proposed method is applied to intersections with varying traffic volumes. The conclusions and future research recommendations are presented.

2. Background

The primary objective of installing traffic signals at intersections is to manage traffic flow at congested intersections, ensuring safe and efficient travel by separating traffic streams to use the intersection at different times. The relevant research literature related to traffic signal control and design is reviewed with the following details. Coelho, Farias, and Rouphail [4] and [5] investigated the impact of speed control traffic signals on emissions, calculating emissions based on the time vehicles spent in various operating modes, such as accelerating, decelerating, idling, and cruising. They discovered that signal control patterns causing more vehicle stops also led to higher emissions. Pandian, Gokhale, and Ghoshal [7] reviewed the influence of traffic, vehicles, and road characteristics on vehicle emissions. Their findings indicated that emissions near intersections depend on factors like driving speed, deceleration rate, idling time in queues, acceleration rate, queue length, traffic flow rate, and environmental conditions. Ma and Nakamura [3] examined cycle lengths at signalized intersections from an emissions perspective, breaking down emissions based on different vehicle operating modes and modeling them as a function of cycle length. They calculated the optimal cycle length by finding the derivative of the emission function with respect to cycle length, revealing that the optimal cycle length for minimizing emissions differed from that for minimizing delays, particularly with higher traffic speeds or a higher proportion of trucks. This study suggested that Webster's method [2], which focuses on minimizing delays, may not be suitable for minimizing vehicle emissions. Lv and Zhang [8] studied the impact of signal coordination on traffic emissions using simulation software, finding that the offset (difference in green phase start times at adjacent intersections) was a key factor affecting emissions, delays, and vehicle stops. They found that vehicle stops were more strongly correlated with emissions than delays. Lv, Zhang, and Zietsman [9] observed that emissions increased with delays but at a decreasing rate, eventually approaching zero. With longer cycle lengths, delays increased while emissions decreased, with increased idling time being the cause of the delay increase. However, idling time's impact on total emissions was negligible compared to the higher emission rate during acceleration. Qian et al. [6] proposed a model for calculating traffic signal timings to reduce emissions at isolated intersections, estimating emissions based on the time vehicles spent in various operating modes. They applied their model to an intersection in Shenzhen, China, finding that while capacity improved, emissions and delays did not. Anya et al. [10] developed a method for calibrating the AIMSUN model to predict emissions, using vehicle position and speed data to create trajectories and calibrate the model, which yielded more accurate results than the uncalibrated model. Khalighi and Christofa [11] developed a method for calculating signal timings using the AIMSUN model to reduce emissions, showing that their model could reduce both emissions and delays. Calle-Laguna et al. [12] used the INTEGRATION model to examine cycle length impacts on delays, fuel consumption, and emissions, developing regression equations to calculate optimal cycle lengths for minimizing these factors. They found that the Webster method [2] resulted in excessively long cycle lengths when the traffic volume-to-capacity ratio exceeded 50%, indicating that signal timings focusing on minimizing delays may not always be suitable for minimizing vehicle emissions.

3. Methodology

This section presents the method for calculating traffic signal timings to minimize vehicle emissions at isolated intersections.

3.1. Estimation of Air Pollution Emissions Due to Traffic Signals

Vehicle emissions depend on the total time spent in each operating mode, multiplied by the emission rate for that mode. At signalized intersections, vehicles approach at a constant speed, decelerate, stop, and queue when the signal is red. When the signal turns green, they accelerate and resume a constant speed as they leave the intersection. This study categorizes vehicle operations into cruising, idling, decelerating, and accelerating based on speed data. Each mode has a fixed emission rate per unit time. The total emissions are calculated by multiplying the fixed emission rate by the time spent in each mode and summing the results. The net impact of signal control on emissions is the difference between estimated emissions with and without traffic signals. As shown in Figure 1, emissions during cruising are similar regardless of the presence of traffic signals; therefore, emissions during cruising can be omitted in consideration.

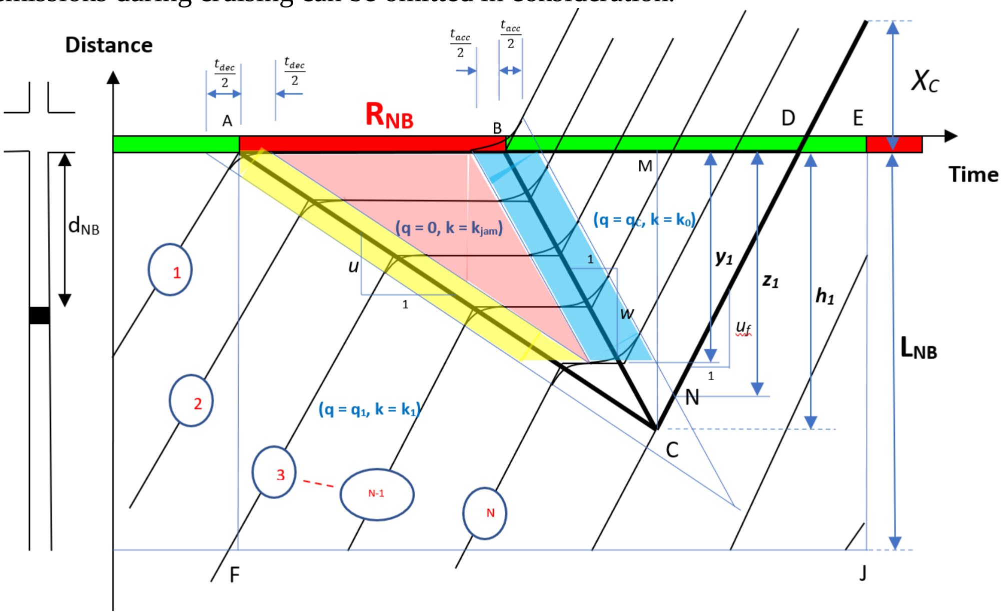


Fig 1: Vehicle Trajectory at a Signalized Intersection.

The emissions due to signal control per cycle can be expressed by Equation (1):

$$E = (e_{Idle})(Delay) + (e_{accel} + e_{decel})(Stop) \tag{1}$$

where E = Emissions per cycle due to signal control

e_{Idle} = Emission rate during idling

e_{Accel} = Emission rate per acceleration

e_{Decel} = Emission rate per deceleration

$Delay$ = Delay per cycle

$Stop$ = Number of stops per cycle

3.2 Optimization of Traffic Signal Timings to Minimize Air Pollution Emissions

This section presents a method for calculating traffic signal timings to reduce air pollution emissions from vehicles. The *emissions per unit time* can be minimized using Equations (2) to (6):

$$Min\ Z = \frac{1}{C}\sum_{i=1}^{N} e_{Idle}\left\{\frac{q_i C^2(1-\theta_i)^2}{2(1-y_i)} + \frac{y_i^2 C}{2\theta_i(\theta_i - y_i)} + \left(\frac{e_{accel}+e_{decel}}{e_{Idle}}\right)\frac{q_i C(1-\theta_i)}{(1-y_i)}\right\} \quad (2)$$

St.
$$\frac{L}{C} + \sum_{i=1}^{N}\theta_i = 1 \quad (3)$$
$$\theta_i \geq y_i \ ; \quad \forall i \quad (4)$$
$$0 \leq \theta_i \leq 1 \ ; \quad \forall i \quad (5)$$
$$\frac{L}{1-\sum_{i=1}^{N} y_i} \leq C \leq C_{max} \quad (6)$$

where Z = Emissions per unit time
q_i = Traffic volume of stream (i) (vehicles per second)
C = Cycle length (seconds)
θ_i = split of phase "i"
y_i = Flow ratio of stream (i) = q_i/S_i
S_i = Saturation flow rate of stream (i) (vehicles per second)
L = Lost time per cycle (seconds)
C_{max} = Maximum cycle length (seconds)

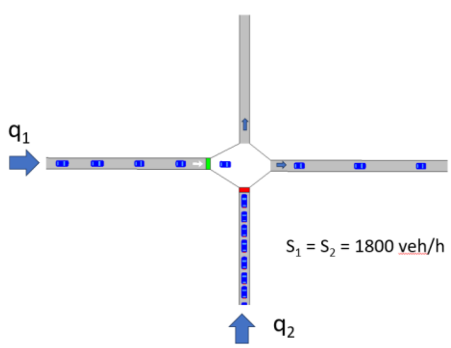
The first term in Equation (2) represents uniform delay, the second term represents random arrival delay, and the third term represents the number of stops per cycle. Equation (3) shows the relationship between phase proportions and lost time per cycle. Equation (4) ensures that capacity is not less than the traffic demand of each phase. Equations (5) and (6) define the upper and lower bounds for phase proportions and cycle length respectively. Solving these equations provides the signal timings that minimize emissions per unit time. If $\left(\frac{e_{accel}+e_{decel}}{e_{Idle}}\right) = 0$, the method reduces to minimizing delay, similar to the Webster method [2].

4. Case study

This section evaluates a case study by implementing the developed method for calculating traffic signal timings at an isolated intersection formed by two one-way streets intersecting. The study compares traffic signal timings and traffic indicators, including air pollution emissions per unit time, average vehicle delay, and the number of vehicle-stops per vehicle. These comparisons are made between the results calculated using the minimum delay method [2] and the method proposed in this research, which aims to minimize emissions per unit time. The details are as follows:

4.1 Case Study Data

The intersection used in the case study is formed by two one-way streets crossing each other, resulting in two signal phases: 1) west to east and 2) south to north. The traffic volumes for three scenarios are shown in Figure 2.



Demand Scenario	q_1 (veh/h)	q_2 (veh/h)
1	700	700
2	900	500
3	1100	300

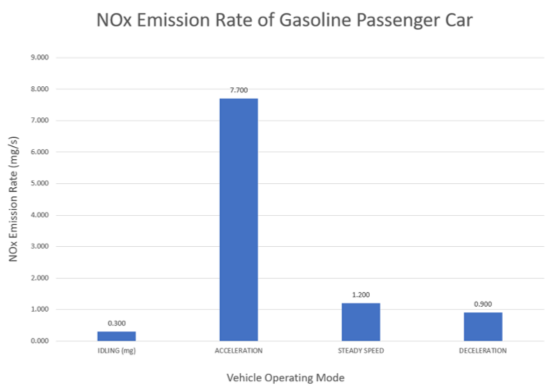
Lost Time (L) = 10 seconds per cycle

Fig 2: Case Study Intersection with Three Traffic Volume Scenarios.

In all three scenarios, the total traffic volume is 1,400 vehicles per hour. The saturation flow rate is 1,800 vehicles per hour in both directions, with a total lost time per cycle of 10 seconds. Thus, the cycle length calculated using the Webster method [2] is the same for all scenarios, which is (1.5*10+5)/(1-1400/1800) = 90 seconds. However, the phase proportions vary based on the flow ratio (traffic volume to saturation flow rate).

4.2 Application of the Developed Method to Calculate Traffic Signal Timings to Reduce Air Pollution Emissions

This study uses NOx emissions as an example. The developed method is applicable to any type of pollutant, provided the emission rate per time for vehicles in different operating modes is known. For this case study, NOx emissions are considered, with emission rates for different engine operating modes displayed in Figure 3, based on reference data [11].



$$e_{Idle} = 0.3\ mg/s$$

$$e_{Accel} = 34.65\ mg/stop$$

$$e_{Decel} = 0.405\ mg/stop$$

$$\frac{e_{Accel} + e_{Decel}}{e_{Idle}} = 129$$

Fig 3: NOx Emission Rates for Vehicles by Operating Mode.

From Figure 3, the NOx emission rate is highest during accelerating, followed by cruising. The lowest NOx emission rate occurs during idling. The emission rates for acceleration and deceleration per event are calculated as shown in Figure 3. The ratio $\left(\frac{e_{accel}+e_{decel}}{e_{Idle}}\right)$ is 129 and will be used to calculate the signal timings to reduce emission rates. Using the traffic volumes and NOx emission rates for the three scenarios, the traffic signal timings and traffic indicators, including NOx emissions, are calculated using both methods: 1) Webster method [2] and 2) the method proposed in this research. The results are summarized in Figures 4, 5, and 6.

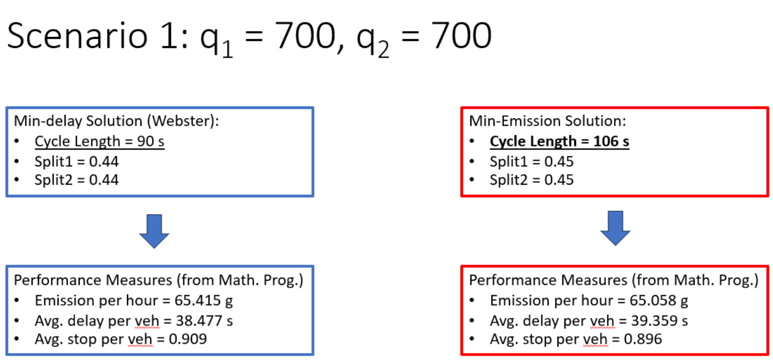


Figure 4: Traffic Signal Timings and Indicators for Traffic Volume (q1 = 700: q2 = 700 vehicles per hour)

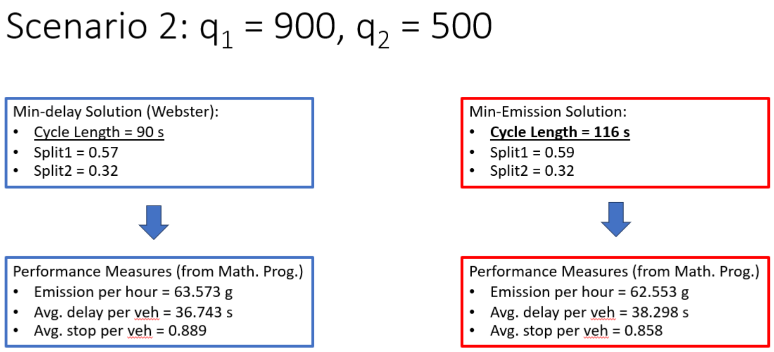


Figure 5: Traffic Signal Timings and Indicators for Traffic Volume (q1 = 900: q2 = 500 vehicles per hour)

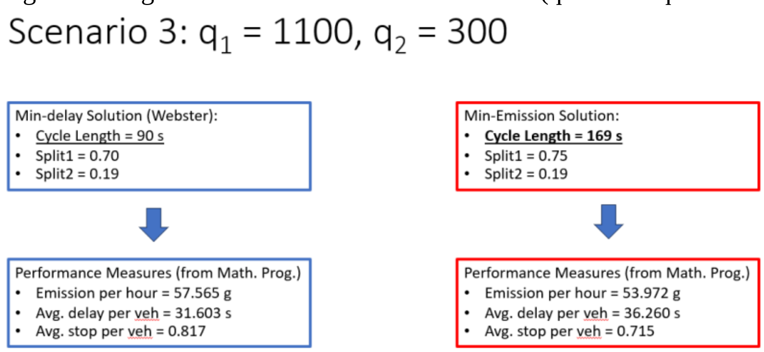


Figure 6: Traffic Signal Timings and Indicators for Traffic Volume (q1 = 1100: q2 = 300 vehicles per hour)

The calculations indicate that in all scenarios, the cycle length using the Webster method [2] is consistently 90 seconds due to the sum of the flow ratios being identical across scenarios. In contrast, the proposed method results in longer cycle lengths in all scenarios. The cycle length increases as the difference in traffic volumes between the two directions grows. This occurs because a greater difference in traffic volumes leads to more vehicle stops, and a longer cycle length reduces the number of stops per vehicle, thereby decreasing emissions from acceleration and deceleration, which have the highest NOx emission rates. When comparing traffic indicators and emissions for the three scenarios using both methods, it is evident that NOx emissions and the number of stops per vehicle are lower with the proposed method than with the Webster method [2]. However, the average delay per vehicle is lower with the Webster method [2] in all scenarios, aligning with its objective of minimizing average delay per unit time.

5. Conclusions

The installation of traffic signals at intersections is intended to manage intersecting traffic flows, ensuring safe and efficient passage. However, improper signal timings can lead to increased travel delays and longer travel times. Currently, traffic congestion is a major issue and a significant cause of air pollution. The severity of pollution worsens with higher traffic congestion and frequent stop-and-go movements at intersections, where vehicles operate in various modes such as idling, accelerating, decelerating, and cruising. As traffic volume rises, the importance of efficient signal control grows. Effective signal control can reduce congestion, while poor signal control can exacerbate congestion and severe air pollution.

This research reviewed literature related to traffic signal timing design. The review found that:

- Different vehicle operating modes (idling, decelerating, accelerating, cruising) affect vehicle emission rates differently.
- Vehicle emissions can be reduced through improved traffic signal control.

- Optimal signal timings for minimizing delays differ from those for minimizing emissions.

This research presents a method for calculating traffic signal timings to minimize air pollution emissions at isolated signalized intersections with traffic volumes below capacity. A case study with three different traffic volume scenarios found that longer cycle lengths reduce the number of vehicle-stops per vehicle but increase the average delay per vehicle. Therefore, optimal emission-based signal timings should balance delays and stops, as vehicle emission rates depend on operating modes. Additionally, Webster method [2], a standard method, may not provide optimal signal timings for all traffic volume scenarios in terms of emission minimization. The research concludes:

- Methods focusing on minimizing delays yield different results from those focusing on minimizing emissions.
- Greater differences in traffic volumes between directions result in greater differences between the two methods' results. Intersections with significantly different directional traffic volumes should prioritize emission reduction in signal timing design.
- Webster method [2], widely used, is not designed to minimize emissions at signalized intersections.
- The proposed method can be used to calculate traffic signal timings considering traffic-related air pollution emissions.

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