“POLITEHNICA” UNIVERSITY OF BUCHAREST

COMPUTER SCIENCE DEPARTMENT

GRADUATION PROJECT

Vehicle Ad-hoc Networks
Adaptive Traffic Signal Control

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1. Introduction

Advances in mobile computing and wireless communication have offered new possibilities for Intelligent Transportation Systems (ITS). Increasing interest has been focused in the last years to deploy these technologies on vehicles and use them as a means of improving driving safety and traffic efficiency.

By adding short-range communication capabilities to vehicles, the devices form a mobile ad-hoc network, allowing cars to exchange information about road conditions. This is often referred to in the literature as Vehicular Ad-hoc Networks (VANETs) or Inter-Vehicular Communication (IVC) systems

The users of a VANET, drivers or passengers, can be provided with useful information and with a wide range of interesting services. One category of such services includes safety applications, like various types of warnings: ice on road, intersection violation, cars in front braking, and collision avoidance and mitigation in situations like: lane changing, lane merging and preparation for imminent collision. Another important class of applications that can be deployed over VANETs is concerned with traffic operations and maintenance: dynamic route planning, weather conditions publishing and adaptive signal control in intersections. Commercial and entertainment applications can be implemented as well, electronic payments, reservations, advertisements or gaming and file transfer are just a few examples.

Thesis statement

This thesis examines the possibility of deploying an adaptive signal control system in intersections, a system that can base its control decision on information coming from cars. Thus, each intersection with traffic lights is provided with a wireless infrastructure node that can extract data from an existing VANET.

For over thirty years now, efforts have been made to create traffic lights systems that can respond to the ever increasing traffic. Most of the signal control systems in United States, for example, are part of the first or the second generation, and rely on timing plans generated offline by traffic engineers using optimization models. These systems are hard to maintain and do not respond well to traffic events, like a football game or road construction. More sophisticated adaptive traffic lights use data coming from sensors, cameras and loop detectors to generate online timing plans.

An architecture based on wireless communications can employ greater flexibility than the ones mentioned before, providing more information for the signal decision process. The cost is also significantly lower, considering loop detectors are usually installed in the asphalt, under each lane approaching the intersections and cameras require high processing power and good orientation.

Project Objectives

TrafficView is a data dissemination system we have implemented. It is an application that runs on vehicles to collect and disseminate traffic information and finally, to provide meaningful data to the driver. It is an example of a VANET platform.

The adaptive signal control application presented here was developed to communicate with TrafficView, a platform for inter-vehicle communication. The main objectives are:

- to increase the throughput and to decrease the average delay, considering either one intersection or multiple coordinated intersections;
- to reduce overall fuel consumption and emissions;
- to increase safety in intersections.

Testing a VANET application is a real challenge because of the number of nodes needed for a typical scenario and also because of the specific vehicle mobility model. We have developed our own custom microscopic simulator that takes into account this mobility model and simulates communication between nodes. With this tool we have emulated the TrafficView application on hundreds and even thousands of vehicles. We have also used the simulator to evaluate the adaptive traffic lights system in various conditions and measure performance parameters.

The rest of this document is organized as follows. Section 2 provides a description of the TrafficView, in the context of vehicular networks applications. A general background and related research is discussed first, and then we present the navigation system and data dissemination module in TrafficView. In Section 3 we introduce an integrated VANET simulator with support for mobility, communication between nodes and code emulation. Our adaptive traffic signal control mechanism, based on communication with vehicles is presented in Section 4 and, finally, we draw some conclusions in the final section.

2. TrafficView Driver Assistant

TrafficView is a data dissemination platform for VANETs that we have implemented. It is an application that runs on vehicles to collect and disseminate traffic information and finally, to provide meaningful information to the driver.

2.1. Vehicular networks

VANETs provide ITS with higher flexibility and scalability then systems that rely on complex infrastructure deployed on the roadside. Because the devices are installed in vehicles, some of the limitations of traditional mobile ad-hoc networks are overcome. Thus, nodes are considered to have unlimited energy coming from the car battery and there is enough space in a vehicle to install a computing device with good processing power. However, the challenges a vehicular network faces are not few and they may refer to rapid changes of the topology because of the high mobility of nodes, to limitations of the wireless bandwidth or to frequent disconnections in the topology. Improvements of this architecture, that could address some of these challenges, may consider base stations or antennas being deployed in critical points along the roadside or using occasionally WAN connectivity (like GPRS or 3G).

One important problem that deployment of car-to-car communication faces is the fact that it is a technology with network effect: its value increases along with its distribution. This makes it difficult to be deployed as the first users could not benefit from car-to-car communication properly. Researchers have also been concerned with the degrees of security such a vehicle network might need and possible ways to achieve them. Having this in mind, electronic license plates seem like a possible node authentication method. [4]

2.1.1. Background and Related Work

As it is an emerging technology, inter-vehicle communication is at the edge of passing from academia and research laboratories to mass commercial production. Although many car manufacturers have announced their intention of deploying this feature on their future cars, relevant results may be found for now mostly in research projects and simulations. Most of these projects try to make use of the collaborative information exchange between vehicles in order to develop safety applications such as emergency, traffic jam, traffic control, collision avoidance or obstacle warnings. A routing protocol suitable for this highly mobile ad-hoc network is also needed in order to provide multi-hop communication.

802.11 has been widely tested in inter-vehicular communication scenarios, though it has a number of features that make it unfeasible for such an environment: flexibility of radio resource assignment and of transmission rate control is low, unlicensed frequency that produces interferences and a small signal range. There have been numerous efforts to create wireless MAC protocols that are suitable for VANETs. For example, Rao and Stoica suggest in [5] a layer on top of 802.11 MAC layer that can solve asymmetric flow and hidden terminal issues.

In US, the Federal Communications Commission (FCC) has allocated 75 MHz of spectrum at 5.9 MHz for Dedicated Short Range Communications (DSRC), a variant of 802.11a [34]. Its goal is to support both safety applications and other Intelligent Transportation System applications over roadside-to-vehicle and vehicle-to-vehicle communication channels [15].

The FleetNet project, which ended in 2003, aimed to develop a communication platform for inter-vehicle communication. The platform is suitable for deploying three types of applications: cooperative driver assistance (emergency or obstacle warning), decentralized floating car data (traffic jam monitor or dynamic navigation) and user communication and user services (i.e. mobile advertising) [19]. For communication between vehicles the system uses UTRA TDD (UMTS Terrestrial Radio Access Time Division Duplex) because of the availability of an unlicensed frequency band at 2010–2020 MHz in Europe. As a routing protocol FleetNet chooses a position-based protocol which is used along with a distributed location service and relies on navigation systems.

The CarTalk 2000 project focuses its efforts on three application categories: information and warning functions, communication-based longitudinal control systems and co-operative assistance systems [9]. CarTALK, like FleetNet, uses the UMTS radio access technology and also uses a position based routing protocol.

California PATH program has been engaged since 1986 in developing solutions to transportation systems problems. Their work is focused on Policy and Behavioral Research, Transportation Safety Research, Traffic Operations Research and Transit Operations Research. Some of the many projects that are part of the program envision inter-vehicle communication or vehicle-to-infrastructure communication in systems ranging from safety messaging (using DSRC technology) to automate driving, vehicle platoons formation and automated highways.

The fact that vehicle-to-vehicle and infrastructure-to-vehicle communication are soon going to influence the way we drive is proved by recent news that show important results coming from the automotive industry. DaimlerChrysler [37] have publicly tested dynamic driving using wireless communication between cars in June 2005 using DSRC technology. Elsewhere, in Japan, Honda have announced the completion of Honda ASV-3 Advanced Safety Vehicles equipped with cameras, radars and communication devices providing new safety features like accidents prevention, information about approaching obstacles and vehicles on the road or drivers assistance in breaking and steering. [35].

For this technology to become ubiquitous there is an obvious need for standardization in order to have compatibility between different car vendors. Efforts are currently being made in Europe, Japan, US and other countries to accomplish this. In Europe, the Car2Car Communication Consortium aims to promote the allocation of a royalty free European wide exclusive frequency band for Car2Car applications and to develop strategies and business models to speed-up the market penetration and standardization.

2.2. TrafficView Navigation System

The TrafficView navigation module is in charge with efficient storage and manipulation of the digital map, as well as accurate mapping of GPS readings to map locations. As input for the maps we use the TIGER files available for free [13], in the format of Record Type 1 (RT1) for and Record Type 2 (RT2). The two files types permit us to construct the road graph. The RT1 files contain all the road segments for a map region, with information like the type, name, direction, or starting and ending points. The RT2 files contain intermediate points of the road segments for the representation of curves. There are TIGER maps for every state in US, and for testing we have built our own, using the same format and representing a part of our campus Figure 1. To calculate distances between points on the map we have used conversion tables from degrees to meters depending on the latitude and longitude. The number of meters per degree of latitude/longitude varies with the degree [14].

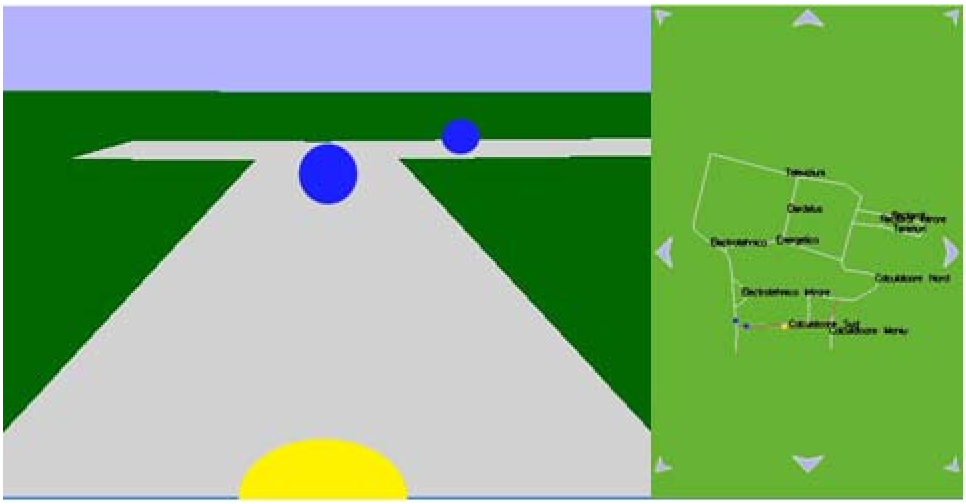

Figure 1 Dynamic map of the "Politehnica" University of Bucharest.

The geographical coordinates of a vehicle, read from the GPS device, are transformed to a point on a road of the map and displayed accordingly to the driver. In order to do this efficiently the system relies on the PeanoKey mechanism, initially described in [1], which is efficient in terms of both search and storage.

A PeanoKey is associated with a point in the 2D space, and it is obtained by interleaving the digits of the two coordinates. Thus, the 2D set of points is represented in a one dimensional set. For example the PeanoKey associated with the geographical point at 26.047800 degrees longitude and 44.435348 degrees latitude is 4246403457384080. When the map is being built, a set of sorted PeanoKeys is also computed, corresponding to all the points of the map. Consecutive PeanoKeys in this set correspond to points that are relatively close on the map.

Finding the closest point on the map, given the two GPS coordinates, latitude and longitude, reduces first to finding the PeanoKey in the set that is the closest to the PeanoKey newly formed and then, performing a linear local search around this element.

2.2.1. Implementation Details

The first action taken when TrafficView is started is to load the map into an appropriate structure. The steps for this task are summarized in Figure 2. First, the Tiger RT1 file is parsed and a set of road segments is built. This has, of course, an O(n) complexity where n is the number of segments in the .RT1 file. For each record in the .RT2 file, additional points are given for a specific segment. This implies $O(n^2)$ complexity as for each record, the corresponding segment has to be located in the set, in order to add the points. Although there may be multiple RT2 records in the file for a single segment, only a part of the segments are given records in the .RT2 file, namely the ones that have curves.

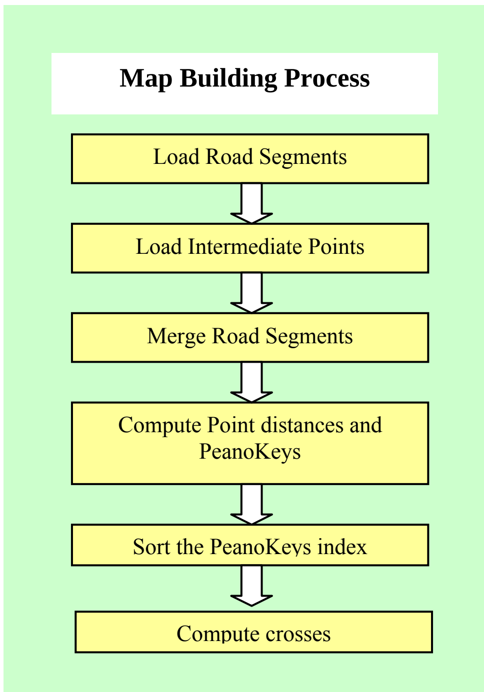

Figure 2. The sequence of actions for building the map structure.

The TIGER files contain points only for a few locations along a road segments, such as curves or intersections. As we need to map a vehicle to a point on a road more accurately, new points are created through interpolation. The points are created with a specified resolution so no two consecutive points will be farther than a configurable distance. This increases significantly the number of points, *m*, and determines the complexity of the map building process.

The next phase takes care of merging the segments. The road segments in .RT1 file are of small sizes and for a long road there may be tens of such records. This makes them difficult to manipulate so they have to be merged. This step normally takes $O(n^2)$ steps, because every two segments that have the same name have to be considered.

For each point of the map, PeanoKey value is computed as specified above along with a distance to the previous point on the segment it is on. The PeanoKey set of all the points will be used for quick location finding and the distance value serves for computing road distances between points.

Next, the PeanoKey set is sorted and this represents the most time expensive step of the process: *O(m log(m))* where *m* is the total number of points. Finally, given the sorted set, finding the intersections between roads resumes to finding consecutive equal values in this set, so it is only a *O(m)* traversal of PeanoKeys.

During the execution of the program, it is often needed to find the closest point on the map, given the latitude and the longitude. This is accomplished by running a binary search on the set of PeanoKeys (*O(log(m))* complexity) and then the closes point is found after a local linear search around the index returned by the binary search.

Figure 3 presents the UML class diagram for the classes related to the map structure. A map object has a collection of roads. Each road (Road.java) has a name, number of lanes, a set of points and a set of crosses and it can be a one-way or two-way street. Each point in the set of points of a road, has a longitude, latitude, distance to the beginning of the segment and a reference to a PeanoKey value. All the PeanoKey values are kept in a collection in the Map class. Likewise, each PeanoKey has an inverse reference to a point on a road.

A road also has a set of crosses (Cross.java). Each cross object contains references to the crossing segments and to the points of intersection.

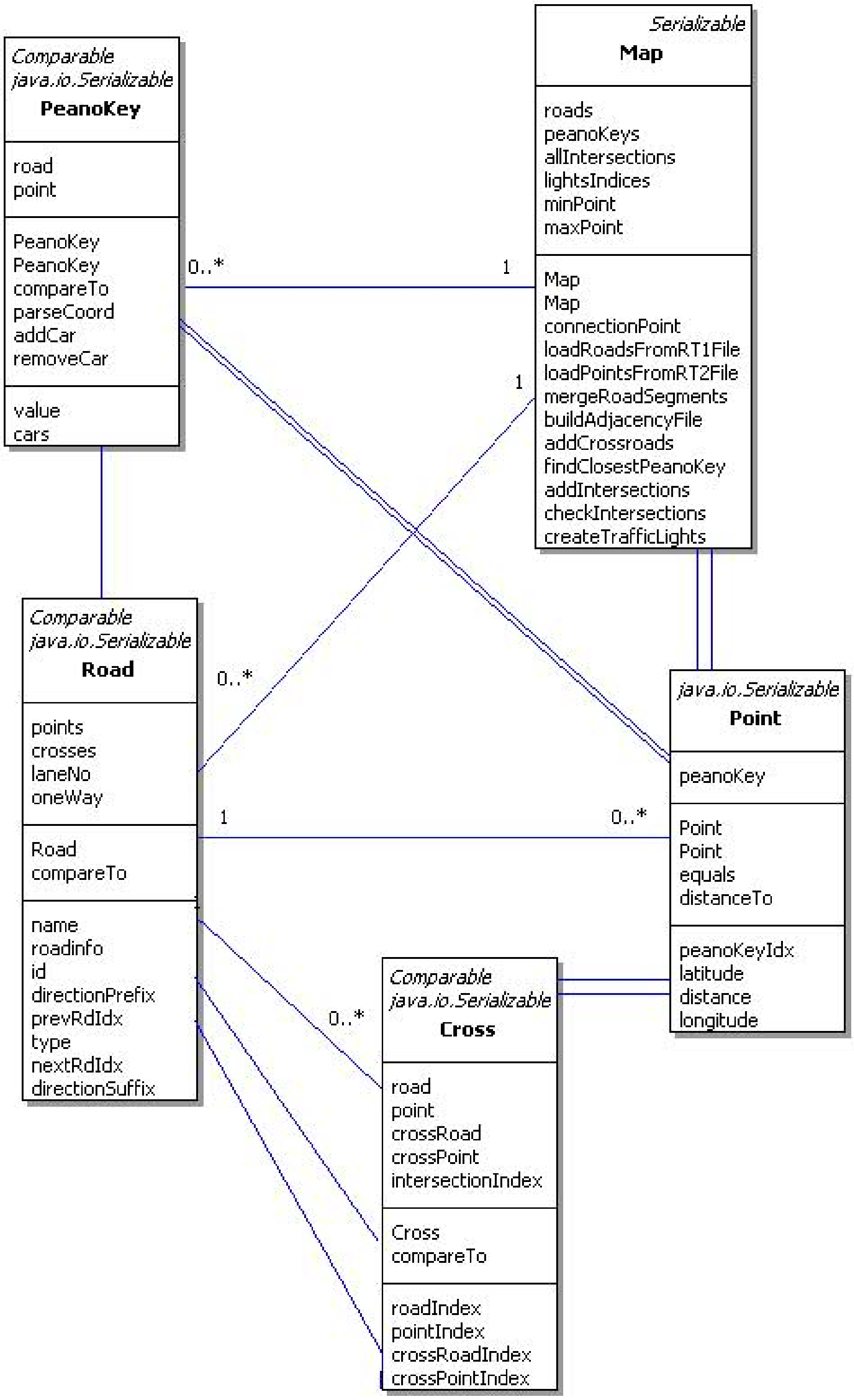

Figure 3. The UML class diagram of the navigation module

2.3. TrafficView Data Dissemination Model

Most literatures suggest as a point of start to VANETs the application of information dissemination between vehicles using periodical and regional broadcasts. The main problem here is that broadcasts can result in flooding the network, also known as the broadcast storm problem, so the number of messages has to be limited in order to keep scalability. Several optimizations have been proposed, such as decreasing the level of detail as the distance increases by using aggregation models [1]. In [16], the authors present an adaptive way to set the broadcast period depending on the significance of the message. In [17] several schemes (probabilistic, cluster based and other) are proposed to reduce redundant rebroadcasts in wireless networks.

A configuration, in which information propagates through periodical broadcasts from node to node, is said to work in the “push” mode. On the other side, in the “pull” mode, information may be obtained on-demand, based on query-reply communication. These two models may be put into balance when it comes to network performance. In the “push” mode, increasing the range of the forwarding area results in greater bandwidth requirements and more useless information. However, using more queries even for shorter distances offers only the needed information but it is less reliable and may increase the number of messages comparing to “push” mode as the distances get shorter.

In TrafficView, vehicles periodically transmit information about themselves and other cars on the road. They use one-hop broadcasts to avoid a broadcast storm and each record consists of a position, identification number, speed, direction, state and a timestamp of the moment when this information was created.

We have chosen to limit the size of the set of cars transmitted to fit in one single packet. This avoids the delay caused by flow control which appears when dealing with multiple packets. It also saves bandwidth and reduces the delay caused by retransmissions.

Sets of car records are forwarded by each node alternatively, for cars running on the same street and in the same direction with the forwarder, and for the opposite direction (bi-directional model). Research shows that a propagation model that makes use especially of the cars on the opposite direction when forwarding may have better results in terms of distance of knowledge, error and delay of information. The bi-directional model can adapt to situations when traffic on one direction is too low switching to a single direction model.

2.3.1. Protocol description

The TrafficView packets for data dissemination in the "push" mode (periodical regional broadcast) have the following format:

1 byte	1 byte	1 byte	1 byte	20 bytes	20 bytes	20 bytes		20 bytes
Type	Map id	State	Cars no.	Sender	Car 0	Car 1	…	Car n

- Type – specifies the TrafficView protocol type used. The type may be information broadcast message, query/reply message or neighbor discovery;
- Map id – defines region of map currently selected. The position of each car will be considered for this region;
- State – the category of cars in the set. It may be current road current direction, current road, opposite direction or other road. The road and direction are relative to the sender's position;
- Cars no. – number of cars in the set;
- Sender & Car – car record:

4 bytes	8 bytes	1 byte	2 bytes	2 bytes	1 byte	1 byte	1 byte
Vehicle ID	Timestamp	Speed	Road id	Point id	Offset	Lane	Extra info

  - Vehicle ID – the unique identification number of the vehicle;
  - Timestamp – of the moment when this information was generated by the specified vehicle;

- Speed – speed of the vehicle;
- Road & Point ids – specify the point on the map where that the car is the closest to. We consider that vehicles have the same map format.
- Offset – distance to the map point;
- Lane – specifies the lane on which the car is running. This field is used mostly in simulation, because current GPS systems are not that accurate.
- Extra information byte:

0	1	2	3	4	5	6	7
direction	signal		state				

  - Direction – the side of the road on which the car is running
  - Signal – this field is the equivalent of the electrical signals of the car and specifies the intentions of turning.
  - State – the state of the car may be damaged, crashed or normal. The state also gives information on the current transmission mode of the car, such as active mode or promiscuous mode.

2.3.2. Probabilistic forwarding

Usually, on a highway or any other road, cars have a tendency to form platoons. If every car uses the data dissemination model described above, redundant information gets transmitted. This redundancy is even more obvious in a city environment, where large groups of vehicles can be observed at intersections. For cars that are moving along a street it is necessary that they broadcast their position, but information about other cars may be redundant in the case of a platoon. In this case, elimination of redundant information will not result in fewer messages (a moving ca has to send minimum one record, itself), but it will result in smaller messages. Studies of wireless networks [18] show the medium access and transmission delays vary significantly depending on the packet size: from 5 milliseconds for 64 bytes, to 60 milliseconds for 2048 for a certain network load.

In TrafficView, we impose a scheme in which a vehicle functions in two different modes: it either transmits a “keep alive” message with only one record with its own data or a complete message with all the car records that it currently knows about. At each broadcast period, the application will decide which type of message to transmit in a probabilistic manner. It will transmit the full set of cars with a probability proportional with the size, in meters, of the platoon that it is currently in. For example, if two cars are very close to each other, it is a great chance that only one will transmit the complete set of cars while if they are a few tens of meters apart probably both will transmit the complete packet. In a wider and denser platoon, it is ensured probabilistically that information (about cars in or outside the platoon) gets transmitted from back to front and vice-versa without great redundancy.

The complete set of cars does not include car records that are older than a certain threshold and it is limited to fit into one single Ethernet 802.11 frame of 2300 bytes.

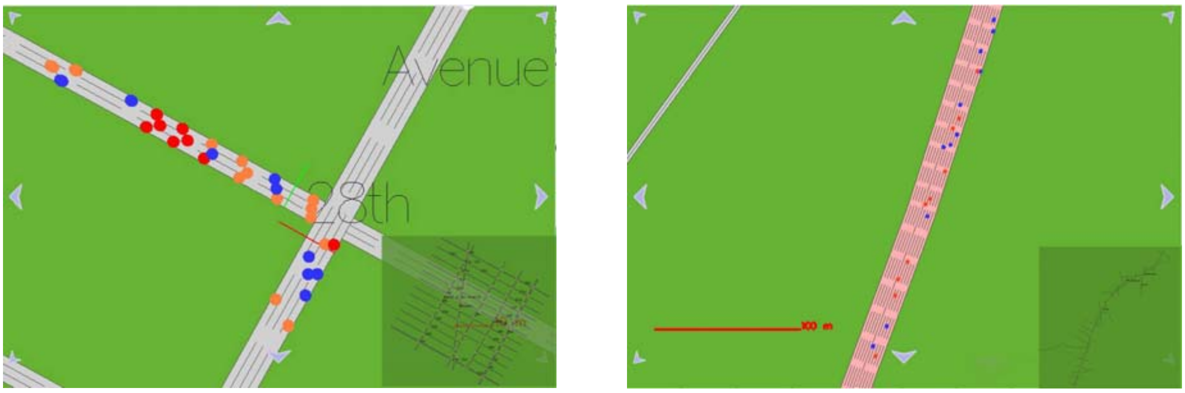

Figure 4 A view of the communication model used by each vehicle in a City Scenario (A) and a Highway Scenario (B). Vehicles are either in promiscuous mode (red), “keep alive” (orange) or complete forwarding (blue).

In a city environment further optimizations can be accomplished by setting cars that are not moving to promiscuous mode. However, such a car will warn the surrounding nodes just before going into this state, in order not to be deleted from their records when the entry would normally expire. As soon as the car starts moving, it will switch back to normal mode. However, during the period a car is in promiscuous mode, it may send complete messages if the probabilistic algorithm decide it that it should.

In this way the number of messages exchanged in intersections or in congested areas is greatly reduced and the performances of the network increase. Figure 4A presents the network configurations in a city environment, near an intersection and on a highway. In both pictures, the blue cars are the nodes that transmit messages with a complete set of cars, while the orange ones send simple messages, informing only on their position update. Furthermore, in Figure 4A, the vehicles that are stopped at the traffic light, shown in red, are in promiscuous mode.

Next, we studied the behavior of probabilistic forwarding presented above in comparison with complete forwarding model in which every node sends its entire database to the neighbors. The test scenario was a 10 km segment of New Jersey Turnpike Figure 4B, a highway in the U.S. We ran our simulation over few hours in which we have varied the flow from 500 to 1500 vehicles/hour/lane.

In both situations we impose a time limit for the age of the records, so that vehicles older than this limit will not be forwarded and deleted from the database. The communication model is a near ideal one and does not account for packet loss or abnormal delays in the wireless protocol.

Figure 5 a) shows that when using the probabilistic forwarding there is a small decrease in the average vehicles' database size, as compared to the complete model. This difference slightly grows towards the high extremity of the flow, when the density of vehicle per km is high and the network is connected over large distances. The reason for this is that, for probabilistic forwarding, the probability of a record to traverse a large distance of the network decreases as the distance increases. The graph of average knowledge range (Figure 5b) or the average distance over which a vehicle "sees" other vehicles has great variations. This is due to the random nature of the platoon formation. Platoons may be dense or sparse, spread over a small distance or a very large distance. However, generally the complete forwarding model has a little larger knowledge range.

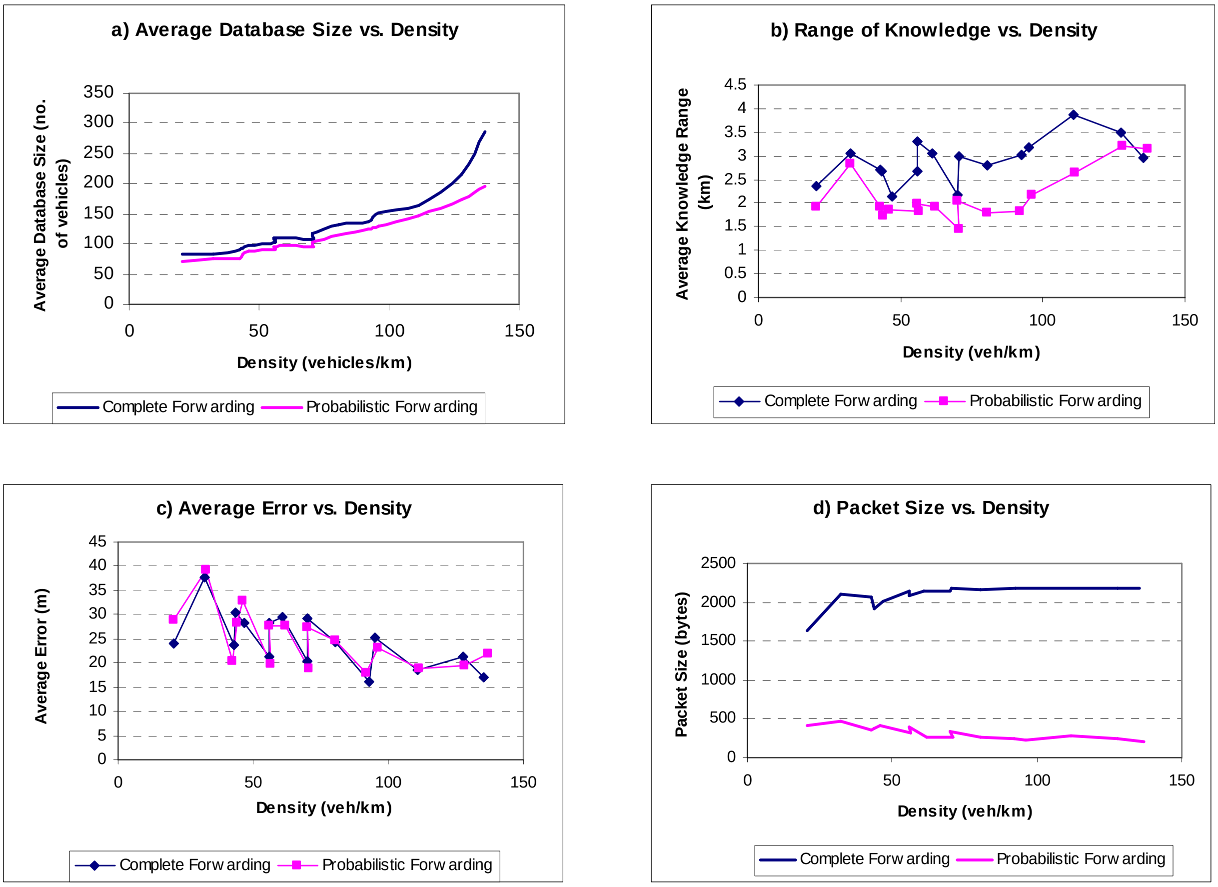

Figure 5. Comparison between probabilistic forwarding and complete forwarding for various densities on a 10 km highway segment.

The average error graph has almost equal values for both models because the average speed is the same and the same aging period of the records is chosen. Improvements of this error are attained when a vehicle hears about another one through fewer intermediate nodes, thus decreasing the delay of arrival. This is the reason why for higher densities, there are multiple paths for a record to be forwarded so the record is forwarded faster and the average error decreases.

Finally, the last graph shows the great improvements of the probabilistic forwarding over the complete forwarding, in terms of average packet size. In the complete forwarding model the packet size increases as the network is denser, because on average each car will see more and more cars. On the other side, for probabilistic forwarding, the size will decrease because as the density of vehicles increases, the probability for a vehicle to transmit the full database decreases.

Overall, in spite of the slight decrease of visibility for the ideal case, the probabilistic forwarding model brings radical improvements in bandwidth. In practice, however, higher bandwidth adds delays that will reduce the visibility, so the probabilistic forwarding model is expected to perform even better than the complete forwarding model.

3. Simulation Environment

The evaluation of VANETs consists of real outdoor experiments, but also of simulation and statistical analysis. The simulation process has to take into account traffic conditions, driving characteristics and wireless communication protocols.

The VANET simulator we have developed is a discrete event simulator. The simulation time advances with a fixed time resolution after executing the application code for the current moment of the simulation time. More specifically, at every moment of the simulation time, all the current events are pulled from a queue of events, and handled in a random order.

3.1. *VANET Simulation*

Network simulators, like NS-2 or GloMoSim, implement the full network protocol stack and simulate the signal propagation model and the physical environment for wireless communications. For IVC, wireless network simulators have to take into account the mobility of nodes that can affect signal propagation.

Traffic simulators can be microscopic or macroscopic. Microscopic simulators model local behavior of individual vehicles by representing the velocity and position of each vehicle at a given moment. Macroscopic simulators model traffic condition in a global manner and may use concepts from wave theory. Usually traffic is represented in terms of flows (vehicle/hour), density (vehicles/km) or average speed.

In relation to IVC, microscopic simulation offers a more relevant representation. CORSIM [36] or VISSIM [38] are examples of microscopic traffic simulators that models vehicle interactions, traffic flows, congestions or streets and intersections geometry.

Considering the way they are built, simulation environments can be time based or event based. In time based models, like meteorological or traffic simulators, time advances with a fixed quantum and the entities act accordingly. Event based simulators (network simulators) increase time variably, based on the occurrence of events.

3.2. Structure

The events queue can hold three types of events: send, receive or GPS. A send event for a specified node triggers the calling of the node's procedure responsible for preparing a message. It also schedules the corresponding receive event(s) for the receiver(s) the simulator decides to deliver the message to, according to the network module. The receive event is associated either with a node, or with a group of nodes (broadcast) and it calls the appropriate handler in each of the receiving nodes. The GPS event is scheduled at a regular time interval for each node, in order to simulate the way a real VANET application collects GPS data periodically.

Besides these three types of events, the mobility module updates periodically the position of each node that is a vehicle, according to the vehicular mobility model. This model takes into account vehicle interactions (passing by, car following patterns etc), traffic rules and various driver behavior.

The main advantage of this architecture is that the simulator can execute (or emulate) the real application's code without significant changes. Practically, we have succeeded to simulate the TrafficView application [1] on each node, by calling the appropriate methods of the application when the corresponding events occur. Some minor changes were in order, because the original application was multithreaded which would be a serious limitation for the simulator. Figure 1 shows the top-down view of this simulation environment.

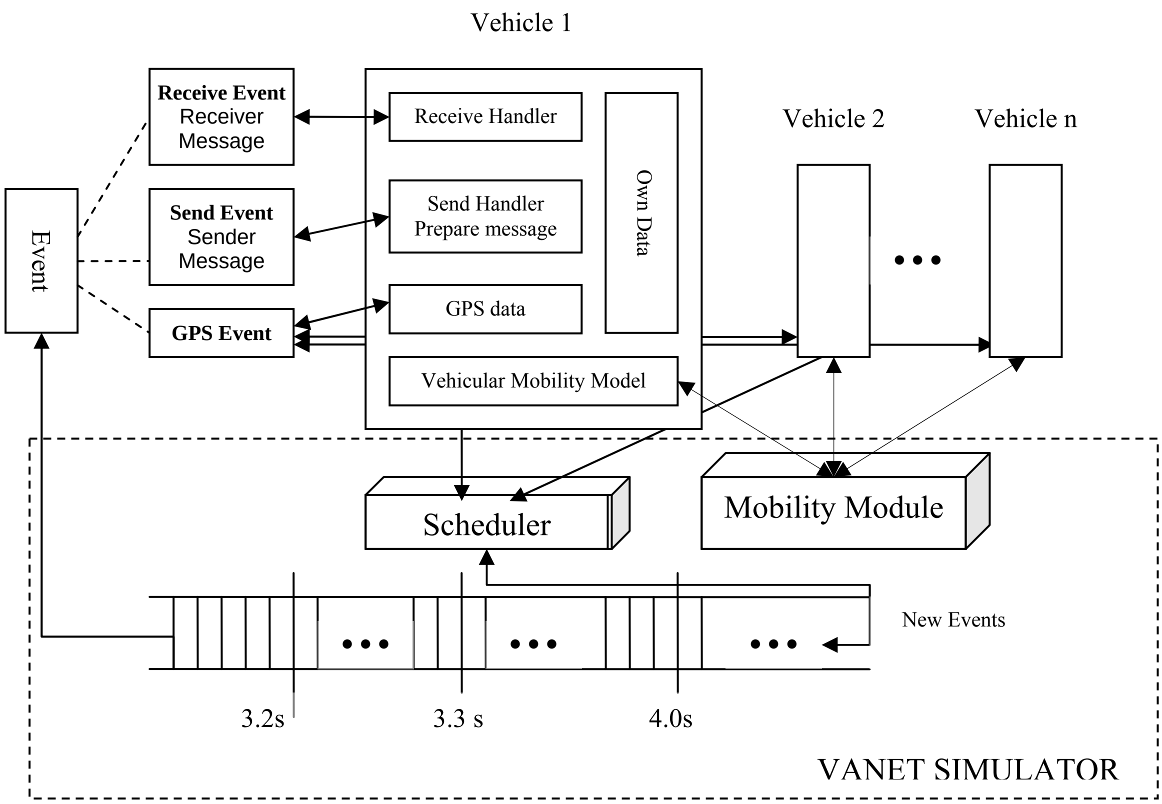

Figure 6. The discrete event simulator that emulates a VANET application**.**

3.3. *Simulation of Network Communications*

The environment can simulate the wireless network along with the mobility of nodes. The more complex this simulation is, however, less scalable the overall simulation process becomes. The basic network model that is used takes into account only the position and the wireless range of the nodes, medium access and the average delays for normal radio conditions reported in detailed study of wireless communications.

Unlike ns-2 and GloMoSim which use a O(n) search through all the nodes, our simulator delivers a message to all the nodes in the wireless range in an optimized way using a local search of nodes. This is possible due to efficient indexing of the map points, using the PeanoKey mechanism described above to scan the geographical area around a point. In this manner the wireless medium of a node is quickly analyzed, its wireless neighbors are discovered and a map of the radio signal is built in order to assure medium access.

To have a more accurate network model, more factors need to be taken into account. The node's protocol stack is one of these factors and the simulator can have the packet encapsulation process simulated by adding all the corresponding headers to the messages being sent. As a transport layer, UDP is preferred, while the IP network layer can be replaced by a geographical routing and addressing scheme. The MAC layer is 802.11b. The signal propagation model takes into account signal fading, gain or loss caused by collisions or interference with other radio devices.

3.4. Fuel Consumption and Pollutant Emissions Estimation

Estimating fuel consumption and pollutant emissions is an increasingly important matter when designing intersection control systems in urban areas. The model we have implemented is influenced by the work of Akcelik and Besley, presented in [11]. Of special relevance to our work, we consider the estimation of the relation between fuel consumption and emissions and the speed and acceleration of the vehicle. The model is simplified to take into account only light vehicles.

The formula we use for the estimation of these parameters, considering light passenger cars is:

$\Delta F = (f_i + \beta_1 R_T v + [\beta_2 M_v a^2 v / 1000]_{a>0})\Delta t$, when $R_T > 0$ or

$\Delta F = f_i \Delta t$, when $R_T \leq 0$,

where

ΔF [mL or g] – the quantity of fuel consumed or gas emitted (HC, CO, NOx) during the Δt time interval;

v [m/s] – vehicle instantaneous velocity;

a [m/s^2] – acceleration;

M_v *[kg]* – vehicle mass (1400 kg on average for light vehicles in a city environment);

R_T *[kN]* – total force, including air drag and rolling resistance;

$$R_T = M_v \cdot a + F_{rr} + F_{ad}$$

F_{rr} - rolling resistance force:

$$F_{rr} = C_{rr} \cdot M_v \cdot g, \quad \text{(for each tire)}$$

C_{rr} – rolling resistance coefficient, 0.15 on average for each tire (depends on road surface)

F_{ad} - air drag force:

$$F_{ad} = \frac{1}{2} \cdot \rho \cdot v^2 \cdot A \cdot C_d$$

ρ - air density (1.29 kg/m^3)

A – frontal car area (2.1 m^2 on average for light vehicles)

C_d – drag coefficient (0.3 for a car)

f_i [mL/s or g/s] – idle fuel consumption rate or gas emissions rate;

β_1 [mL or g per kJ] – fuel consumed or gas emitted per engine energy unit;

β_2 [mL or g per (kJ·m/s^2)] – coefficient for fuel consumption or gas emissions per unit of energy-acceleration, reflects the function behavior on positive acceleration.

The values of the last three parameters are given in the following table. They are based on the work reported by Akcelik and Besley, presented in [11].

	f_i	β_1	β_2
Fuel consumption	1350 [mL/s]	900 [mL/kJ]	300 [mL/(kJ·m/s^2)]
CO	50 [g/s]	150 [g/kJ]	250 [g/(kJ·m/s^2)]
HC	8 [g/s]	0 [g/kJ]	4 [g/(kJ·m/s^2)]
NOx	2 [g/s]	10 [g/kJ]	2 [g/(kJ·m/s^2)]

The CO_2 is calculated based on the fuel consumed:

$$\Delta F(CO_2) = \Delta F(fuel) \cdot f_{CO_2},$$

where f_{CO_2} is the CO_2 emission rate given in grams per milliliter of fuel [g/mL].

f_{CO_2} = 2.5 g/mL for light vehicles

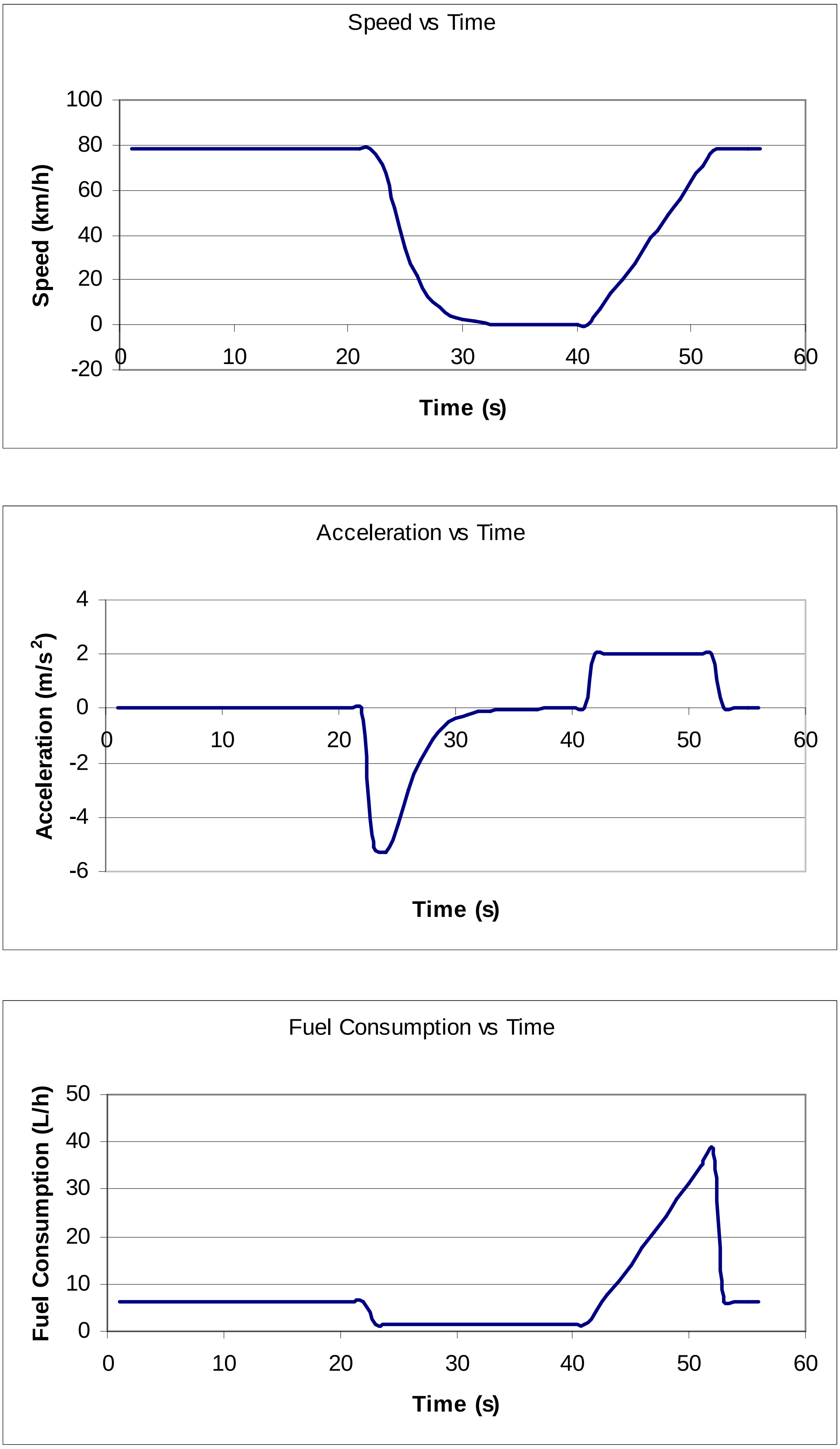

Figure 7 Example of fuel consumption estimation for a vehicle that passes through an intersection

3.5. Performance study

As described above, three main parts can be distinguished in the simulation process: mobility, simulator engine and emulation of the nodes' application. Optionally, the simulation may run with a graphical user interface we have implemented, but additional time is consumed with display functions and the synchronization mechanisms. The mobility model works as a micro-simulator. It consumes time on moving each car independently, considering all the nearby cars that may affect it and the traffic rules that apply. The simulator engine manages the events queue and establishes communication between nodes. Each time a node sends a message, the engine searches for all the cars in the node's wireless range to deliver the message. It performs a linear search on a limited set of elements around the geographical position of the node, using the PeanoKey mechanism described in the previous sections.

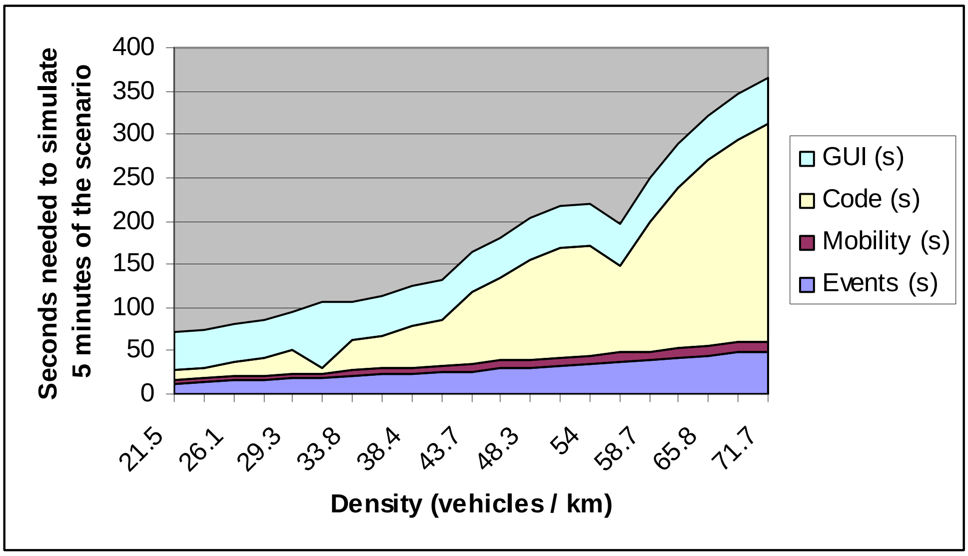

Figure 8 Time measurements for the simulation process and its components, depending on the density of vehicles. Test scenario: 10 km of highway with a traffic flows varying between 500 and 1500 vehicles/hour/lane.

The most time consuming part of the simulation is code emulation (Figure 3). The TrafficView application, which functions on each node, has to parse all the incoming messages, update the local vehicle records and create new messages for broadcast. Figure 8 shows that for high densities, when the network is widely connected, messages are propagated easily from car to car and more than half of the simulation time goes on processing the messages received by each of them.

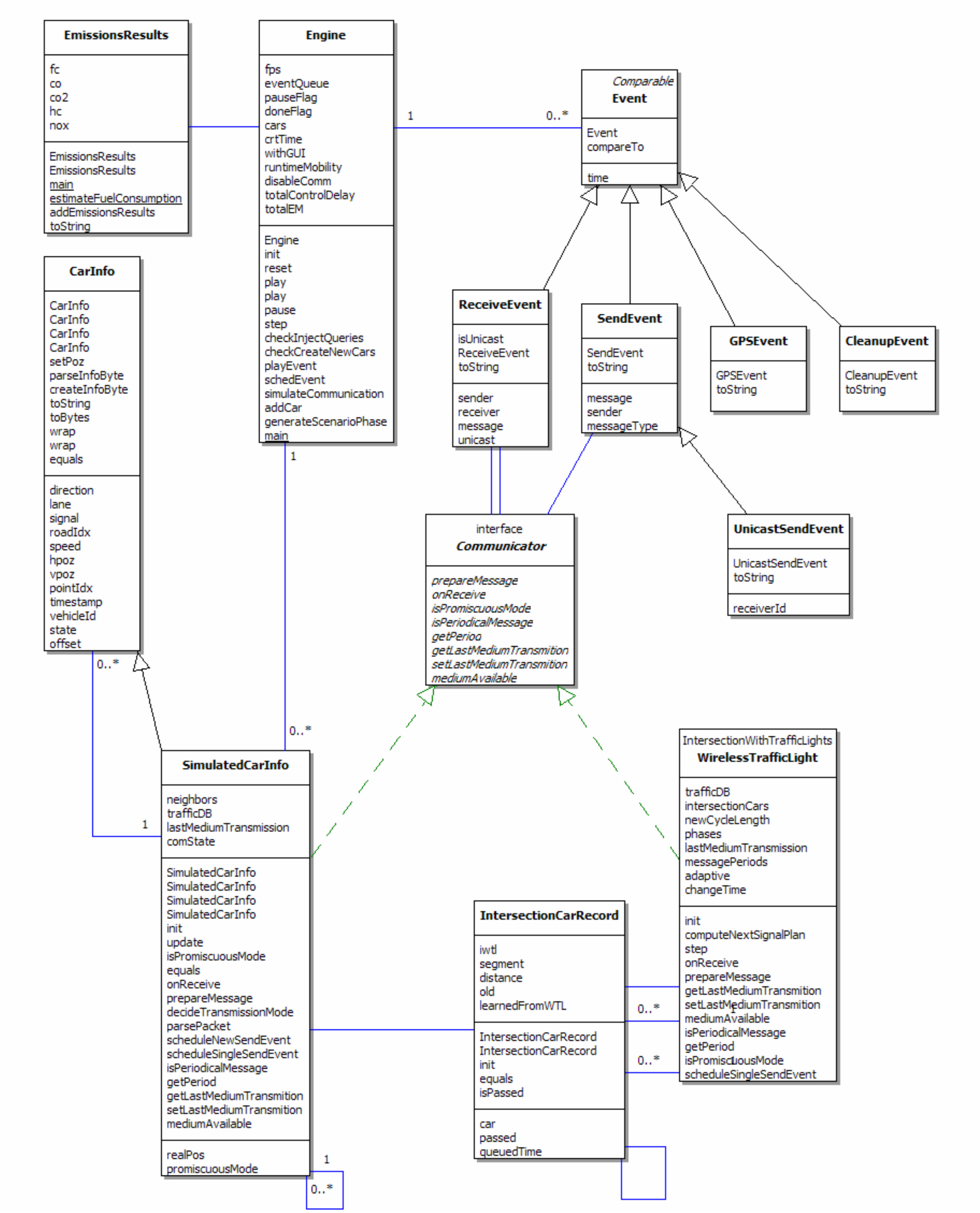

Figure 9. UML class diagram of the simulator engine module (JAVA)

3.6. Implementation Details

The UML class diagram in Figure 9 shows the core structure of the simulator written in Java. The main class, Engine, manages the nodes of the network and the interactions between them, which are triggered by events. The GUI and the communication between nodes can be switched off for particular studies or improvements in performance.

Each car node of the network is represented by the SimulatedCarInfo class which extends the class CarInfo, which contains basic data needed for representing the car such as vehicle id, speed, latitude, longitude, direction, timestamp and a few others. The timestamp is the time when the GPS device of that car got the data. The class SimulatedCarInfo adds the methods that come with the TrafficView application that runs on each node. The class also implements the Communicator interface which contains the methods for needed for a node to communicate with the network. The map is loaded into memory only once, as a global object, and all the entities in the simulator may have access to the map structure. The methods that are called whenever the state of a node needs to change are basically three:

- SimulatedCarInfo.update() – is called periodically, when the node's new position and speed are read from the GPS. The role of the GPS is simulated by the mobility module which moves the vehicles on the map;
- SimulatedCarInfo.prepareMessage() – is called when the node is supposed to send a message previously scheduled, either as a periodical or single message.
- SimulatedCarInfo.receive() – is called when a node receives a message from another node. The engine decided that the node received this message, based on its position and the message protocol address.

Each of these methods is called whenever the specific event occurs in the engine. They are handlers that the engine knows to call when appropriate.

When the engine advances the simulation time, it pulls out from the main event queue that it manages all the events for the new moment of time. The Event class holds a time variable, for the moment when it will occur. This class is extended by classes representing particular types of events that add more information; for example, the Receive event has 2 communicators (a sender and a receiver) and the array of bytes that form the message. The SendEvent class is used for broadcasts, and it is extended by UnicastSendEvent for one hop unicasts. The CleanupEvent is used to when the cars need to cleanup their databases of old records. It replaces a cleanup thread in the real TrafficView application.

The network also permits communication between nodes, other than cars, such as infrastructure nodes. The WirelessTrafficLight class, used to implement the logic described in the following section, also implements the Communicator interface, has a geographical position and may communicate with the other nodes.

Finally, the engine receives input from the emissions and fuel consumption module that is connected to the mobility model. Each time a car is moved on the map, its speed an acceleration determine an estimation of the fuel consumption and pollutant emission as previously described.

4. Adaptive Signal Control Based on Wireless Communications

For over thirty years now, efforts have been made to create traffic lights systems that can respond to the ever increasing traffic. A first step in adapting traffic lights to the traffic demand was signal timing according to the time of the day. This solution is based on signal plans generated offline by traffic engineers and requires consistent maintenance effort as traffic changes. A possible improvement represents the use of input from sensors to select a signal plan that best suits the situation and modify it online. A limitation of this strategy is encountered in situations where events that influence traffic often occur, like touristic regions or intersections near stadiums or malls. Fully adaptive or fully actuated traffic signals generate timing plans online, based on input from sensors that measure traffic parameters.

This thesis examines the possibility of implementing an adaptive traffic light system, based on wireless communication with the vehicles. It proposes the use of network infrastructure nodes that can benefit from the information exchange in TrafficView and get a clear real-time view of the traffic.

In the following section we will present the basic theoretical aspects that are taken into account when designing signal control systems. Then, a brief history and the current achievements in the field are discussed. In section 4.2 the design of TrafficView Signal Control system is described. Finally we will present the simulation tests cases we have run and the results we have obtained when using our system.

4.1. Theoretical aspects

A timing plan for a signal control at an intersection is specified through three parameters: cycle length, green splits and offsets. The <u>cycle length</u> is the time it takes for a traffic light to pass through all its phases before it repeats the first phase. The <u>split</u> of each phase is the duration of the phase expressed in percentage of the cycle length. The offset is the difference between the start times of green periods at two adjacent intersections and is used for coordination between traffic lights.

There are several goals that can be taken into consideration when designing a signal control mechanism [6]:

- **minimizing the average delay** of vehicles approaching an intersection
- **increasing progression,** by coordinating vehicle platoons between intersections
- **reducing the queue length** of all approaches to an intersection
- **maximizing overall throughput,** by analyzing traffic at the intersection, arterial or network level

Achieving two or more of these goals may be contradictory. For example, increasing progression may not be the optimum for minimizing total delay, because traffic on arterials is encouraged at the expense of congesting minor approaches.

However, we will consider the main measure of effectiveness (MOE) for an intersection is the control delay, which is the component of the intersection delay caused by the presence of the signal control [30]. It is measured in comparison with the travel time calculated in the absence of a control mechanism. Another relevant parameter is *v/c* or volume per capacity ratio which reflects the degree of saturation of an approach to the intersection. For saturated intersections the degree of saturation is calculated through the demand per capacity ratio which is greater than 1. The queue length, calculated in number of cars, might also be an important parameter that would help analyze the geometrical configuration of the intersection and detect downstream congestions. Downstream congestions are traffic jams that occur immediately after passing through an intersection, possibly caused by the queue at the next intersection. This process seriously affects the traffic flow, or even freezes it, and may be also referred to as starvation.

Minimizing the delay at intersections, suggests the selection of a cycle length as short as possible, in order to produce less red time and shorter queues. The intuition here is that the cycle length should be shortened until a critical value is reached, a value under which the overhead of phase changing starts to significantly influence the delay. Figure 10 shows the behavior of delay vs. cycle length relation.

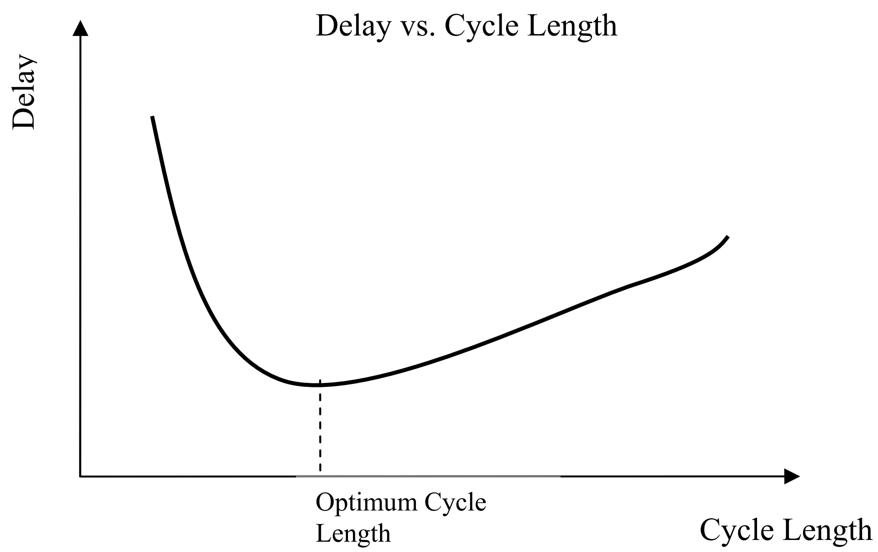

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Figure 10. Typical shape of delay vs. cycle graph for an isolated intersection

In theory, the optimum cycle length is expressed with the Webster's equation, as a function of lost times and critical flow ratios:

$$C_O = \frac{1.5 \cdot L + 5}{1 - \frac{1}{X_C} \cdot \sum_{1}^{n} \frac{v_i}{s_i}}, \text{ where:}$$

C_O – Optimum cycle length;

L – Sum of lost times for all the phases;

n – is represents number of critical lane groups. A critical lane group is a group of movements that can access the intersection concurrently;

$\frac{v_i}{s_i}$ - is the maximum flow ratio for the critical lane group i;

$\frac{1}{X_C}$ – is the desired degree of intersection utilization (1.0 for operation at full capacity, usually 0.95).

The lost time is calculated as the sum of inter-green periods. The inter-green period for a phase is the sum of yellow time and all-red time, and represents the interval when usually no car enters the intersection. For an intersection with pedestrian crossings, the sum of green time and inter-green time for one phase has to be long enough to permit pedestrians to safely cross the street.

The flow ratio for a lane group is computed as the actual flow of the lane group, for which the timing is considered, per saturation flow. The saturation flow is calculated as the maximum number of vehicles that can enter the intersection, if the signal would be green for an hour. A typical value for the saturation flow is 1900 vehicles per hour per lane, but there are several factors that can reduce this value, such as narrow lanes, large number of turning movements, or large number of trucks and busses.

In city environments, coordination between multiple intersections along arterials is crucial. The goal of traffic lights coordination is to have large platoons of vehicles move through a sequence of intersections without stopping. The intersections can be best coordinated when they are uniformly spaced. Too great distances between signals can cause the cars in platoons to spread, thus reducing the effect of coordination.

Coordination of the traffic signals in a sequence of intersections means setting an equal cycle length for all the signals. For optimum results this cycle length is chosen by analyzing the critical intersection in the sequence, the one with the maximum flow. Considering Webster's formula presented above, the global cycle length will be equal to the maximum of the optimum cycle length for each signal along the path. If the cycle length of a signal differs significantly from the remaining intersection, than it can function in using double or half of the value selected for the other signals.

4.2. Existing products and related research

The evolution of traffic signal control systems is divided into three generations:

- **First Generation** – The signal control systems in this category use pre-calculated signal plans, generated offline, that are selected based on time of the day. The plans change every 15 minutes and the devices are non-computerized.
- **Second Generation** – These systems choose online the signal plans, based on surveillance data and predicted values. Optimization of timing plans may occur every 5 minutes but choosing new plans is limited to 10 minutes. Usually the data is processed by a central computer that may implement coordination between intersections.
- **Third Generation** – Fully responsive traffic control systems that also rely on sensors, but can change the plans more rapidly (3-5 minutes). These systems are more independent, having their own processing module, and may be part of a distributed system that achieves coordination.

Thus, there are two different strategies to creating suitable signal control systems. The first alternative is using offline optimization models that generate signal plans for intersections based on simulations or input parameters. The other alternative is online adaptive control systems that implement signal plans based on data from sensors, running their algorithms online.

4.2.1. Offline timing optimization models

There are several software tools on the market, which are used in cities all over the world to create timing plans based on input traffic measurements. The output of these tools is used by traffic engineers to pre-set the traffic lights. Following we describe the models behind the most important of these tools.

TRANSYT is a software program that implements a, so called, mesoscopic traffic model for the analysis and optimizations of intersections and network of intersections. A mesoscopic traffic model estimates at each moment of the simulation the traffic flow that enters each segment, the number of vehicles that stop at red lights, or the number of vehicle that depart on green or the platoon formation along a street. The optimization techniques TRANSYT uses try to reduce the total delay and the number of stops of a network of intersections. This are the main MOE (measures of effectiveness) this tool analyzes for the generated traffic flows.

In the signal optimization process, TRANSYT first searches through all possible cycle lengths, and analyzes each value in order to find the best results. For each cycle length it computes the green splits that produce equal saturation degrees on all approaches. The splits are further optimized by searching the best solution around these values, also taking into account offsets between adjacent signals [21].

The latest version uses genetic algorithms to find the most suitable sequence of phases.

SYNCHRO is a tool that is widely accepted in USA and used to optimize intersections all over the world. Its philosophy is to minimize a performance indicator that is a function of delay, number of stops and queue length. The traffic model used is similar to the model of TRANSYT. SYNCHRO analyses a group of intersection limited to 10 for the simple version and to 300 for the distributed one [20].

The optimization process has several stages. Like TRANSYT it analyzes all cycle lengths in a specified domain. The offsets and splits are optimized using a search in steps: first with 4-second increments, then 2-second and finally 1 second. For coordination between two adjacent intersections SYNCHRO calculates a factor reflecting the extent to which they can be coordinated, based on link distance, travel times and volume.

PASSER II and V are similar optimization tools that uses a genetic algorithm to find the best timing plans at several intersections along an arterial so they focus mostly on coordination [6]

4.2.2. Adaptive signal control systems

Several adaptive traffic control systems have been implemented for intersections all over the world. The most important ones include Split, Cycle and Offset Optimization Technique (SCOOT) [24], Sydney Coordinated Adaptive Traffic System (SCATS) [22], Los Angeles Adaptive Traffic Control System (LA-ATCS), Optimized Policies for Adaptive Control (OPAC) and Real-time Hierarchical Optimized Distributed and Effective System (RHODES) [23].

SCOOT [24] is the most widely used, with hundreds of installation worldwide. It is based on loop detectors placed on every link to an intersection, usually at the upstream end of the approach. Thus, based on the actual field demand, SCOOT creates Cyclic Flow Profile (CFP) and models platoon movements, queue formation and discharge. To measure demand, it uses LPUs (Link Profile Units), a fundamental measure of flow and occupancy.

The optimization process takes place at central location, where all the data from the monitored intersections arrive, and then timing plans are adjusted and sent back to the traffic lights controllers in the intersections. There are three optimization stages: Split Optimizer, Offset Optimizer and Cycle Optimizer. They work in small increments that are evaluated according to a performance index, a function of predicted delays and stops for the approaching vehicles. The Split Optimizer runs at each phase change and analyzes how the modification of the current phase with up to 4 seconds (in any way) would influence performance. The Offset Optimizer runs once per cycle and based on CFPs predicted for adjacent nodes may decide modifications of the offset also with up to 4 seconds. The Cycle Optimizer runs periodically, every five minutes, considering a group of coordinated intersections. A critical intersection is identified in the group, and then an optimum cycle is calculated for a saturation degree of 90%. The old cycle is modified with up to 16 seconds towards the new calculated cycle.

For incident detection SCOOT has two special modules. ASTRID (Automatic SCOOT Traffic Information Database) is a system that offers historical information like daily flow profiles and expected congestion levels. INGRID or Integrated

Incident Detection is a module that detects unusual events in the traffic that affect traffic. It looks for sudden changes in flow and occupancy on a link or important deviations from the historical data. Incidents are indicated when there is significant decrease in flow and occupancy at the downstream detector.

Other systems, like **SCATS**, have detectors placed immediately before the stop line at an intersection. Thus, it cannot get accurate data when the queue grows beyond the length of the detector, or the link is over saturated. Since it uses a model based especially on occupancy, it also has difficulties in differentiating between high flows or intersection stoppage. Reported research shows poor performance when incidents occur. [25]

RHODES suggests a hierarchical architecture of the control system. At the highest level it predicts traffic flows at the vehicle and platoon resolution level. Then, it allocates green based on various demand patterns and finally runs intersection optimizations algorithms. The detectors are usually placed 200-300 feet upstream the intersection, which may also represent a limitation for longer queues.

The problem of intersections management as a cooperation problem in a distributed network has been intensively studied. Dresner and Stone propose a reservation-based multiagent control policy for a simplified traffic model, which allows car to schedule their intersection access [26]. However, their system assumes margins of error more appropriate for automated driving the human drivers. Coordinating traffic signals, which are agents in a distributed environment, has also been implemented using evolutionary game theory techniques [28] or other self organizing methods [27].

4.3. System Design

The adaptive traffic light system we have designed relies especially on wireless communication with the approaching vehicles. The controller listens to all the information the cars are exchanging via the TrafficView dissemination protocol (section 2.3), and forms an opinion on how crowded the intersection approaches are. In a city environment, traffic lights in adjacent intersections may communicate through a wired network, in order to provide each other with additional information. The upstream signal, forwards to the downstream signal TrafficView packets of the cars that enter the link between the two. Thus, the downstream intersection can decide its timing based on information known in advance. This model is depicted in Figure 11. For every vehicle record received, the controller checks it against its local database. If the vehicle wants to pass through the controlled intersection, and there is no newer record about this vehicle in the database, the record will be stored and taken when calculating link parameters (demand, queue length etc.).

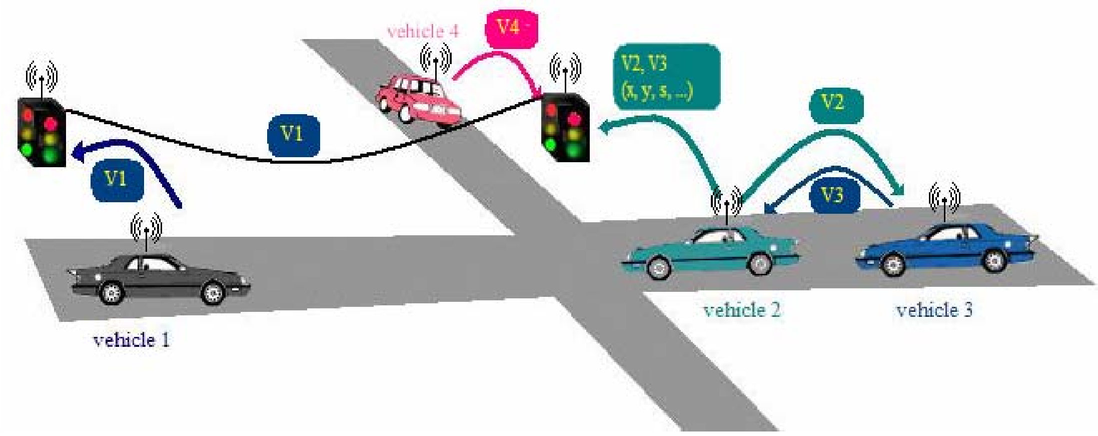

Figure 11. Adaptive Traffic Lights Control System based on wireless communication.

Our traffic signal control model uses several metrics to measure its efficiency, such as average delay, queue length or number of stops. The existing models estimate these metrics using complex mathematical models based on driver behavior assumptions and statistical facts. The Highway Capacity Manual [30] is a complete guide that explains these well accepted models and gives directions on applying them in software tools that analyze traffic and in real traffic control devices. However, the real situations are very complex and traffic conditions depend on a large number of variables so estimation models can sometimes have significant errors.

Our control method benefits from the wireless communication system with vehicles and can measure accurately traffic metrics. Next we describe the most important metrics we use and how are they computed by the system:

- **Control delay** – is calculated for each car that passes through an intersection. As mentioned in section 4.1 it is the difference between the travel time that would have occurred in the absence of the intersection control, and the travel time reported by a vehicle, in the presence of the intersection control. At the simulator level the delay is calculated from the moment the simulator determines a car to be influenced by the traffic light either directly or indirectly through other cars that are slowing down. At the controller application level, as it would be the case of a real device, this delay is calculated from the moment the car and the controller agree that the car has been influenced by the signal. The average delay over an analysis period is the main measurement of effectiveness.
- **Queue length** – is computed by the traffic controller, who knows the traffic configuration at every moment. To find the end of the queue, it has to check the database, and advance form car to car starting from the traffic light, until a gap larger than threshold or a vehicle speed higher than a threshold is encountered. The queue length value is saved at every 10 seconds and offered in the 95th percentile form for a period of analysis (the value greater than 95 % of the set).
- **The number of stops** – is calculated for each car that passes through the intersection; the traffic light knows the vehicle's queuing time and pass through time so it can compute the number of stops based on the timing history.

The way the controller takes its timing decision is based on the volume per capacity ratio, as described in section 4.1. It is important when calculating the saturation degree of a link to differentiate between the volume and the demand of the link. The volume is the traffic flow measured at the point where the cars enter the intersection. On the other hand, the demand is the traffic flow measured at a point upstream of any queue that forms at the intersection, and reflects the number of cars that desire to pass through the intersection. For example, SCOOT, the system described in section 4.2.2, measures demand by placing the detectors at the upstream end of the link and estimates the volume. In contrast, SCATS has the detectors placed at the stop line, before entering an intersection, and calculates the volume and the queue while it estimates the approach demand.

Our system maintains contact with the vehicles throughout the entire period they are in a few miles range around the intersection, so it is able to measure accurately both volume and demand. Due to the fact that, on a road, there may be gaps of connectivity between vehicles, the system may rely when measuring the demand on information sent by the adjacent traffic signal over a wired network.

The timing plan generation process takes place once, during each cycle and establishes a plan for the following cycle based on the measured parameters. During a cycle, further optimizations may occur, such as phase skipping, phase extension or interruption. The timing generation procedure has two stages:

a. Phase sequence selection

In the first stage, a sequence of phases is selected, which suites the traffic demand best. For this purpose the dual-ring concurrent phasing concept, illustrated Figure 12 is used.

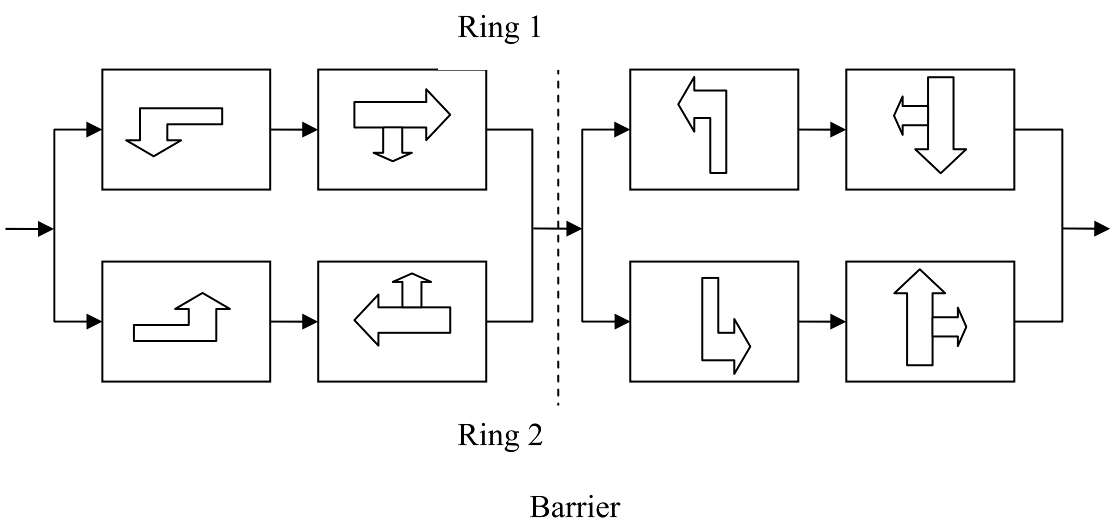

Figure 12. The dual-ring concurrent phasing scheme

Figure 12 shows the eight possible phases at a four-way intersection, one for each left or right-through movement. The barrier separates the left-right movements from the north-south ones. The dual-ring concurrent phasing concept states that each phase in the top ring may run concurrently with any phase in the bottom ring as long as they are on the same side of the barrier.

In normal conditions the controller starts with the classic two-phase signal plan for a four-way intersection. If a few traffic conditions are met the traffic controller may switch to a phase sequence with protected left movements. These conditions are in conformity with the recommendations of the Highway Capacity Manual 2000 that identifies two situations when protected left movements should be used:

- the left turn has a demand over 240 vehicles/h over 1 hour or
- the cross product of left turn demand and opposing through demand for 1 hour exceeds 50,000 for one opposing lane, 90,000 for two opposing through lanes, or 110,000 for three or more

More than that, it can be assumed that the in-vehicle TrafficView application may transmit to the signal controller information on turning intentions when a driver signals. This allows our system to estimate the number of left turning vehicles in the queue. According to this number considered for two opposing movements the controller may decide to extend the green phase of an approach, to create a separate phase for protected left movements or select other combination of phases with protected left turn.

b. Signal plan generation

The first step of this stage is to calculate the cycle length using Webster's formula presented in section 4.1. For this, the system calculates the critical flow per capacity ratio (v/c ratio) for each group of concurrent movements. The v/c ratio for a link is considered as the link demand per link saturation flow. The critical ratio is the maximum v/c ratio of the concurrent movements. The demand volume of each approach is calculated once per cycle just before computing the cycle length and it is considered for an analysis period. For the same period it is also calculated the service volume, which is the number of vehicles that have entered the intersection. If the demand is greater than the volume, a correction is applied, by adding the difference to the demand. This correction represents the number of cars that did not manage to pass in the analyzed period so they have to be counted for the demand for the next period

Having a cycle length, the green splits for each phase are allocated to produce equal degrees of saturation on each link. The formula that is used here is:

$$G_i = (C - L) \cdot \frac{\frac{v_i}{s_i}}{\sum \frac{v_j}{s_j}},$$

where G_i is the green time for phase i, C is the cycle length, L the total lost time during a cycle (yellow and all red times), and v_i/s_i the critical volume per capacity ratio for the movements in phase i.

This preliminary signal plan is adjusted to meet various limitations such as a maximum cycle length or pedestrian minimum green time. The green time for pedestrians is usually calculated considering the average pedestrian speed of 4 ft/s, the road width and a minimum WALK light time before the last pedestrian starts crossing the road.

After the minimum green time for an approach has passed, which allowed pedestrians to cross the conflicting approach(es), the phase may be interrupted if no incoming vehicles are detected. On the other side, if the green phase for an approach has finished, but cars keep coming while there is no demand on the conflicting approach(es) the green phase may be extended until an acceptable pedestrians waiting time. Another special event that may occur at the end of a green phase is when the controller detects left turning vehicles with unusual waiting times, comparing to the through movement. This may be because of high volumes on the opposing movement, that cause the formation of a queue on the left lane, that may influence and cause delays on the right-through movements as well. In this situation the green phase for the approach with the left lane queue will be extended to allow protected left turns and discharge the queue.

Finally, after the new signal timing plan has been developed, the traffic light may broadcast feedback messages for the incoming cars. These messages give information on when the phase will switch and how large the queue is on each lane of every approach. Feedback messages have several purposes:

1. They regulate the incoming traffic on an approach because in-vehicle software can recommend appropriate speeds based on when the current phase will end, and how many cars are already queued. This has an obvious beneficial impact on safety as drivers know precisely if they can pass or not on the current phase.
2. Delay in intersection is reduced because the drivers know in advance when the phase changes and they can act accordingly (either avoid decelerating too much on red or react faster on green).
3. Fuel consumption and pollutant emissions are reduced. In the situations when the vehicles aren't forced to stop because the drivers know they will catch a green light, less acceleration occurs. It is known that the acceleration and speed of a vehicle greatly influence the fuel consumed (Figure 7)

4.4. Simulation results

In this section we present the test cases and the results we have obtained when using our system. For testing, we have used the simulator described in section 3 and ran hundreds of hours of simulation for each scenario. The results show that the wireless adaptive solution managed to perform better in all the cases, when comparing to the existing solutions.

4.4.1. Test Case 1: Four-way Intersection in Bucharest

The first test scenario we evaluate is the intersection Iuliu Maniu / Vasile Milea in Bucharest. We will study the operations at this intersection without considering the effect of adjacent intersections. We will focus on comparing two types of signal control strategies: pre-timed fixed signal control as it currently is and an adaptive strategy based on communication between the controller and approaching vehicles. We assume a majority of vehicles equipped with wireless communication devices.

Figure 13. Aerial photograph of Iuliu Maniu/Vasile Milea intersection in Bucharest

The intersection is located in the south-western part of the city, having residential areas in the south-west and an important entry into the city (and exit as well) to the west.

The pre-timed strategy uses a three-phase timing plan: one phase for the west approach, one for the east approach and one for the north-south movements. All phases are equal, lasting 40 seconds (green + yellow time) with an all-red time of 2 seconds. The reason why the west and the east approaches do not function in the same phase is that they both have large number of vehicles that turn left.

Usually, in the morning rush hour long queues form on the west and south approaches, as people go from the residential areas towards downtown, while in the after-noon rush hour the other two have increased flows. An important part of the east-west flows are due to vehicles that are entering or exiting the city.

We have chosen to test this intersection under stressed conditions in the after-noon peak hour period. The input flow on each approach is shown in Figure 14.

The flow values are approximations real traffic, which we have measured in the studied intersection. Usually, on the northbound and eastbound approaches large queues can be seen at this hour.

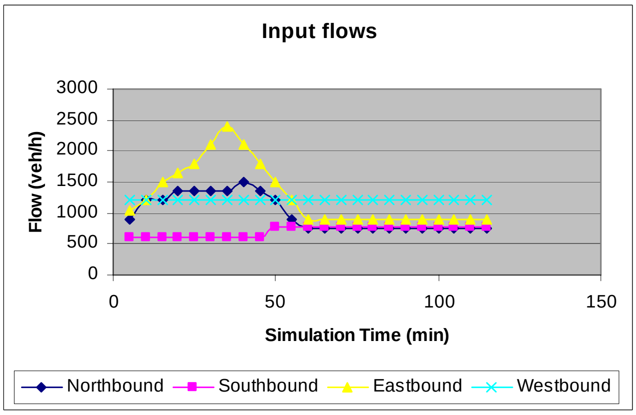

Figure 14. The input flows for the simulated scenario

We have run the simulation for both control methods: pre-timed and adaptive based on wireless communications. We have studied the behavior of the traffic for a period of time long enough to catch all the influences of the peak period (150 min).

The main MOE evaluated was the average control delay as defined in section 4.1. The adaptive method clearly out-performs the pre-timed one, as the intersection recovers faster from the congestion (Figure 15). This is due to the fact it tries to obtain equal saturation degrees in each approach, by reducing the green phase for the less demanded approaches.

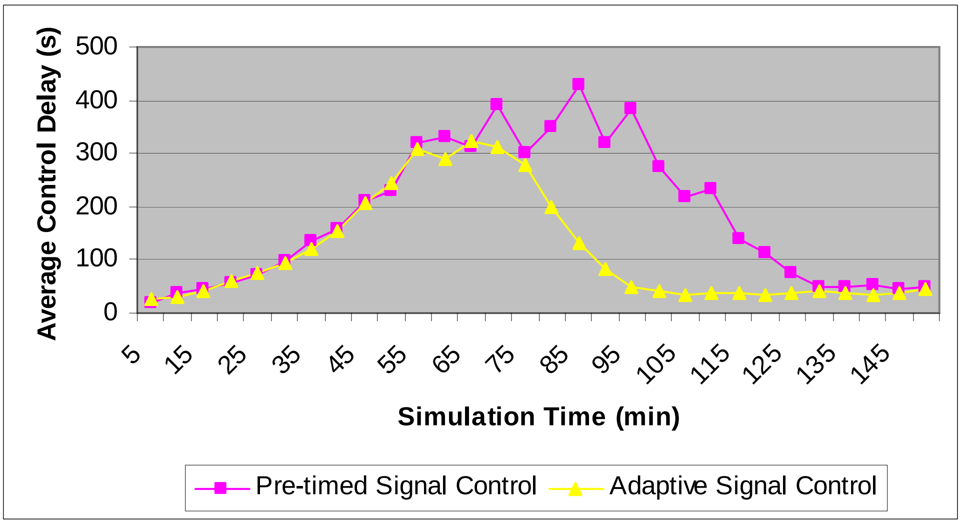

Figure 15. Average control delay for the after-noon peak period in pre-timed control and adaptive control

In fact, the differences between how queues form for the two cases can be seen in the following graphs. Figure 16 a) shows that queues lengths that form under pre-timed control vary significantly among the approaches. Thus, when the shorter queues are completely discharged there will still be a large number of vehicles queued on the more demanded approaches. From this moment on, some approaches will function on less then full capacity, while other will be over-saturated.

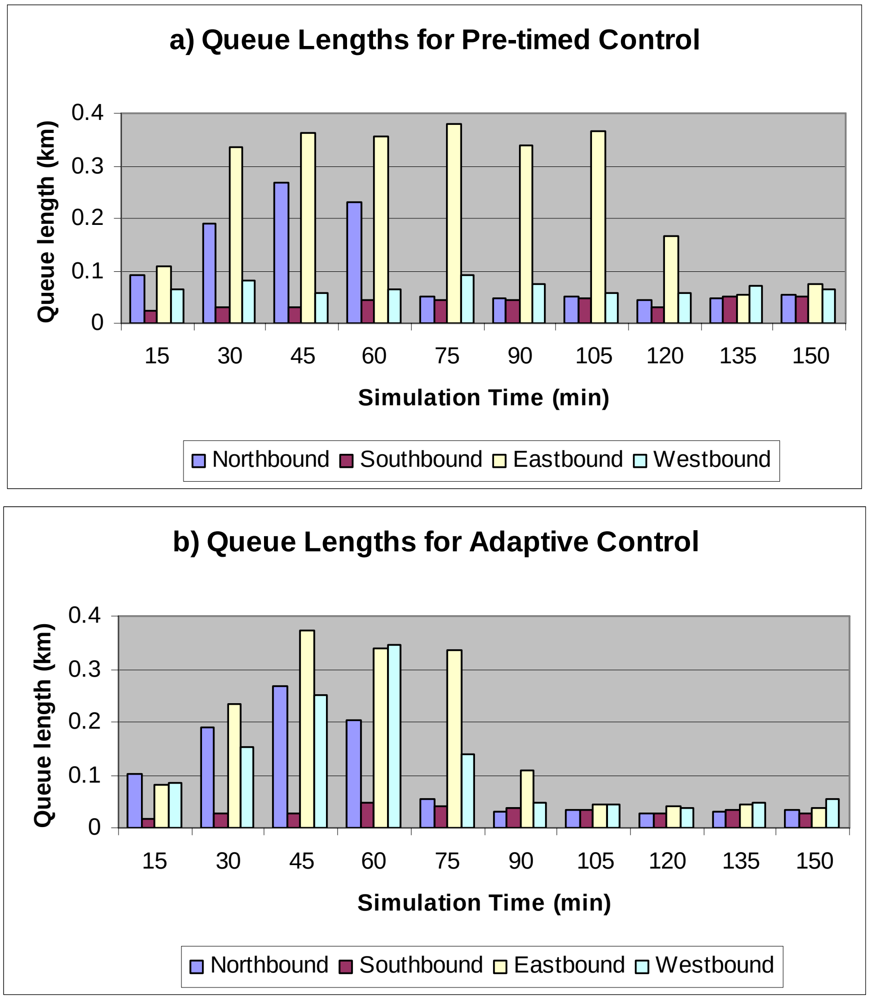

Figure 16. Queue lengths for a) Pre-timed Control and b) Adaptive Control

Figure 16 b) presents the queue formation under adaptive control mode. It can be seen how the differences among the queues on the approaches with critical flows tend to equalize. In theory, the queues on the critical paths should be equal, however, in practice several limitations appear when generating the signal plan. These limitations refer to the minimum green time, that permits pedestrians to cross, and a maximum cycle length.

The effect of queues equalization is better reflected in the next graph Figure 17), that shows the maximum control delay during the two and a half hour of the simulated scenario.

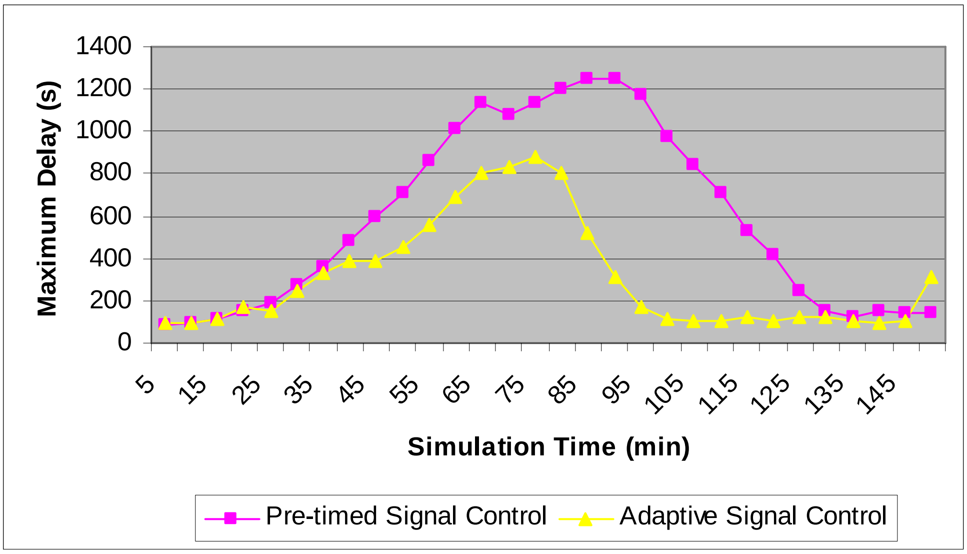

Figure 17. Maximum control delay during the simulated period.

As mention in the previous sections, the wireless adaptive controller works by measuring the demand flow and service volume on each approach, according to which it establishes the signal plan. Figure 18 presents the demand flows as they were measured by the controller and Figure 19 shows how the signals were set during the simulated period.

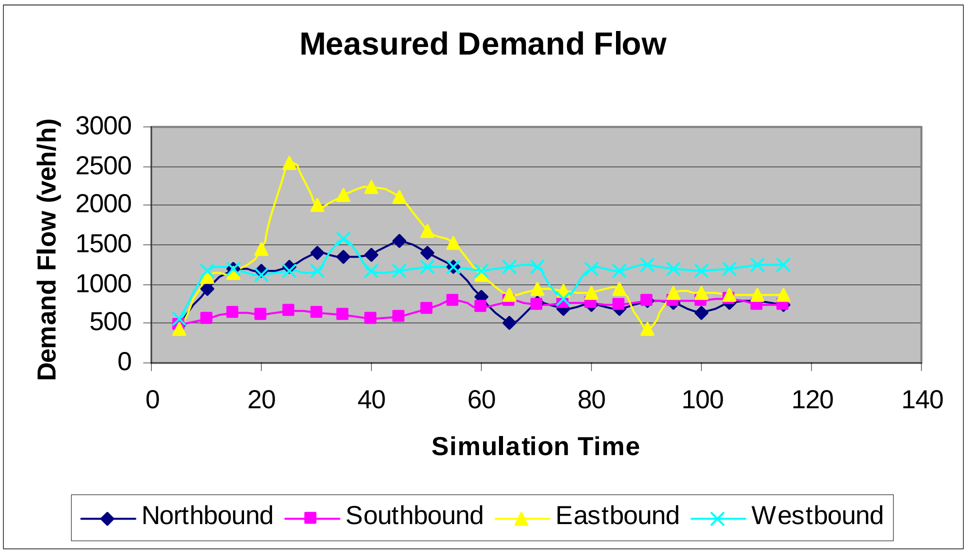

Figure 18. The demand flows on each approach during the simulation measured according to messages received from vehicles.

Although the demand flows are not exactly the same as the input flows (Figure 14), because of the random speeds and driver behavior, small errors may also occur due to loss of connectivity that prevents vehicles to announcing their approach to the intersection.

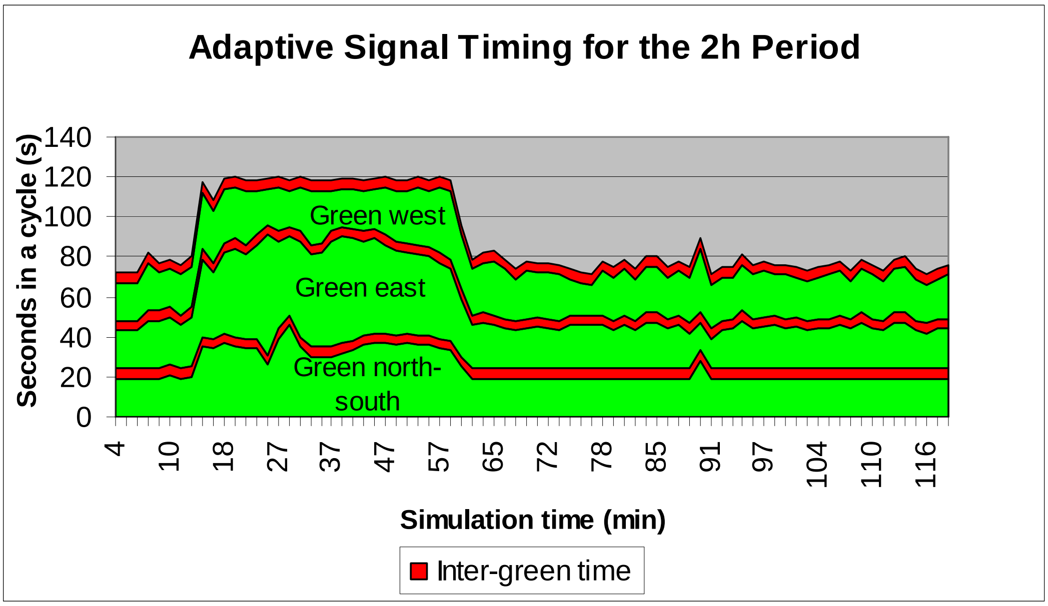

Figure 19. The adaptive allocation of green phases during the simulated period

Finally, the benefits of the adaptive control method over the pre-timed are summarized in the following tables.

c	Total Intersection Delay [vehicle hours]	Maximum Intersection Delay [min]
Pre-timed Control	523	20.8
Adaptive Control	344	14.6
Adaptive Benefits	34 %	29 %

Table 1. Delay comparisons

	Fuel Consumed [L]	CO_2 [Kg]	CO [Kg]	HC [Kg]	NO_X
Pre-timed Control	1683	4209.34	334	6.9	11.12
Adaptive Control	1597	3994.343	328	6.4	10.9
Adaptive Benefits	5.1 %	5.1 %	1.8 %	7 %	1.8 %

Table 2. Fuel consumed and pollutant emissions comparisons

It must be taken into consideration that this analysis was done in a worst-case scenario of a congested intersection. It is assumed that the pre-timed signal plan was developed by the authorities especially for this scenario. Therefore, the benefits of the adaptive method are expected to be even more important for less congested scenarios.

4.4.2. Test Case 2: T-intersection in Bucharest with left turn demand

The next intersection we have studied is a T-intersection, in the east part of Bucharest (Figure 20). The residential areas are to the south, and usually in the morning peak hour traffic, endless queues form as people drive towards north and east to get to work. The opposing traffic coming from the north is also considerable, and a left lane is available for the percent of vehicles that turn left here. The current signal plan works in short green phases of 30 s for the north-south movement, 15 s of the protected left turn on the southbound approach, and 20 s of green for the eastbound approach

Figure 20. Aerial photograph of the studied T-intersection in Bucharest

We try to demonstrate the efficiency of pro-active detection of the need for protected left movement. As the number of left turning vehicles varies from cycle to cycle, our system allocates enough green time for the protected left on the northbound approach, which ensures acceptable delays for both the southbound and the northbound approaches. If the queue on the left lane grows too large it may influence the through movement on the northbound, while too much green for protected left would increase delays on the southbound approach.

The scenario we have simulated is a three hour period of morning traffic with input flows on the three approaches as shown in Figure 21. The percent of left turning vehicles on the northbound approach randomly varies around 15 %.

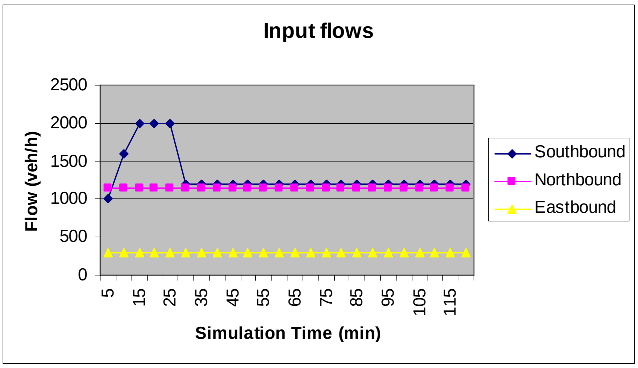

Figure 21. The input flows for the three approaches, along the two hour simulated period

Simulations have shown once again positive results when comparing the average delay. Figure 22 shows the average delay along the simulation time, computed on 5 minutes intervals. Under the adaptive control method, the intersection recovers sooner form congestion.

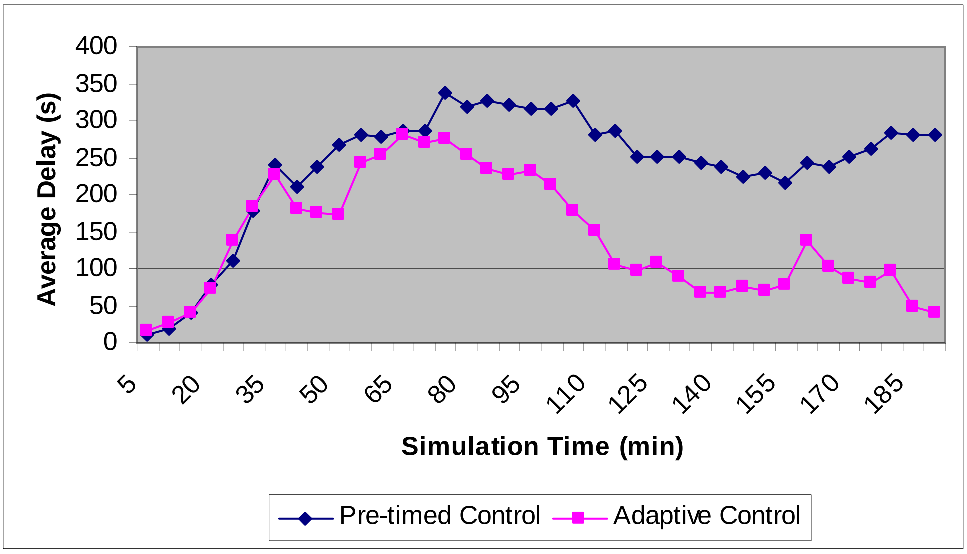

Figure 22. Average delay under pre-timed and adaptive control

The improper green allocation under the pre-timed control but also the effect of the left queue spillback on the north approach can be observed by analyzing the maximum delay graph and the queue lengths graphs for the two situations (Figure 23 and 24).

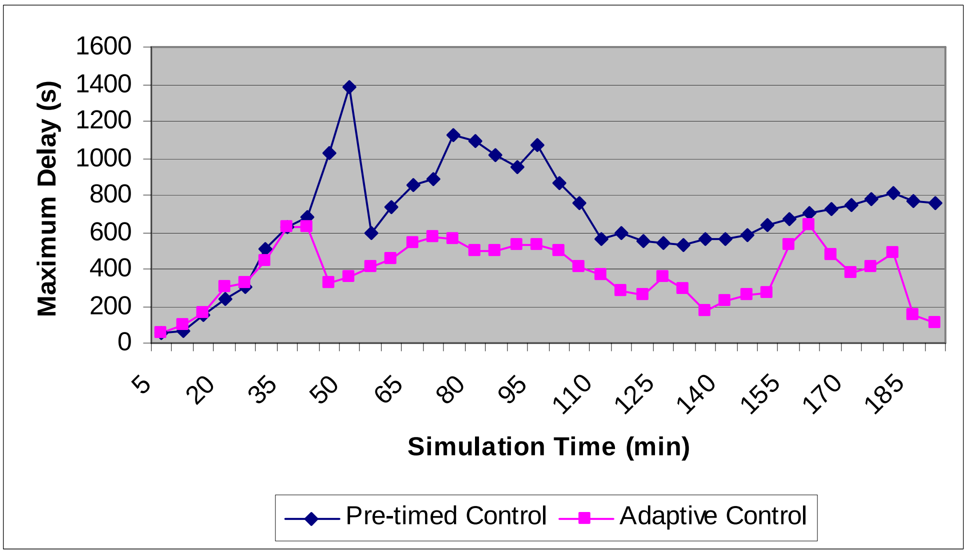

Figure 23. Maximum control delay during the simulated period

Unlike the smooth curve from the previous test-case, here the irregularities of the curve are caused by the existence of the left movement on the northbound approach. Discharging the left lane queue implies a separate phase of varying length under adaptive control, which prevents abnormal delays on this lane but deviates from the ideal timing plan established in previous cycle.

Figure 24 emphasizes the way the adaptive method works when compared to the pre-timed one. In the first case, the signal plan tends to equalize queues on all approaches while the latter produces highly disproportionate queues which result longer congestion times.

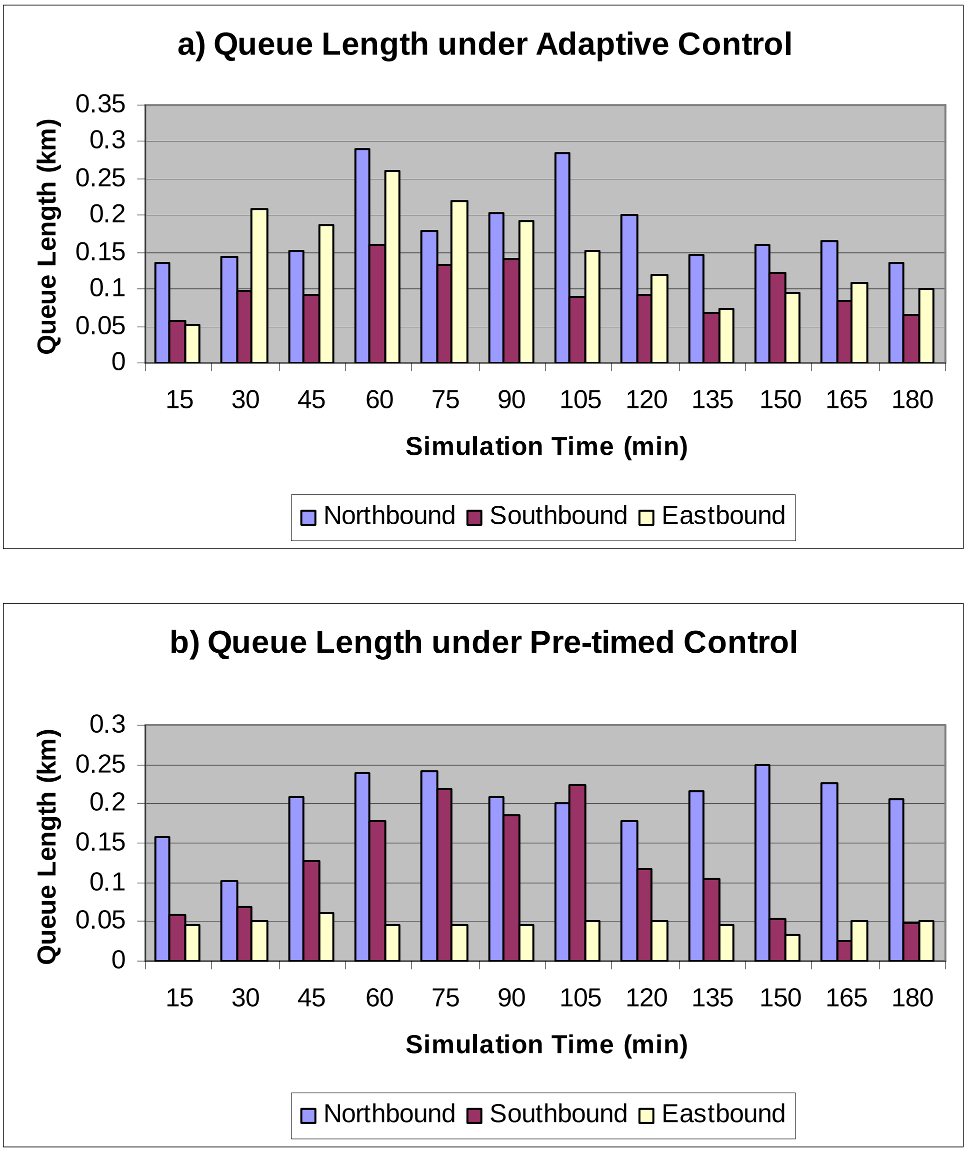

Figure 24. Queue lengths under a) Adaptive Control and b) Pre-timed Control

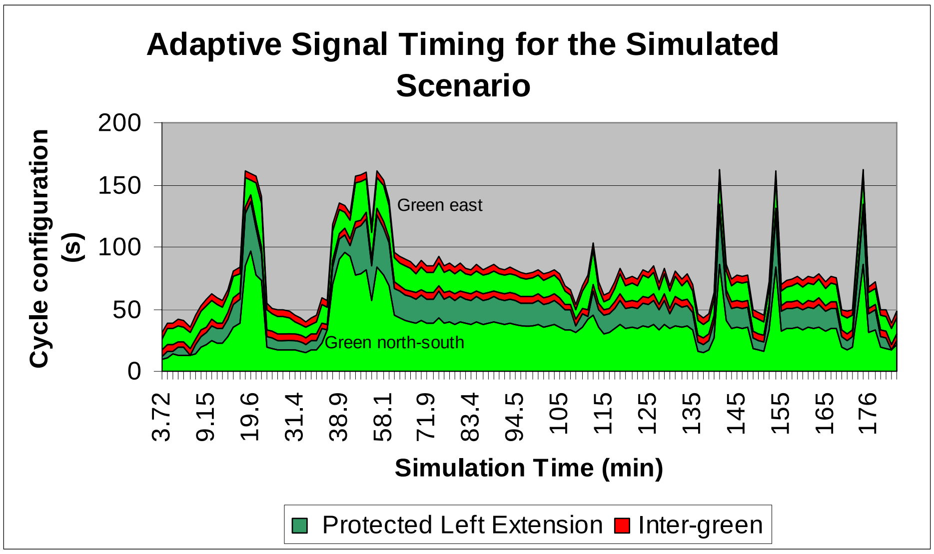

Figure 25. The timing plans chosen during the simulated scenario. The dark-green band represents the extension of the green light for protected left turn, and varies depending on the left demand at each moment.

The use of our system proved significant improvements in delays and fuel consumption and gas emissions (Tables 3 and 4). Like in the previous example, the simulated situation was an extreme one. For light traffic hours the improvements are even greater.

	Total Intersection Delay [vehicle hours]	Maximum Intersection Delay [min]	Total number of vehicles
Pre-timed Control	625	23	8079
Adaptive Control	403	10.6	8526
Adaptive Benefits*	38 %	53 %	5.5 %

Table 3. Delay and throughput comparisons for the 190 minutes of simulation
*The benefits were calculated on average per car.

	Fuel Consumed [L]	CO_2 [Kg]	CO [Kg]	HC [Kg]	NO_X [Kg]
Pre-timed Control	1456	3641	290	6.1	9.4
Adaptive Control	1396	3491	300	5.6	9.8
Adaptive Benefits*	9 %	9 %	1.9 %	13 %	2 %

Table 4. Fuel consumed and pollutant emissions comparisons for the 190 minutes of simulation.
*The benefits were calculated on average per car.

4.5. Strategies for improving traffic safety

Current studies show that accidents in intersections are the second most numerous accidents. In [31] it is reported that in 1998, 1.7 millions of accidents happened in intersections causing around 6 700 fatalities. Parts of the accidents in the other categories are also related to intersections. In [32] it is estimated that about 45% of the accidents are intersection related.

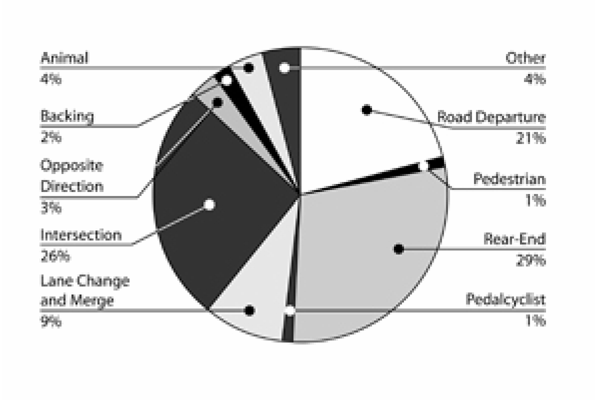

Figure 26. Crash-Type Distribution. Source: IVI Report (2005, U.S. D.O.T.) [32]

For uncontrolled intersections or intersections with no communication infrastructure, TrafficView can provide drivers with information about approaching vehicles, such as speed, position. This could eliminate an important part of the accidents as it is stated in [33] that almost all the accidents in intersection could be prevented if the driver would be warned half a second earlier.

Our signal control system adds more security measures to prevent increase security.

First, accidents implying the left turn maneuver can be reduced if the proper phase sequence is selected. Protected left turn at a signalized intersection is the situation left turning vehicles have a separate green phase and they do not have to yield to the vehicles coming from the other direction. Our controller detects when the left turning maneuver is too dangerous by analyzing by analyzing the demand for left turn and the opposing traffic volume. Depending on this analysis it may decide to have a separate phase for protected left turn or to extend the green phase of an approach while holding red on the opposing approach.

As described in section 4.2, the traffic light broadcasts feedback messages to the vehicles, publishing their current timing plan, time until phase change and current queues. The simple interpretation of these messages by in-vehicle applications may determine drivers to adapt their speed faster. This is expected to reduce the number of rear-end collisions in queues near intersections.

Another safety measure can be taken for red or late yellow crossings that cause violent crashes in intersections. When the wireless controller detects such situations it extends the all-red phase until the intersection is cleared.

4.6. Comparison with Existing Adaptive Solutions

Conceptually speaking, the adaptive control based on wireless communication is different in its design from the one that is based on sensors. Its strength is that communicating with the vehicles implies more information to the decision process. It may benefit from knowing the position, the speed and the driver's intention, as opposed to loop detectors, for example that detect only flow and occupancy. Its strength is also its weakness, as it requires vehicles to have GPS and wireless communication devices and run software that publishes private data. Existing adaptive solutions function independently of the cars by using sensors and cameras. However, the two technologies do not exclude each other as they may work together. It is important to identify the benefits each solution brings.

A first perspective to look at the functionality differences is the method of detecting traffic demand.

The solutions that rely on loop detectors have to set the detectors at a fixed location upstream the intersection. This raises questions about where is the best place for installing them. If the detector is placed too close to the intersection and the queue grows beyond this point the demand volume cannot be estimated and it is limited to the service volume (vehicles that pass on each green phase). If the detector is placed too far on a link and there are vehicles that exit or enter the link along this distance, the flow measured is inaccurate.

However, our system monitors the vehicles throughout the entire period they are in the area of the intersection. The only limitation is when a queue grows that much that the dissemination model fails to propagate information from the back of the queue to the front. This is because the maximum packet size limitation described in section 3. This limitation can be eliminated by installing additional antennas along the road.

An important advantage our system has over existing solutions is that drivers can send their movement intentions in advance. This makes the control method more responsive. For example, the pro-active detection of left turning demand is an effective measure of reducing total delay and increasing security. Current solutions can accomplish this only through video image analysis which has several limitations. Cameras have to be pointed towards each approach, they are costly and require increased computational power, and they can detect only the cases when there is a larger queue on the left lane which is reactive.

The fact that the traffic signal controller knows the position and speed of every vehicle for the whole period it is driving in, demand and occupancy are easier to calculate as compared to vehicles being detected at a fixed point on the approach. Current models measure flows at fixed locations on roads and estimate occupancy based on complex mathematical model for platoon formation and dispersion, average speeds. However these models may often provide erroneous data, because the numerous random factors that affect traffic.

One important aspect that needs to be taken into consideration is that a solution based on wireless communication needs an adequate wireless protocol. DSRC (dedicated short-range communications) is a variant of IEEE 802.11 that is expected to boost vehicular applications with wireless communication.

5. Conclusions and Future Work

This project has three main contributions. First, it describes the dissemination model that was implemented in TrafficView, a platform for Vehicle Ad-Hoc Networks. A model that propagates information in a probabilistic manner is evaluated in comparison with a model in which each car forwards complete records. The study shows that, while there is a slight decrease in the average database size on each vehicle, the average packet size is drastically reduced saving bandwidth and medium access delays.

Second, an integrated simulation platform was developed for the analysis of VANETs. The simulator is discrete event oriented and has support for the complex vehicle mobility patterns, node communication and application emulation. Its functionality was proven in the simulation of real traffic scenarios with thousands of vehicle-nodes. A module for the estimation of fuel consumption and gas emissions was also implemented and validated.

Finally, a system for adaptive signal control in intersections based on wireless communications was developed and evaluated. The control method relies on data collected from vehicles and adjacent traffic lights. The system was fully implemented in simulation and managed to out-perform the pre-timed solutions for the scenarios we have tested.

In the first test-case, a congested intersection at the peak traffic period, our system improved delays with over 30 % and fuel consumption and gas emission with 2-7 %. The second scenario emphasized the adaptive behavior in the case when left turning maneuvers influence intersection performance. Our system used its pro-active control method that takes into account the moving intentions the drivers transmit. This is a unique feature of such a system that can be better accomplished through communication, rather than image processing or sensors.

When considering traffic safety, we have described a set of measures for accident prevention in intersections that would reduce the increasing number of fatalities.

The limitations of our system mainly refer to the wireless communication protocol in terms of performance in congested traffic environments. However, the adoption and use of DSRC will be a step forward for inter-vehicle and vehicle-to-infrastructure communication.

As part of the future work, we plan to analyze the problem of coordination of traffic flows through adjacent intersections in city environments and how to solve this issue as in a cooperative manner involving both traffic lights and vehicles.

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