Adaptive Traffic Light Control of Traffic Network

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Abstract — **Our objective is to reduce the delay experienced by the green wave in a traffic network. The main concern is to ensure that the vehicles in the dominant direction experience the least amount of delay. In order to achieve that, we propose two algorithms based on conventional green wave and phase fairness. We adjust the offsets of the conventional green wave by using the local information to make vehicles flow without being stopped, and allocate the green length to other phases fairly. We also use the predictive total waiting time based on the idea of phase fairness. We compare the proposed two algorithms with the baselines in different traffic flow densities and green wave strength and study their impacts on both green wave delay and average delay.**

Keywords — Adaptive Traffic Light Control, Green Wave, Phase Fairness, Offset Adjusting, Prediction

I. INTRODUCTION

For a traffic network, it is common that there is a dominant direction where most vehicles are traveling in one direction. In this paper, we are concerned about the average delay of the green wave and the average delay of the whole network. At present, conventional green wave are widely used, but the fixed offset does not adapt to current traffic situation. Instead of assigning the offset fixed, we make it adaptive independently at each intersection. Another baseline, phase fairness introduced in [1], does good job in decreasing average delay, and the green wave delay can be decreased if we predict the arrivals to turn lights earlier and longer for dominant direction.

Trying to decrease the delay for dominant flow in the network is meaningful because a large fraction of people moves in that flow so that decreases the their delay will decrease the average delay if we do not punish others too much. The way to decrease the delay for dominant flow is referred to the term as creating "green wave". A green wave is a phenomenon where a series of traffic lights are coordinated to allow traffic flow over several intersections in one direction. The coordination requires lights to be turned green when vehicles approach so that they don't have to stop through the trip. If an ideal green wave is created, then all vehicles in the dominant road do not have to stop through the dominant road.

The brief introduction of two baselines, conventional green wave and phase fairness, are discussed in section II. The first one is all fixed beforehand with the green length allocated according to traffic flow and the offset is the time needed to travel between two intersections with expected speed. The phase fairness uses total waiting time of all cars in one phase as metric to control lights. By minimizing this sum, it gets a small average delay.

In our work, we build a Manhattan torroidal traffic network that has no edge effect, and set the traffic flows as we want by adjusting the turn ratios and the total number of cars put in the network. This model is stated detailed in section III. All the algorithms are implemented in the Green Light District Simulator, which is an open source simulator [2], [3].

In section IV, our two proposed algorithms are described. The first one can be improved by emptying the queue ahead of time and assign other phases fairly by using phase fairness, and the second one has potential to give advantage to dominant flow by predicting the arrivals.

We apply all four algorithms under two different turn ratio settings and three traffic loads. By comparing the green wave delay and the network average delay, we find that the adaptive green wave performs best in decreasing the green wave delay. It even has nearly no delay if the load is low and medium. The predictive algorithm does not create green wave very well, but it has improvement on the phase fairness, and it has the smallest network average delay if the prediction parameter is set reasonable. The results are presented in section V and then section VI is the future work suggestion and the conclusion.

II. BACKGROUND

This section describes the two baselines we use in our work and the reason we think it is worth making modifications on them.

A. Conventional Green Wave

The conventional green wave mechanism has been widely studied and used in many cities. It creates green wave by assigning a fixed offset to a sequence of traffic lights. The offset is the time needed for vehicles to travel from upstream intersection to the downstream one at an expected constant speed. While this works well comparing to non-coordinated fixed-time control, the fixed offset values do not take care of vehicles that just turn into the dominant road from other directions. If there is a queue accumulating before vehicles arrive, approaching vehicles have to stop at the intersections. With the number of vehicles turn into the dominant direction increasing, the queue length increases and thus increases the delay faced by the vehicles in the dominant direction.

The conventional green wave we simulate have all things fixed in advance including fixed cycle time, fixed green length for each phase and fixed phase sequence in every round. With all information of traffic flow known in advance, the fraction of the cycle time assigned to each phase is proportional to the fraction of the traffic flow in that phase, we can form a fixed green light time for each phase that satisfies the amount of vehicles of each lane of each direction.

According to Webster's equation [4], the optimum cycle length is a function of lost times and flow ratios. The delays experienced by the conventional green wave can be reduced by adjusting the cycle time according to the load. The optimum cycle time is designed to minimize the average delay, and increases with increasing load. This increases the average delays for low utilization phases more than for high utilization phases, and increases the unfairness with increasing load. We decide to keep the cycle time fixed in both conventional green wave and the proposed conventional green wave. This does not minimize the average delay, but is fair to compare these two.

B. Phase Fairness

The other proposed algorithm is based on phase fairness. In phase fairness, the average waiting time for vehicles in a phase is inversely proportional to the average number of vehicles waiting at the traffic signal. The objective is to minimize the sum of the waiting time for each phase. A system is fair when we cannot reduce the sum of the waiting times for a phase without increasing the sum of the waiting times for a phase with a larger sum.

The fairness metric used is the sum of the waiting time of all vehicles for each phase. The decision is made every cycle by selecting the one has the largest total delay. The minimum green length time for each selected phase is 10 seconds unless there are no vehicles approaching in 2 seconds. Every transition of lights has 2 seconds for amber light when no vehicles can enter the intersection.

The phase fairness has small average delay and standard deviation overall ranges of traffic densities. The vehicles in a phase with fewer vehicles may wait longer, but a single vehicle waiting at a red signal will eventually accumulate a longer delay than a larger number of vehicles in a more heavily travelled lane.

With its good performance in keeping the average delay small, we modified this fairness mechanism baseline by predicting the arrivals instead of only looking at current total delay. If so, then the dominant direction which has more vehicles approaching can force the light to be green before reaching the intersection or keep the light green longer than before.

III. NETWORK MODEL

This section presents the model we build in the aspect of intersection unit network features, and the balance equations used as a tool for picking turn ratios given desired traffic flow distribution.

A. Intersection

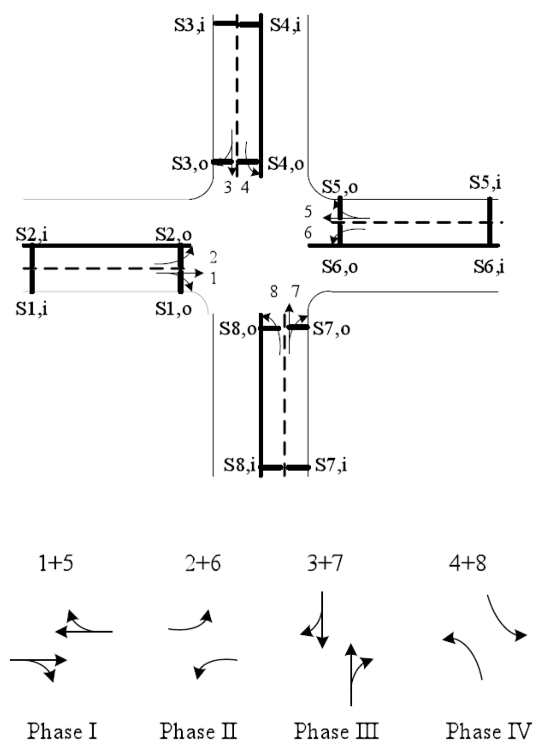

Figure 1. Single Intersection Model and 4 Phases

Each unit in the traffic network is a crossroad with traffic approaching from four directions. Roads are two-way and there are separate lanes for different heading directions. One lane is for going straight or turning right and the other one is a separate lane for left-turn.

The traffic light configuration has four un-collided phases. Figure 1 shows the phase arrangements. The transition between two phases has 2 second of amber light time when no more vehicles can cross the light, so that the intersection will be cleared before the next phase to be green.

B. Traffic Network Configuration

In our project, we run our simulation in a 10 by 10 intersections traffic network, which includes totally 100 single intersections.

Furthermore, we modeled the network with a wrapped-around traffic flow, which means that when vehicles go out of the network, they will immediately come back into network from the side-node which has the same column or row number with the one they goes out away from. Under this configuration, there is no edge effect so that every node in the network is the same.

C. Balance Equations and Turn Ratios

We assume that in each intersection, the number of vehicles that turn into one direction equals the number of vehicles turn out of that direction. This requires that there is no gridlock in the network. Taking southbound flow as example let f_N be the flow from the north. x_{ij} is the probability from flow *i* turning into flow *j*, i.e. x_{NE} is the probability of flow from north turn into east. Then the balance equation of this southbound flow is shown as Equation (1).

$$(1-x_{NE}-x_{NW}) f_N = x_{EN} * f_E + x_{WN} * f_W \qquad (1)$$

All flows can write down the balance equations. After solving the sets of balance equations, we can get the relationship between two flows with regarding to two turn ratios.

For simplicity, we make all non-dominant flows the same traffic density *f*, and assign the dominant flow *3f* and *6f*. According to solutions of the equation set, if we make the flow *nf*, then the probability of turning into the dominant direction is *n* times as the probability of turning out.

IV. ADAPTIVE CONTROL ALGORITHMS

In this section, we describe the two adaptive algorithms in detail and explain how it works when it faces different traffic density. We state the changes that made based on the conventional green wave and the phase fairness. Moreover, we use the theoretical knowledge and analysis to make an educated guess and explain who should do better in average delay and in green wave delay.

A. Adaptive Green Wave Algorithm

The main idea of this algorithm is to clear the vehicles before other vehicles from the green wave enter the lane. The reason behind such an idea comes from the fact that since the lane is being emptied earlier, the new vehicles that approach the intersection would experience rather no or very less delay.

We get information about the traffic flow from the previous intersection that it comes from and according to that we adjust the green wave timing. We have introduced a memory that stores the timings at which the light is supposed to turn green. Then the timing of the green wave is adjusted according to the queue length. If there are more vehicles waiting, then the timing is shifted back more.

While we change the offset value adaptively, the time length allocated to the green wave is fixed. It has the same phase length as the conventional green wave, which is derived according to the traffic flow density. However, what differs is that the remaining time allocated to the rest of the three phases is according to the total waiting time. The phase with the maximum total waiting time is allowed to go first. This is using phase fairness combined with the green wave to improve the fairness and the average delay.

One thing worth noticing is that because of giving priority to the green wave, we will always turn light green for that phase if there is a need to do so, so for the phases that turn green later in this round will be punished more. Common situation is that the last phase to be green in this round may get much shorter time than it required or even has no chance to be green. But due to the adaptive nature of the green wave, the phase that has been punished in this round will have a higher total waiting in the next round and hence it will have a higher priority of getting green light.

B. Prediction Algorithm

In prediction algorithm, we would like to construct an algorithm whose main idea is based on the proportional fairness, with a prediction concerned to the incoming traffic flow. The predicted delay both for the waiting vehicles and for the incoming vehicles would be taken into consideration. With different prediction time, we can compare the results for average delay and green wave delay in order to figure out the most suitable prediction for specific traffic density.

In this algorithm, for each intersection, we made a 5 second, 10 second and 15 second prediction for each 4 phases and make the comparisons among them to figure out which phase take the priority to get green light time. The delay for proportional fairness right now is the predicted delay if the light remains red in the following 5, 10 or 15 seconds, as we have mentioned above. For example, if we apply the 10 second prediction into network, then for each phase, we would take the incoming traffic flows in the following 10 seconds, which probably will join the queue that is facing the red light, into consideration. In the other hand, if it occurs that a vehicle has just left the previous intersection and is entering the lane currently, which will take more than 10 seconds for him to reach the queue, then it will not be taken into the predicted delay.

From what we have discussed above, we can see that for relatively low traffic density, it is enough for us to take just 5 second prediction because there are a few vehicles in the network and for each lane and each phase, the queue length is short and the difference between dominant direction and others are relatively small.

Therefore, the prediction serves significantly when the difference between the amounts of vehicles coming toward the intersection from each lane is large. It will also decrease the amber light time for each intersection. It contributes more to the green wave direction compared with traditional proportional fairness.

From the theoretical analysis we have done above, we can conclude that phase-shifting algorithm made much more improvement on dominant delay than prediction algorithm. Nevertheless, with more reasonable fairness assumption, the prediction algorithm played a better role in improving the average delay than phase-shifting one. As we can imagine, both of them improve a lot compared to the fixed green wave and traditional proportional fairness.

V. SIMULATION RESULTS

This section lists the parameters in the simulation. Results are compared in respect of green wave delay and average delay.

The simulation parameters are shown in Table 1. We refer the case with $3f$ dominant flow as Case 1, which has turn ratios 0.05 vs. 0.15. The one with $6f$ dominant flow as Case 2 and the turn rations are 0.05 vs. 0.3. We put 1000, 2000 and 4000 vehicles in the network. In the figure we show below, the x-axis is the green wave traffic load.

A. Green Wave Delay

For the two baselines, the conventional green wave has a relative low green wave delay, and the other one, phase fairness algorithm, has the largest green wave delay among the four methods. For the two proposed algorithms, the adaptive green wave algorithm performs the best in reducing the average delay in green wave, while the prediction method has higher delay than conventional green wave so it actually does not create green wave effectively.

Parameter Name	**Value**
Time Unit(s)	1
Length Unit(m)	1
Maximum Speed(m/s)	8
Lane Length(m)	216
Simulation Time(s)	4000
Amber Light (s)	2

Table 1: Simulation Parameters

Figure 2 and Figure 3 show the result of green wave delay of four methods in two cases with different

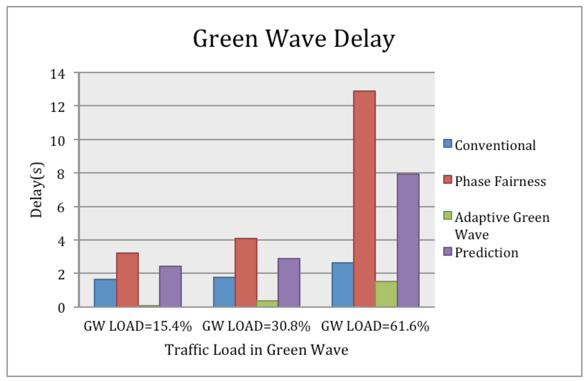

Figure 2: Green Wave Delay of Case 1

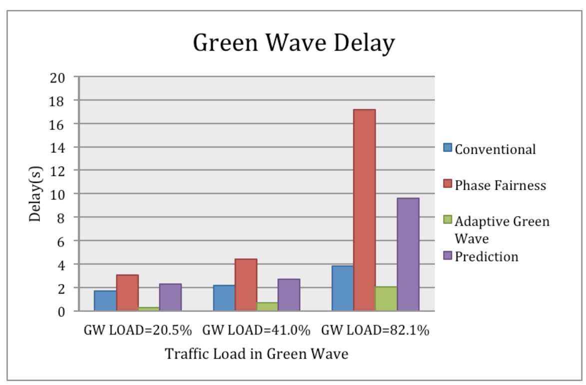

Figure 3: Green Wave Delay of Case 2

traffic settings. Adaptive green wave method has very small delay in low and medium load. This is because when we keep the phase length of the green wave fixed, clearing the vehicles turn into the street in advance greatly improves the fluency of green wave flow. When it comes to a high load, this does not improve much. In case 1, the improvement comparing to fixed green wave is only 43% under high load, while there is 95% and 80% improvement under low and medium load. This decrease is due to the longer time needed to empty the queue, which makes the last several vehicles in the coming green wave fail to cross the intersection in this round. The prediction method improves the green wave comparing to the phase fairness, but has larger green wave delay than the conventional one. By predicting the arrivals, it decreases the delay of the green wave, but it still requires the vehicles by suddenly asking green wave to stop to when other directions have accumulated very high total waiting time.

B. Average Delay

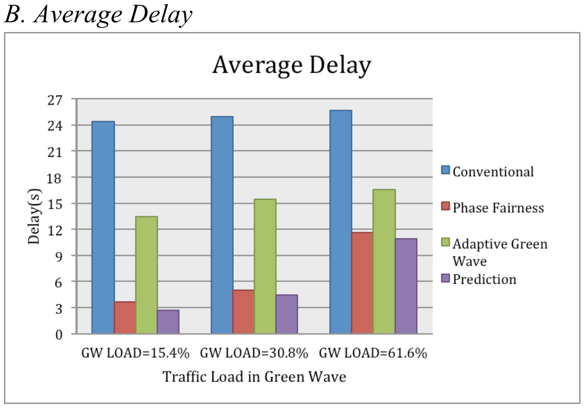

Figure 4: Average Delay of Case 1

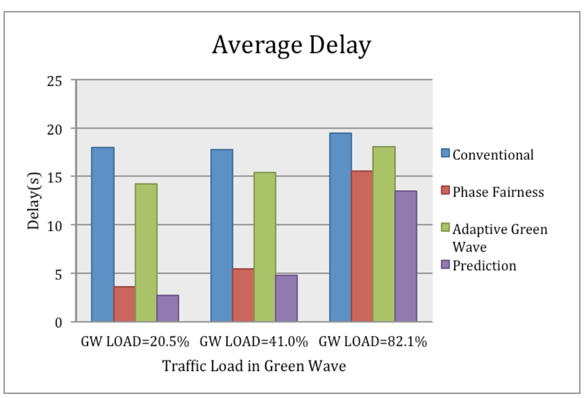

Figure 5: Average Delay of Case 2

The average delay of all methods increases as the traffic load increases. Conventional green wave has the largest average delay, while the prediction method performs the best over all ranges. Both the adaptive green wave and prediction method have improvements comparing to their own baseline.

Figure 4 and Figure 5 show the average delay of four methods in two cases. We expect big increase in average delay when the number of cars increases, but the result shows there is only a small increase. We think that it is due to using the fixed 90s as cycle length. The green wave is affected and has an increase in green wave delay. But other phases still have enough time and since the green length for green wave is the same, so their delays are not increased. So the increase in average delay only affects the increase in green wave delay.

Table 3 is the improvement performance for average delay. Adaptive green wave reduces the average delay by 39.4% on average in case 1 and reduced by 13.8% in case 2. The reason why the improvement is much higher in case 1 is because of the relative high average delay of conventional green wave which reach up to or higher than 24 seconds in all densities. This high average delay is not caused by the green wave because according to Figure 2, the green wave delay is not high. We think that it should be caused by the non-green wave direction where have higher amounts of vehicles than case 2, but we did not assign enough long time to those phases.

Predictive algorithm has the smallest average delay. While phase fairness already does a good job of decreasing the average delay, reasonable prediction still helps in reducing the delay further. In case 1, it improves 14.1% and improves 16.9 in case 2.

	Baseline Compared	**Average Improvement**	
		Case 1	**Case 2**
Predictive Algorithm	Conventional Green Wave	-	-
	Phase Fairness	30.9%	36.6%
Adaptive GW Algorithm	Conventional Green Wave	72.4%	66.4%

Table 2: Improvements of Green Wave Delay

	Baseline Compared	**Average Improvement**	
		Case 1	**Case 1**
Predictive Algorithm	Conventional Green Wave	76.2%	63.0%
	Phase Fairness	14.1%	16.9%
Adaptive GW Algorithm	Conventional Green Wave	39.4%	13.8%

Table 3: Improvements of Average Delay

VI. DISCUSSION AND CONCLUSION

In our work, we use the 4-phase model, however, if we add 4 more phases, then we can have more options to decide which two lights should be on according to current traffic condition. For example, if we add 4 phases of lane 1&2 (phase V), 3&4 (phase VI), 5&6 (phase VII) and 7&8 (phase VIII), then when it comes to the situation that lane 3&4 have the heavy traffic density, which is not originally in one phase, we can shift phase IV to phase VI, which means we borrow the green light time of lane 8 and give it to lane 4, which might also decrease the average delay and green wave delay if we borrow time for green wave also. It can be constructed in the future to form a "shared" timing phases.

In a word, this paper proposes two adaptive control methods and compares the delay with respect to the conventional green wave and the phase fairness algorithm. We can conclude that using adaptive predictive control, the average delay is significantly decreased in comparison to the fixed green wave. When focusing on the green-wave direction, the adaptive green wave algorithm with fair allocation works better than any other algorithms.

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