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Intersection Control Systems with Dynamic Wait Time Applying Vehicle to Vehicle Communication

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Intersection Control Systems with Dynamic Wait Time Applying Vehicle to Vehicle Communication

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Abstract: Although automated vehicles are becoming more popular due to the development of technology, semi-automated vehicles with auxiliary devices such as automatic braking and Adaptive Cruise Control(ACC) are now the mainstream. On the other hand, fully automated vehicles are expected to improve safety and fuel economy by providing optimal driving by a machine compared to semi-automated vehicles. This paper (1) compares previous traffic method, Autonomous Intersection Management(AIM) and Virtual Traffic Light(VTL), and (2) proposes a new traffic control scheme Dynamic Virtual Traffic Light (D-VTL), which could be replaced to VTL and improve 29% traffic efficiency in AIM4 simulation.

Keywords:
Transportation control, Computer communication networks, Vehicle simulator, Interconnection technology

1. INTRODUCTION

Recently, interest in self-driving vehicles has gradually spread around the world, but at present, only semi self-driving vehicles are available, the main components are automated braking, automated steering, and adaptive cruise control. Thus, the self-driving vehicle finds a way for solutions of safety and efficiency by using communication equipment. The advantage to introducing a self-driving vehicle is that it could be an efficient, safe, and economical means of travel. According to the research, self-driving vehicles consume less gasoline, are safer to ride, and experience fewer transportation delays in intersections than do manual driving vehicles Li and Sun (2016).

With regard to efficiency on the road, the greatest contribution of a self-driving vehicle is its capability for managing traffic jams. Through Vehicle to Infrastructure (V2I) or Vehicle to Vehicle (V2V) communication, traffic can be controlled more efficiently and precisely than using a typical intersection control system such as a stop sign or a traffic light. Intersection jams are caused by difficulties adjusting to traffic light duration for different traffic volumes depending on the day, or traffic light needing a long time for all lanes due to the high traffic volume. If a self-driving vehicle has introduced on the real life, it decreases the delay of intersection trip without the traffic light and it does not need to wait before intersection due to a traffic light or a stop sign thanks to its frequent communication.

Intersection control systems for self-driving vehicles with communication capability fall into two categories; centralized and decentralized control. Centralized control uses V2I communication and is controlled by communicating with a centralized system based on traffic light. Decentralized control uses V2V communication where communication is controlled by individual vehicles or devices. Autonomous vehicles usually travel through the intersection by adopting either of control type or a combination of both. Types of centralized control systems include: an agent-based online adaptive signal control (ASC) strategy based on real-time traffic information available from connected vehicle technology Kari et al. (2014), an arterial traffic light (ATL) controlling algorithm which has adopted the ITLC algorithm to design a traffic scheduling algorithm for an arterial street scenario Younes and Boukerche (2016), and the AIM method which we use in this paper and explain it later Dresner and Stone (2005). Types of decentralized control systems include: there are Intelligent Traffic Light Controlling (ITLC) algorithm Younes and Boukerche (2014) which considers the real-time traffic characteristics of each traffic flow that intends to cross the road intersection of interest, whilst scheduling the time phases of each traffic light, improved adaptive Traffic Signal Controlling Systems (TSCSs) Shaghaghi et al. (2017) which decreases vehicle waiting time by using Webster's methodWebster (1958), while reducing their pollutant emissions at the intersection, and Virtual Traffic Light (VTL) which we use in this paper and explain later Ferreira et al. (2010).

According to previous research presented in Section 2, the two control systems have been independently evaluated in terms on their efficiency and compared with typical intersection control such as stop sign or traffic light, but very few attempts have been made a direct comparison of these systems within the same environment. Intuitively, centralized control could potentially have better performance at the intersection, but has the disadvantage of needing an intelligent infrastructure. To judge the requirements for infrastructure, it is necessary to compare quantitatively.

Hence, we compared these two control systems using a traffic simulator Dresner and Stone (2005) and observed the differences in effectiveness between decentralized and centralized control and determined that the most effective traffic control system was centralized control.

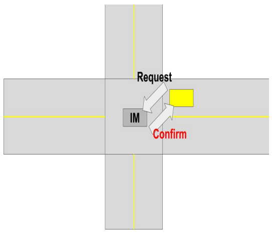
Intelligent equipped with communications devices, may not exist until the future due to the high cost of construction. However, though it was found that a decentralized system is less efficient than a centralized system, we identified a possibility to improve the efficiency of decentralized systems. i.e. change the wait time dynamically at the intersection depending on the number of vehicles. We implemented the dynamic control system called Dynamic Virtual Traffic Light (D-VTL) and demonstrated the gain of efficiency.

In summary, we will first explain decentralized control and centralized control with those representative examples. Next, we will study a decentralized control system in order to compare its efficiency to that of typical intersection control systems and centralized control systems. Finally, based on the results of the comparison, we will argue that the improved decentralized control is more efficient than original, compare it with the original decentralized and centralized control systems and present the results of that comparison.

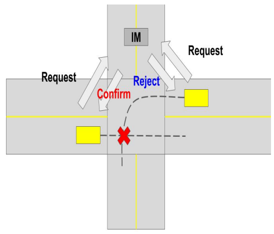
The remainder of this paper is organized as follows. In the next section, we present examples of various centralized and decentralized control systems. Also, we will introduce related papers about the design of both types of control systems. Section 3 describes the results of the comparison of centralized and decentralized controls. In section 4, using the results described in Section 3, we will present some disadvantages of the typical method and suggest D-VTL that is more efficient than original. Section 5 provides the design of a D-VTL that its efficiency. In Section 6, we introduce D-VTL with some formulae, then we consider whether D-VTL solves the problems that are mentioned in Section 3, and show the result. Finally, Section 7 concludes the paper.

2. CENTRALIZED AND DECENTRALIZED INTERSECTION CONTROL METHODS

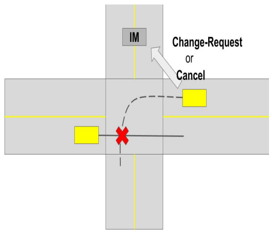
Generally speaking, there are mostly two ways that can manage the intersection travel with a manual driving vehicle on a road with infrastructure, traffic light and stop sign. Meanwhile, with a self-driving vehicle, there are two common control methods, centralized and decentralized control. In this paper, as representative methods of centralized and decentralized control methods, we evaluated Autonomous Intersection Management (AIM) Dresner and Stone (2005), which uses Vehicle-to-Infrastructure communication (V2I) via intersection manager containing intelligent infrastructure and Virtual Traffic Light (VTL) Ferreira et al. (2010) which uses Vehicle-to-Vehicle communication (V2V) respectively. In the following subsections, we describe each method.



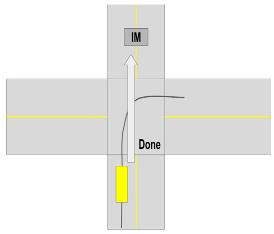
(a) Vehicle demand and IM response



(b) Accept/Reject



(c) Change content and demand again



(d) Finish transportation

Fig. 1. AIM Logic

2.1 *Autonomous Intersection Management*

This protocol is based on a multi-agent intersection travel method involving a driver agent and the intersection manager to the extent that it is a reasonable approximation of reliable wireless communication. In this method, an intersection manager is equipped for each intersection. It decides which vehicle to let cross the intersection. Vehicles communicate with an intersection manager to request to cross the intersection and receive an acceptance or rejection for the request. Under this control method, we accept for policy a commonly used algorithm "first come, first served" (FCFS), which divides the intersection into an $n \times n$ grid of reservation tiles, where the parameter n represents the granularity of the policy Dresner and Stone (2005). Generally, this policy is aimed at the vehicle which arrives first, can send messages and be managed by the intersection manager.

Message Type In Vehicle-to-Intersection (V2I) messages have 5 types, Request, Change-Request, Cancel, Done, and Away. Intersection-to-Vehicle (I2V) messages have 3 types, Confirm, Reject, and Acknowledgement. At first, we describe the V2I message.

- Vehicle to Intersection
  1. REQUEST – If the vehicle does not have a reservation yet, the vehicle would send this message. This message includes the parameters of the vehicle and the proposed reservation.
  2. CHANGE-REQUEST – This is the message used by a vehicle that has a reservation but it needs to change other parameters.
  3. CANCEL – The message used by a vehicle canceling its reservation.
  4. DONE – The message a vehicle will send after crossing the intersection.
  5. AWAY – The vehicle will send this message after sending DONE, to notify that it is moving away from the intersection.
- Intersection to Vehicle

(1) CONFIRM – This message is sent in response to a REQUEST or CHANGE-REQUEST message from a vehicle. The reservation parameter in this message is admitted.
(2) REJECT – This message is sent to notify that a REQUEST message has not been approved, and it does not accept counter-offer. There is a field in this message which indicates whether the rejected vehicle does not enter the intersection. This forces the driver agent to have to request another entering the intersection.
(3) ACKNOWLEDGMENT – The message is used to confirm receipt of a CANCEL or DONE message.

Protocol Actions This section describes the sequence of vehicle actions.

(1) The vehicle cannot enter the intersection without reservation.
(2) If the vehicle tries to enter the intersection, it travels optimally in accordance with the parameter included in CONFIRM messages received from the intersection.
(3) If the vehicle sends additional new messages to Intersection Manager before intersection manager responds, intersection manager can ignore them. Thus, the vehicle sends a new message only after it has received the response to its last message.
(4) If the vehicle has not entered the intersection and does not have a reservation, it sends REQUEST message. If the vehicle has not entered the intersection but has the reservation, it has the option to sending a CHANGE-REQUEST or a CANCEL message. If the vehicle sends these messages when it is not allowed by the intersection manager, these messages can be ignored.
(5) If the vehicle has a reservation and successfully crosses the intersection, it sends DONE message.
(6) If the vehicle receives a CONFIRM message, this is confirmation that the vehicle has a reservation.

Intersection Actions This section describes the sequence of intersection actions.

(1) When the intersection receives a REQUEST message, it needs to respond with a CONFIRM or a REJECT message. If it sends a CONFIRM message, it is guaranteed there will be no collisions in the intersection provided the vehicle travels in accordance with the parameter in the message.
(2) When the intersection receives a CHANGE-REQUEST message, it responds with a CONFIRM or a REJECT message. If it sends a CONFIRM message, it is guaranteed there are will be no collisions in the intersection provided the vehicle travels in accordance with the parameter in the message. The previous guarantees are now invalid.
(3) When the intersection receives a CANCEL message, it sends an ACKNOWLEDGEMENT message. The previous guarantees are now invalid.

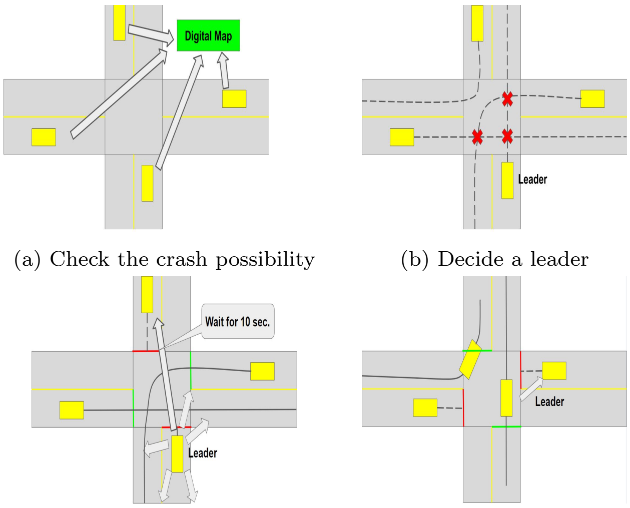
2.2 Virtual Traffic Light

In this method, there is no intelligent infrastructure that decides which vehicle crosses the intersection. Vehicles or devices on a vehicle communicate with each other and decide which vehicle to cross the intersection in a decentralized manner. Hereafter, we explain the decentralized decision mechanism Ferreira et al. (2010); Zhang et al. (2018).

System Design VTL has the following assumptions Ferreira et al. (2010).

- All vehicles are equipped with a Dedicated Short Range Communications (DSRC) device which can communicate with vehicles in short range
- All vehicles have the same digital map
- All vehicles have a Global Positioning System device which accuracy enough
- Under VTL protocol, there is no deficit of security or network delay beyond the problems that are defined here

In VTL method, we assume there is a virtual traffic light at each intersection. Each vehicle in the intersection can communicate with each other, and they share the status of virtual traffic light.



(a) Check the crash possibility (b) Decide a leader (c) Decide Wait Time and tell others (d) Transfer/Discard the leader's authority

Fig. 2. VTL Logic

VTL Logic

(1) Sensing: While the vehicle approaches the intersection, it starts detecting the vehicles approaching the same intersection using a digital map.
(2) Leader Election: If other vehicles use the same intersection and there is a possibility another vehicle might collide with it, they choose the cluster leader which is the nearest of the intersection on each road and choose the intersection leader which is nearest the cluster leaders, and the intersection leader temporarily has control of the virtual traffic light.
(3) Broadcast: The leader broadcasts information about the virtual traffic light. The leader sends a red signal, that is a wait time which denies entering the

intersection for a vehicle, to the opposite line to itself and sends a blue signal to the orthogonal line.

(4) Handover: The leader decides how long red signal lasts after being chosen. The time is a fixed value such as 10 and 30 seconds. After the time completes, the leader hands over its leadership right to the closest vehicle on the orthogonal lane. If there are any vehicles approaching the intersection on the orthogonal lanes, the leader hands over the leadership right.

(5) Release: When the leader's time expires, the leader releases its leadership right to the intersection functionality if there are no more vehicles at risk of colliding. When there is no leader in the intersection and it is found that there may be a collision soon, vehicles choose next leader again and the process repeats from step 1. It should be noted that it does not occur only except for either Handover or Release.

It is shown that the AIM method is better as an intersection control system than traffic lights and stop signs VanMiddlesworth et al. (2008). Several recent papers have demonstrated that V2I communication is more efficient than the original traffic control systems and as is V2V VanMiddlesworth et al. (2008); Zhang et al. (2018). On the contrary, this report provides the result of a comparison of AIM and VTL methods and presents the increase of performance of D-VTL in regard to efficiency.

3. PERFORMANCE COMPARISON

3.1 Method

We evaluated the performance through agent-based simulations. As an agent-based simulator for vehicle transportation, we adopted AIM4 Dresner and Stone (2005). Because AIM4 is a simulator for AIM method, we modified AIM to simulate VTL, TL, and stop sign as follows.

Originally, AIM4 was designed for the AIM protocol. It is based on Vehicle to Infrastructure communication. To show the result of intersection travel, we applied the vehicle identification number (VIN), the lane number the vehicle occupies, and the travel time by measuring the time between entering and exiting the intersection. Then, we used this information to calculate the variance of completed time and the average traveling time for the vehicles.

For each experiment, the simulator simulates one lane in each of the 4 cardinal directions. The total area modeled is a square with sides of 250 meters. The speed limit for all lanes is 25 meters per second. Figure 3 shows a screenshot of the graphical display. Each time step in the simulator represents .02 seconds of real time. Additionally, the simulator has 4 types of vehicles coupe, sedan, SUV, and van, and they have different length and other parameters such as acceleration or velocity.

3.2 Main Points of Modification

To set up the environment for the experiment, we modified the configuration of the simulator. Assuming the one-lane scenario as a condition, the simulator makes it simple to achieve the purpose of this paper. Additionally, because

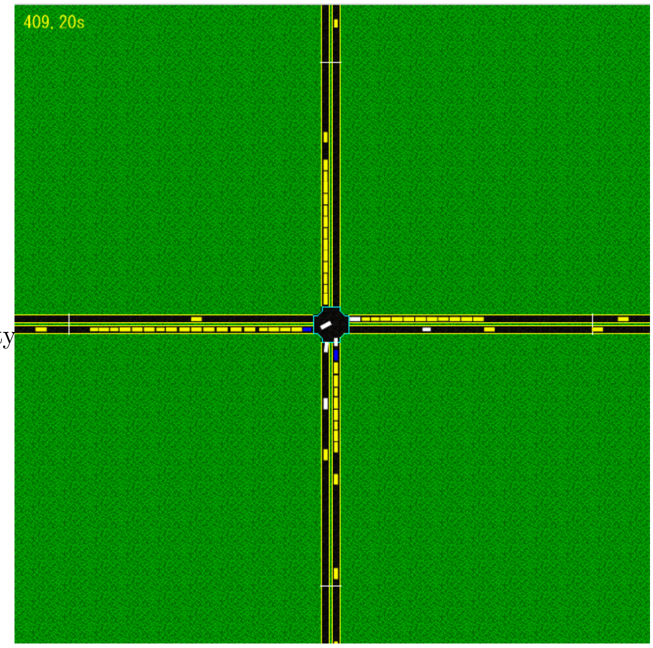


Fig. 3. A screenshot of our simulator in action

AIM4 originally only supported travel straight across the intersection, we added support for random directions including left and right.

To evaluate the VTL system instead of AIM, we updated the simulator to support the VTL regulations mentioned in Section 2. At first, to simulate V2V communication, we updated the infrastructure transparently transfer messages to other vehicles. The vehicle should travel based on the specification. We updated the intersection manager to send a REJECT message whenever there is a chance a vehicle might collide with other vehicles while crossing the intersection. If the vehicle receives a REJECT message and it is the closest vehicle in the intersection, that vehicle becomes a leader. After becoming a leader, the leader vehicle waits for a certain period of time defined by "WAIT TIME". According to the protocol for a REJECT message, the leader does not resend REQUEST or any other message while waiting before the intersection. Additionally, the vehicle traveling on the opposite lane from the leader waits for the same time as the leader, while the vehicle on the orthogonal lanes crosses the intersection. Finally, after the leader's wait time finishes, the leadership right will be handed to any vehicle on the orthogonal lanes if there is any vehicle which receives a REJECT message from the intersection manager.

3.3 AIM Result

We evaluated the performance of intersection control systems in terms of travel time, which is the time between entering and exiting the intersection. We changed the traffic volume, which is the rate of the number of vehicles entering the lane per unit of time and calculated the average and variance of travel times. Then, we compared the respective performances of AIM, the traffic light, and the stop sign.

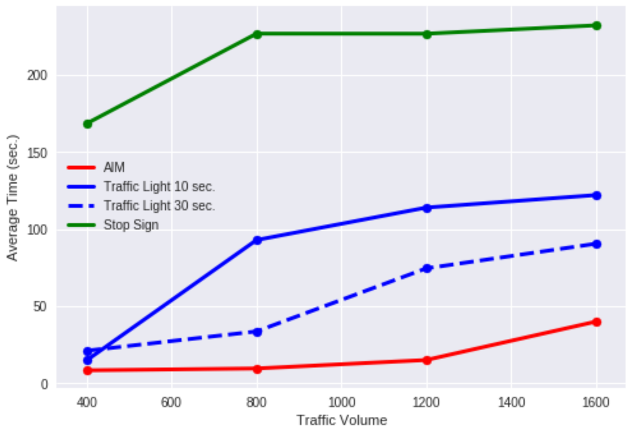


Fig. 4. Average Traveling Time of AIM

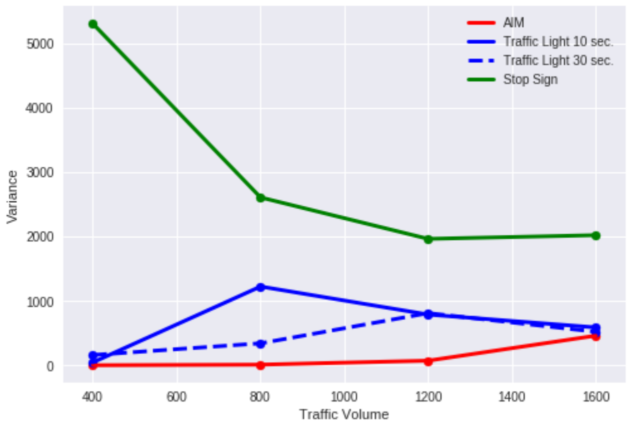


Fig. 5. Variance of AIM with Various Wait Time

Considering evaluation conditions, a good result if average traveling time is shorter, and variance of completed time of the vehicles is less.

According to Figure 4 and 5, AIM is the most efficient way of the intersection travel, and traffic light and stop sign follow in this order. In other words, if the road is congested, it would be inefficient travel in all methods, and AIM will be the most efficient method.

It should be noted that traffic light with 30 seconds long is more efficient than traffic light with 10 seconds long. This is for the same reason that the stop sign is the least efficient method. As a wait time decreases, traffic light changes more frequently, and vehicles tend to stop at the intersection. It leads to a lot of delays. Thus, we thought vehicle cluster can travel faster than the individual vehicle.

3.4 VTL Result

The result between the average travel time of vehicles completed the intersection travel, and traffic volume and the variance of completed vehicles' travel time. We evaluate among VTL, the traffic light, and the stop sign.

According to Figure 6, VTL is an efficient method of the intersection travel, and the performance of VTL equals to that of traffic light in 30 seconds and follows by traffic light in 10 seconds, and the least efficient method is the stop sign.

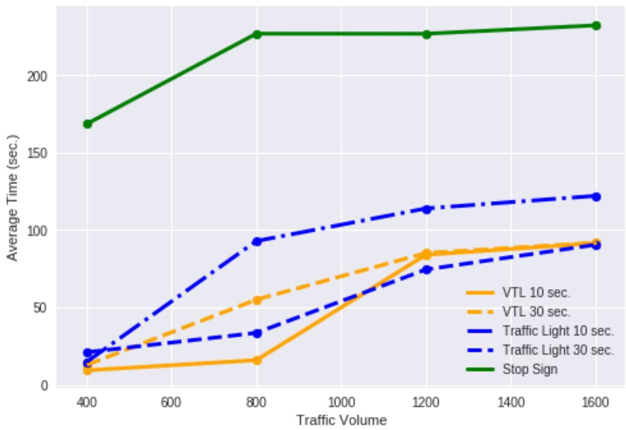


Fig. 6. Average Traveling Time of VTL, TL and SS

Fig. 7. Variance of VTL, TL and SS

The travel time does not vary at high traffic volume. On the other hand, VTL in 30 seconds and traffic light in 10 seconds have higher variance than others in terms of dispersion at traffic volume 800.

3.5 VTL with Different Wait Time

We also evaluated VTL method's varying wait time, other than 10 and 30 seconds, to confirm the optimal wait time.

Figure 8 and 9 describe that shorter wait time such as 5 or 10 seconds is more efficient when traffic volume is little because there is no traffic jam in the intersection. Meanwhile, there is a small difference when traffic volume is large among all wait time because the capacity of the intersection is almost full when traffic volume is large and throughput of traveling would be fixed in this wait time.

On the contrary, when wait time is larger than 50 seconds, the average time of the intersection travel gets shorter when traffic volumes are 1200 and 1600. This is because the throughput of the intersection travel gets improved due to the change of the rotation of traveling vehicles. Figure 10 shows that the throughput of VTL with the different wait time. Throughput gets larger until traffic volume gets 1200. After 1200, it does not increase because of the limit of the intersection capacity. Also, throughput gets higher in accordance with the length of wait time, that is the shortest wait time results in the most efficient intersection travel.

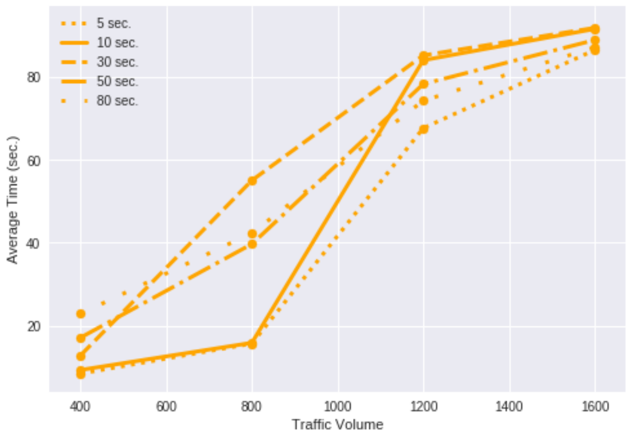


Fig. 8. Average Traveling Time of VTL

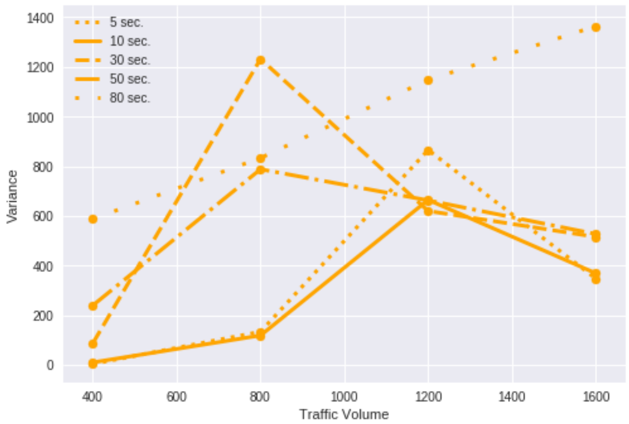


Fig. 9. Variance of VTL with Various Wait Time

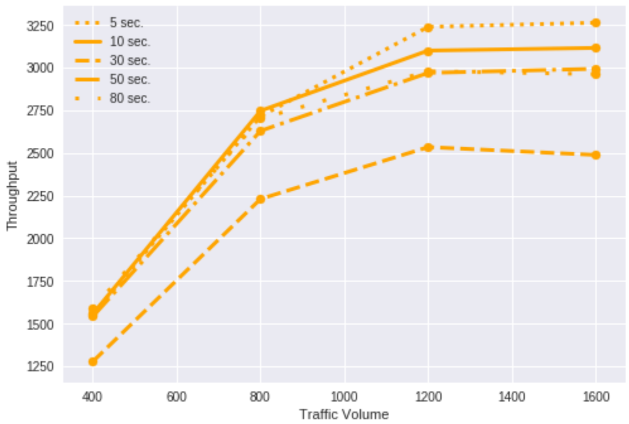


Fig. 10. Throughput of Travel with VTL

Moreover, the variance of completed vehicles' travel time over 50 seconds gets increasingly large depending on wait time. According to Figure 10, due to the improvement of throughput, one vehicle does not have to wait before the intersection, but one vehicle should wait for "WAIT TIME" which gets longer depending on the VTL wait time. Until the number of vehicles traveling is beneath the intersection capacity, the variance would be almost the same as at high traffic volumes. On the other hand, variance varies greatly at low traffic volume depending on whether there is a traffic jam.

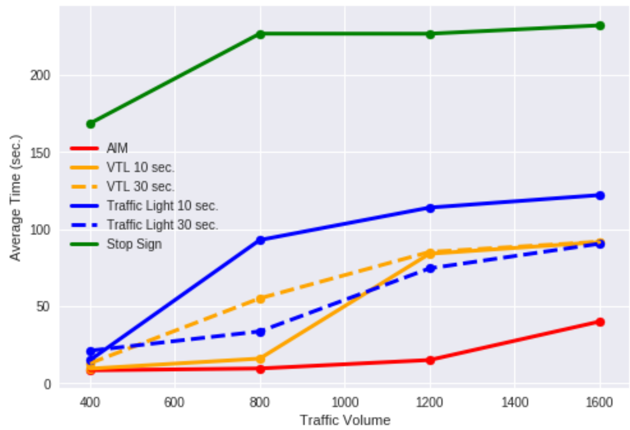


Fig. 11. Average Traveling Time of AIM and VTL

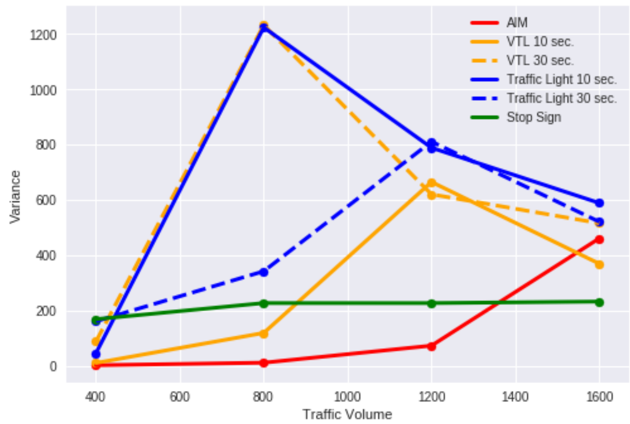


Fig. 12. Variance of AIM and VTL with Various Wait Time

3.6 Comparison of AIM and VTL

In this section, we compare AIM and VTL in terms of the average time and variance of completed vehicles' traveling various different traffic volumes. In VTL, we experimented with different wait times before the intersection, 10 seconds, and 30 seconds.

According to Figure 11 and 12, AIM is the most efficient way to manage intersection travel at any level of traffic volumes. VTL has almost same efficiency with the traffic light set to 30 seconds because once the vehicle in VTL system receives a REJECT message, the leader sets the virtual traffic light and it continues until the end of the simulation, that is substantially the same as with a traffic light. By comparison, a traffic light set to 10 seconds and a stop sign is less efficient. Thus, AIM is the most efficient method for intersection travel. As we describe in the next chapter, however, VTL could be a better method if the wait time is adjusted depending on traffic volumes.

The results of intersection travel with a traffic light and a stop sign used in a manual vehicle environment, AIM and VTL used by the self-driving vehicle demonstrate the superiority of using a communication system. In addition, we can see differences in efficiency with different traffic volumes in each approach to intersection management.

3.7 Restrictions

Here, we mention some differences between the simulator and real traffic, and their effect on our results.

- Because the simulator is based on FCFS policy, it sometimes happens that vehicles turning at the intersection have priority over vehicles continuing straight while vehicles continuing straight has priority in real life.
- VTL is targeted at manual vehicles but our simulator is based on self-driving vehicles and does not consider the lag introduced from the human decision making in perceiving the environment around the vehicle. It affects the length of wait time and its result.
- As we only experimented with restricted traffic volumes because of time constraints, there might be other optimal settings.
- The vehicle in this simulator communicates with the intersection manager while we expect vehicles with VTL to communicate with other vehicles.

Addressing these differences may lead to different results.

4. IMPROVEMENT OF VTL METHOD

This chapter first begins with a description of the problems of original VTL and their causes. Then, we propose a method to improve the original VTL called Dynamic-VTL (D-VTL).

4.1 Problems and Their Reasons

This section describes the problems of original VTL from the standpoint of efficiency. As we saw in the last chapter, original VTL is inferior to the AIM method. In fact, the performance of original VTL equals of a traffic light set to 30 seconds even though we expected VTL should be better than traffic light with any time.

Indeed, VTL is the new method to replace traditional traffic control systems such as traffic lights and stop signs which means VTL needs to be more efficient than others. According to the results, the vehicle with VTL travels faster depending on the length of wait time. Longer wait time introduces a greater variance of travel time; that is, once a vehicle gets caught by traffic light, the vehicle will have to wait a longer time than that typical for a traffic light.

The biggest problem is the wait time duration. From the comparison between VTL set to 30 seconds and AIM, the average time for AIM is faster than VTL at any traffic volumes, especially low traffic volumes. In spite of the low number of vehicles on orthogonal lanes, vehicles will wait for a certain time due to the period of virtual traffic light. Otherwise, the vehicles with AIM can cross the intersection without delay. This dead time results in the delay of intersection travel at certain traffic volumes.

Moreover, comparing VTL at various different wait times, it can be seen that the vehicle transits faster when the wait time is short and traffic volume is low and takes more time to transit the intersection when the wait time is long and traffic volume is high. This is because clustered vehicles can cross the intersection more efficiently rather than individual vehicles.

According to the results comparing AIM and VTL, the performance of AIM is obviously better than that of VTL. However, AIM can exist only where there is infrastructure such as traffic signals or signboards that can contain communication device, and not all locales have such an infrastructure. Also, it takes time and is expensive to install new devices across all the infrastructure. Moreover, AIM focuses on a self-driving vehicle society, in which all vehicles on the road are completely autonomous, so this method is not available given the current market penetration of self-driving vehicles. Thus, it is important to improve the performance of VTL.

4.2 Proposed Method

Key Idea To solve the problems, we propose D-VTL which is more efficient than original VTL by introducing a dynamic wait time.

In the original VTL, a wait time is configured with a fixed value. However, if there is no vehicle on orthogonal lanes while VTL still shows red to the driver, waiting introduces needless delays to intersection travel. On the other hand, if the wait time is too short even when the number of vehicles waiting in the orthogonal lanes is large, then it causes excessively frequent signal changes leading to inefficient travel through the intersection.

Thus, we introduced a dynamic wait time to replace the fixed wait time. When no vehicles approach the intersection while the leader vehicle waiting, a wait time will be zero seconds. Conversely, when traffic jam happens on each lane, a wait time will be set longer because there is optimal time delay depending on the traffic volume and number of the waiting vehicles. As a result, improved VTL uses dynamic wait time for efficient travel in any situations including redundant waiting. In the next section, we will mathematically derive the optimal wait time according to the number of queued vehicles.

4.3 Mathematical Formulation

D-VTL adopts a dynamic wait time depending on the number of vehicles on each lane. Specifically, each vehicle shares the information on the number of vehicles and lane numbers in the intersection, and the leader vehicle calculates the wait time according to the traffic volume of orthogonal lanes based on the formulae derived in Mingzhe (2015).

We introduce mathematical formulae to solve an optimal wait time. In Mingzhe (2015), the traffic light is assumed as intersection management and it has yellow signal time and red signal time on all lanes. Comparing with Mingzhe (2015), there is no yellow signal time all red phases under our method. Thus, we set parameters with little change.

(1) T : Cycle time
(2) a : The red light duration
(3) b : The green light duration
(4) λ : Average arrival rate from each lane

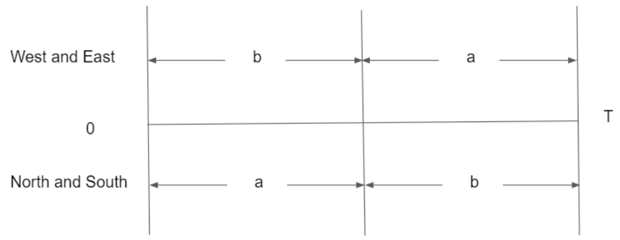


Fig. 13. Relation between each parameter in Traffic Cycle

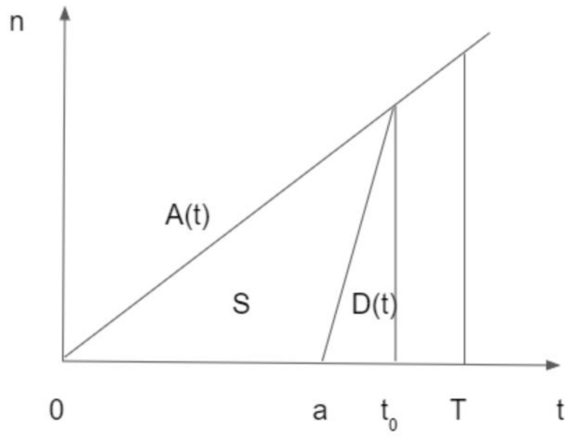


Fig. 14. Vehicles Flow

(5) μ : Average service rate of the vehicle (the number of vehicle which can travel through the intersection per unit time)

In Mingzhe (2015), T, standing for traffic cycle time, is a fixed value, but in our method, T is a dynamic value depending on the length of wait time which is the same as with a red signal. Figure 13 shows the relation between each parameter.

Also, we have limiting conditions.

$$\begin{cases} a = b \\ T = a + b \\ \lambda T \leq \mu b \\ a, b, T \geq 0 \end{cases} \tag{1}$$

Let cumulative inflow and cumulative runoff as $A(t)$ and $D(t)$ until time t in one cycle, the formulae are

$$A(t) = \lambda t \tag{2}$$

$$D(t) = \begin{cases} 0 & (0 \leq t < a) \\ \mu_1 t - \mu a & (a \leq t < t_0) \\ \lambda t & (t_0 \leq t \leq T) \end{cases} \tag{3}$$

Figure 14 demonstrates this formula. Here, t on the horizontal axis expresses time and on the vertical axis, n expresses the total number of queued vehicles with zero acceleration.

If we regard the time for solving the full traffic congestion as t_0, t_0 is $t_0 = \frac{\mu a}{\mu - \lambda}$. Thus, it is found that the most efficient wait time is the time until traffic congestion is solved. In Figure 14, S is total wait time which the vehicles have to wait while at a red light or the time which all queued vehicles would need to finish traveling the intersection.

Cumulative inflow is increased in accordance with the ratio of the average number of arrival vehicles. On the other hand, cumulative runoff is increased differently as a function of time. When the traffic signal is red (variable a), there are no vehicles going into the intersection. While the period from a to t_0, the vehicle finishes the intersection travel depending on the ratio of cumulative runoff. After all queued vehicles finish the transit, the rest of the vehicles are arriving at the intersection while the intersection processes queued vehicles.

5. EXPERIMENT RESULTS

In this section, we describe empirical evaluations of our D-VTL method using a modified AIM4.

5.1 Program Setting

We added new code for this method. First, we put the information on the number of vehicles and lane number. Note that this number can be collected by the leader in a distributed manner. Second, we implemented a different wait time depending on the traffic volume of orthogonal lanes. The capacity on each lane is 22 or 23 vehicles.

5.2 Empirical Results

We applied model Mingzhe (2015) to D-VTL. To solve the optimal wait time, we found variable μ using manual inspection. In particular, we counted the time for completing travel of the queued vehicles and found an intersection transit of one vehicle per one second. Then we calculated a wait time depending on queued vehicles in the orthogonal lanes. As a result, we found optimal μ as 0.412. For example, if the number of queued vehicles is 10, the most efficient wait time becomes 24.2 seconds. Additionally, we multiply a 5 % error rate because we could count the number of vehicles traveling in each lane, but not the number of queued vehicles.

According to these conditions, we ran the simulator and compared the improved VTL with AIM and original VTL.

From both of the figures for D-VTL, shown in Figures 15 and 16, we observed D-VTL is more efficient than original VTL. When traffic volume is large such as 1200 or 1600, D-VTL is better than VTL in 5 second wait time. However, the variance of completed vehicles with D-VTL is larger than original VTL because vehicles on any lane travel smoothly, on the other hand, others were stuck in a traffic jam due to the ratio of driving direction. The vehicles should wait in accordance with FCFS policy, so it sometimes happens that turning left has prior over going straight.

5.3 Discussion

Thus, D-VTL enhances the efficiency of intersection travel. It increases efficiency by about 29% as compared with

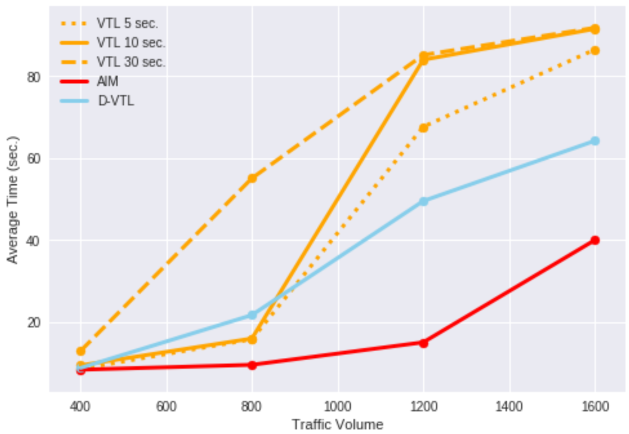


Fig. 15. Average Traveling Time of D-VTL

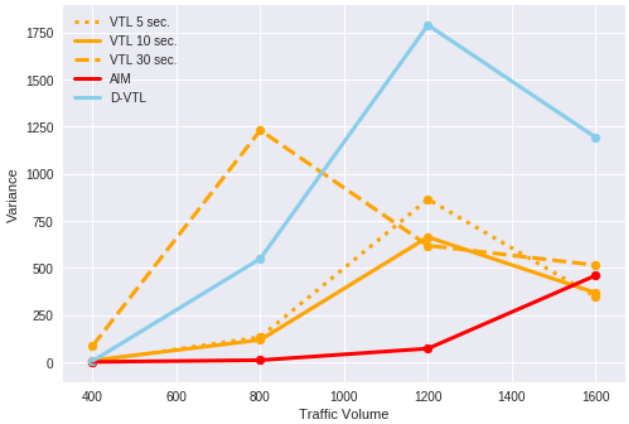


Fig. 16. Variance of D-VTL with Various Wait Time

original VTL when traffic volume is at 1600. On the other hand, original VTL is better when traffic volume is low because of the number of queued vehicles. Thus, the method of fastest intersection travel depends on how the intersection decreases the number of queued vehicles.

6. CONCLUSION

In this paper, we made two contributions as follows. First, we compared typical traffic control systems such as stop signs and traffic lights, and control systems with a communication-based method such as AIM, and VTL. Second, we found drawbacks in original VTL in terms of efficiency of the intersection transit and introduced a dynamic wait time depending on the number of queued vehicles on each lane, and we compared that with AIM and original VTL.

Firstly, we showed the results of the comparison of a typical control system such as stop signs and traffic lights, and the communication-based methods, AIM and VTL, respectively. As previous researches explained and our experiment has reproduced, AIM is more efficient than the stop signs and the traffic lights. However, it is observed that VTL is not a very efficient intersection travel method. When it comes to the various wait time of VTL, the shortest wait time applies the fastest intersection travel and the longest results in the slowest intersection travel. Therefore, fixed wait time using in original VTL proves to lead to the deficit of the system.

Next, we created D-VTL and figured out that it is useful in the real world. Although we could not exceed the performance of AIM method, we showed that D-VTL is more efficient than original VTL when it comes to heavy traffic in the intersection though a wait time of D-VTL is longer than the original, that is contrary to the fact that the shorter wait time could bring better results. D-VTL results from a way of selection of wait time depending on the queued vehicles with zero acceleration. By introducing a dynamic wait time, we achieved a better performance with 29% comparing to the original. In this way, we believe we have accomplished a portion of the research of the intersection travel.

As for the future works, first is in larger simulation applying Vehicle to Vehicle communication, and ultimately with real physical vehicles. In addition, the vehicles could send messages safely, or detect failure of sending messages in the intersection.

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