# Cooperative intersections for emerging mobility systems

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# Cooperative intersections for emerging mobility systems

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**Abstract**

Traffic lights allow to efficiently manage conflicts between dense traffics in urban area. Nevertheless, emerging mobility systems, such as car sharing systems or high frequency bus lines, require more flexible and precise signalization systems. Indeed, the traffic lights display the green to all vehicles without selecting the ones that really deserve the right of way.
This paper relies on a real project in order to highlight the interest of the onboard signalization coupled with the negotiation of the right of way. It exhibits the problem and then deepens the proposed protocol for cooperative intersection management. The main problem is the respect of bus timetables. The protocol allows to determine the sequences of buses that cross the intersection. A real-time policy for resolving the problem of delayed buses is proposed. The protocol is first tested through a real intersection of cars driven by human. This test shows that the sequence optimization is feasible. Simulations are finally presented in order to show the interest of the approach before concluding.



*Keywords:* Autonomous intersection management ; Mobility systems ; Urban traffic

## 1. Introduction

The traffic control systems are designed to warrant a high level of safety while enhancing the performance of the road network at the intersections (Papageorgiou & al., 2003). Several approaches have focused on the traffic lights in order to minimize the delays and queue lengths (Gradinescu & al., 2007). There is a unanimous recognition of the performance based logic in so far as a smoother traffic contributes to moderate the resulted pollution. Indeed, the traffic lights have widely contributed to enhance the traffic conditions. Nevertheless, the increase of the intersection throughput encourages the use of private cars in urban area. Thus, the problem of efficient control of the intersection is continuously raised by additional polluting cars. At the same time, alternative modes of transport suffer from some inherent difficulties. Today more than ever before, the issue of the flexibility of the traffic control systems is raised. The main objective is to allow to a denser public transport, clean vehicles or many other mobility systems to efficiently share the urban infrastructure.

Many efforts have been done to improve the bus priority at intersections (Hounsell & Shresta (2012), D'Souza & al. (2010) and Eichler & Daganzo (2006)). The bus priority concept is adapted to the intersections between bus and cars. Nevertheless, a denser public transport with a high coverage of population draws the attention to the intersections between buses. Indeed, many bus corridors intersect and each corridor supports high frequency lines of buses. Recently, new concepts of controlling the intersections are proposed (Dresner & Stone (2004), Abbas-

Turki & al. (2012)). Instead of considering the traffic as a flow, they optimize the sequence of vehicles. The concepts are based on the wireless communication, positioning technologies and onboard signalizations in order to adapt the right of way according to each vehicle. This allows defining a hierarchy between vehicles and a better consideration of the vehicle states such as a late bus. However, the feasibility issue is raised.

Fortunately, a bus network eliminates many apparent feasibility obstacles. All buses of the network can be simultaneously equipped since they belong to the same operator. Moreover, the bus itineraries are predefined. This contributes to lighten the positioning problems which query the integrity of the cooperative intersection management. Thus, in this paper we will focus on the protocol that we have proposed in (Wu & al., 2011). This protocol contributes to overcome other feasibility obstacles that will be discussed hereafter.

This paper exhibits through a study case a new signalization system that contributes to improve the bus punctuality. The feasibility issues of the signalization system as well as the performance evaluations are discussed through tests of an intersection of real vehicles. A policy for improving the bus punctuality is proposed and simulated. Simulation environment is developed according to the data of the future network.

## 2. Raised issue

The presented work is motivated by a real project which aims to significantly increase the number of users of buses in Belfort city. The city policy is based on renewing strategic bus lines by providing higher frequencies and shorter travel times. Each strategic line has to provide a bus for passengers every 5 minutes, which doubles the present line frequency. This policy is encouraged by the already received success of the present bus network. It has contributed to lighten the continuously increasing use of private cars since the first stage of service enhancement in terms of coverage, frequencies and travel times. Nevertheless, such an ambition requires a smart sharing of the urban infrastructure.

### *2.1. Project challenge*

For the sake of service regularity, a high frequency bus service requires dedicated bus lanes that are unfortunately limited by the available space in the city area. Hence, buses have to resort to moving in dedicated lanes that intersect with roads of ordinary traffic and even to sharing some congested roads with private cars. Several bus priority systems are proposed and widely used for intersection between buses and ordinary traffic. There are many intersections in the project where a bus priority system is able to provide a good solution. Nevertheless, the bus priority reaches its limitations in some intersections that gather the following outlines (see Fig 1):

- Intersection with a congested road;
- High frequency bus lines;
- Intersection between bus lines.

The first one requires a political choice between cars and buses. Even if it is widely admitted that busses are eco-friendly, the service must be proved to be as attractive as it is assumed. In other words, buses should be an efficient alternative, able to reduce the use of private cars. Moreover, car penalization can delay bus traffic, since the congestion can reach some roads, shared between cars and buses. As an answer to the issue, the city has chosen a progressive approach based on the empirical observation of the success of the provided bus service. Hence, the signalization must be initially able to evacuate the recently estimated traffic of privet cars. The studied intersection needs to fulfill this political requirement

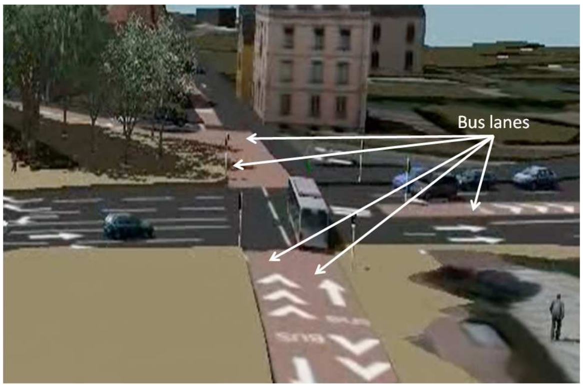


Fig. 1. 3D representation of the studied intersection (Voxelia Simulate)

The other challenge is the requirement of an accurate management of the intersection of buses. Indeed, an efficiency issue is raised by the number of conflicts resulted from the intersection of dedicated lanes that involves more than one line of bus. More precisely, the intersection of buses multiplies the real-time workload for providing punctual and regular service.

### 2.2. Studied intersection

The scheme of the studied intersection is given in Fig. 2. Time and space accesses are divided between buses and private vehicles. Indeed, three accesses are reserved to buses and two others to ordinary vehicles. The arrows indicate the possible movement directions in each lane. Only some buses are able to reach one ordinary traffic road after crossing the intersection. Each mode, i.e. bus and ordinary vehicles, has its own signalization, that's why each lane has a traffic light. Even if one bus lane (movement 2) is parallel to an ordinary road, the signalization is separated because of the turn-left.

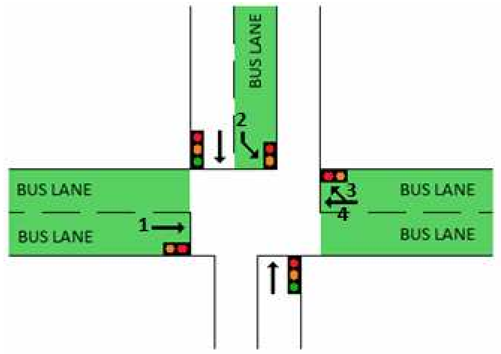


Fig. 2. Representation of the intersection

The cycle has a total duration of 90 seconds and is split into two stages. One stage is entirely dedicated to buses. Its duration is limited to 28 seconds in order to avoid congestion. The other stage is dedicated to ordinary vehicles and its duration is at least 62 seconds with 56 seconds for the green, 3 seconds for the yellow and 3 seconds for the integral red (see Fig. 3). We draw the reader attention to the fact that all bus lanes are authorized simultaneously. However, movement 2 is in conflict with movements 1 and 4. A classical solution to this problem is to resort to the priority rules or traffic lights. These solutions may amplify the delay as it is described hereafter.

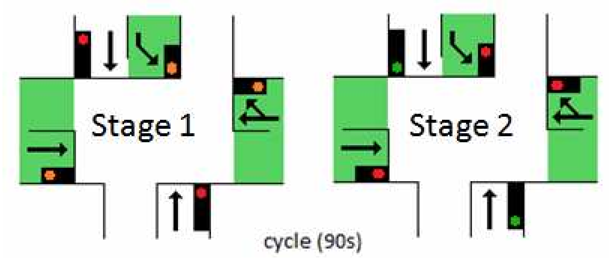


Fig. 3. Cycle time and split

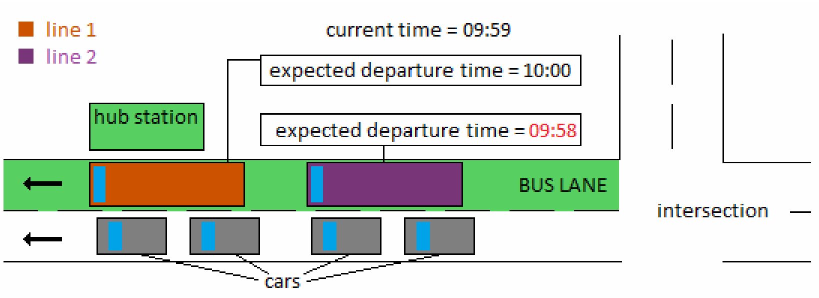


Fig. 4. An example of an additional delay problem caused by an imprecise management of the intersections

### *2.3. Problem of delayed bus*

Bus lanes improve the bus punctuality. However, irregularities are still possible since bus lanes don't cover the entire bus network. Indeed, all buses share some roads with the ordinary traffic. Moreover, the travel time strongly depends on the stop time for loading and unloading passengers. In a bus lane, a bus in advance can wait at the station whereas a delayed bus requires an empty bus lane to recover the lost time. This draws our attention to the bus arrangement in the bus lane.

Bus lines require a stringent order of buses in such a way a bus in advance cannot precede a delayed bus. Indeed, most of the time there is no way for a bus to overtake another, thus the delayed bus increases its delay at least according to the timetable of the precedent one. This happens when two buses arrive to an intersection. A delayed bus can cross the intersection after a bus in advance. The example given in Fig 4 clearly illustrates this matter. The bus of line 1 must respect its departure time while the bus of line 2 is obliged to wait 1 minute and thus extends its delay to 3 minutes. It is obvious that such a problem requires an advanced signalization at intersections.

The main limitation of dynamic traffic lights in such a situation is the lack of precision. The traffic color is given to a lane for a period of time instead of a particular bus. More precisely, the green that theoretically targets one bus can be used by two successive buses. It can also be missed by both if the green time is short. Moreover, the traffic lights are greedy in terms of time since the system is not informed when the last bus has left the intersection (approximate clearance time). However, the treated intersection does not admit significant modifications in the cycle time and split. This situation highlights the need of a more precise traffic control where the green is given to only the concerned buses.

## 3. Cooperative intersection management

Wireless communication and positioning systems are able to allow a more precise traffic control at intersections by selecting exactly the vehicles that deserve the right of way. Several protocols are hypothetically possible. Nevertheless, the target application and some technological limitations eliminate many possibilities. For this reason we have considered the protocol presented in (Wu & al., 2011). It assumes a client-server model. Each bus is equipped with an onboard unit (client), able to communicate with a server located in the intersection.

### *3.1. Main principles of the protocol*

Some protocols have been successfully tested in intersection of unmanned vehicles or robots. However, in our case the protocol must match the behavior of human drivers. The human drivers must be able to interact with a complex driving environment that potentially contains some unexpected events such as a pedestrian who suddenly traverses the lane. The three main principles of the protocol are as follows:

- Centralized architecture: The right of way is given by the server. The client is not allowed to authorize itself or another client to cross the intersection.
- Two decisions and three colors: The whole system can take only two decisions per vehicle "go" or "stop before the conflict zone" but the onboard signalization displays three colors which are green, red and yellow. The yellow means that the access to the intersection is based on sight because of the system failure. It is accompanied with a beep.
- Permanent green: The server cannot remove the green that has been already distributed except in the case of the system failure (yellow).

The centralized architecture allows the basic safety policy of "default deny". In other words, each client device displays the "red" to the driver until it receives the right of way from the server. The opposite architecture is a fully decentralized architecture. Without a server the client has the green until it detects the presence of another bus. In a fully decentralized architecture, an undetected bus causes a high collision risk whereas the centralized architecture allows avoiding such a problem. Only a momentary stop is possible if some buses are not detected by the server.

The main objective of the two last features is the reduction of the workload supported by the driver. Indeed, a speed indication or a time reservation will permanently catch the driver attention. The same permanent attention is required if the green is predisposed to be removed. Indeed, the driver has to cast his eyes over the device at the moment he has to take a decision and not all the time. However, the last principle requires an accurate estimation of the exit time of the last allowed bus in order to do not penalize the stage (green) given to ordinary cars.

In this paper we limit our considerations to these basic safety functions. Only "red" and "green" colors are considered, since the paper is focused on efficiency parameters under normal conditions. The basic operation of the protocol is presented in Fig 5. Moreover, buses can receive the green only if the current stage is stage 1 (see Fig 3).

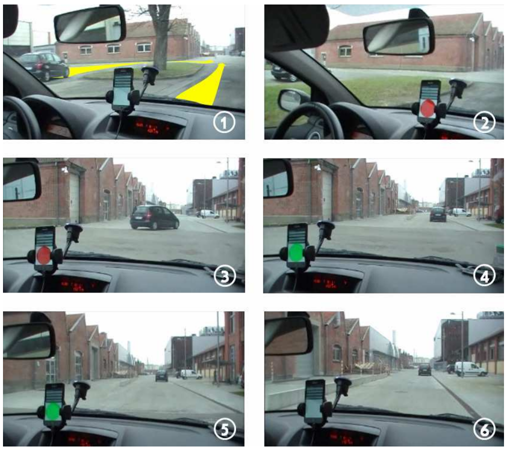


Fig. 5. An example of basic operation of the protocol through a real intersection of two vehicles (UTBM's test)

### *3.2. Brief description of the protocol behavior*

First of all, the protocol relies on a spatial division of each lane into four zones which are the entrance, storage, conflict and exit zones (see Fig 6). Each zone is associated to a behavior (see Table 1). A client in an entrance zone begins the communication with the server, in order to prepare together the good conditions for crossing the intersection. The communication delay is checked as well as the speed limitation versus the positioning accuracy and sampling frequency. For safety reasons, if the vehicle moves faster than the speed limitation, the client exceptionally displays the red to the driver in the entrance zone.

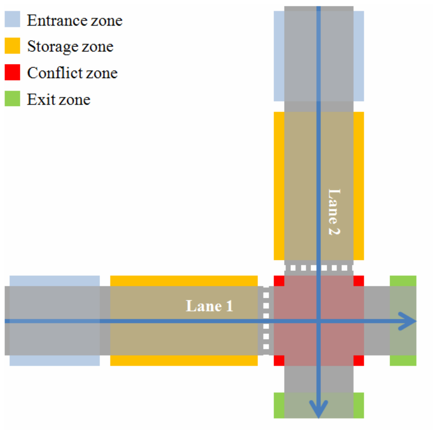


Fig. 6. The four zones of the intersection

The storage zone is dedicated to the signalization. In this zone the client begins the negotiation of the right of way by permanently sending a request with a growing priority until it gets the right of way from the server. During the negotiation, the client displays the “red” to the driver. The driver sees the green after the server validation of the right of way. The conflict zone is delimited for observing collision risks. If there is no safety problem, in this zone the green is still displayed until the bus accesses to the exit zone.

Table 1. The system behavior in zones

| Zones | Actions |
|---|---|
| Entrance | Preparation stage |
| Storage | Negotiation and signalization |
| Conflict | Checking safety parameters |
| Exit | Removal |

Finally, the client sends a removal request to the server while the bus is moving in the exit zone. The client stops sending the removal request only when the server removes the bus from its presence list. Under normal conditions, the removal requests have the highest priority for efficiency reasons. The server permanently broadcasts the presence list and the provided right of way.

## 4. Priority based policy

In this subsection we consider the two main tasks of the server which are the computation of the sequence (master) and the filtering of the distributed right of way (slave). The first task reorders the presence list according to the bus priorities and positions while the other executes the received list in such a way that two or more buses that move in the same lane or in parallel lanes can simultaneously receive the green.

### *4.1. Priority*

The master has an access to three lists that are ordered according to the bus arrivals. Each list corresponds to a lane. For instance, the buses that are involved in movements 3 and 4 are ordered in the same list. Each entry of the list represents a bus and its corresponding data. These data are the priority and a logical value that logs whether or not the bus has already received the green. From these three lists the master builds a sequence in the following way:

- First orders all buses that have already received the green,
- While buses remained not treated, selects the first remained bus with the highest priority.

Each client $i$ estimates the time $\tau_i$ taken to cover the distance between its current position and the exit zone plus the bus length, in order to consider the clearance time. $\tau_i$ is calculated by dividing the total considered distance by the commercial speed. The priority $P_i$ is computed by the client $i$ (each bus) as follows:

$$P_i=max(\tau_i,-D_i+d_i,,0)$$

where $D_i$ is the time required to cover the storage zone and the conflict zone plus the clearance time and $d_i$ is the estimated delay that is negative if the bus is in advance.

### *4.2. First filter of the right of way (movements matching)*

We have the four movements presented in Fig. 2. Instead of considering the conflict matrix, the slave owns the trees of admissible movements (see Fig 7). Each movement has its corresponding tree. When a sequence list is received, the slave selects the tree that corresponds to the first bus. In this stage we have a path with one node (origin). A next bus is said to be admissible if its movement is a direct descendent of the last node of the path or belongs to the path. In the former case, if the bus is admitted, the path has a new destination node that corresponds to the movement of the bus. The next bus is submitted to the same condition and so on. These iterations stop when a bus of the list does not satisfy the condition or it is not admitted according because of the time constraint discussed hereafter. At this stage, all green can be distributed simultaneously.

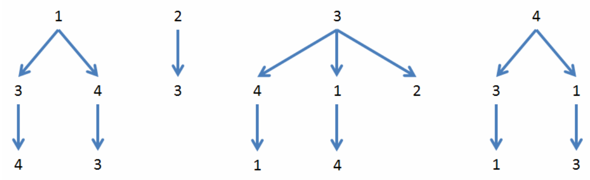


Fig. 7. The trees of admissible movements

Each node of the path holds the number of admitted buses. When a bus leaves the intersection the corresponding number is decremented. If a node is empty, the node is removed. If the removed node is the origin, the algorithm rebuilds the path in a new tree that corresponds to the new origin node. Otherwise, the new path is rebuilt in the same tree. In the first case, new iterations can starts again (from the refused bus of the list) in order to authorize new buses.

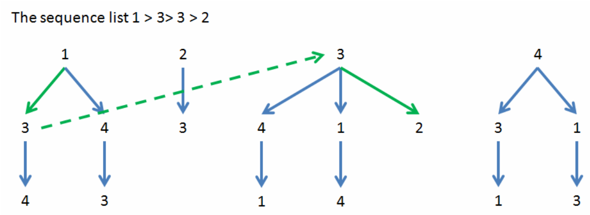


Fig. 8. An example of a sequence

Let us consider the sequence list given in Fig 8. The first greens are distributed to the three first buses by building the path (1>3). The iterations stops at the forth bus of the list. When the first bus leaves the intersection, a new path is rebuilt in the third tree. The last bus receives then the right of way.

### *4.3. Second filter (Temporal constraints)*

In the previous subsection we have exhibited only one admissibility condition. But remember that the buses share the conflict zone with the ordinary traffic. Thus a bus can receive the right of way only if the estimated time for leaving the intersection does not exceed the end of the current stage 1 (see Fig 3). This requires an estimation of the crossing time.

The temporal constraint is checked simultaneously with the condition of the movement matching. At each iteration, a time $T_k$ of the $k^{th}$ bus in the list is considered as follows:

$$T_k = max(\tau_k, T_l + h) + s_k$$

where $l \leq k$ refers to an admitted bus that moves in the same lane in which moves the $k^{th}$ bus, $h$ is the minimum headway time and $s_k$ is an adjustment parameter. If $T_k$ does not exceed the remained time of stage 1 then the bus receives the right of way. Otherwise the exploration of the sequence list is stopped.

## 5. Real tests

The protocol is tested through a real intersection of four ordinary cars (See Fig 9). The speed limitation is 25 km/h. The main objective of the tests is to check the feasibility of the system and the temporal parameters. There are two main feasibility matters that can be raised, i.e. collision and deadlocks. In (Abbas-Turki and al., 2012), we have discussed the main cause of both problems. The accuracy and sampling frequency of the positioning system is the main reason of collision. This is the reason why we have added an entrance zone in order to slow down the bus and make it able to detect its position into the storage zone. We have also tested DGPS/EGNOS system to increase the accuracy of GPS. Moreover, the bus itinerary is already known which allows an accurate map matching (Chen and al., 2011).

Deadlock situation is caused by a simultaneous occurrence of two problems: a high communication delay and a high error of the estimated bus position. The bus length overcomes the first problem if the error is less than 5 meter. Moreover, the minimum headway time that is generally close to 2 seconds reduces significantly the risk of receiving a request from the follower bus before the request sent by the leader. However, during the tests both problems were not raised, even if the test has involved vehicles instead of buses.

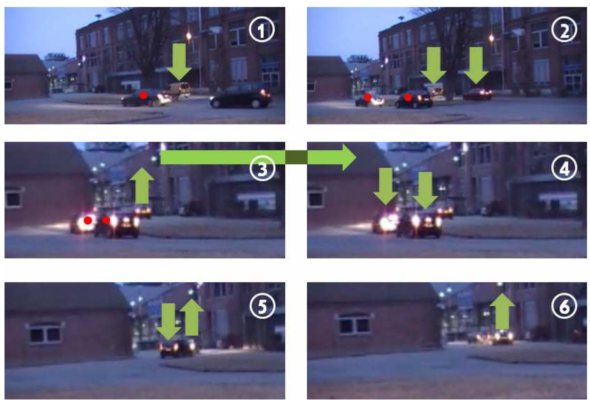


Fig. 9. An example of a test (see: http://www.youtube.com/watch?v=D6s8tXlGSLA&feature=youtube_gdata)

An additional feasibility issue is related to the human behavior. We have observed two kinds of behaviors, i.e. novice and expert. The main distinction between both behaviors is the moment when the driver decides to stop. Novice stops at the moment it observes the red while expert slowdowns to stop before the conflict zone. Fortunately, the novice behavior is corrected after few uses of the system. Indeed, the shape of the tested intersection allows the novices to quickly trust in the system.

The test allows us to estimate $D$, $h$ and $s$, through several experiences of two vehicles that traverse the intersection. $D$ and $h$ have been computed according to the average speed of vehicles and the average headway time. $s$ is estimated through logged data as un upper bound of the error. From the experience we have observed that $s$=3 seconds. Then we have tested four vehicles with many arrival sequences. All estimated evacuation times are covered by the $s$ value. $s$ is due to many parameters but the most important ones are: the time spent by the system to detect a car that is moving in the exit zone, the driver reaction time and the number of vehicles in the lane. The estimated value of $s$ may refuse a bus that is able to cross the intersection. But, the four vehicles were able to cross the intersection within a time less than or equal to 25s, whatever the tested sequence. This includes the time required to the first vehicle for moving into the storage zone.

## 6. Simulations

For the simulation we have used "Simulate" of Voxelia. It is a 3D simulator. Simulate considers many physical parameters of the simulated buses. It is also based on the microscopic model of Gipps (1981) for simulating the driver behavior. We have modeled the treated intersection (See Fig 1) and simulated many buses arrivals. The bus arrives into the intersection according to a randomly generated delay that follows a uniform distribution. The delay varied between -2 to 2 minutes. The results of 1000 buses arrivals are showed in Fig 10.

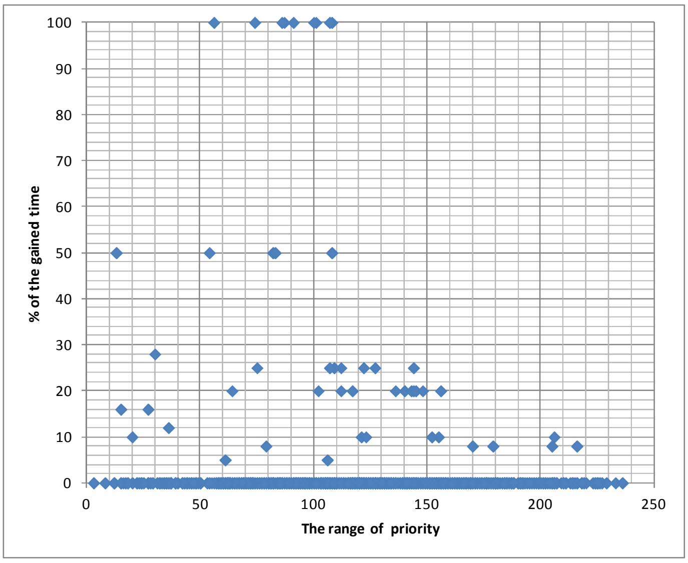


Fig. 10. An example of a test

The range of the priority is the difference between the maximal observed priority of a bus and the minimal one (of another bus). The percentage of the gained time is the percentage that results from the ratio between the saved time and the delay caused by a priority to the right. One can observes that there are many values close to zero. This is due to the fact that the delay problem presented in subsection 2.3 is not frequent in the simulation and even if it is raised, in certain cases the priority to the right is enough to resolve the problem. However, 1000 buses arrive in a period of time that is less than two days. One can note that there are many cases where the proposed approach contributes to significantly reduce the delay that may happen during only two days.

## 7. Conclusion

In this paper we have presented a new approach for controlling the traffic at intersections of buses. This approach allows a denser bus network to smartly share the infrastructure. It allows also to save the time that can be wasted because of a bad sequence of crossing the intersection.

Several issues deserve a particular attention to complete our local investigation (isolated intersection). The first one is to simulate the whole traffic in the city and to assess the saved time of the proposed approach. The second one is to propose a global approach able to consider the positions and delays of all the buses of the network.

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