Equitable Traffic Signals Controls Games

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Abstract

In the intersection design, every driver has a unique individual value of time and a different way of perceiving delays and savings. The current traffic signal controls policy in the intersection (e.g., First-Come-First-Serve and System Optimal objective) often neglects the heterogeneity of time value and creates aggregate disparity across the drivers. In improving the equity issue in the intersection, this work develops mechanisms to achieve the Envy-minimizing condition where the envy among drivers in the intersection at any time instance is minimized. The Envy-minimizing mechanism considers two mechanisms, i.e., the fixed time and bid-based time. These mechanisms are constructed to examine the Envy-minimizing condition dynamically across time. The output of these two mechanisms includes the ordering rule of the right of way in an intersection and time allocation for each traffic signal. Finally, the application of these mechanisms is conducted to the simple intersection problem with a 4-legged intersection application.

1 Introduction

Optimization of traffic signals to improve the performance metrics such as wait times, throughput, and emissions by controlling the vehicles at an intersection is a well-researched area. However, the current objective in achieving the System Optimal (SO) traffic condition often creates disparities among the users. Consequently, we encounter situations where an approach or phase of an intersection has more green time allocation, which leads to increasing waiting times for other approaches and conflicting phases. Despite improving the overall performance over the signals that have equal green time for all phases, the aggregate disparity between the users of the systems increases as more intersections implement this preferential treatment.

The current traffic signals also implement the practice of a First-Come-First-Serve (FCFS) rule that has been widely perceived as a fair option in intersection control. However, the fairness of the FCFS rule holds only if we assume that every user has the same valuation of time and has no preference regarding the delay. In real-life practice, every user might have heterogeneity in their valuation of time. Each person values their time consumption differently. Hence, the FCFS rule is inefficient and unfair while considering the heterogeneity in user's valuation of time. Neglecting the heterogeneity of valuation of time would exacerbate the aggregate disparity between the users of the systems. The ordering rule of the right of way in an intersection, which considers each user's valuation, becomes another essential element in achieving equitable traffic signal conditions.

In creating such desired traffic signals, this project studies the fairness concept of traffic signal allocation in the intersection modeling. We consider two types of output allocations, i.e., fair order rule of the right of way and fair green (release) time or fair red (waiting) time allocation for each phase. The fairness concept could be achieved by evaluating the Envy-Freeness (EF) condition among users. Envy-free holds if every user with its current allocation does not envy the allocation of other users. However, considering the heterogeneity of the preference in time consumption among users leads that the EF condition does not exist in such intersection control.

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If the waiting times at an intersection are considered cost or money, then each individual using different approaches pays a different cost to use the same commodity. From an economic standpoint, such a system is not equitable and creates envy. Next, analogous to the cake cutting problem, the green time for a cycle can be treated like a cake, and equal green time can be allocated for all approaches (which is not optimal for performance). However, the cake or green time cannot be consumed at the same time by all users. When a phase receives green, users of other phases are worse off and always envy the current phase with the right of way.

Through the non-existence of EF condition in the intersection problem, we relax the notion of EF and introduce the concept of Envy-minimizing. The envy-minimizing minimizes the envy among the users, where this minimized envy improves the overall fairness of the systems. The project develops two mechanisms to provide the Envy-minimizing allocation, i.e., the fixed time and bid-based time.

Notice, importing the envy-minimizing mechanism in the intersection is challenging. In contrast to other multi-agent resource allocation, each user only demands one particular bundle, their phase/trip. Hence, even though the time allocation is continuously divisible, the order rule of the right way is indivisible and non-transferable across the users. The second challenge is that the intersection is a dynamic problem, which leads the resource allocation to evolve in time. We need to construct the mechanism that could dynamically trace the envy from the previous stage to achieve fairness in the intersection.

The project is initiated by conducting the literature review of the equitable signals. There are two interesting related works regarding the improvement of fairness in traffic signals, i.e., Auction-based mechanism [1] and Pricing Scheme mechanism [2, 3]. Then, we define the two proposed Envy-minimizing mechanism rules. Next, we apply these mechanisms to the simple intersection problem with a 4-legs intersection application. We discuss the gaps in the literature reviews, the limitations of the proposed mechanisms, and plausible extensions of this work.

2 Related Works

2.1 Second-Price Auction Mechanism

2.1.1 Problem Definition

Carlino et al. [1] study the application of auction mechanism to model the flexible and fair intersection traffic control schemes. The increased adoption of autonomous vehicles to the roads could bring new opportunities in improving the fairness in intersection policy. This paper constructs the auction mechanism to allow each driver to compete to win the right of way, claiming that such a bid mechanism would improve fairness compared to the traditional FCFS rule. In this model, the paper applies the concept of a "second-price" auction where every driver will bid in each intersection policy.

The general procedure for running the intersection auction is outlined as follows:

In the auction intersection policy, the auction will be played in each intersection policy to find the winning driver. There will be only one winning driver from a certain phase that has the right of way. After the winning driver leaves the intersection, we will begin the next auction intersection rule. In this game, before we determine the winning driver, we will determine the winning leg. The leg of the intersection is one face/one roadway in the intersection. For each leg, it is possible to have a collection of drivers queuing in the leg line and bidding in the auction. The winning leg is determined by choosing the intersection leg with the highest cumulative bid. This winning leg will pay the second price of the auction. Then, this work defines the winning driver as the first driver that queues on the face of the winning leg. The second-price bid of the leg will be paid by each driver in such leg proportionally to their original bid.

The formal rule of the mechanism is defined as follow:

1. Form a list of candidate C
2. Ask all participating drivers to bid on an item, and collect the *bids*
3. Determine the *winner* and *secondprice*
4. Collect payment from each driver who bid for the winning item. If a contributed *amount* to *winner*, which won with $total := sum(bidswinner)$, then pays: $\frac{amount}{total} \times \frac{secondprice}{R(item)}$

C (the list of candidate items for a particular auction) and **losers** (the drivers who experience delay due to the outcome of an auction) are defined per intersection policy
participants are all drivers traveling on a lane that leads to the intersection
R(item) is a rate by which an item's total bid is multiplied, described in Section III-E
bids $:= \{ask\_bid(a, C) \mid a \in participants\}$
where each bid is a tuple $(a, item \in C, amount)$
sum(bids) $:= \sum_{b \in bids} amount_b$

winner $:= argmax_{item \in C}(R(item) * sum(bids_{item}))$
where $bids_{item} := \{b \in bids \mid item_b = item\}$
runner_up $:= argmax_{i \in C}(R(i) * sum(L_i))$
where $L_i := \{b \in bids \mid item_b = i \wedge driver_i \in losers\}$
second_price $:= R(runner\_up) * sum(losing\_bids)$
where $losing\_bids := \{b \in bids \mid item_b = runner\_up \wedge item_a \in losers\}$

Figure 1: Second-Price Auction Problem, Carlino et al. [1]

2.1.2 Example

In this section, we explore the intersection auction problem example to illustrate the mechanism of the rule. Consider Figure 2 where driver A won the previous auction and is about to leave the auction game. Recall, only one winning driver exists in the mechanism. In the next auction, we have four leg competitors where the faces of each leg are drivers B, C, D, and E. We also have the second-line driver or more behind each leg's face driver that joins the auction. Here, the left leg consists of driver B bidding 30 and driver G bidding 20; hence, the total bidding value of this leg is 50. We calculate the bidding value of every other leg. From this setup, the winning leg is the left leg (driver B and G), and the second price of the auction is 40. The winners – B, who bid 30, and G, who bid 20, must together pay the total of the runner-up's bid: 40. We distribute the prize of 40 proportionally to driver B and driver G according to their initial contribution in the bid. Since B comprised 60% of the winning bid and G made up 40%, B pays 24 and G pays the remaining 16. After the payment, driver B has the right to cross the intersection, but driver G stays. After B crosses the intersection, a new auction is run, and G is now a candidate of the face of the leg with drivers C, D, and E.

2.1.3 Limitations

We examine two limitations concerning the fairness and the feasibility of this application to real-life intersection control. The first concern is that the mechanism is ruled unfairly. According to the example (Figure 2), after B crosses the intersection, a new auction is run, and G is now a candidate. Note that G must bid again; the fact that it contributed to the previous auction winner does not affect the next auction. Also, there is a risk that new drivers, not shown, could appear behind C and D and repeatedly outbid G. The effect is that G wastes its money paying for B to move earlier. The driver G becomes discriminated against in the game. This setup clearly shows that the second-price auction mechanism could not assure equitable traffic signal controls.

The next important concern is in terms of the feasibility of this application. Recall, this auction mechanism only allows one winning driver to have the right of way to cross the intersection in each auction game. However, in real-life application, the intersection policy considers two main elements, i.e., the ordering rule of the right of the way and the allocation of time for each signal. This mechanism provides us the order of the rule who could cross the intersection from each intersection's leg. However, the allocation assumption used in this mechanism is unrealistic. First, the intersection policy cares more about the phases (direction between north-south movement and west-east movement). When the upper leg is allowed to move, the bottom leg

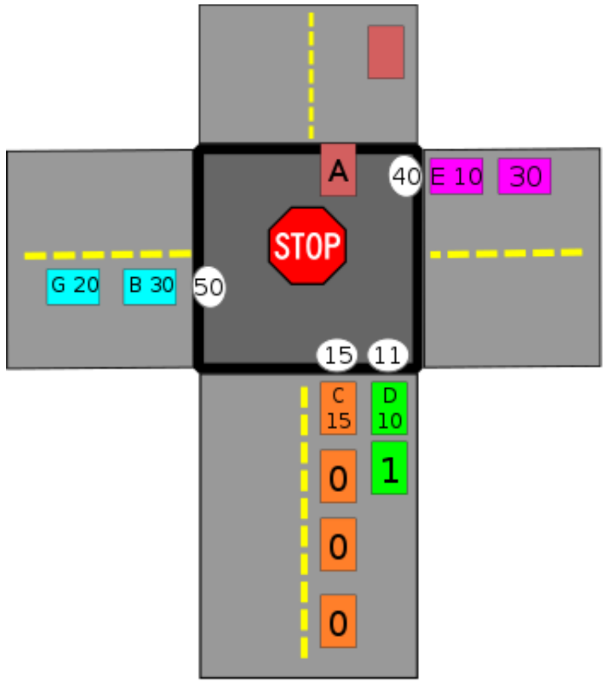

Figure 2: Intersection Auction Problem, Carlino et al. [1]. The amount each driver bids (in units of money) is shown below or beside their name, and the total bid for each choice is circled. Assume for simplicity that all drivers wish to cross straight across the intersection.

will likely be allowed to move because those legs are in the same phase (north-south). A similar condition holds between the left and right legs. Second, the mechanism allows only one driver in each auction, which is also unrealistic. In the application, we consider the time allocation in each signal that allows more than one driver to move in that period, not necessarily controls the number of cars that pass.

2.2 Envy-minimizing Price Scheme

2.2.1 Problem Definition

Lloret-Battle and Jayakrishnan [2, 3] propose the pricing scheme that achieve the minimized envies among the drivers in the intersection control. In this work, the authors consider the heterogeneity of Value of Time (VOT) in each driver. The heterogeneity of the VOT leads to a heterogeneity of perceived time pressure due to the perceived lateness at the intersection. Hence, any delay saved by traffic signal controls will have its own valuation, defined as Value of Delay Savings (VDS). The work focuses on developing the specifications and a control algorithm that manage the VDS.

Let define I as the set of driver and i to indicate a certain driver in the intersection. Due to the heterogeneity in the VDS, each driver i is assumed to have a quasi-linear utility function as the following equation.

$$u_i(d) = -\theta_i d_i + \pi_i \; \forall i \in I \tag{1}$$

where $\forall i \in I$,

$$\begin{aligned} \theta_i &= \text{the value of delay savings (VDS)} \\ d_i &= \text{control delay} \\ \pi_i &= \text{the price charged} \end{aligned}$$

Definition 1 (Envy-free Allocation in Intersection) *Envy-freeness in intersection is achieved if this condition holds:*

$$u_i(\theta_i, d_i, \pi_i) \geq u_i(\theta_j, d_j, \pi_j) \forall i, j \in I, i \neq j$$

Every driver in intersection does not envy other signal allocation on other player

However, the this EF condition would not exist in intersection. The simplest interpretation to show the non-existence EF is by considering incoming driver that joins the intersection queue. This driver will always envy other driver that currently has the current right of the way. This work uses pricing scheme that minimize the EF to improve the fairness in the intersection.

Definition 2 (Intersection Price) *In the intersection problem, there is a price applied for each driver dynamically in each indecent of time. The price $p_{i,h}$ is the price of driver i in time step h*

This price is calculated dynamically. Define H as the time window that we would like to evaluate in the intersection and h indicate the discretized time step in window H. The price will be assigned for each time step h, hence, the utility function would be the function of θ_i, d_i, the previous charged price, $\pi_{i,h-1}$, and the current price, $p_{i,h}$. We have the utility function as $u_i(\theta_i, d_i, \pi_{i,h-1}, p_{i,h})$ $\forall i \in I, \forall h \in H$

Definition 3 (Envy Excess) *In the intersection problem, there is an envy excess suffered by driver i from driver j, notated as $\epsilon_{i,j} \geq 0$.*

Using definition 2 and 3, we construct the definition of Envy-minimizing Price Scheme as follow,

Definition 4 (Envy-minimizing Prices) *The traffic signals are equitable and fair signals if the traffic signals achieves Envy-minimizing Price condition, as follow:*

$$\min_{p_{i,h}} \sum_{i,j \in I, i \neq j} \gamma_i \epsilon_{i,j} \tag{2}$$

$$s.t. \;\; \epsilon_{i,j} + u_i(\theta_i, d_i, \pi_{i,h-1}, p_{i,h}) \geq u_i(\theta_j, d_j, \pi_{i,h-1}, p_{j,h}) \; \forall i, j \in I, i \neq j \; \forall h \in H \tag{3}$$

$$\sum_{i \in I} p_{i,h} = 0 \; \forall h \in H \tag{4}$$

This work defines the mechanism M as pair of functions $k : \Theta \to K, p : \Theta \to P$. The space of K refers to the traffic signal allocations, including the order of rule and time allocation. The space of P represents the pricing scheme strategy to achieve the Envy-minimizing Price condition. The first function is defined as the phase allocation rule that maps the information of each driver, Θ, into allocation space, K. The problem is solved using the traditional traffic signalizing theory. The second function is to solve the Envy-minimizing Price condition. These functions are solved in an iterative rule until converged to the optimal pricing scheme.

2.2.2 Limitations

We examine two limitations regarding the application of this mechanism. The first concern is that this mechanism could not guarantee truthfulness. In this setup, each driver can selfishly manipulate the control outcome for personal benefit. The second issue is the guarantee of the existence of the solution. This work assumes that such a price minimizes the slack term, $\epsilon_{i,j}$. However, there is no guarantee that there is such minimization exists. In the worst scenario, we could only achieve such given slackness with no further improvement exists in the optimization search.

3 Model and Fairness Concept in Equitable Traffics

3.1 Notation

$$
\begin{aligned}
p_i &- \text{Player i}\\
\theta_i &- \text{Value of Travel Time Savings (VTTS)}\\
d_i &- \text{Wait Time at the current intersection}\\
\pi_i &- \text{Cumulative Profit/Loss}\\
v_i(d) &- \text{Utility function for } p_i \text{as a function of delay } d\\
s_i &- \text{Strategy of } p_i\\
\phi^k &- k^{th} \text{ phase of the signal}\\
\phi_i &- \text{Proposed phase by } p_i \text{ according to } s_i\\
\pi^t &- \text{Cumulative sum of dis-utility for the phase decision at time } t\\
\pi_i^t &- \text{Profit/loss for } p_i \text{ for the phase decision at time} t\\
\tau &- \text{Fixed signal green time} p_i\\
\tau_i &- \text{Proposed green time by } p_i \text{ according to } s_i
\end{aligned}
$$

3.2 Envy-minimizing

For traffic signals, the notion of envy is slightly different from the conventional one and is usually interpreted in multiple ways. If wait-times at the intersection are considered good(chore as the utility is negative), then a player could envy other players if their wait time at the intersection is higher than the few or all the other players. Then alternatively, if the green time at the intersection is considered as good. Then a player can also envy other players if the green time they are receiving is lesser than few or all other players queuing at the intersection. Other criteria for envy could be that a player only envies other players if they arrive later and get right of the way later. For this project, we assume the wait time or delay at the intersection is the chore and that everyone tries to minimize it.

As mentioned in the earlier section, the notion of Envy-Freeness (EF) does not exist as only 1 of the competing players receives the good(the green time)/chore (wait time) at a time and the order in which the competing set of players receive matters. Therefore, the idea is to minimize envy rather than eliminating it. Thereby the characteristics of an Envy-minimizing signal is that it tries to minimize the envy of all players collectively and over multiple intersections tries to minimize the envy of almost all players. One of the key assumptions is that every player has utility, and it is expected that everyone wants to maximize their utility. The utility of a player 'i' is modeled as

$$
\begin{gathered}
v_i = -\theta_i d_i + \pi_i\\
\theta_i > 0\\
d_i \geq 0\\
v_i, \pi_i \in \mathbb{R}
\end{gathered}
$$

Here θ_i is intrinsic to player i, and π_i is a proxy for the cumulative advantage or disadvantage the player has received overall previous intersection. Notice that the v_i decreases with an increase in wait time; hence, everyone tries to minimize it.

3.3 Game Design

The game can be represented by the state as

$$'n' \text{ players} - \{p_1, p_2, ..., p_n\}$$
$$'p' \text{ phases} - \{\phi^1, \phi^2, ..., \phi^p\}$$

$$v_i(d) = -\theta_i d + \pi_i, \{\theta_i, \pi_i\} \in p_i \tag{5}$$

We assume that the game setting has 'p' phases competing with each other, and only one phase can be served at a particular time. The idea can also be extended when a combination of phases can be allowed at the same time represented by a ring and barrier setting. There are 'n' players competing for green time trying to minimize their delays. The players are competing only when they are within the range of the intersection and have not crossed the intersection. Player 'i' arrives at the intersection with a θ_i and π_i which are communicated with the traffic signal. From the information obtained from all competing signals, the traffic signal comes up with an allocation and payment rule that minimizes envy and compensates players based on their service/delay.

Therefore, the objective is to come up with a suitable mechanism along with these following desired characteristics.

- Social Welfare Maximizing
- Budget Balanced
- Fast Running Time

3.4 Mechanism 1 - Envy-minimizing Fixed Time

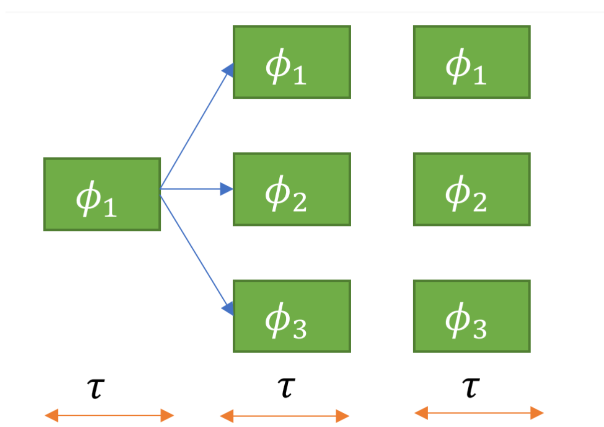

Figure 3: Fixed Time Mechanism

In this mechanism the allocation phase is chosen every τ time and for a time period of τ the phase is allocated the green time. In the allocation phase, the phase with minimum dis utility (i.e. maximum utility) is assigned the green time represented by

$$\underset{\phi^p}{\operatorname{argmax}} \sum_i v_i(\tau), \forall p_i \notin \phi^p \tag{6}$$

Suppose kth phase(ϕ^k) is the allocation obtained from the mechanism then the cumulative dis utility for the allocation is given by

$$\pi^t = \sum_i v_i(\tau), \forall p_i \notin \phi^k \tag{7}$$

The π_t is added as a penalty for all players in phase and subtracted from all players out of phase. The addition or subtraction is proportional or weighted according to the valuations of players.

$$\pi_i^t = \begin{cases} \frac{\theta_i \pi^t}{\sum_j \theta_j} \forall p_j \in \phi^k & \text{when } p_i \in \phi^k \\ -\frac{\theta_i \pi^t}{\sum_j \theta_j} \forall p_j \notin \phi^k & \text{when } p_i \notin \phi^k \end{cases} \tag{8}$$

The mechanism is envy-minimizing and social welfare maximizing as for any phase ($l \neq k$),

$$\sum_i v_i(\tau) < \sum_j v_i(\tau), \forall p_i \notin \phi^l, p_j \notin \phi^k$$

The mechanism is budget balanced as,

$$\sum_i \pi_i^t = 0, \forall p_i$$

The mechanism has a fast running time as the complexity is O(n). However, there is limitation to this mechanism. As the players do not have a say in time for the signal, they may end up paying more/less for the service. Given the opportunity, the players may choose a different green time allocation. Also, in the fixed time τ, there could be a case that none of the vehicles cross the intersection.

3.5 Mechanism 2 - Envy-minimizing Bid-based Time

To address the issues in Mechanism 1, we propose an alternative bid-based signal mechanism. In this setting, each players propose a strategy besides communicating their θ_i and π_i with the signal. The strategy includes the phase ϕ_i and green time τ_i

$$s_i = \{\phi_i, \tau_i\}$$

Then, the allocation is given to the strategy with minimum dis-utility similar to mechanism 1.

$$\underset{s_i}{\text{argmax}} \sum_j v_j(\tau_i), \forall p_j \notin \phi_i \tag{9}$$

Suppose $s_i - \{\phi_i, \tau_i\}$ strategy is accepted. Then, ϕ_i is the phase allocation and τ_i is the green time allocation obtained from the mechanism. The cumulative dis utility for the allocation is given by

$$\pi^t = \sum_j v_j(\tau_i), \forall p_j \notin \phi_i \tag{10}$$

The π_t is added as a penalty for all players in phase and subtracted from all players out of phase. The addition or subtraction is proportional or weighted according to the valuations of players.

$$\pi_i^t = \begin{cases} \frac{\theta_i \pi^t}{\sum_j \theta_j} \forall p_j \in \phi_i & \text{when } p_i \in \phi_i \\ -\frac{\theta_i \pi^t}{\sum_j \theta_j} \forall p_j \notin \phi_i & \text{when } p_i \notin \phi_i \end{cases} \tag{11}$$

The mechanism is envy-minimizing and social welfare maximizing as for any strategy ($s_l \neq s_i$),

$$\sum_k v_k(\tau_l) < \sum_j v_j(\tau_i), \forall p_k \notin \phi_l, p_j \notin \phi_i \text{and}$$

The mechanism is budget balanced as,

$$\sum_i \pi_i^t = 0, \forall p_i$$

The mechanism has a fast running time as the complexity is O(n) similar to the mechanism 1. The mechanism satisfies all the desired properties and also addresses the issue in mechanism 1. However, the only limitation is about that the player need not be truthful about their VTTS(θ_i).

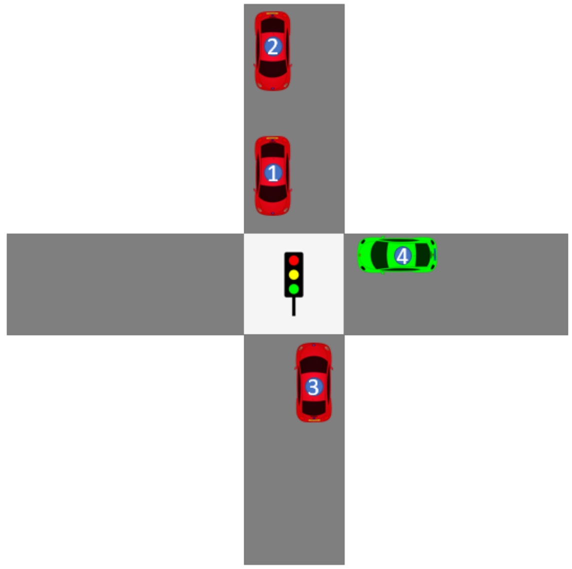

Figure 4: Traffic Signal Game

4 Examples

For this project, we consider a two-phase intersection example where vehicles in N-S directions move in one phase(ϕ_1) and vehicle in E-W move in other direction(ϕ_2). Although this is fairly simple assumption, the idea can be extended to multiple competing phases. Here players $p_1, p_2, p_3 \in \phi_1$ and $p_4 \in \phi_2$ are competing for the green time. Assume their VTTS and profits/loss at some time t are

$$\theta_i - \{10, 20, 30, 40\}, \pi_i - \{20, 10, -30, 40\}$$

4.1 Mechanism 1 - Envy-minimizing Fixed Time

Let the fixed time for which the phase is decided be $\tau = 5$. Therefore decisions are made for 5 sec and at every 5 sec multiple. Suppose ϕ_1 is chosen, then the dis utility is

$$\sum_i v_i(\tau), \forall p_i \notin \phi_1$$
$$= -40 * 5 + 40 = -160$$

Suppose ϕ_2 is chosen, then the dis utility is

$$\sum_i v_i(\tau), \forall p_i \notin \phi_2$$
$$= -(10 + 20 + 30) * 5 + (-20 + 10 - 30) = -340$$
$$\therefore \phi_1 = \underset{\phi^p}{\text{argmax}} \sum_i v_i(\tau), \forall p_i \notin \phi^p$$

Hence ϕ_1 is chosen in the allocation. For the payment,

$$\pi_t = \sum_i v_i(\tau), \forall p_i \notin \phi_1 = -160$$

$$\pi_t^1 = \frac{\theta_1 \pi_t}{\sum_j \theta_j} \forall p_j \in \phi_1 = \frac{10 * -160}{10+20+30} = \frac{-160}{6}$$

Similarly,

$$\pi_t^2 = \frac{-160}{3}, \pi_t^3 = \frac{-160}{2}, \pi_t^4 = +160$$

$$\therefore \pi_t^1 + \pi_t^2 + \pi_t^3 + \pi_t^4 = 0$$

4.2 Mechanism 2 - Envy-minimizing Bid-based Time

Here each player p_i is asked to propose a strategy $s_i - \{\phi_i, \tau_i\}$. For allocation the strategy with the minimum dis utility is chosen. Suppose the strategies are $s_1 = \{\phi_1, 6\}, s_2 = \{\phi_1, 8\}, s_3 = \{\phi_1, 6\}, s_4 = \{\phi_2, 2\}$

Suppose s_1 is chosen, then the dis utility is

$$\sum_i v_i(\tau_1), \forall p_i \notin \phi_1$$
$$= -40 * 6 + 40 = -200$$

By observation s_1 is same as s_3.Therefore, s_3 also has same dis utility

Suppose s_2 is chosen, then the dis utility is

$$\sum_i v_i(\tau_2), \forall p_i \notin \phi_1$$
$$= -40 * 8 + 40 = -280$$

Under s_4, the the dis utility is

$$\sum_i v_i(\tau_4), \forall p_i \notin \phi_2$$
$$= (10 + 20 + 30) * 2 + (-20 + 10 - 30) = -160$$
$$\therefore s_4 = \underset{s_i}{\text{argmax}} \sum_j v_j(\tau_i), \forall p_j \notin \phi_i$$

Hence s_4 is chosen in the allocation. For the payment,

$$\pi_t = \sum_i v_i(\tau_4), \forall p_i \notin \phi_2 = -160$$

$$\pi_t^1 = -\frac{\theta_1 \pi_t}{\sum_j \theta_j} \forall p_j \in \phi_1 = \frac{-10 * -160}{10+20+30} = \frac{160}{6}$$

Similarly,

$$\pi_t^2 = \frac{160}{3}, \pi_t^3 = \frac{160}{2}, \pi_t^4 = -160$$

$$\therefore \pi_t^1 + \pi_t^2 + \pi_t^3 + \pi_t^4 = 0$$

5 Conclusion

The idea of equitable signals stems from the fact that people value their travel time savings differently, and every player's VTTS being treated the same could be unfair. The VTTS for each player could be different due to individual ways of living or personal choices. Even for an individual, the VTTS could change with time depending on the importance of the trip. Often, work trips are valued more than leisure trips where there is no deadline to reach a place. The goal of this project was to come up with an efficient and scalable mechanism for traffic signal control that makes it more equitable.

Although an envy-free setting is impossible, most researchers attempt to develop mechanisms that minimize envy (envy-minimizing). For this to be possible individual players should be able to communicate their value of travel time savings. However, if the mechanism is solely based on VTTS, everyone can pose high VTTS. Therefore, the idea is to compensate the players for the green time or delay they receive. In this setting, they should be able to communicate cumulative loss/profit as well.

Assuming these two variables can be communicated with the signal in real-time, we develop a utility representation for each player and propose a mechanism for envy-minimizing fixed time signals. We have shown that the mechanism is envy-minimizing, the budget balanced, and had fast computation time. Therefore, the mechanism can be implemented in real-time. However, the only trade-off here is the efficiency of the intersection being compromised as the fixed time has to be efficiently designed. Thus, at least one of the passengers crosses the intersection, and the players are only compensated for most of the time needed to cross the intersection. To address the issues, we propose the Envy-minimizing bid-based time signal mechanism. In this mechanism, each player proposes a strategy to cross the intersection. The strategy with a minimum this utility is chosen as the outcome of the mechanism. This mechanism ensures that at least one player crosses the intersection for every decision and that players only pay according to the green time they bid.

The key issue with most of the current work is that the players need not be truthful about their valuations. It is worth studying to which point players can manipulate the control outcome for personal benefit and how to prevent selfish manipulations. For the future direction, we would like to explore the strategy to control truthfulness in the mechanism design game. It is also interesting to explore the policy implication of this mechanism in real-life application. The equitable traffic signals that are not following the FCFS rule would rise socio-political questions as this involves payments across drivers. The rapid adoption of autonomous vehicles is believed to open new opportunities to allow transfer payments across space and time simultaneously. However, the deep research on its implementation remains an open question. This work only presents the initial exploration of the effort in achieving equitable traffic signal controls. Still, we hope that this work would inspire and initiate the next progression of this topic.

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