Toward Equitable Vehicle-based Intersection Control in Transportation Networks

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ABSTRACT

Efficient intersection control is an interesting problem in traffic management, and may collaborate to reduce traffic jams as well travel times. New technologies, such as Vehicular Ad hoc NETworks (VANETs) and ubiquitous computing, may collaborate to the implementation of new policies to intersection control, thus providing flexibility and performance to transportation networks. While these technologies are not widely available, new policies to intersection control can be intensively evaluated in simulation environments. In this paper, we evaluate different intersection control policies and different scenarios using as support SUMO, a transportation network simulator in the context of multiagent systems (MAS). In the evaluation, we concern in equitability which measures the fairness to attend a request from a vehicle to pass a given intersection. Our simulation results indicate that different policies are suitable to different scenarios leading us to believe that adaptive policies must be proposed.

Categories and Subject Descriptors

H.4 [**Information Systems Applications**]: Miscellaneous

General Terms

Experimentation

Keywords

Intersection control, Simulation, Multiagent system, Transportation networks.

1. INTRODUCTION

With the increasing number of vehicles circulating in urban areas, and the consequent increase in demand, the development of services supported by information and communication technologies (ICTs) to improve traffic management and the provision of urban mobility are indispensable. In this scenario, new technologies such as VANETs (Vehicular Ad hoc NETworks), ubiquitous computing and cloud computing allow adequate infrastructure for such services. In the future, vehicles will be able to share information in transportation networks, and will be able to collaborate to reduce traffic jams, travel times, accidents and vehicle emissions.

Intersection control represents a major challenge in traffic management, and it means to decide which vehicle should pass an intersection and which vehicle should wait. In real traffic systems, intersection control is solved by traffic lights, or using priority signs, or by *the priority to the right* rule, when the intersection is not signalized. Traffic lights traditionally control vehicles' flow using signal-timing plan with unique set of timing parameters. The large majority of traffic lights cannot apart in presence of changes in traffic conditions and it can result in inefficient service.

With the availability of VANETs infrastructure and services, traffic lights would be eliminated. Vehicles will be provided with GPS devices and vehicle to vehicle (V2V), and vehicle to infrastructure (V2I) communication, installed and operational. Road intersection control would be performed by the vehicles themselves, modeled as autonomous agents. In this scenario, each autonomous agent independently obeys its own behavior and interacts each other and/or with the infrastructure allowing the decision-making process.

Thus, adaptive solutions can be applied. Dynamic solutions adapt behavior according to the traffic flow and can be centered at the vehicle flow, and, alternatively at the vehicles themselves. Semaphores based on adaptive flows have been established in some Brazilian cities (e.g. Curitiba, Porto Alegre, Belo Horizonte, and Fortaleza). They are calibrated using information provided by the vehicles' flow and aim to eventually reduce congestion and travel times. The mode of operation is simple: sensors are installed on the tracks and

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capture the presence of vehicles. This information is used as input to calculate the proper *split* and *cycle length* in signal-timing plans. This solution would avoid, for example, the exposure of green light for a prolonged period in a road with few vehicles, if the traffic is heavy at the concurrent flow. However, it does not eliminate the need of having a physical device installed and in operation.

Installation and maintenance of traffic lights is considerable expenses in Brazilian cities and in many world wide cities. For instance, in Porto Alegre, there are more than 1,007 signalized intersections. The cost of installing each semaphore is between $5,000 -$7,000 (Source: EPTC March 2011). In São Paulo, there are more than 4,800 signalized intersections (Source: CET 2013). In Fortaleza, there are 656 traffic lights and the mensal cost to maintenance is about $160,000 (Source: AMC June 2013). According to Ferreira *et al.* [6] maintenance of traffic lights is considerable expenses in the budget of cities. Thus, eliminating traffic lights can result in budget savings.

In a futuristic scenario, with the deployment of VANETs and the concept of autonomous vehicles, traffic lights would be completely eliminated. Intersection control will be undertaken by vehicles themselves. Indeed, the ability to implement policies to intersection control with VANETs support contrasts with the traditional signal-timing plans, which uses a mathematical model to describe the traffic flow. Therefore, new policies to deal with intersection control, beyond the traditional signal-timing plans adopted by traffic lights, must be proposed and evaluated before the availability of new technologies. For instance, policies to deal with CPU scheduling, such as FIFO (first in first out) and SJF (shortest job first), would be used to control the vehicle passage through intersections, with the support of V2V and V2I communication.

Since VANETs technology is not yet widely available, computer simulation gives a way to evaluate possibilities before being implemented them in practice. Thus, in this paper, we evaluate different intersection control policies using simulation supported by multiagent systems (MAS), and V2I communication. Each vehicle is represented as an autonomous agent that follows a behavior independently and interacts with other agents and/or infrastructure for decision-making. Bazzan [1] and Chen *et al* [3] emphasize the benefits of using MAS to model and to evaluate solutions target to transportation systems. Experiments were conducted in SUMO [2]. In the evaluation, we concern in equitability which measures the fairness to attend a request from a vehicle to pass through an intersection. Our simulation results indicate that different policies are suitable to different scenarios leading us to believe that adaptive policies must be proposed.

The paper is organized as follows. Related works are described in section 2. Algorithms and metrics we used in experiments were described in Section 3. Experimental evaluation results are presented in Section 4. Finally, conclusions and future works are presented in Section 5.

2. RELATED WORKS

The idea of removing traffic lights or at least to improve its use is not new. In the following we discuss some existing research projects.

Krajzewicz *et al.* [7] focused on efficient flow-sensitive traffic lights. With the support of SUMO, Krajzewicz *et al.* compares the size of different of vehicle queues' to decide about which vehicle will pass an intersection first. The decision is made using the support of V2I communication. Vehicles in the larger queue have the higher priority to cross the intersection. Intersection control is performed by a physical device implemented by the infrastructure (i.e. not by the vehicles themselves). V2V communication is not taken into account.

Vehicle centered-solutions would be one step further, and would use some mechanism to promote not only efficient traffic flow, but also fairness to attend user service. However, vehicular communication technology must be widely available. Dresner & Stone [4] describe a reservation scheme where the vehicle should allocate a slot, in a central, concerning space and time to cross an intersection of two roads. According to the experiments presented in this article, this technique would be more efficient in terms of throughput in comparison with the traditional semaphore. However, if a vehicle cannot book a slot necessary to cross of the intersection, it can suffer indefinite hold. This drawback was fixed in [5]. Another problem is the existence of a central to apply the intersection control policy. If the system fails, the service becomes unavailable. An extension of the work of Dresner & Stone for the context of multiple intersections was conducted by Vasirani & Ossowski [9]. The idea is to provide an adequate service to the public, but still without collaboration among vehicles.

Finally, in Ferreira *et al.* [6], through the support of V2V communication and AVL (automatic vehicle location), the nearest vehicle to an intersection is elected to coordinate the passage of vehicles at a particular intersection. When the driver finally passes the intersection, a new vehicle is chosen to manage the intersection. However, given that two vehicles v_i and v_j may be placed in distinct pathways S and W, but share the same distance d with respect to the intersection, a guarantee of election only one coordinator needs to be imposed. Furthermore, fairness to attending user service is not taken into account.

We may conclude that there is a need of research works to evaluate more effectively intersection control and to explore more broadly these mechanisms. The response to the request of vehicles passing through an intersection must be performed efficiently (through a solution that delivers traffic flow) and in the direction to minimize the waiting time of each vehicle individually. By minimizing the waiting time, we mean that the policy applied to intersection control must look for equitability or fairness. Vehicles in different queues should not waiting so long to pass through an intersection. In addition, starvation must be avoided. This work is a step toward this direction.

In general, new mechanisms to intersection control need to be proposed and should be analyzed extensively before putting them into practice and before VANETS technology would be widely available. Additionally, it would be interesting the use of policies preferably focused on vehicular communication to enable the exclusion (physical) traffic lights. This will be the focus on our future work.

3. MODELING THE PROBLEM

3.1 Applying the agent model to transportation networks

Autonomous agents is a convenient abstraction to model transportation networks. Vehicles are described such as autonomous units with independent behavior. In our scenario, a group of agents (vehicles) follows a policy to pass of an intersection point.

Each vehicle v_i (to $i \in \mathbb{N}$) is uniquely identified (in practice, the Vehicle Identification Number (VIN) can be used) and belongs to an unique queue or segment called S or W. Queue S is placed in the route SN and queue W is placed in the route WE. All the vehicles in S move from South to North, while all the vehicles in W move from West to East. The queues share a critical section (intersection point P), where vehicles must pass to reach an ultimate goal. Only one vehicle may pass the critical section at a time. Who decides what is this vehicle is the **intersection control policy**. Figure 1 depicts this scenario.

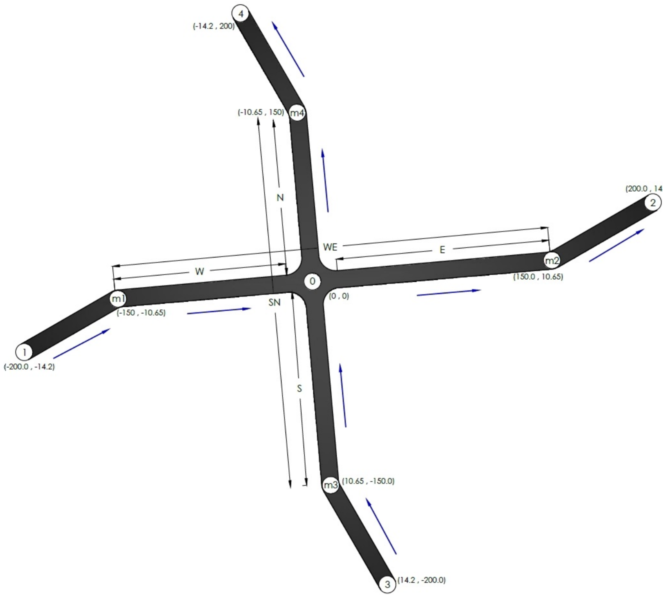


Figure 1: Scenario with routes SN and WE and segments S and W

Also, in Figure 1, there is the information used to code this intersection and routes in SUMO, the transportation network simulator in the context of MAS we used to implement and compare policies.

In our approach, basically, each vehicle v_i from S or W comes in contact with the infrastructure, through the emission of a message m_i to order a ticket to allow passing through the intersection, according to the policy in question. The infrastructure applies the policy and decides the order in which the vehicle must pass the intersection, and informs it to the vehicle through a reply message $m_i - 1$. The infrastructure can be implemented in distributed or in a centralized fashion, and will be focused in our future work. In practice, V2I communication could be supported by the IEEE 802.11 p protocols (Wi-Fi) or by GSM/GPRS and 3G/4G (i.e. mobile phone networks).

3.2 Intersection control policies

The scope of this work, we implemented five policies to intersection control, including: (i) the right of way, (ii) signal-timing plan, (iii) the largest queue always, (iv) the largest queue first, and (v) at least k vehicles each time. These policies are described more in detail in the following.

3.2.1 The right of way

The default policy, *the right of way*, results from the settings taken by SUMO to generate the simulation. This policy is based on assigning the highest priority for the passage of vehicles through intersections using the right of way policy. Considering two road segments S and W that meet at an intersection point P, and suppose that the highest priority of passing vehicles by P is assigned to S, vehicles on W only pass through P when no vehicles are queuing on S.

3.2.2 Signal-timing plan

The signal-timing plan is the policy applied by traditional traffic lights to deal with intersection control. It is based on the scheduling traffic signal phases at intervals given by phases.

The major drawback of signal-timing plan applied in large majority of traffic lights is that it cannot apart in presence of changes in traffic conditions, and it can result in inefficient service. For instance, it cannot avoid presenting the green signal for a long period of time even if there is only one vehicle or a few vehicles in a queue.

3.2.3 The largest queue always

The largest queue always policy consists of giving the higher priority to the passage through the intersection to the segment with larger queue of vehicles outside the critical section.

Considering two road segments S and W that meet at an intersection point P, the algorithm of longest line always starts capturing all vehicles outside the critical section in S and W, calculating the number of vehicles on each track segment, and comparing the two values. If S is the largest queue, vehicles on queue W need wait, until the last vehicle in queue S passes through P. Next, the lengths of the queues are compared again to decide who will pass through P. The same process is repeated until the end of the simulation.

The drawback of this policy is that it can suffer from starvation in case of a queue is typically shortest than the other, even if new vehicles are continuously added on queues.

3.2.4 The largest queue first

The policy defined by *the largest queue first* is similar to *the largest queue always*, except that it does not only give priority of passing through the intersection to the track segment with the line of vehicles outside the critical section. However, it lets the lower queue of the other track segment to cross the intersection, before returning to compare the two queues lengths' again.

Considering two road segments S and W that meet at an intersection point P, *the largest queue first* starts capturing all vehicles out of the critical section in S and W, calculating the number of vehicles on each track segment, and comparing the two values. If S is the largest queue, vehicles on queue W need wait, until the last vehicle in queue S passes through P. Then it passes the entire row in W before comparing again the next queues in both segments. The same process is repeated until the simulation ends. Contrasting with *the largest queue always policy*, in *the largest queue first* starvation does not take place.

3.2.5 At least k vehicles each time

The policy *at least k vehicles each time* constitutes successive passage of vehicles of each road, since the number of vehicles on the road that has the slot to spend is greater than or equal to k, k being an informed integer.

Considering two road segments S and W that meet at an intersection point P, and S the track segment chosen to start the time. The policy *at least k vehicles each time* starts capturing all vehicles out of the critical section in S, and calculating the number vehicles on that queue. If this is greater than or equal to k, the vehicles on queue in W need to stop until the last vehicle in the queue S passes through the intersection. Otherwise, it turns passes to W. The same process is repeated until the end of the simulation.

3.3 Metrics

To compare and evaluate policies described in item 3.2 regarding equitability, we used a sort of specific metrics. Equitability measures the fairness to attend a request from a vehicle to pass through an intersection. In the following, we define these metrics.

Definition 1: state of traffic flow. A **state of traffic flow** or **state** E_i, for short, is the behavior the traffic flow, described from the period, the preference from a route with respect to another (i.e. priority), and maximum speed allowed in a given route (MaxSpeed). All these values are configured in SUMO.

Definition 2: scenario. A **scenario** C_i is the result of applying one of the algorithms described in item 3.2 in on the defined traffic states E_i.

Definition 3: rate of change of vehicles. Considering a scenario C_i, with an intersection point P, and two track segments S and W. The **rate of change of vehicles** in the range of k steps, represented by T_k, is the ratio of the passage of vehicles originally in $X = \{S \text{ or } W\}$ by P in the range of k steps, defined by the following formula:

$$T_X k = \frac{\sum v_k}{\sum v}$$

where:

- $\sum v_k \in [0, \mathbb{N}]$ and $\sum v \in (0, \mathbb{N}]$, where $\mathbb{N}$ is the total of vehicles in a simulation.
- $k \in (0, N_s)$, where N_s is the total number of *steps* in a simulation.
- v_k represents a vehicle from S or W that passed through the intersection P at the step k.
- v represents a vehicle from S or W that still does not cross the intersection P.

Note that if $T_S k > T_W k$ at *step k*, then there were more vehicles from S than in W that pass through P when the simulation reaches the *step k*.

Definition 4: total rate of change. Considering a scenario C_i, with an intersection point P, and the two track segments S and W, the **total rate of change** of N vehicles in the simulation, represented by $\overline{X}_N$ is the sum of the rates of variations in N. The total rate of change of a segment X is defined by the following formula:

$$\overline{X}_X = \sum T_X$$

If $\overline{X}_S > \overline{X}_W$, then there were more vehicles S that have passed through P than in W.

Definition 5: difference of total variation rates. Considering a scenario C_i with two road segments S and W that meet at in an intersection point P. The **difference of total variation rates** of S and W in C_i, represented by $d\overline{X}$, is the magnitude of the difference between $\overline{X}_S$ and $\overline{X}_W$, and is expressed by the following formula:

$$d\overline{X} = |\overline{X}_S - \overline{X}_W|$$

Definition 6: distribution of the traffic flow concerning two road segments. The **distribution of the traffic flow concerning two road segments** S and W crossing at an intersection point P in scenario C_k, compares the proportions of vehicle crossings of S and W in P. Considering two scenarios C_i and C_j and the same E, and let $d\overline{X}_i$ and $d\overline{X}_j$, their difference in total charges in C_i and C_j:

- if $d\overline{X}_i > d\overline{X}_j$, we say that the flow distribution in C_i is better than C_j. In other words, C_i is more distributed than C_j,
- if $d\overline{X}_i$ is tending to zero, we may say that the distribution flow in C_i tends to be equitable, or C_i tends to be equitable distributed with respect to the flow.

Finally, a policy a is considered more effective than another b based on a state of traffic flow E_i if and only if the scenario C_i generated by a applied to E_i is more equitable distributed than C_j generated by b applied to the same E_i.

4. EXPERIMENTAL EVALUATION

4.1 Configuration of traffic flow

To conduct experiments, we configured three different states of traffic flow, E_{1-3}, which are summarized on Table 1 and Figure 2. Each state of traffic flow occurs in a time interval of 14,400 steps. In SUMO, it represents 4 hours since a time step is, by default, one second. We believe this time interval is satisfactory to evaluate policies to and decide which algorithm implements the most efficient policy, since 4 hours represent a half-journey.

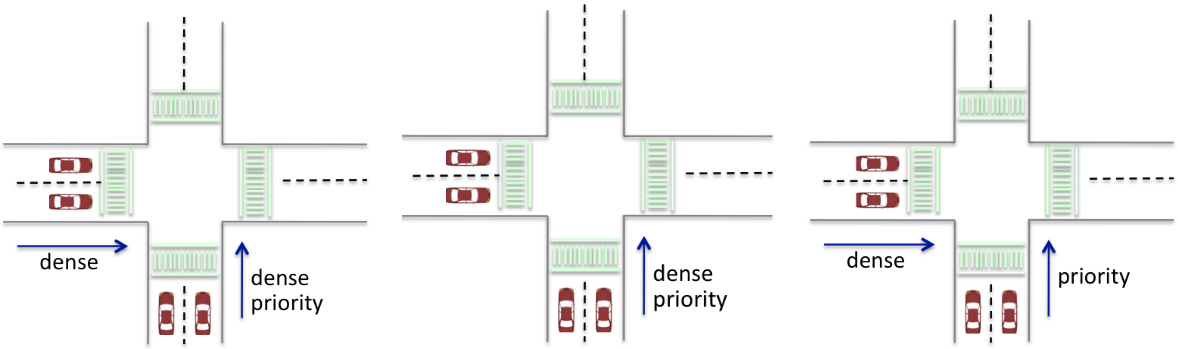
In the experiments, we used three parameters to configure traffic states: priority, period and *MaxSpeed*. If the priority of a road is higher that the priority of another road, that means if there are two vehicles on a intersection, the vehicle on the road with the highest priority goes first.

Period describes the traffic flow in terms of dense and rarefied. If a road has a shorter period than otherwise, it means that the road is denser than another road. With regard to the maximum speed, the value used is 16.7 m/s. In addition, the time interval used in *signal-timing plan* was 20s to the *green* phase, 0s to the *yellow* phase and 20s to the *red* phase.

States	**Priority**	**Period**	**MaxSpeed**
E_1	SN > WE	SN = WE	SN = WE
E_2	SN > WE	SN < WE	SN = WE
E_3	SN > WE	SN > WE	SN = WE

Table 1: States simulated in the experimental evaluation

In Table 1, the column *States* identify each traffic state. The column *Priority* displays the comparison of priority



(a) (b) (c)

Figure 2: Configuration to states (a) E_1, (b) E_2 and (c) E_3

in routes SN and WE, and column MaxSpeed display values used as maximum speed in the two routes. Remember that SN represents the entire segment of road regarding an intersection P from South to North, while WE represents the entire segment of road regarding an intersection P from West to East.

More specifically, as seen in Table 1, the state of traffic flow E_1 is defined as the state where the route SN has the high priority in the passage of vehicles through the intersection P with respect to via WE. The traffic flow is dense in the two ways, i.e. vehicles access the two routes with the same frequency, and are subject to the same maximum speed.

The state of traffic flow in E_2 and E_3 is the same used in E_1. However, in E_2 the traffic flow is dense only in SN. The traffic flow in SN is ten times higher than in via WE. But all vehicles are subject to the same maximum.

The state of traffic flow E_3 has a back-flow to the E_2. The path SN continues to have priority in the passage of vehicles through the intersection with respect to via WE, and the maximum speed achievable remains the same in both pathways. However, the traffic flow is dense only on via WE, i.e. vehicles access route WE at a rate ten times higher than vehicles in via SN.

Given states E_{1-3} and algorithms/policies described in Section 3, we combined them to obtained different group of scenarios. The scenarios generated are classified into three **groups of scenarios**, based on states of traffic flow in which the algorithms were applied. Basically, a scenario C_i is a combination of a E_i and a given policy.

4.2 Evaluating the results

To decide which policy is appropriate to a given scenario, we conduct experiments using SUMO and the previous given scenarios and values. The objective of the comparison is to find which is the most distributed scenario of each group in order to decide what the best algorithm that distributes the passage of vehicles through the intersection for each scenario group. The target variable used in the experimentation is the difference of total variation rates $d\overline{X}$ in each scenario.

Considering a scenario C_i with two road segments S and W that meet at an intersection point P, and T_S is the rate of change of the vehicles in segment S in step k and T_W is the rate of change of vehicles at W in step k, we may have that:

- C_i is viewed through a graph, such as in Figure 3, that has two types of lines: those that represent rates of variation T_w per step unit, and those that represent rates of variation per T_s by step unit.
- T_S indicates the percentage of vehicles in S that passed by P in step k and T_W indicates the percentage of vehicles in W that passed by P in step k.
- When T_S is 0, it indicates that there is no vehicle in S that have passed through P in step k and when T_W is 0, it indicates that there is no vehicle in W that have passed through P in the step k.
- When T_S is maximum, this indicates that all vehicles in S have passed through P in step k and when T_W is maximum, this indicates that all vehicles in W have passed for P in step k.

More specifically, in Figure 3, the scenario shown results from the application of *signal-timing plan policy* to traffic flow state E_i. Between 0 and 20 steps, for instance, T_S and T_W are equal to 0. Therefore, no vehicle from S or W has passed through P in that interval. In addition, in any step in T_S or T_W is maximal. Therefore, there was never happened a situation in which all vehicles placed in S or in W passing through P.

Another example of a scenario is given in Figure 4, where the scenario results from the application of *the right of way policy* to the state of traffic flow E_2. Again, between 0 and 20 steps, for instance, T_S and T_W are equal to 0. Therefore, no vehicle from S or W has passed through P in that interval. In addition, in step in T_S or T_W are maximal. Therefore, there was happened a situation in which all vehicles in S or in W passing through P.

At the total, 15 graphs were generated. Due lack of space in this document, we will not present all the graphs here. Our discussion will be based on tables, which will be addressed below. Each table is associated with a previous described scenario, E_{1-3}, grouping the three different categories. In the following, we discuss these group of scenarios.

4.2.1 *Scenario Group* G_1

Table 2 summarizes the results obtained by the application of state E_1 to the implemented policies within the range of $14,400$ steps in SUMO.

Regarding the obtained results, one can observe that the policy *the largest queue first* is the most widely distributed

Policy	X_s	X_w	$d\overline{X}$
The right of way	1,626.13	41.62	1,584.51
Signal-timing plan	463.71	196.59	267.12
The largest queue always	400.18	301.56	98.62
The largest queue first	277.21	334.54	57.32
At least k vehicles each time	395.33	282.58	112.75

Table 2: Traffic flow distribution $d\overline{X}$ concerning two road segments obtained by the application of state E_1 to the implemented algorithms within the range of $14,400$ steps in SUMO

of all with a $d\overline{X}$ = 57.32. Remember the smallest $d\overline{X}$, the most effective in terms of equitability. The worst policy is *the right of way* with $d\overline{X}$ = 1,584.51.

Thus, we can conclude that the policy implemented in *the largest queue first* proved to be the best choice to control the passage of vehicles through the intersection between two lines with the same flow frequency and maximum speed, a priority which is higher than the other, so as defined by state of traffic flow E_1.

In the following, we have the policy *the largest queue always* similar to *at least k vehicles each time*, which proved to be the second and the third most suitable policies for the control of such traffic. The *signal-timing plan* is the forth choice and *the way of right* policy is the least suitable for such transit.

4.2.2 Scenario Group G_2

Table 3 summarizes the results obtained by the application of state E_2 to the implemented algorithms within the range of $14,400$ steps in SUMO.

Policy	X_s	X_w	$d\overline{X}$
The right of way	1,619.45	43.75	1,575.70
Signal-timing plan	456.85	589.28	132.43
The largest queue always	1,156.05	300.90	855.15
The largest queue first	1,057.24	428.57	628.67
At least k vehicles each time	1,294.14	127.17	1,166.97

Table 3: Traffic flow distribution $d\overline{X}$ concerning two road segments obtained by the application of state E_2 to the implemented algorithms within the range of $14,400$ steps in SUMO

One can observe that the *signal-timing plan* policy was the most widely distributed of all with $d\overline{X}$ = 132.43. Secondly, we have *the largest queue first* policy with $d\overline{X}$ = 628.67, then *the largest queue always* with $d\overline{X}$ = 855.15, then *at least k vehicles each time* policy with $d\overline{X}$ = 1,166.97, and finally, we have *the right of way* with 1,575.70.

Thus, we can conclude that the policy implemented in the *signal-timing plan* proved to be the best suited to control the passage of vehicles through the intersection between two paths with the traffic flow as defined by the state of traffic flow E_2.

In the following, we have the policy *the largest queue first*, this time, the second proved more suitable for the control of this type of traffic, following by *the largest queue always* which is in the third position. The next one is *at least k vehicles each time* following by *the way of right* policy, which is again, the least suitable for such transit.

4.2.3 Scenario Group G_3

Finally, Table 4 summarizes the results obtained by the application of state E_3 to the implemented algorithms within the range of $14,400$ steps in SUMO.

Policy	X_s	X_w	$d\overline{X}$
The right of way	899.00	385.64	513.36
Signal-timing plan	751.75	233.57	518.18
The largest queue always	282.58	547.90	265.32
The largest queue first	227.80	545.51	317.71
At least k vehicles each time	505.64	515.40	9.76

Table 4: Traffic flow distribution $d\overline{X}$ concerning two road segments obtained by the application of state E_3 to the implemented algorithms within the range of $14,400$ steps in SUMO

One can observe in this scenario that *at least k vehicles each time* policy is the most widely distributed of all with $d\overline{X}$ = 9.76, reaching almost to equitable distribution between the two pathways, noting that the distribution of vehicles driving by the intersection of two roads in a given scenario tends to evenness as plus the difference of $d\overline{X}$ tends to zero. In second place, we have *the largest queue always* with $d\overline{X}$ = 265.32, then *the largest queue first* with $d\overline{X}$ = 317.71, then *signal-timing plan* with $d\overline{X}$ = 513.36, and finally, we have *the right of way* with 518.18.

Thus, we can conclude that the policy implemented in the *at least k vehicles each time* clearly proved the most suitable to control the passage of vehicles through the intersection between two roads with traffic flow as defined by the state E_3.

In the following, we have *the largest queue always* that proved to be the second most suitable policy for this type of traffic, and *the largest queue first* is in the third one, *the way of right* in fourth position and, finally, we have *signal-timing plan* policy.

5. CONCLUSION AND FUTURE WORKS

This work demonstrated that the intersection control, typically implemented in Brazilian cities by traffic lights, can have a significant improvement with the application of algorithms based on the traffic flow. The proposition of mechanisms, in general, more suitable to intersection control is necessary, since efficient traffic management is a problem present and constant in our daily lives. As argued previously, the existing solutions are preferably based on signal timing plans with no adaptation. However, it is clear that different policies can be implemented to improve results.

Our target application involves transportation networks and urban mobility, issues that have aroused much interest in the whole contemporary society. And, in fact, solutions and mechanisms to improve urban mobility and transportation processes have been implemented and proposed, and are more affordable currently. Some examples are the adaptive traffic lights recently installed some Brazilian cities (e.g. Porto Alegre, Belo Horizonte e Fortaleza) and many ATIS (advanced traveler information systems) such as *Google Transit, Waze, Olho Vivo*, (from São Paulo, which provide to users information about public transport status), for instance.

More specifically, this paper presented a simulation in the context of transportation networks to deal with intersection control. Different policies for intersection management were evaluated. The simulation was configured with two roads: one from south to north (SN), and another from west to east (WE), and an intersection point P. Then three states of traffic flow were created: E_{1-3}, based on the preference of SN on WE at passing vehicles by P. Finally, we defined 15 different scenarios from the application of policies to defined traffic states. They were classified into three groups of scenarios according each traffic situation.

Experiments with these three scenarios were run to evaluate equitability. After experimentation, we may conclude that if the traffic is of the type defined by the state E_1, the policy implemented by the *the largest queue first* algorithm is the most suitable for control the passage of vehicles by P. While, when traffic is the type defined by the state E_2, the policy implemented by the *traffic lights* is the most suitable for the control of P. Finally, when the traffic of the type defined by the state E_3, implemented the policy by *at least k vehicles each time* is the most appropriate place for intersection control in P.

With these results, we can conclude that applying only one policy to intersection control is not the best solution. Since traffic is subject to dynamism and delays, different traffic scenarios need different policies. In this direction, this work represents a further step in efficient traffic signal control.

Future works include the implementation of more sophisticated policies. For instance, we could develop a hybrid policy, which is the junction of several policies. Furthermore, one can define other states that describe the traffic with more emphasis the realism in the simulation, taking into account other variables that influence the traffic flow, among others: variation of the maximum speed of the road, different types of vehicles and priorities (such as ambulances, firemen service), addition of passages through intersections, pedestrian accidents and other incidents that block and change the traffic flow.

Decentralized intersection control policies also need to be effectively proposed and evaluated before put them into practice. In this case, only V2V communication should be considered as well as the use of simulators target to transport networks and VANETs. Finally, such as in Vasirani & Ossowski [9], the transportation network can expand with the addition of new roads and lanes, and several intersections.

Acknowledgments

This work was supported by the Brazilian Government agency FAPERGS/CNPq (Project RS-SOC - Rede Estadual de Simulação Social) under grant number 10/0049-7 and CTIC/RNP SIMTUR Cidades Inteligentes.

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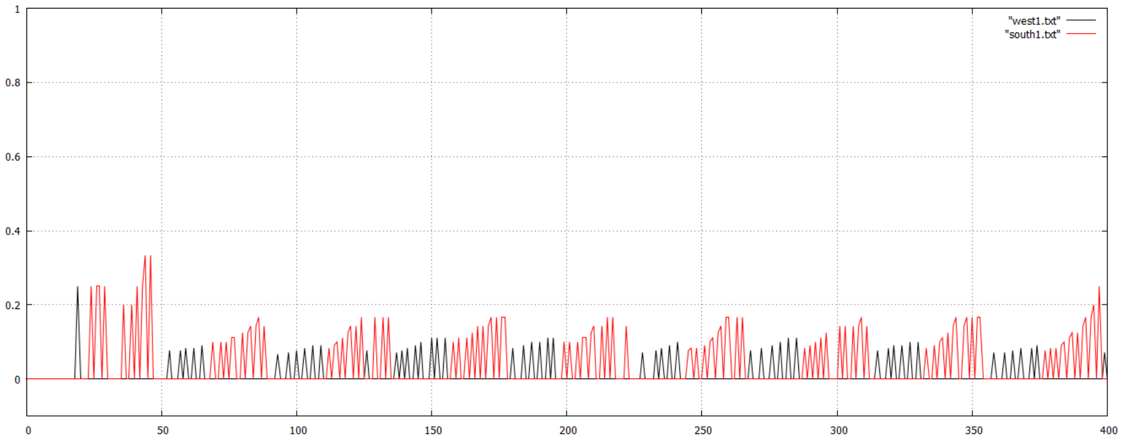

Figure 3: Scenario resulted from the application of *signal-timing plan policy* to the state of traffic flow E_1

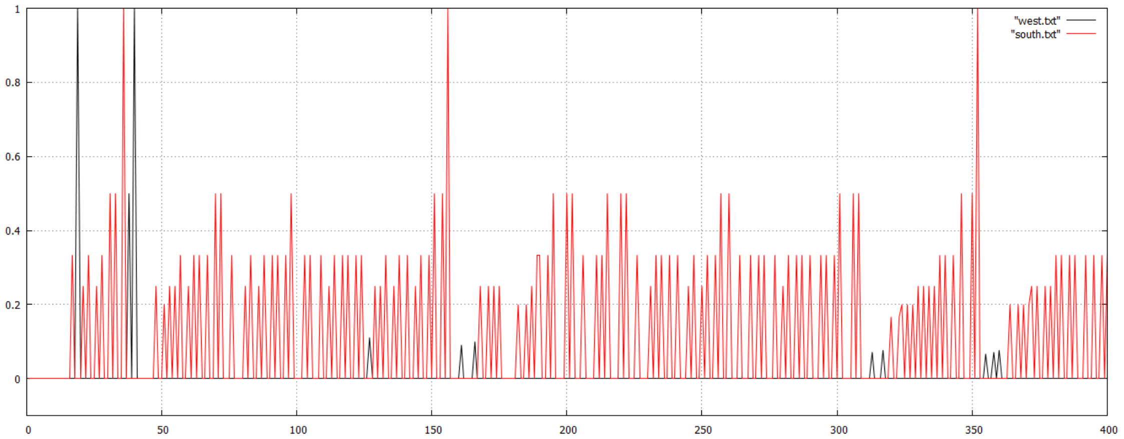

Figure 4: Scenario resulted from application of *the right of way policy* to the state of traffic flow E_2