Adaptive Traffic Control
Using Bio-Inspired Optimization

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Rezumat,

Aceasta teza abordeaza problema optimizarii traficului rutier definit de retele urbane ptin implementarea de Intelligent Transportation Systems, astfel încât, pe de o parte, capacitatea infrastructurii existente să fie utilizată în totalitate și, pe de altă parte, să existe o reacție promptă și adecvată a infrastructurii la schimbările neprevăzute a condițiilor de trafic.

Această teză propune o abordare neconvențională asupra optimizărilor traficului rutier, bazată pe analiza unor parametri proprii rețelelor complexe, ținând cont de aspectele sociale definitorii pentru traficul rutier real (spre deosebire de cel din rețelele de comunicații), îmbinată pe căutarea genetică a unor scenarii optime de coordonare a intersecțiilor.

În acest sens se folosesc metode împrumutate din Analiza Rețelor Complexe pentru analiza rețelei urbane de trafic din mai multe puncte de vedere, pentru a identifica elementele specifice care influențează calitatea traficului rutier. Sunt propuse o serie de metode inovative care aduc elemente originale și un plus de valoare acestui domeniu prin îmbinarea aspectelor specifice Ingineriei Calculatoarelor. Infrastructura actuala este transformată astfel întruna inteligenta prin folosirea unor semafoare capabile să se adapteze și să comunice între ele pentru a raspunde condițiilor de trafic mereu în schimbare.

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1. TRANSPORTATION SYSTEM AND THE INFRASTRUCTURE

Present times indicate a request for fast and efficient transport infrastructure. One of the unsolved problems of modern days is coping with increasing and dynamic changing of traffic conditions in large cities around the world. For example, in Copenhagen, a report from 2008 shows the increase of traffic values with over 50% since the 80's. The same study reports that in 2002 people were spending over 100,000 hours in queues, corresponding to an economic loss of more than 750 million Euros, only in the urban area of Copenhagen [1]. It is a well known fact that traffic environment and time spent by drivers in their vehicles may have a significant impact on personal life, career or safety. It is also a cause of stress and frustration not only for drivers, for the most inhabitants of large cities, and it is also decreasing life quality by increasing the environmental pollution.

Transport infrastructure plays the main role in the economic system of any country. It supports both personal well-being and economic growth. Along with its development and its central economic role, transport infrastructure is recently referred to as the backbone of any modern economy. The direct relation between them is shown by the financial crisis in 2008 and 2009 which slowed down the demand for road transportation in several countries across Europe, as the International Road Transport reports [2].

The entire transport infrastructure refers also to transcontinental railways or canals linking oceans with all their implications. Of particular interest is the road infrastructure which is the most used in terms of human users and which has currently reached its limitation in terms of space, compared to the growth of users. International Energy Agency shares their predictions of the land infrastructure requirements capacity for the next decades. It is expected that the world will need to add almost 25 million paved roads kilometers and 335 000 rail tracks kilometers to support the expected increase of travelers. This is an increase of almost 60% increase over the values reported in 2010. Combining the infrastructure investment, roads, railways, parking lots is expected to sum up between 250 000 km^2 and 350 000 km^2, which is roughly the size of United Kingdom and Germany in land area [3].

However, the interest remains in the number of personal vehicles, which is the most used transport mode and will continue to be so for the next decades, see Figure 1. This increases the interest in managing their high number moving inside cities, which already have reached their limit of expansion. It will be hardly possible for the infrastructure to expand any further in large cities due to residential areas that have developed adjacent to the existing roads. So, another way to improve network performance is to use more efficient the current one and this can be done using intelligent solutions to control the traffic moving inside [1].

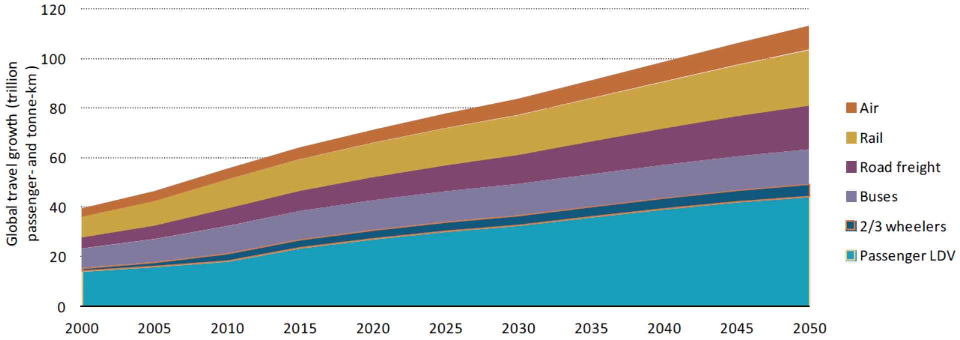


Figure 1. Expected global travel growth in the next 4 decades **[3]**

Transportation systems evolution is moving at high speeds, with autonomous vehicles and experimental virtual drivers already being deployed on the roads. The entire infrastructure has gone from a passive one to an active and smart one. Vehicles already "talk" to the "road", exchange information and influence each other before taking any decision for the next step. Traffic-light-to-vehicle-communication (TLVC) is an application that uses wireless technology to broadcast information to the vehicles in range, making them adapt their speed to avoid stopping at traffic lights. The goal of TLVS is to reduce fuel consumption, decreasing this way the emissions and the air pollution [4]. In this context, an infrastructure that adapts itself to traffic conditions, reacting promptly to changes and taking the decisions necessary to keep the traffic flow moving and all without any human intervention is the step to follow in this evolution process.

The current state-of-the-art shows a continuous interest in this subject and also points out the lack of a generic solution[5],[6]. By combining different areas of expertise, from road constructing technologies, transport planning knowledge, to hardware and software systems, this problem merges concepts to the same goal, to optimize traffic movements in order to obtain a continuous flow.

In the recent years, there is an interest in the research of *time use data.* This is an interdisciplinary research that studies the empirical data gathered on people's time use to determine people's activity choices. In transport domain this is useful in determining and modeling traffic behavior. Using this data, traffic demand can also be estimated as the result of personal factors, such as socioeconomic characteristics (age, gender, education or employment) or supply side. But, possible one of the most valuable information provided for transport engineers is the travel time value which is used for traffic conditions assessment [7]. For example, the survey in [7] shows the number of trips and their purpose over the day, see Figure 2. The distribution of trips and their purposes follows the distribution of general activity patterns, with higher values for work and education trips in the morning peak hours and significant increase in the evening for the social life and entertainment. This states the influence of social life over traffic in any urban network and the presence of personal factor, known as *free will*. The unpredictable character of traffic is determined mainly because of this unique characteristic of human beings to change their mind any time with respect to the aspects of society.

In the same time, the increased number of trips is strictly related to the dominant transport means which is the car, see Figure 3. Even though personal car totals 58% from the overall most used means of transportation, the load on the transport infrastructure must take into consideration also the other means of road transportation, such as taxis, vans, buses, motorbikes, reaching to the an almost 70%. These values reveal that the road infrastructure supports most of the traffic in a city, no matter the purpose of the trip. Of particular interest is the relationship between the overall travel time and the general activities patterns. The same study indicated that people tend to reduce their sleeping time and take less time for meals when they spend more time in travelling. This conclusion points out the importance of the time spent in traffic, how it is involuntary altering our quality of life and day by day activities. Another important aspect that influences the way each of us travels during the day is the society with all its implications, from personal travels to sports activities, from family related travels to social events that each has to attend. In Figure 2, maybe except working activity which is not necessary related to a social need, all other activities present a strong social influence, from education trips to other purpose travels. All they have in common is the presence of social aspect feeding the purpose of interacting with people.

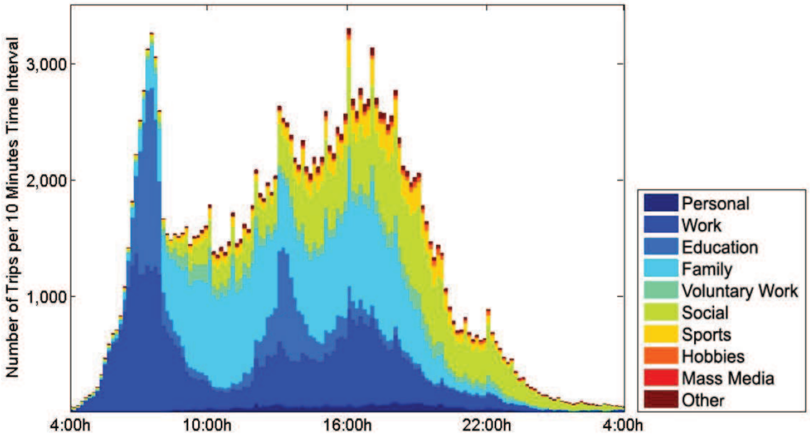


Figure 2. Number of trips and trip purpose over the day **[7]**

Now that society and personal relations prove to have a major impact in traffic conditions, a high level analysis is required to determine the relationship between transport infrastructure and economic development. In this way, the decision-making on individual projects is based on its costs and benefits, so that the best projects are carried out and the non-viable ones are eliminated. A more detailed analysis is necessary to evaluate the specific impacts of individual transport infrastructure projects in terms of efficient resource allocation and improvements brought by each project[8]. Dedicated methods and software tools necessary to evaluate the infrastructure investments were developed in time, but only some of them had success, while others are still searching for it. The need for new modern approaches to evaluate the already deployments of intelligent traffic monitoring systems and the continuous request for cost effective solutions, drives the research in this thesis, to search and propose efficient methods to optimize costs with system development and installation.

The correlation between data in Figure 2 and Figure 3 shows the real scale of social implications and impact over traffic. The fact that we live in a society where we need to interact with other people every day, to fulfill our activities and to follow our hobbies, connects us while sharing the same road infrastructure. These aspects emphasize the interest in this thesis in approaching traffic optimization using aspects specific to social network analysis applied on real transportation networks. Because specific social aspects cannot be separated from the road infrastructure, we have to make sure that these are taken into consideration when performing large urban planning or when deploying a new intelligent control system.

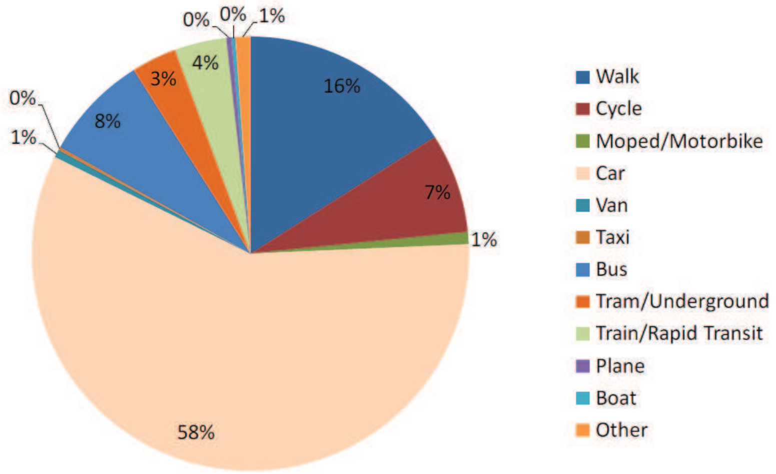


Figure 3. Overall transport mode used **[7]**

1.2 The Evolution of Road Transport Infrastructure

Terrestrial transportation is by far one of the oldest ways of moving and connecting people and their interests. History points that cities were built along the main roads because of the quick access to resources and for the better connection with other parts of the same continent. The evolution of entire countries was also influenced: the more complex the infrastructure, the easier it was to develop the industry, assuring efficient means to move resources. Today, modern societies require fast and efficient transportation infrastructures for the entire population to sustain the growth of economy.

Earlier in the days, things were not evolving so fast, with road transport infrastructure consisting in a small number of roads, several intersections and less traffic. These were the existing circumstances prior the automotive industry development and expansion. Carriages were rapidly replaced by cars, which became accessible for everyone [9].

Today’s infrastructure has more key components, starting from basic entry points which developed in time to complex and intelligent assemblies. Cars, which in our days represent smart mobile computers, are not the only ones that have evolved, roads also have evolved. They are now connected to cars and influencing their decisions to improve overall safety.

1.2.1 Intersections: The Key Elements for Infrastructure

Before modern infrastructure started to develop, roads were constructed to establish the main access routes between two distant points creating in this way a communication route. Since ancient times, people needed to find routes to get to their points of interest such as homes, markets or even to find food. As the civilization progressed, so did the number of roads increased and developed along with the entire infrastructure. Quickly people realized that their roads started to intersect, either by accident or because the geography imposed it. The routes rapidly expanded along with the civilizations progress, from the first roads built 4000 years BC to the well known Roman roads built to move the Roman legions quickly through the Empire. Roads slowly became the answer to the need for communication. News spread much faster, people started moving a lot more and all of these because roads started to expand and to intersect.

Since the intersections emerged, often referred as crossroads, they had the key role of switching directions and routing people, making them active elements in managing incoming and outgoing traffic. The crossroad definition in [10] uses the following formulation to explain this term: "a point at which a vital decision has to be made", marking the importance of this concept. More and more intersections emerged as people started to optimize their routes and to reduce their journey time. But it was the late 18th and early 19th centuries when the industrialization reached road construction and expansion of road infrastructure really begun [11].

This would not be possible without the new technologies, at that time, proposed by Thomas Telford and John Loudon McAdam who opened a new era of building roads. Telford's interest to analyze road characteristics such as: road traffic, road alignment or gradient slopes was innovative for that time. But it was McAdam that provided the greatest advance in road construction, once he proposed the method to cover roads with broken stones, that lead to the well known "macadam roads" [12].

Today's modern infrastructure is built from hundreds of intersections, reaching thousands in large populated areas. But the problem lays not in the number or the density of intersections, but in the high number of vehicles passing through a specific direction. These values define traffic flow. The dictionary definition for traffic states: "1. The passage of people or vehicles along routes of transportation; 2. Vehicles or pedestrians in transit", see [13]. Traffic on roads consists in pedestrians, vehicles, streetcars used for the purpose of travel. Organized traffic usually has well known rules, priorities and traffic control at intersections. This organization leads to the increase of traffic safety and efficiency of traffic movements. But traffic values increased in the last century from several vehicles per intersections to thousands during a normal day.

To address this increase and to prevent blocking intersections, traffic officers were sent to make sure that accidents are prevented and rules are obeyed. As the number of vehicles and traffic operations increased, more and more intersections became so called "traffic hotspots" which concentrated traffic from several directions into one point. Shortly, events like traffic jams, started happening on regular bases causing portions of roads to not respond to movements. In the late 80's it became almost impossible to sustain this traffic growth only with human local control.

To analyze and define the state of an intersection in a specific moment in time, several traffic parameters are being monitored. One of the most relevant is traffic flow. It studies the movement of drivers and vehicles between two points and the interactions they make. In a more common understanding this is the number of vehicles coming and going in a street. But studying traffic flow is more difficult than it seems because only counting the number of vehicles is not enough. For a traffic engineer to be able to analyze and to change the conditions in an intersection and to propose new control schemes, he needs to simulate driver's behavior [14]. Predicting driver's behavior is still a real challenge nowadays [15] as there is no method found yet that can replicate human decision making with one hundred percent accuracy [16].

For a complete analysis, other parameters have to be analyzed. Traffic density represents the number of vehicles that occupy a specific section of road. This is usually measured by photographs taken from a high vantage point, usually aerial. Compared to the traffic flow parameter which is measured by specific road sensors installed on the road, traffic density gives a more complete overview of the current situation in an intersection. Other parameters can be mentioned further, some of them refer to physics, like the average speed, while others count the number of stops or queue lengths. The complexity of defining parameters determines the evolution of traffic road infrastructure and it also lead by the higher number of interactions.

Managing such high number of crowded intersections makes it impossible to deploy so many officers for each newly created hotspot. The need for smart control devices became real with this rapid evolution of road infrastructure. Transportation engineering proposed a new hardware to substitute the control officer in an intersection. Once his movements became repetitive, it was obvious what the intersection needed: a virtual traffic officer to simulate his job by stopping conflicting directions from moving in the same time and allowing all directions to pass in a specific order.

1.2.2 From Traffic Signs to Smart Traffic Signals

The need for special traffic regulations and new set of traffic signs is clear since the complexity of traffic operations increased. More direction changes, priority to special vehicles are only some that can be mentioned. It became clear that more and more complex signs need to be deployed and developed because vehicles are starting to intersect with other means of transportation, such as railroads and naval transport. It is not a feasible option to stop at every intersection or to hire traffic responsible to watch the traffic in each intersection once an interaction happens. Traffic control was first enforced by rules and signs only, which coupled with the steadily increasing number of vehicles. Along with this increase, the need to rationalize traffic movements quickly led to the development of modern traffic signal or the traffic light controller.

Traffic control is by definition the supervision of the movement of people, goods, or vehicles in order to ensure efficiency and safety. Traffic regulations are one method of controlling traffic; however, many inventions are used to support this control and one of the well known is the traffic light. Also known as stoplights, traffic lamps, traffic signals or semaphores, they are devices positioned at road intersections to control competing flows of traffic. They use standard colors, red, amber/yellow and green, and a precise sequence to allow understanding for the ones that are color blind.

History marks several attempts of manual and automatic traffic lights and one of the first such control device was installed near London, in 1868, by J.P Knight, and it was used by the railway engineers. Along time, many other traffic signals were created, with the same scope: to control traffic movements. Several have to be mentioned here: Earnest Sirrine, Lester Wire, William Potts or Garret Morgan, each with significant contributions to today's well known T-shaped traffic signal functionality [17].

Ever since traffic signals were introduced as additional controlling devices, their role was to bring a deterministic behavior over the road network by controlling and creating an organized, predictable traffic flow [18]. The prediction of traffic conditions has not yet been achieved as current traffic jams that happen all over the world on a daily basis prove this.

But the evolution of traffic signals did not stop. Today, smart traffic lights are being developed and deployed along with complex traffic control systems. They are built to communicate with cars and to alert drivers of immediate light changes reducing in this manner the number of accidents. Trials are currently being conducted for the implementation of these advanced traffic lights but there are still many aspects to deal with, before these technologies are widespread used. One of these aspects is the fact that few cars yet have the required systems to communicate with these intelligent traffic lights.

International forums prepare the regulations to introduce in standard production a vehicle to infrastructure (V2I) communication mechanism in order to improve road safety [17]. There are some predictions that the first V2I systems will be deployed in the time frame 2015-2020 [19]. But the fact that makes this technology to not be used on a large scale is the implementation cost. It can reach important values that cannot be supported only by the authorities without the increase of usage costs. All these additional costs are going to finally affect the drivers which will have to support major part of them.

In this context, smarter solutions and low cost implementations to control traffic movements are of interest in the last years. Fixed time solutions were first developed to answer the observed patterns in traffic changes, such as morning rush hours or bad weather conditions [20] which determine more people to use their private vehicles to increase their confort. Static plans soon proved their limitations, failing to response to sudden traffic changes. So, the concepts of fixed time and recently the dynamic control of traffic signals determined the evolution of traffic control systems towards real Intelligent Transportation Systems (ITS) [21].

According to transportation engineers, traffic lights can have both positive and negative effects on traffic safety and traffic flow which must be taken into account before deploying them. A positive consequence is the separation of conflicting streams of traffic that can reduce the chances of collisions. On the other hand, it can cause significant delays in traffic on the main roads since they stop and release traffic to allow crossing directions to pass. But this is an acceptable trade off since it reduces the number of casualties over introducing delays and increasing intersection capacity. For instance, it is estimated that the proper use of intelligent traffic lights and smart systems could improve the road capacity network in the area of Copenhagen with almost 10% [1].

1.3 Congestion: The Traffic Problem

Studies indicate an increase in traffic demand, so the question that arises is: "Can the growing traffic be managed on a network with far less growth?" The answer to this question is in the impact of the demand for more space in different parts of road network. The balance between demand and new roads availability must be kept, as demand can easily be increased even in a newly constructed road. The lack of a strategy to take into consideration traffic growth and the physical possibility for network expansion leads to an inefficient and rapid consumption of the new constructed infrastructure.

The consequence of this lack of additional free space is the so called congestion. It is defined as the situation in which traffic participants are not moving towards desired direction in a continuous manner. One of the reasons of this phenomenon is the limited capacity of the infrastructure which is exceeded. From this perspective, traffic flow is defined by the number of traffic participants passing per time unit and moving in the same directions. Obtaining a continuous traffic flow is the best quality indicator for a traffic road infrastructure and it is still the goal for traffic engineers. [22]

Congestion does not have an exact definition, as it is difficult to define when the state of congestions really begins or even when it ends. Different points of view are to be discussed. One is the economist's point of view and in his opinion congestion causes economic losses and should be avoided by increasing the capacity of the infrastructure. On the other hand, transport planners state that following this policy has not solved this problem yet. From their point of view, supplying more transport capacity would only increase the demand for transport services, instead of rationalizing it. According with the economists, the cost-benefit analysis of transport values monitors the time savings of the road users between their origins and the destinations. So, the definition of congestion could be updated to, the reduction of service quality in infrastructure due to excessive demand or to other reasons in which traffic users need to reduce their speed. [22]

Congestion can have different causes. Some are due to maintenance activities and other due to a higher traffic demand than the road's capacity itself. If, for the first reason, one can agree that the operations are necessary and cannot be avoided, since they are directly related to road safety, for the last categories solutions have to be found. Several cases are pointed as root causes for the high traffic demand. One possible cause is the high amount of vehicles moving to a specific direction that finally exceeds the road capacity. Another cause is the reduction of lanes at a certain point due to infrastructure restrictions. The consequence of congestion is the well known phenomenon of queuing. Usually queues form in the originating directions and grow rapidly. In response, authorities address these cases installing static traffic signals to set priority to crowded directions and to make sure that the intersections do not block again. These events happen by accident or systematic. For the systematic cases, a set of static plans are defined, but most of the time they fail to respond if traffic conditions change suddenly, eventually causing much more damage. Some other reasons for congestions need to be mentioned such as border control, extreme weather or social events. Their occurrence is lower and the already described approaches are used for these cases also.

What each of us is experiencing in traffic day by day are the effects of congestion. They are in direct relation to our society and they are affecting our normal life by changing our behavior. For instance, a day with more time spent in traffic due to congestion is a day in which delays replace several minutes with your family or friends. Effects of congestion are split in several categories: environmental, economic and social consequences, according to [22]. Whereas some of them have direct impact on human health, others address strictly the amount of resources, time and money, spent due to time lost in traffic. The social aspect is not to be neglected, since the reduction of travel speeds reduces the distances covered in the same amount of time, leading to less time spent socializing.

There are several approaches proposed to prevent congestion from happening. One is to use traffic signals to define plans that address different changes in traffic patterns. These are called static signal plans and use previously recorded data to define signal plans that are loaded into the system and applied according with the time of day they represent. The drawback of this approach is the continuous need to maintain these plans up-to-date to be sure that they respond to current traffic situation. But today’s working plans will not apply after several months or even days if during this time a new street, a new shopping center or a stadium is built. So it seems that these static plans are not able to respond to traffic changes.

A real need for real intelligent systems arises, a request for systems that are capable to adapt, to determine traffic changes and to quickly respond to them. Following this trend, adaptive traffic signals were developed with the intent of replacing the old implementation of static signal plans and to solve their main problem: lack of response to dynamic traffic conditions.

The so called “Shared Space” networks represent the opposite, innovative, approach, which remove traffic lights, signs, crosswalks or lane markers so that all traffic participants, from pedestrians to drivers negotiate their way by reacting to one another. Hans Monderman, the innovative Dutch traffic engineer and the pioneer of these schemes [23], was skeptical of traffic lights role, and is quoted as having said of them: "We only want traffic lights where they are useful and I haven't found anywhere where they are useful yet." To respond to the above statement, a new perspective needs to address the way congestion is managed and one way to do this is to combine different technologies in a modern approach.

1.4 A Computer Science Perspective

Technology has always been the key element in developing any known field, and it is mainly because of the latest advances in computer science and communications technologies. This has deep implications on the way in which transportation systems develop, leading to new opportunities to improve them, particularly in real time, in response to the continuous traffic growth in modern societies.

In the recent years, there has been an increased focus on improving road infrastructure and making it smarter, to the point where it is able to take automatic decisions based on the current conditions. As one shall see in the next sections, different systems are already deployed, each with considerable results in terms of increasing the traffic flow. Usually these systems have a major impact over the infrastructure. To be fully operational, each system requires additional installed hardware, from pavement installed sensors and monitoring cameras, to computers and data centers that evaluate all gathered traffic data to propose new solutions for traffic improvements.

Transportation infrastructure sustains the economic development of any urban area. Even if you speak about the food chain supply or just merchant going to the shopping centers, the road infrastructure flows like blood flows in the veins of our human body, supplying all needed sub-systems with vital resources. The blood is like traffic flow, carrying goods in different parts of a city or country. Without them the economy would suffer from a severe lack of resources and our life quality would definitely decrease.

In addition to the transportation’s impact on the economic development, there is also the environmental concern. The entire road infrastructure has changed lately to a more ecological one, with more concern for the clean air and water, global warming, energy and the efficient use of land resources. Society's concerns in these matters changed the transportation field and brought it closely to the modern technologies and to computer engineering in special. Despite temporary solutions proposed to quickly reduce pollution by restricting traffic these act only as temporary solutions, see [24] or [25], new alternatives need to be developed to cope with the increasing traffic values.

All these changes of conditions created new opportunities for engineers. Transportation domain is now closely related to computer engineering field, as the entire traffic domain is digitalizing quickly. Vehicles rapidly become smarter, they are controlled by computers, so the infrastructure needs to keep up the pace and use what modern technology is providing: sensors, cameras, embedded microchips, real-time movement detectors and the list goes on [6].

The above arguments suggest redefining transportation field, to a more digitalized and intelligent one. As the problem becomes more complex, smart systems, new hardware infrastructure, new methodologies, simulators and frameworks need to be defined and used by the transportation systems [8]. Computer engineers should come in and provide help. They have to provide the new high-quality, low-cost, energy efficient technologies to integrate with the already existing hardware for the common goal of responding to evolution in transport field.

Transportation influences the main aspects of the society, from social ones, to political and economic. It is a domain that is being related to the complex systems analyses and to social network analysis that can give great insight into transportation investment, operations and design [26].

A new definition of this field is needed since it addresses in a real-time manner and on all geographic areas, from urban to rural areas aspects. This modern approach needs to include advances from all related engineering branches and to be more attached to the real time control through IT and communications. It is obvious that the large amount of information that is coming from the entire traffic network has to use more complex and qualitative frameworks. Digital information revolution is changing the world to the point where the amount of information that is available improves our society. The most promising advances relate to the ability to use the information in an effective way. Information technology is the driving force of innovation, in domains like health care system, mobile communications and now is changing transportation [27]. Even though industrial revolution produced today’s modern vehicles, digital information revolution it is the one creating intelligent transportation systems.

This is where Computer Science is emerging with transportation, using the innovative and in the same time the well known concepts to transform this field of transport into really intelligent systems. Charles Vest, President of the

Massachusetts Institute of Technology, states, "Humankind's advances will depend increasingly on new integrative approaches to complex systems, problems and structures. Design synthesis and synergy across traditional disciplinary boundaries will be essential elements of both research and education". [26]

1.4.1 Intelligent Transportation Systems

The result of a good collaboration between the transportation field and the information technology is the new field of Intelligent Transportation Systems analysis. These systems combine together the so called "ITS-4" major concepts. One is the ability to sense and identify the presence of vehicles on the infrastructure, in real-time. The other two are the ability to communicate and to process all the data gathered through more reliable methods. Last but not least, is the ability to process all data and based on specific algorithms and complex methods to propose new network control strategies that will improve traffic conditions. [26]

With the continuous increase of road users and the limitation of the infrastructure, intelligent control of traffic operations becomes an interesting issue in the near future. Maintaining an efficient transportation system is one of the main concerns for public authorities' nowadays. Public transport is also addressed in the quest for a more efficient transport system [28]. Cities are still confronting with multiple traffic jams each day, causing large parts of it to become irresponsive to traffic movement.

The field of intelligent traffic control is very dynamic because of the unique traffic networks which are found on every continent, country, city and which are differentiated by geography, economic development or landscape All these features lead to areas where traffic has different characteristics: from isolated villages with almost nonexistent traffic, to cities with busy traffic, where the number of vehicles operating at any given time must be checked every day [29]. In order to maintain under control and to reduce the number of problems that arise with the continuous growth of the need to transport goods or people, different systems developed solutions on each traffic structure that predict and prevent worsening these specific problems.

The most common cause of congestion in urban areas is the overcrowded intersections. To sustain traffic growth, each intersection should be redesigned and to support new traffic values, like in the case of the Big-I reconstruction and modernization project, see [30]. But this is not possible in a city with a limited amount of space or in a smaller community where there is no financial support to make such investments to rebuild an intersection. Scientific literature review describes approaches for automatic optimization of traffic signal operations, which are used by various mathematical methods to develop strategies for network control [8]. But results show the lack of a general solution that is not yet available.

Information technology (IT) has transformed many industries, from education to health care to government, and is now on the edge of transforming transportation systems. The future of transportation relies on the IT to sustain the evolution of old infrastructure into a new smart one, where vehicles, roads and traffic lights become intelligent by embedding them with chips and sensors to communicate each other for a correlated decision making [5].

All major technology advances in information systems, communication, sensors, and mathematical methods are all combined with the conventional world of surface transportation infrastructure into Intelligent Transportation Systems. Systems like SCATS [31] and SCOOTS [32] require a significant amount of deployed hardware equipment, ranging from pavement-installed sensors up to a centralized entity that monitors traffic and takes decisions based on the gathered information [21]. Such systems introduce significant costs, both in personnel and associated infrastructure.

It is convenient to think of ITS in terms of six areas: Advanced Traffic Management Systems (ATMS), Advanced Traveler Information Systems (ATIS), Advanced Vehicle Control Systems (AVCS), Commercial Vehicle Operations (CVO), Advanced Public Transportation Systems (APTS), and Advanced Rural Transportation Systems (ARTS). J. Susmann states in [26] that "ATMS represents overall network management, while ATIS is the provision of information to travelers and AVCS is the level of control technology applied to vehicles and infrastructure." This affirmation points the interconnection and dependency between technologies inside ITS and the infrastructure.

Transportation network has become a collection of intelligent devices that communicate using the existing infrastructure. The infrastructure is moving towards a real active one, where vehicles can communicate with vehicles (V2V), and the infrastructure itself can exchange information with vehicles (V2I, I2V) for a better decision making [33]. Acting as routers, each active element, a car or a roadside station, connects to the devices in range and establish an ad-hoc network to communicate. This results in a distributed system where messages are exchanged to control traffic conditions creating a real Intelligent Transportation System.

1.4.2 ATCS - Adaptive Traffic Control Systems

As the number of vehicles increases, so does the interest in optimizing traffic movements. This is can be achieved by adjusting the infrastructure and/or control signaling. Complex ITS solutions are deployed all over the world, mostly in large cities [6] but traffic congestion also affects smaller communities [34]. Adaptive Traffic Control Systems (ATCS) prove to be the cost effective solution that can be deployed locally and prove effective. Even though this solution may appear to be an underinvestment, it is not a waste of resources, because the mechanisms running locally at intersection level can be later included as a part of any ITS. Without the innovative technologies proposed by Computer Science, adaptive systems would have not been able to provide this current modern approach for optimizing traffic conditions in urban areas. High computing power, efficient communication methods or video surveillance are only some of the most important means used by ATCS to respond to new challenges in transportation.

The evolution of ITS is also related to the one of the Adaptive Traffic Control Systems (ATCS). A quick analysis reveals that a major problem lies in the number of intersections and their coordination in terms of controlling traffic. In this context, traffic lights play an essential role, because they control which route has priority at a specific moment in time. Using relevant information, traffic lights may improve their decisions in order to respond to continuous change of traffic conditions [5]. This way, each traffic light controller acts as a virtual traffic officer, reducing the need for human resources and potentially improving decisions through superior data management.

These systems represent the traffic management strategy in which traffic signals timings change or adapt according to the traffic demand. The need for this kind of systems arises because of the failure of an efficient response to dynamic changes in traffic pattern. First, traffic engineers considered that fluctuations in traffic flows could be addressed through several timing plans covering different traffic demand scenarios and a good selection of the appropriate one. That proved to be hard to implement and inefficient, as traffic responsive matching had operational problems. By the time one scenario was applied, traffic conditions changed again making it not to match to current situation. Increasing the frequency of change may lead to a system spending all the time transitioning to one state to another, causing inevitable traffic disruption. [21]

Technological progress changed the meaning of "adaptive traffic control". A system was considered to be adaptive if it could adjust green times or cycle lengths within a period of time after reading a set of traffic values. Now, these systems collect real time data, compare them periodically and use a responsive process to adapt to changes. Even though, tests show significant improvements after testing various solutions, deployments are not yet on large scale and the major reason for this is the complexity of the logistics. [6]

However, from a round total of over 270,000 traffic signals installed in the entire USA, it is stated that there are less than 1% operating adaptively [34]. In the same time, there are an estimated 50% of traffic signals in Australia to be working with adaptive methods [34]. The difference is mainly caused by the difficulties in deploying them, the installation impact over the infrastructure is considered here. On the other hand, there are countries that tried different approaches, developed many systems and this led to a small progress overall. This is argued by the high number of solutions deployed only in USA, while in Australia the well known SCATS is used on a larger scale, making it more efficient in developing new strategies.

ATCSs have been in practical use since the early 1980s and up until now, there have been a series of deployments in the entire world and they can be categorized in several ways. Some of these systems are known as 'traffic-responsive' (e.g. SCOOT and SCATS) while some others are known as 'truly adaptive' (e.g. RHODES and OPAC). Some of the ATCSs are known to operate well on arterial networks (ACS Lite and SCATS) while others are known to do a good job in grid networks (e.g. SCOOT and UTOPIA).

1.4.2.1 ATCS Deployments

Several systems are to be mentioned as the most widely used ATCSs and these are: Coordinated Adaptive Traffic System (SCATS) [31] and Split Cycle Offset Optimization Technique (SCOOT) [32]. Used in over 140 cities worldwide and with a control of over 31,700 intersections [34], SCATS calculates the cycle length, splits and offsets cycle-by-cycle to respond to traffic changes. SCOOTS has been originally designed to control urban networks in large towns and cities, but proved to be successful in smaller cities also. There are around 200 deployed systems worldwide. SCOOTS searches for a coordination pattern for a group of signals and applies it in real time.

However, there are other systems that are to be mentioned, because each of them brought their innovations to this field, like the use of The Optimization Policies for Adaptive Control (OPAC) and Programming Dynamic (PRODYN). These are two approaches based on different mathematical programming techniques, instead of conventional timing plans approach. Countries begin to race to find the most suitable solution to obtain an adaptive traffic control and following this trend, new programs emerged, like the Real Time Traffic Adaptive Signal Control Systems (RT-TRACS) or the Real-Time Hierarchical Optimized Distributed and Effective System (RHODES), both with deployments on the US territory and with support from authorities [35], [29]. RHODES is one example of a system developed by researchers of a university in the USA, the University of Arizona which is still being used for research by the Federal Highway Administration of Washington (FHWA). It uses cycle lengths, splits and offsets to determine the specific moment to change the states of the traffic signal, based on the traffic demand and the future predicted values for an intersection. But there were also ATCSs, like LADOT, which were developed independently by the city of Los Angeles for the 1984 Olympic Games [8]. This system used volume and occupancy data collected every second and used in every cycle to recalculate cycle lengths, splits and offsets to determine new timings for an intersection. LADOT used centralized area computers communicating with local area workstations, making the architecture of this system to be a complex one. More than 400 traffic signals were controlled using LADOT, with plans to increase their number in the next future [36].

Although tests showed benefits over the fixed-timed solutions, these systems continued to develop as there is no general solution found yet. ATCSs started to become more “user friendly” and compatible with the already deployed infrastructure (pavement sensors, cameras, traffic signals) on their quest to reduce the perception of the amount of logistics needed. ACS Lite is an example in this direction and this is still under development [37]. Each solution is implemented to solve specific local problems and by this reason they tend to be more “city related”.

Interest in ATCSs is also present all over Europe, French system CRONOS[38] and Italian UTOPIA [39] showed encouraging results and improvements in traffic conditions or in public transport operations. But, notable systems are the German ATCSs, MOTION [40] and BALANCE [41], which started as scientific research tool before deployments were made in other cities outside Germany. These last two systems are well known for working with industry standards for traffic controllers, increasing their area of deployment.

1.4.2.2 ATCS Characteristics

A more complete overview of the most important features provided by major ATCSs is described in [6] along with their working principles. In all cases, concepts and operational features of all these systems, which are sometimes different, do not always result in significantly different field performances. So, the question to be answered is “how much are these systems really conceptually different?”

An answer to this question has to take into consideration that each of the ATCSs has unique characteristics. But, general principles describing their workings can be identified: detection, type of action, adjustment method, timeframe for adjustment, hierarchical levels, estimation through traffic modeling, adjustments to signal timings, flexibility (to add and remove intersections from a system in real time), support for vehicle actuated operations from a local controller, and transit operation. Presented in [6], Table 1 synthesizes the above mentioned principles for some of the major ATCSs deployed. This list is not complete and can be extended, for example, handling pedestrian operations can be of importance for other studies.

Detection addresses the location of traffic detectors placement used by an ATCS. The most used types of detectors are: stop-line (SL), upstream near to the stop line (NSL), mid-block (MB) and far-side (FS). These are used to determine specific parameters, for instance, NSL estimates short queue lengths, while MB determines long queues. FS go even farther and are usually installed near the exit point of the upstream intersection for the prediction of traffic conditions.

Type of action refers to the type of adjustment method used to control traffic and usually it is based on the type of detection it is used. Two different concepts are known, one is proactive and the other is reactive. In the proactive approach, traffic control system is adapting its operations based on the data estimated to be on a certain moment of time. On the other hand, reactive systems respond to traffic changes with a certain delay, caused by the read time needed to determine actual traffic conditions.

ATCS	**ACS Lite**	**BALANCE**	**LA ATCS**	**MOTION**	**OPAC**	**RHODES**	**SCATS**	**SCOOT**	**UTOPIA**
Detection	MB, SL	NSL	SL	NSL	MB, SL	MB, SL	SL	US, SL	US, SL
Action	P, R	P, R	R	P, R	P	P	R	P, R	P
Adjustment	A/LO	CO	A	CO	CO	CO	A	LO	CO
Timeframe	5-10 min	5 min	Cycle	5-15 min	Phase/Cycle/5min	Phase	Cycle	Cycle/ 5 min	3sec Cycle
Level	C/L	C/L	C/L	C/L	C/L	C/L	C/L	C/L	C/L
Model	Yes	Yes	Yes	Yes	Yes	Yes	No	Yes	Yes
Timings	S,O	S,CI,O,PS	S,CI,O	S,CI,O,PS	S,CI,O	S,PS	S,CI,O	S,CI,O	S,PS*
Flexi Region	No	No*	Yes*	No	No	No	Yes	Yes*	Yes*
Vehicle Actuated	Yes	Yes	Yes*	Yes	No	No	Yes	No	Yes*

Table I. Categorization of basic adaptive principle with various ATCSs

The adjustment method is related to the optimization of traffic signal operation, which can be "Limited" to avoid high fluctuations of signal timings, it can also be "constrained", where several limits are set by local policies and then it is the free adjustment method, without constraints, which can use any heuristic method. In correlation with this parameter is the timeframe used for adjustment, which sets the interval for changing traffic control schemes.

Hierarchical levels respond to the question "Do ATCS have a local component or only a centralized one?". Based on the results in Table I, one can see that each system needs a local and centralized component to take decisions.

Model parameter is used to mark the systems that have a specific method of building a prediction of traffic values based on the data read from the installed detectors. Even though this traffic flow "modeling" is used, there are systems that perform their computations and take decisions based on real time traffic data.

For several systems it is useful to divide the control area into smaller regions and coordinate locally traffic conditions. In case a system is capable of reconfiguring its area of interest it is known as a system capable of forming flexible regions.

Of interest is the possibility to have support for actuated operations. This means making the local control unit responsible to take decisions to change locally traffic light functioning in terms of altering green times, cycle lengths or phase order.

Many factors influence the costs of an ATCS deployment. Most of them are related to the installation and operation of such system. There is not a general understanding if on long term evolution the ATCSs are more cost-effective than traditional signal systems or not. Traditional signal re-timing has the advantage of being a non expensive solution to implement, but the real challenge for this solution is to determine when and how to re-time each traffic signal, being almost impossible to have a responsive implementation. On the other side, ATCS improves the automatic retiming solution, along with other benefits, but the users remark other costs such as the physical maintenance or software licensing. A review of ATCSs deployments show that licensing may increase the overall costs with 10% to 15% [6].

Even though ATCSs are known to have several advantages over traditional traffic signal timing, the belief that they "are the answer" for any situations is only a myth. They work best in conditions with variable levels of congestion, like special events and in areas with fluctuating traffic demand. ATCSs are tools that can help reducing traffic congestions by implementing the control and management of transportation network. The main benefits these systems bring are seen in the reduction of delays, stops and other measure of traffic performance.

1.4.4 Traffic Simulation and Evaluation: Software Tools

As the vehicular travel demand is increasing throughout the world, particularly in urban areas, the need arises for traffic simulating. Computer Science and Information Technology supported the rapid expansion of complex tools capable of processing large amounts of data. Traffic simulations were developed to facilitate the evaluation of an infrastructure before implementing it on the road. For example, different changes at road level, new direction implementation or even traffic lights control algorithms can be tested in simulation before deploying them in the real world.

Most of the solutions mentioned before are already deployed. This means that they rely on real traffic data, gathered by the actuators, sensors, cameras and other hardware installed equipments to enhance and adjust their parameters. But for the development phase tools are needed to simulate traffic conditions in order to test new theories. Literature review, mentions several tools that are used in correlation with traffic simulation. Of particular interest are VISSIM from PTV Vision Group, Paramics from Quadstone and Sumo, the freeware software available. Each of them brings unique features and in the same time they all share the same problem: traffic simulation and analysis.

I will start with VISSIM, because I had the chance of using it for a longer period of time, thanks to the full version license available for scientific applications provided by PTV Group. VISSIM allows the user to simulate traffic patterns at microscopic level. The software offers the possibility to use links and connectors to model any infrastructure. Also, you can define attributes for drivers, vehicles parameters and interfaces for traffic signal operations and traffic management to make a real experience in simulation. VISSIM offers the platform to a complete analysis for traffic planning, being able to use 3D models for a more real simulation. All generated data are stored in explicit databases, along with results from simulations correlated to traffic specific elements. This software has great value for simulation presentations. [42]

Paramics software was started as a project in the University of Edinburgh in the early 1990s and it is now a microsimulator used to build, calibrate and analyze different traffic models. It is used to simulate and to analyze different transport infrastructures, by offering tools for detailed reporting and measure of effectiveness (MOE) [43]. The user also has the possibility to define its own network and run it under different scenarios. As a remark, the lack of a license available for scientific application makes it less accessible for students and researchers.

SUMO is an open source microscopic and continuous traffic simulation package capable of handling large road networks. It offers a set of tools developed to implement a set of tasks such as route finding, visualization and network import. Custom models are used for simulating real traffic scenarios and analyzing resulting data. [44] Compared to the previous tools mentioned, this has the advantage of being available for free and also there is a consistent online support available.

Even though software tools like the ones described before, try to predict as accurate as possible real human decision, it is impossible to have a human behavior simulated. Social component cannot be decoupled from the traffic conditions. Traffic flow is generated by vehicles driven by people and each of them has specific interests: school, job, social life. It is clear that social life influences traffic conditions, whether it is a sport event happening or a live concert, people share common interests.

This social need is also the reason for the partial success of public transportation which fails to deliver a suitable solution to social request. One can see that by having specific stops which do not necessary match the exact schedule or destinations for passengers make them neither flexible nor reliable solution if we add the possibility of uncontrolled delays. Specific ITS solutions are implemented and tested nowadays, several with encouraging results after using integrated applications and automated processes along the way [45].

Traffic system can be considered at certain levels an organization with thousands of “employees”, where each traffic signal is an employee and every driver is a possible client. Like every organization it has to establish what kind of decision-making policy, or in terms of traffic control, uses: centralized or decentralized. Each approach has advantages and disadvantages. In a centralized system organization the decision comes from the upper controlling layers, creating a top-down management style. Centralization allows for the entire system to efficient share resources, but in the same time it not allow for the lower layers to take decisions without the approval of the higher level. Meanwhile, decentralized control uses a distributed approach, allowing for the lower layers to work independent and to focus on solving their own local problems, without the upper layer command it.

The approach used for the solution chosen in this thesis is one that combines the advantages of each control techniques, a hybrid of centralized and decentralized, with a decision making more decentralized. This way, the centralized control leads to decentralized decision-making, where each local traffic controller knows system’s mission of creating a continuous traffic flow and is able to take decisions according with this goal.

This thesis proposes a new perspective in simulation and modeling of road traffic infrastructure by introducing the social component into analysis. In order to improve traffic conditions, new methods and tools need to be defined to generate new solutions. Complex network analysis (CNA) provides a fresh approach that is still at its beginnings of application into traffic systems, but which provides some tools necessary to add consistent value to this domain. Of particular interest is also the Social Network Approach (SNA) which derives from CNA and takes social aspects into consideration.

The dynamics of traffic is often compared with fluids flowing through a road system, but this comparison is not so accurate when it comes to the urban traffic. A better comparison was made in [46] where the author speaks about urban traffic being comparable to a gas that expands to fill the available space. In [47], the authors explain why building new roads are not solving the traffic problem, because urban traffic congestion maintains its equilibrium. The increase of road capacity has short term visible improvements, because once the roads are expanded or constructed, vehicles will divert from their regular routes to use the new road. But on long term, conditions will regenerate, only that this time the impact will be larger as the road capacity is higher now.

The so called "fundamental rule of traffic" states that "people drive more when the stock of roads in their city increases" [48]. It also says that commercial driving and trucking increase with a city's stock of roads and usually people migrate to cities which are relatively well provided with roads [48]. This means that building new roads only encourages people to drive more and this is usually a consequence of free or low taxes for driving on a road. Authors suggest congestion pricing as the solution to the increasing traffic conditions. London and Singapore introduced this type of measure to try and discourage people of using vehicles in specific parts of the city at peak hours, but they ended up in shifting conditions to a different time of day. This is not an acceptable solution, as it has a regressive part: it affects the people that cannot afford paying the taxes and really need to use the road.

So first of all, the benefits of building new roads must be studied closely before implemented. Second, other types of transportation improvements should be studied before altering the infrastructure.

2. A NEW PERSPECTIVE OVER TRAFFIC BASED ON COMPLEX NETWORK ANALYSIS

We are surrounded by networks: electric power networks, communication networks, transportation networks, all influence our life even if most of the times we are not aware of it. For example, power networks represent the fuel of all modern societies, without energy no industry could have progressed. Communication network had one of the most dynamic increases in the last decade. It evolved into current high speed form, expanding year by year and covering more and more of the globe surface. Practically there is no more modern city or urban area that is not covered by a communication network. By making it available to everyone it increased also social interaction making it more efficient.

2.1 Urban Network Topology

One of the most important parameters when dealing with traffic is the road structure also known as the road network. The structure depends on the city map and on the existing city infrastructure. It is responsible for the existence or not of a possible route between two points in a city. Traffic control depends on the topology of each structure. If the infrastructure is a “simple” one, similar to a grid configuration, with parallel roads and few junctions, the control can be achieved using synchronization between intersections and operations. On the other hand, if the structure is more complex, with concurrent roads, many junctions and random layout, the control becomes more complicated. General solutions need to be investigated, new approaches that rely more on traffic conditions and find specific patterns in the road structure that can be further applied to other structures without losing generality of the solution. This leads to the need of a more comprehensive study of road network using specific methods from other fields of science.

The study of networks was from the beginning associated with graph theory, but in time it evolved and it started focusing on the relationships among social entities such as communication between members of a group or economic trades among countries. Classical approaches in science have some problems in describing large systems that are composed from non-identical elements. The problem lies usually in their topology, even though many of them form complex networks with vertices representing the main elements of the system and the edges representing the interactions between them. We are confronted with these systems every day, every living system represents a genetic network with the proteins and genes being the nodes and chemical interactions between them being the edges. Nervous system is another example of a large network, with the nerve cells and axons being the vertices and edges. In the same spirit, complex network specific elements are identified in social science, where the individuals and their social interactions are the nodes and edges in the network. [49]

Placed at the crossroads of several distinct sciences like mathematics, computer science and sociology, complex network analysis (CNA) deals with large networks. It analyzes the connections following a pattern that cannot be described deterministically and are composed of nodes and links between nodes (connections). In a classical graph theory, the links usually represent physical links but in CNA they can also represent friendships like in the field of Social Network Analysis. This applies for any other relationship one can define. Graph theory sets the basics in CNA, but there is an extended set of metrics that can describe any pattern in a statistical manner and can be used to analyze large networks from different points of view.

In the last decade there was an increasing interest in complex networks that present an irregular and complex structure. The focus changed from the analysis of small networks to systems with thousands of nodes with special attention to the properties of networks with dynamical units. Several papers [50],[51], increased the interest in complex network analysis (CNA) by pointing the advantages of using the computer power increase and also saw the possibility to study large databases of real networks. These included transportation network, phone call network, Internet and also scientific collaboration networks, medicine and biology. All these networks had in common large real systems that are already deployed and cover critical aspects of our day to day life. [49]

Of interest for all previous mentioned networks is their topology. Medicine teaches us that "structure affects the function" [52], but this principle is also true for networks. For example, the topology of social networks affects the spread of information while the topology of power grid affects the stability of power transmission [51]. In the same way, the topology of urban transport network influences the time spent in traffic and the quality of life of each city inhabitant. The research of complex networks focuses on defining methods to characterize the topology of each real network. The following paragraphs will introduce key concepts and metrics applied further in this research.

2.1.1 Node Degree and Intersection Degree

Graph is the abstract representation of a network and it is defined by a set of nodes and a set of edges, indicating the connection between two nodes. Graphs are usually described as directed or undirected. For an undirected graph there is no distinction between the two vertices associated to each edge, while for the other, edges are directed from one node to another, see Figure 4.

In both cases, the common attribute of a node is the degree. This is defined as the number of edges incident to the node. In case of a directed graph, node degree is referred in two ways, as out degree, the number of outgoing edges and as the in degree, which is the number of incoming edges. Using these values, the average degree of a graph is defined by the arithmetic leverage of all node degree. Analyzing only this metric was not enough to speak about nodes, so the degree distribution was defined as a statistical property which represents the probability that a node chosen uniformly at random has a degree as the fractions of nodes in the graph having the same degree. [49]

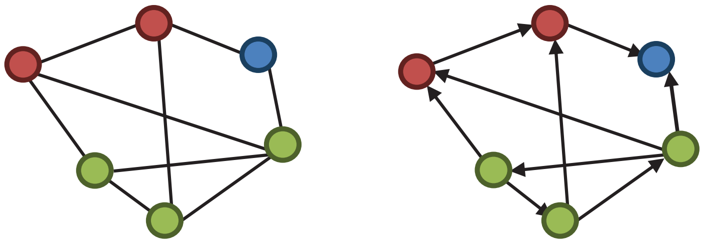


Figure 4. Graphical representation for a non directed and a directed graph

The road network can be considered as a weighted graph where each node is an intersection and links represent the road segment between them. The weight of the edges can have multiple understandings: it can represent the length of the road segment, it can be the time needed to pass that road or it can be the cost of travelling along that specific road. The directed character of each edge is associated to the way of streets. Traffic network analysis shows the influence of physical restriction of constructing high degree intersections. Empirical findings show an average value of 3 to 5 degree per intersections.

2.1.2 Shortest Path Length, Betweenness and Traffic

The main problem to solve in graph theory is finding the shortest path between two different points. The shortest paths in a graph are the specific sequence of adjacent edges that represent the fewest number (not weighted graph) or the lowest value (weighted graph) necessary to reach two different nodes. The average path length of a network is computed as the mean distance between two nodes, averaged over all pairs of nodes [53]. This is a measure of efficiency of information transport on a network. It is one of the most flexible and robust metrics of network topology along with clustering coefficient and degree distribution. Both will be discussed later in this chapter. The so called betweenness is defined as the number of minimum length paths between any two nodes in the network. But, betweenness centrality is an indicator of node's centrality in a network. It is equal to the number of shortest paths from all nodes to all other that pass through a specific node. The higher the betweenness centrality, the larger is the influence of that node in the network.

Of particular interest when dealing with transportation networks is finding intersections that present high importance in terms of traffic aggregation, the more cars have to pass through that specific intersection, the more importance it has. The empirical findings in [44] show that, from a statistical point of view, drivers instinctively choose routes as short as possible, which makes betweenness centrality a viable metric for finding key intersections [54]. The distribution of this metric has a major importance when analyzing transportation network, the location of the highest values being the indicator of major intersections in a road network.

2.1.3 Clustering Coefficient and Transport Infrastructure

Clustering coefficient is a measure that states how well nodes tend to cluster together. In social networks, it is like two individuals with a common friend are more likely to know each other. Network average clustering coefficient is computed as the average of the local clustering coefficients of all edges. Using this coefficient, a graph can be further discussed if it is a small-world or a random one, details which will be provided in the following sections.

A high clustering coefficient shows how strong are the relations inside a graph and this aspect has a direct implication in determining how well nodes are connected inside a sub-graph. Centrality measures the influence of a node inside a network, being computed by assigning higher scores to nodes connected to high ranking neighbors, and lower scores otherwise. Using this definition, several ways to compute centrality emerged [55].

In analogy with intersections and roads, a network that has a clustering with a high value, it suggests that intersections influence each other and cannot be decoupled to analyze them separately. Moreover, finding isolated, standalone solutions to optimize local traffic conditions at local intersection level will not be able to bring any improvements at network level and could have an unwanted negative impact to traffic conditions.

2.1.4 Community Detection in a City

Communities can be defined as groups of nodes (sub-graphs) with a high density of edges between them. Usually these structures have a lower number of edges between other communities. Figure 5 contains three communities denoted by the dashed lines.

Generally speaking, this approach allows community overlapping because the same node belongs to more than one community, which is a common case. There are numerous approaches formalized into algorithms for finding communities, usually dependent of the specific application and on the relevance of link density [56], [57]. In a real world urban transport network, identifying communities is similar to dividing it into smaller neighborhoods. Tests performed on specific known cases of city maps, showed similarities in terms of size and shape. This aspect comes as another argument of using CNA for a topological analysis of road infrastructure.

Related to community concept is the modularity, which is a metric that shows how well a network can be divided into distinct communities, the higher the modularity, the well-delimited are the communities [55].

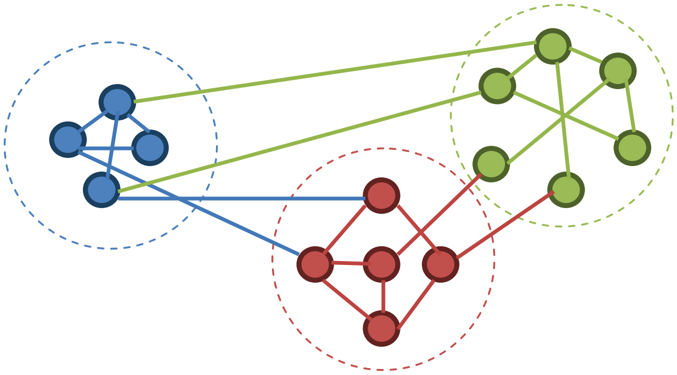


Figure 5. Graphical representation of communities identified in a network

This could be of interest if we think of these methods to as a step to split the problem optimizing traffic flow inside the network, and provide a decentralized problem, by searching it into the smaller communities generated. Finding the exact number of neighborhoods is not a straightforward method, as algorithms work with a specific resolution that influences the size of a community in terms of number of nodes and edge density. Fine tuning this resolution proves to be a challenge in applying community detection in order to meet problem expectations and provide the relevant communities for each specific problem.

2.2 Network Topologies

Real world systems are made of large number of interconnected units, each communicating inside a network to perform specific task. In order to be able to analyze such systems, researchers saw the possibility to reduce these systems to graphs and to associate nodes with the units inside them and also the edges to the specific connections between them. For example, transport network can be translated into a graph, if intersections are identified as nodes and roads to edges. Of course one can argue that the approximation is too relative and that for a real system usually there is the time dependence or a spatial influence and many other aspects that make each system to be unique. So reducing all these complex implications to the existence or not of a node or an edge, could be missing some of the important parameters with direct influence in a real world situation. But with these approximations and reduced number of variables, the practical aspect increases its importance, keeping the entire system representation simple and in the same time informative enough.

As the interest in developing powerful tools to simulate and generate large networks increased in the last years, so as the possibilities to analyze complex systems. Topological aspects started being of interest, especially for transport networks. In the last years different tools were developed to export the online information about the entire road infrastructure and to translate it to a known graph format. Having the nodes and edges, weights and directions, even coordinates for a geographic layout study, allowed topological studies of interactions inside large networks. Not only transport networks were of interest, systems like communications, biological and even animal and human societies were analyzed. Studies revealed that despite the differences between systems, several topological characteristics are common for each system: small path lengths, high clustering coefficients and a strong presence of communities [49]. These aspects had the attention shifted towards the analysis of network topology and how new models can be developed to influence their structure and dynamics.

Topological assessment of networks pointed the existence of different network properties, that act as criteria for differentiate them. These are the small-world property, degree distribution and clustering property. Small world property refers to the existence of shortest path lengths between any two nodes inside large size graphs. Even though it was first studied in social context to estimate the number of steps necessary for a letter to reach its destination, this property is important for traffic networks because the presence of short path length between two intersections will be of interest for drivers. But the small-world property is related to the clustering coefficient as a high value contributes to a higher number of shortest paths possibilities.

As studies continued on real networks, it was found that the degree distribution of a real network has a power law shape, different from the classical binomial distribution of a homogenous graph that has all nodes almost topological equivalent, see Figure 6. This power law distribution is the result of several important nodes, called hubs that are linked to many other nodes and a consistent number of nodes that have fewer connections.

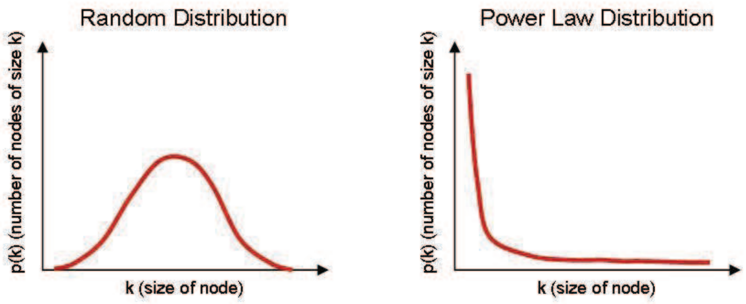


Figure 6. Binomial (Random) distribution versus Power Law distribution

Based on these properties, different classes of complex networks are referred by the literature today: scale-free, small world and random networks, see Figure 7.

A scale-free network is a network that has a power-law degree distribution. Recent interest in these type of networks started with the mapping the topology of a portion of the World Wide Web. Findings in [50], showed that some nodes had many more connections than others and that the studied network had a power-law distribution of the number of links connecting to a node. They called these nodes “hubs” and their main characteristics is that they have a higher than average degree distribution. But having these kinds of “hubs” could make this type of networks to be prone to errors, as a failure of one key node could affect the connectivity level inside the network. Another specific characteristic of scale-free networks is the clustering coefficient distribution which decreases as the node degree increases.

A small-world is the type of network in which the nodes are not neighbors of one another. In this understanding, each node can be reached from every other by a small number of hops. Using the clustering coefficient and the shortest path length, a small-world network could be characterized as follows: sub-networks have connections between almost any two nodes within them and in the same time, most pairs of nodes are connected by at least one short path.

Even though there are some specific features that tend to define them, there is no common agreement that a network is purely a scale free or a small world type. But, as a general agreement, few examples are of interest in a scale free context, such as: social networks, the World Wide Web, semantic networks and airline networks. On the other side, typical examples of small world networks include: power grids, phone lines, food chains and usually have applications in sociology, computing and also neural networks.

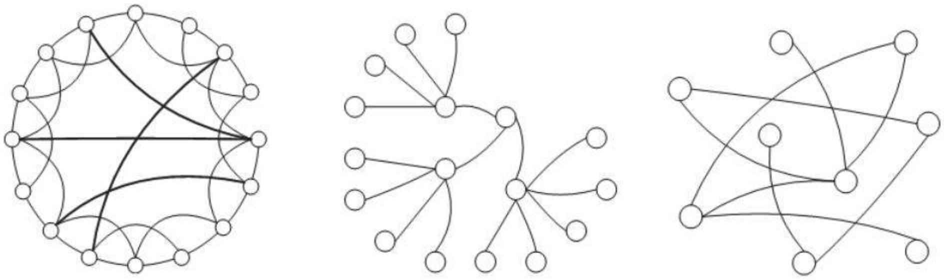


Figure 7. Complex Networks (from left to right): small-world network, scale free network, random network **[58]**

One can see that transportation network can be referred as a scale-free and also as a small-world network type. Pros and cons can be identified for both approaches. Seen as scale-free, the presence of hubs identifies with the possible points of heavy traffic conditions that finally lead to traffic jams. On the other hand, the presence of well delimited communities can help identify possible problems at lower level such as in a city neighborhood.

2.3 Bridging Transport and Social Networks

Social network is the reflection of a normal social structure, composed by actors and their ties. The actors from social networks represent the nodes and the information flow and relations between them are the links between nodes. In this way, social network analysis becomes an interdisciplinary method, with applications in almost all types of networks [59].

Because it studies the "relations" between network "actors", several approaches are to be discussed when applying these concepts in a real world situation. One is the analysis of the entire network, as a whole, where the relationships between different actors are studied. One important aspect is to study how a new actor can influence the strong relations developed already inside the group. The second is how each individual is influenced by the group and by the relationships he has inside the networks he is part of.

Social network analysis found its applications in domains like healthcare, military, national security issues and in the recent years in transportation optimization problem. In healthcare studies were conducted on phenomena like disease contagion and more recently in physical collaboration. In [60] a case study is proposed to identify key players in communication about pain management inside a hospital and to point the dimension of relations in the effort of improving pain management. In the context of national security, the community detection algorithms, especially social networks analysis have a great potential in isolating the groups with suspect intentions. An interest in applying social networks in transportation aspects, such as optimal placement of traffic monitoring units was addressed in [54]. Betweenness centrality metric was applied to optimize the locations of traffic monitoring units, while keeping the solution a low cost one.

Network planning and traffic flow optimization require the analysis of large amount of data consisting in road topology and traffic flow data.

Daily traffic is generated by people moving to fulfill professional obligations or only for personal entertainment, responding to their every day social requirements. Therefore, direct interaction between human and traffic aspects prove the opportunity to apply principles from complex network analysis (CNA) and social network analysis (SNA) into road network optimization.

One can see the relation between networks in general, concepts that are used, such as graphs, nodes, links, and the road network. If we identify and map each of these elements onto a city map, the entire infrastructure will act as any oriented graph, making it a subject for the complex network analysis techniques. Following the similarities, traffic road network is an oriented graph, with links representing the roads and intersections defining the nodes in it. Even if the relationship between the layout of the streets and the character of the urban traffic can be regarded as straightforward, until recent years [29] there was no significant involvement in analyzing it in a systematic manner.

Any traffic network planner can argue the importance of the network topology [61]. At microscopic level this aspect could be ignored but at the macroscopic level it was identified how aspects from complex networks apply and influence traffic behavior. In this context, I believe that proven metrics for describing the structure of a complex network can be used successfully for finding the key intersections in any urban network. These intersections are subject to intense traffic flow and require careful regulation in order to maintain this flow. By consequence, optimal policies and strategies for deploying traffic lights are essential in an Intelligent Transportation System.

With the advent of modern tools and methodologies for computer aided urban planning and the rapid spread of (Geographical Information Systems) GIS tools in the public services and administration, significant research has been carried towards finding alternative approaches in analyzing the structure of cities. The approach based on graph theory was a clear choice and much work was put into this segment [62].

Much work was done in the application of complex networks theory and metrics in the analysis of urban environment. In [63] it is described a comprehensive methodology and a framework for analysis of urban environments in terms of both classical graph theory but also using complex networks specific metrics and algorithms. Of particular interest for this study is the quite abstract concept of centrality which is the key subject for [64].

Several research directions put together traffic behavior and complex interaction in the effort to create the “most real artificial driver”, which acts as close to a real driver as possible [65]. In this context, separating the driver from its driving context cannot be achieved because the adaption process is closely related to the environment. Understanding how drivers interact and how road networks are created around specific points of interest (schools, shopping centers, concert halls, sports arenas) could lead to identifying the patterns that can apply at different scales over several road networks to achieve increased traffic flow and consequently, less congestion.

In [66] authors focus on the analysis of macro traffic in a mobile network as a way of investigating complex networks. They have investigated the impact of human relations and the obtained cluster structure and concluded that based on their values they should be able to obtain the behavior of a service process by observing traffic volume values.

Several papers address the subject of the complex network behavior identified in the structure of the urban traffic [67]. The authors identify the 80/20 behavior because roughly 20% of the streets account for more than 80% of the urban traffic, leaving the rest of them not used. Another interesting and important aspect presented by the authors and which is also the subject of [68] is the hierarchical view of the urban structure. There is a clear distinction between some important streets (few) and some which are less important (many), making the less important ones behave as feeders for the important ones. The authors also take into consideration the complex behavior of the actors (drivers and pedestrians) with respect to route learning and adapting, which can lead to a daily dynamic behavior.

Still one of the problems to be solved is the interest in deploying systems. The most challenging aspect of this operation remains the installation of traffic signal lights. They act as the main actuators routing all the traffic between adjacent intersections which makes them the most versatile elements in the road infrastructure. An efficient method to place traffic lights into any city’s network has no general solution so far. An innovative approach is to study the topology of any city, using concepts and tools provided by network analysis, to identify hotspots inside that network. These points could be of interest in dealing with high traffic loads in a real traffic network.

Complex network analysis (CNA) techniques are used to extract another view for the layout of modern urban areas by taking into account their topology: the way streets connect and the direction of each connection. The optimization of traffic movements and improvements in traffic flow at local intersection level is addressed with the tools provided by the CNA. This thesis proposes a distributed approach where a continuous “handshake” between local intersections is implemented. Compared to other implementations, distributed control is preferred instead of the classical centralized control, where a command center monitors and takes decisions based on local conditions. The results show a decentralized control and a more robust network without having to build new roads.

In the following chapters I will show a method where betweenness centrality metric is applied for efficient placement of traffic signals and also how betweenness can be applied in a genetic algorithm to redistribute traffic flow in crowded parts of a city. Using a topological analysis of the network, congestions can be avoided and the time spent in traffic can be reduced by applying the proposed methods.

3. THE QUEST FOR TRAFFIC COORDINATION

The search for a global network optimization is not a problem that can be solved using the classical top-down approach. This happens because the entire urban traffic network is composed of smaller communities. The particularities of each neighborhood, of each social community, transform this problem into a set of specific solutions that can describe different local communities in different ways. A set of distinct solutions can therefore be obtained, but they will lack correlation if there is no coordination between them. In this thesis, coordination exists if notifications about traffic values are exchanged between intersections so that an agreement on traffic passing from one intersection to another (adjacent) intersection is reached. So, the quest for coordination starts at the lower levels of traffic network, at intersection level, and with an active agreement that defines the correlation between the nodes for this network.

I propose a bottom-up approach in order to search for methods to improve local traffic condition, following the proposed Three Layer Formalism (described later in this chapter) which will guide me from local optimizations to network improvements through correlation and coordination. As actuators at intersection level I will use the traffic light controllers, also called semaphores or traffic signals. They will transform into real smart traffic lights, being able to adapt their timings to respond to dynamic traffic changes. In our days, these are already installed in almost every intersection, maybe in too many as a personal remark. This is what makes them suitable for the job of a local controller. Traffic lights have become “the eyes and ears” of this modern urban traffic network.

A set of parameters need to be selected before using traffic signals as local actuators. Their value must represent consistent data that has to be relevant when changing their values. For this thesis, I have identified and selected several parameters to detect when a real problem is present at intersection level. Before any solution is generated, the problem has to be defined in order to know what set of variables need to be controlled. As showed in the previous chapters, congestion is the modern day’s problem. There are methods that try to estimate the level of traffic congestion using available mobile sensors [69], [70], but consequences are still visible and road users still experience every day road blockages. ITS and ATCS come with a complex infrastructure, able to provide complete data about traffic conditions with the sophisticated hardware deployment [26]. For these systems, using more parameters is not a real problem, as their deployed infrastructure has the means to gather and centralize large amounts of data. In this case, the problem is more one of dealing with the right quantity of data that creates the possibility to understand traffic movements and to react to them.

A real scientific interest is shown in developing new hardware and software solutions (smart cameras, pavement sensors [71]) for collecting in an efficient manner real traffic data. New methods are currently changing the way data collection is done, with GIS being one of the techniques proving efficient in gathering real traffic data [72]. The Internet of Things also reached ITS field [73], and wireless communication is nowadays connecting the infrastructure and drivers increasing their comfort and safety.

Behind my decision of selecting the specific set of parameters, that best define any intersection behavior was to use an efficient data collection method which is not time consuming or expensive. This is how I managed to reduce the number of variables of interest and also not to have the physical variables, such as speed or acceleration. One of the real challenges, which also motivated me to choose only two parameters, is to keep the number of variables necessary to compute new local solutions to minimum. First one is queue length, which is the number of vehicles, waiting to pass an intersection on a specific direction. The second one is the green time value, which is defined per each direction for a specific traffic light controller. Methods that determine the length are not of interest for this thesis. There are commercial solutions available on market that already solves this problem. A discussion is to be made only for different possible mechanisms of detection. For this, image processing solutions are preferred instead of pavement installed sensors, because of the reduced impact on installation time.

Nowadays, a significant part of semaphores work following specific hardcoded sequences that are upgraded manually, once in a while, depending on the local authority's availability. Also known as static plans, these fail to respond to dynamic traffic changes, making them many times the main reason for traffic failures and road blockages. A possible solution to these sudden changes is to determine traffic conditions and switch between static signal plans. This is not an easy task, as local conditions can change from hour to hour. Sending any specialist to update signal plans and bringing him/her back to change it again after a short period of time will only cost money and time, increasing the costs. Reducing human interaction with the control devices is the desired approach in this situation and this is the context for the described mechanisms. I propose a system that responds to traffic changes by adapting signal plans dynamically for an intersection, the same way a traffic officer would control it.

Throughout this thesis I will focus upon achieving traffic flow optimization at a global scale by efficiently combining coordination and optimization at a local scale. In my view, these optimizations cannot be achieved without considering the impact of various social aspects on traffic. Simulations are done using specialized software tools, but with no real human interaction. All simulators try to assume and replicate as close as possible the human behavior, but any of them is really capable of doing so. Instead they use complex probabilistic methods that get closer to the free will of drivers but without notable success so far that can be applied and used in the traffic simulations.

This chapter proposes a self-organizing approach to control traffic changes by altering traffic signal timings to improve traffic movement over a global road network. Next, I will describe a new fast method that recalculates the green times for an intersection that has a problem in managing inbound traffic. The further goal is to interconnect optimized intersections in order to achieve a distributed self-adapting system using intelligent correlation of traffic controller phases. For the confirmation of the results, VISSIM simulation [42] environment was used. This is a tool that provides the means to evaluate the proposed adaptive algorithm. The case study was conducted over the city of Timisoara, Romania [74] and results are synthesized and discussed in more details in the last part of this chapter.

3.1 Current Optimization Methods

Studies show the continuous increase in traffic values [22], despite the new policies being used to reduce personal cars usage and taking instead public transportation. Authorities even restricted city access by introducing taxes in different parts of the world. The London Congestion Charge is the most well known tax that users pay to enter and use a specific charging zone [25]. But this solution did not seem to influence drivers in using personal vehicles in urban areas. Road traffic forecast shows an increase in terms of number of vehicles with percentages varying from 4-5% to 50% in large urban areas [22], [75]. The increasing interest in optimizing traffic movements has been visible in the recent years. Specific methods for adjusting the infrastructure and/or control signaling are of interest nowadays, to cope with this continuous traffic expansion. Complex ITS solutions are deployed in large cities, as seen in the previous chapters but traffic congestion also affects smaller communities.

In most cases, traffic congestion is generated by the high number of intersections and lack of coordination between their operations of releasing or stopping traffic. In this context, traffic lights become key players in any modern urban infrastructure. Their role is essential because they have control over driver’s next choice: they can decide which route to take or it can even recommend changing the route through intelligent GPS software. Traffic lights may improve their decisions in order to respond to continuous change of traffic conditions, by using relevant information collected in a real time manner [5].

Literature review shows different approaches and results related to optimization of traffic flow. In [76], authors focus their work on decreasing the total delay time and the number of stops to have in traffic. To achieve this, they propose a cell-transmission model to simulate traffic conditions and check the obtained results for improvements. They use the model to analyze the impact of an emergency vehicle passing through normal traffic conditions and how traffic supports recovery after this event. Their described algorithm uses a 0-1 coding scheme for a mixed red-green times that provides encouraging results. A cell transmission model, along with genetic algorithms implementation is used in [77] to address traffic signal optimization problem to generate new signal timing schemes. Their case studies reveal maximized system throughput and a reduced number of spillovers, even if there are local blockages inside the system. However, their research is hard to be applied in a real-life traffic system because it was conducted on a grid-type network, which is not the case for a regular city.

A more comprehensive and interesting study was conducted in La Almozara District in Saragossa for a real non-grid-type network, see [78]. The proposed solution combines the traffic simulation capabilities and genetic algorithms to create several test scenarios that apply in real traffic conditions. Their system optimizes the traffic light cycles and the signals times, based on several predefined parameters using a static approach. Author’s intention is to extend to dynamic optimization architecture for better results. One of their conclusions was that on low traffic values, the optimization of traffic signals timings does not bring any benefit to traffic conditions. The remark is true, since for low traffic values, less optimization is required.

Evolutionary algorithms tend to offer the needed flexibility in generating new solutions when dealing with traffic signal operations problem. This statement is proved by different proposed solutions. For example, the approach used by the authors in [79] targets two goals: evolving the structure and adjusting the parameters of the intersection. Specific to evolutionary computation, setting goals represents defining the needed fitness function. Results proved that a well-defined structure reduces the complexity of the problem and changing the number of phases could help improving traffic conditions. The problem of evolving control rules at local intersection level to get results for a network of traffic signals is addressed in [80]. Their results showed that they succeeded to coordinate individual traffic signals for aggregate goals.

On this direction, I support the idea of not changing the phase order or the number of phases because negative impacts are to be expected, especially at social level. A well known consequence is the "road rage" phenomenon which is not only the reaction of drivers to what they consider bad driving habits [81], it is also the human response to the unexpected negative changes in traffic conditions. Several studies about road rage state, see [81], that it is caused by the road system itself and that it cannot be avoided. This explains why infrastructure itself can be the cause for it.

Another studied approach is the VISSIM green-time optimization method which determines the mean delay for each route. This method marks the best and worst stages for traffic lights and it uses them to adjust by one time unit per cycle the corresponding green time values. It performs this continuous changing until traffic flow values improve on the impacted direction [42]. The solution represents an interesting and efficient approach, except for the case when traffic values change rapidly. For that scenario, the change rate should be higher than one unit to respond quicker to dynamic traffic changes in order to increase the efficiency of the adaption process.

The main challenge of any traffic optimization problem is to adjust the existing transport infrastructure to maintain traffic growth. Road network is able to support some minor alterations [82], but usually geographical limitations prohibit building new roads. Costs also play a major role in avoiding this kind of solutions. Instead, the preferred solution is to optimize traffic conditions over the already existing road network. There are different ways in achieving this goal and in [83] the authors identify two major directions: optimizing the network and optimizing intersections. Optimizing the network means changing its topology by modifying the use of the streets. This solution seems to be quite limited in terms of number of possibilities. But, the idea of introducing clever routing by coupling several intersections' signals operations opens a wide variety of options [84].

The optimization of traffic movements at each intersection level, means handling specific traffic parameters that are influenced only by the intersection's local environment. For example, in [85], the authors use a sensor network that is defined to collect and analyze data in order to control traffic lights operations. The lack of a centralized coordinator makes this solution much more interesting, setting the premises for a future self adapting system. Sensors are organized as a four layer hierarchy with several communication paths between them. Traffic signal cycle is not used among the parameters of their model as they propose to reevaluate each phase and select the next phase based on sensors output. This local improvement algorithm can be extended to several interconnected intersections to monitor the impact of removing cycle length over the entire network.

There is a large amount of metrics and parameters that can describe best traffic conditions. From the number of vehicles, queue lengths and green time durations, to weather conditions or ecological impact, each characterize traffic from different points of view. But, the number of variables used by a system to function is strictly related to its complexity requirements. That is why increasing the number of monitored aspects is correlated with the amount of data collected by traffic engineers to control the entire system. This means that, the larger the hardware deployment is, the higher the number of read parameters. This is not a problem for the large scale adaptive traffic control systems (ATCS) [31],[32] or [39], but it could be one for smaller communities, where decisions should be made based on a minimum amount of information which is collected with less effort.

The first step that should be performed before adapting a real road network is to map the entire road structure onto a structure that offers different tools to analyze it. For example, each intersection can be mapped on a specific node in a graph. Next, several specific traffic metrics, such as route length, number of connections and movement directions are selected to define as accurate as possible the actual environment, generating a directed graph that can serve as a road topology model.

In this chapter, an efficient resource consuming solution is addressed to encode the minimum amount of information required to react quickly and efficient to traffic changes. The approach focuses on adapting green time values while keeping the same cycle length, to avoid creating unnecessary chaos among drivers, who will not be able to follow the order of operations. The fixed cycle length is also used to provide coordination with adjacent intersections, which is envisioned to be used in for this approach. Structured on "three layer formalism", the optimization process starts from the lower layer, represented by local intersection controllers. But improving conditions at first layer is not enough for obtaining network optimum. An active correlation of all local values is required to achieve this. Specific methods for each layer to obtain collaboration will be developed and discussed later in this thesis following a multi scale approach.

As already stated, the particularities of each social community make the problem of traffic flow optimization to not have a generic solution yet. Specific solutions can be developed for each neighborhood that can address best local traffic conditions. But, without an active coordination between these local solutions, there will be no correlation between them, so a possible global improvement cannot be visible, unless a distributed approach is followed.

The three layered formalism described in the following section present the independent stages that traffic optimization process follow to reach a global improvement at network level. The first layer uses local optimization methods to generate solutions that can improve traffic conditions at intersection level. Specific methods are proposed to adapt traffic signals to optimize traffic flow through intersections. The next layer makes sure that correlated decisions are reached using coordination between traffic signals. The main concern at this level is to assure a reduced communication overhead. Algorithms must be developed to describe efficient placement of key nodes such as selecting intersections to work in a master-slave configuration. Layer three provides methods to improve traffic flow using a high level analysis of the entire traffic network and propose algorithms that use genetic computation to generate new dynamic lane changing schemes. This formalism becomes necessary since there are specific working models that can apply at each different layer. In addition, methods can be exchanged between different implementations around the globe, making this formalism the standard optimization stack for traffic networks.

3.2 The 3-Layer Formalism

With the arguments provided so far, the local intersection's behavior should not be decoupled from the entire network. Instead, it has to be addressed locally in the quest for the global improvement. Traffic lights from each intersection lead to several local improvements. Each can be correlated as an intermediate step to network improvement. In this way, each traffic signal acts like a virtual traffic officer in intersections. To further formalize traffic flow optimization for the entire network, I propose the "3-layer stack", presented in Figure 8. Each level defines specific operations for each level. The optimization of traffic signals is considered a Layer 1 operation, because traffic lights are control devices that are already installed in intersections. Their running programs can be programmed to update dynamically and communicate each other to reach correlated decisions for network global improvements. Finding the appropriate phase order that responds to traffic changes is a problem that does not yet have a general solution. The fact is being argued by the high number of systems that are still being deployed and developed all over the world, from simple local solutions to more complex.

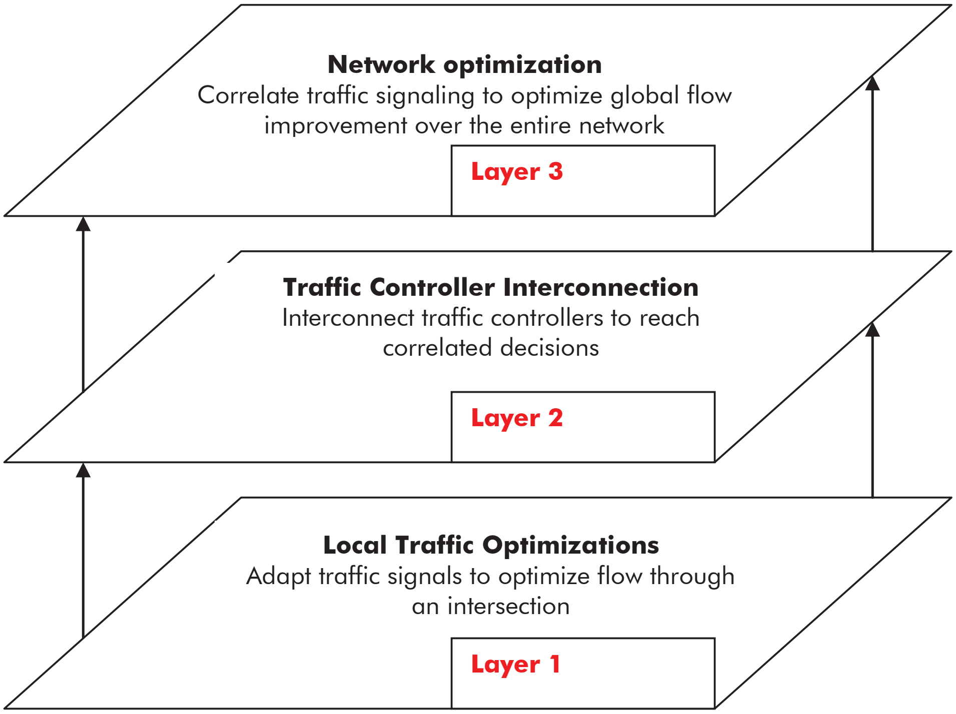


Figure 8. Traffic Optimization Stack

There is an increased interest in determining major changes in traffic values. As for a well developed system, traffic signal should do its own adjustments in terms of timings based on traffic values. This local improvement should be correlated to intersections that are connected directly in an urban network. This justifies the existence of communication between intersections at a higher level, layer 2 from Figure 8. In this case, each time a change in traffic signal timings is performed, there will be a correlation in signaling transforming traffic optimization into an adaptive process. Solving traffic issues at Layer 1 and 2 creates the scene for a global network optimization approach, defining layer 3 specific operations. Under these circumstances, a successful traffic optimization in [78] has to implement the succession of the three layers from Figure 8. Further in this chapter I will argue on an energy-efficient implementation of Layer 1, conceived to allow and operate in conjunction with Layer 2 and to expand towards a physical implementation.

In the next subsections details are provided regarding the method that implements Layer 1 specific operations and it is described the method that modifies the traffic signal settings for adjacent intersections using a heuristic approach.

The main target of the optimization process is to ensure a continuous traffic flow between key intersections. Any intersection can be seen either as a standalone entity or part of a complex network described by green times, traffic flow and cycle lengths. If nodes are left to operate independently, local solutions can be found based on the algorithm described below, leading to faster flow at local intersection level. However, nodes are envisioned to operate in synergy, by correlating intersections to achieve faster flow at global, road network level.

3.3 Layer 1 – Local Traffic Optimizations

The dynamic of any traffic light-controlled intersection can be described by a set of parameters. Each of them can be measured using sensors, calculated using well defined rules, or predicted using previous traffic information. Depending on the desired goal, different sets of parameters can be chosen. Physical ones like speed or acceleration are important for any real time system and cannot be skipped especially when designing road infrastructure. But more complex parameters, such as traffic flows and volumes for specific roads are used more often in optimization processes as they create a more general view of the urban network.

The proposed approach derives traffic signal timings based on three parameters: green time, traffic flow and cycle length. Green time is defined as the traffic allowed to flow on a specific direction in a time unit. Traffic flow represents the number of vehicles passing on a specific direction. Last, cycle length is computed as the timeframe difference between two consecutive green times. This approach is different from [83] and [4] because in these approaches the systems also use parameters that refer to vehicles physics. With these three variables, it is covered the behavior of any intersection and it can be provide the information needed to assess new timing plans. Due to reduced number of operations this will also allow for a low computational power. Since collecting traffic data falls outside the scope of this thesis, all the computations in the following section are based on observations conducted over real intersections in the city of Timisoara. Also, synthetic data simulations were performed using VISSIM software simulator.

3.3.1 Encoding intersection’s behavior

In a real-world system, measuring and collecting data traffic values still represents a challenge. In time, solutions have evolved from home and roadside interview surveys towards license plate recognition and roadside sensors that count and log in real time information. Collecting real traffic data is still a problem to solve and there is no unique solution. Deployments vary from one network city to another, from one system to another and so on. Each traffic control system has its own collecting data method mechanisms and based on these it uses specific hardware components: from city camera monitoring systems to pavement installed sensors. This is one of the main criteria in determining the cost when deploying a traffic control system.

All optimizations require major data acquisitions, which fall outside the scope of this thesis and could be a standalone subject for a future research. However, one may observe an increasing interest in what Floating Car Data (FCD) concept provides to ITS engineers [71]. The principle behind FCD is to collect real-time traffic information, like speed, car location or moving direction, using mobile phone and GPS technologies. Congestion monitoring, journey time studies and planning studies are still identified as necessary for the FCD technology. For example when the traffic values of the semaphore reach a specific threshold value, it can mark a traffic jam and send information to the FCD users, thus collecting traffic data. A weak point of this technology is the load on the communication channels, which could be avoided by using the information collected from the traffic signals timings.

So, a less expensive data gathering method automatically lowers the price of a system. But, the need for more and more road actuators is directly connected with the system’s requirement for data necessary to take decisions. A high number of computations require a high processing power leading to an exponential increase of needed resources. One can observe that a higher number of components and resources increase the cost for a complex traffic management system, as the cost with the installation and operations increase at a higher rate.

In this thesis, the method proposed for collecting traffic data is a simpler method and also an efficient one in terms of energy consumption and, more important, time needed to compute gathered data. By using a round robin method to collect data from traffic signals for an intersection the resulting method is a more cost-effective method in terms of required hardware. Another aspect to be taken in consideration is keeping to minimum the amount of information needed by a system to take decisions. An efficient traffic management system takes decisions and optimizes traffic conditions based on the minimum amount of traffic data. This is where this approach focuses, providing with the means to work efficient and take decisions with few parameters. In the next sections it is described the methodology proposed for the implementation of Layer 1 specific operations.

For the case study, a typical 4-way intersection in central part of Timisoara was chosen, see Figure 9. First step was to mark each of its four directions starting from one reference in counterclockwise direction. For each direction traffic flow values were recorded and added during a green time cycle. The values in this case study are read from traffic using a manual countdown of vehicles moving in different parts of the day. The value of “-1” marks the directions from which the traffic is leaving, meaning that on that direction the traffic signal is on green phase.

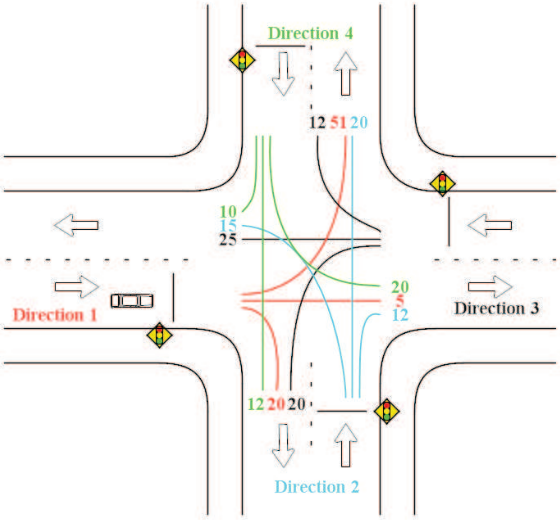


Figure 9. Traffic flow distributed over a four way intersection

The case study was conducted following a typical situation in an intersection from Timisoara, at 9 o'clock AM, on a typical working day, resulting in the average values from Figure 9. Each value represents measured traffic, in number of cars moving along the corresponding direction. Note that only one direction out of four has the green phase set at a particular moment of time. Changing green phases simultaneously for non-conflicting movements are not covered by this methodology.

Reading one intersection is straightforward, based on the following observations. In the first green time, 20 vehicles move to direction 2, 5 move to direction 3 and 51 move to direction 4. At the next step, 12 move to direction 3, 20 move to direction 4 and 15 move to direction 1. Each traffic flow value is marked during 4 steps, step 1 corresponding to direction 1 having the green time, step 2 corresponds to direction 2 having the green time. The negative value -1 marks the direction with the green phase active. Using a round robin-like method, reading data defined in Table II can be easily followed for a fully operational intersection.

Step \ Direction	**1**	**2**	**3**	**4**
1	-1	20	5	51
2	15	-1	12	20
3	25	20	-1	12
4	10	12	20	-1
Green Time	**30**	**25**	**30**	**25**

Table II. Green Time values defined for a specific intersection

The described encoding of traffic data can be generalized for any type of intersections. The number of steps required to read traffic conditions and green times equals the number of directions the intersection has. Table II can be translated into a multi-array data structure defined with the previously described rules. The last row saves the green time values as they are at the current step. Similar to the classical Origin-Destination matrix, traffic flow matrix, Td, is defined in (1) to encode all traffic values for a specific intersection into a single data structure.

$$Td[4][4] = \begin{pmatrix} -1 & 20 & 5 & 51 \\ 15 & -1 & 12 & 20 \\ 25 & 20 & -1 & 12 \\ 10 & 12 & 20 & -1 \end{pmatrix} \tag{1}$$

To summarize, the behavior for an intersection I, can be analyzed using three parameters: Gt = green time; Cl = cycle length; td[i] = traffic flow on direction i; I = {Gt, Cl, td[i]}. When coding the intersection it must be taken into account the number of vehicles passing through the intersection on a specific direction in relation to traffic signal phase, so a matrix type structure will cover the collected data. Traffic flow matrix, Td, is defined in (2) to describe any intersection behavior, with Ns representing traffic signal step and Nd, marking direction number.

$$Td[Ns][Nd] = \begin{pmatrix} -1 & d_{12} & d_{13} & \ldots & d_{1Nd} \\ d_{21} & -1 & d_{23} & \ldots & d_{2Nd} \\ d_{31} & d_{32} & -1 & \ldots & d_{3Nd} \\ \ldots & \ldots & \ldots & -1 & \ldots \\ d_{Ns1} & d_{Ns2} & d_{Ns3} & \ldots & -1 \end{pmatrix} \tag{2}$$

Without losing generality, it is considered that the number of vehicles that enter an intersection must be equal with the total number of vehicles that exit the intersection, allowing none to remain trapped between two consecutive green phases. Figure 9 gives the structure of a minimal intersection but it can be easily expanded to suit any specific intersection geometry using (2).

3.3.2 Proposed coding scheme - Modifying Traffic Signal Green Times

In this chapter, it is introduced a method to modify the traffic signal settings for adjacent intersections using a heuristic approach. First step is to adapt these values to achieve green times according to the traffic flow values in order to avoid overhead build-up on certain directions. Computing green times too often can be computationally exhausting and changes in traffic conditions are not noticed when adapting so fast [6]. There is no consensus over the frequency of reevaluating the green time values, depending on particular characteristics and requirements [1]. Their continuous adaptation can contribute to the global traffic optimization by promptly adjusting to its dynamics.

After each cycle, several computations are done, generating new green times according to traffic flow values. Two variables are defined to determine traffic conditions: *MaximumOutput* and *Local Minimum*. *MaximumOutput* is calculated as the maximum vehicle count for each outgoing direction per cycle length and it determines the direction which supports the most traffic. *MaximumOutput* also determines the direction that will feature an increase in green time. In order to keep the same cycle length for the entire intersection, at least one of the other green times is required to decrease. To achieve this, the *LocalMinimum* value is determined as the minimum traffic entering any direction. This is calculated as the minimum value from the sum of values moving each direction using (3).

$$LocalMinimum = min(\sum_{j=1}^{4} Td(1,j), \sum_{j=1}^{4} Td(2,j), \sum_{j=1}^{4} Td(3,j), \sum_{j=1}^{4} Td(4,j)) + 1 \qquad (3)$$

Equation (3) can be generalized easily to describe any intersection, see (4). After computing the local minimum, we will mark the corresponding direction where it was calculated and the directions where the green time will be reduced with a specific value. The methodology used in [85] changes phase order during a cycle length, in order to give priority to the most used directions in a cycle. The phase order will not be changed because of the determinism it introduces. The above mentioned mechanism can be coupled with other techniques used to correlate traffic movements like using offsets between traffic signals.

$$LocalMinimum = min(\sum_{j=1}^{Nd} Td(1,j), \sum_{j=1}^{Nd} Td(2,j), ..., \sum_{j=1}^{Nd} Td(i,j)) + 1 \qquad (4)$$
$$where\ i = 1..Ns$$

Using information in Table II and applying (5), *MaximumOutput* value is 51 from line 1; *LocalMinimum* is 42 and it is reached on line 4. This means that the green time on direction 1 needs to be increased with a specific value allowing more traffic to pass the intersection from that direction. Also, the green time on direction 4 will be decreased with the same value as there are fewer vehicles compared with all the other directions.

$$MaximumOutput = max(Td) \qquad (5)$$

Several rules are defined to adjust the green time on one direction. My proposal is to find out the percentage, P, defined by the maximum value from the total traffic value on that direction and apply (6) to determine *greenTimeIncrease*, further used for a new set of green times. As the average green time phase length for the case study is 25 to 30 time units, the increase will be defined as percentages. If P is greater than 33%, the green time will be incremented with 15 % of the green phase length, while if it is greater than 66% the green time will be incremented with 30%. The maximum output value represents 67% of the total number of vehicles entering that direction. Therefore the green time on direction 1 will be increased with 10 time units and decreased with the same value on direction 4. The new green times are listed in Table 2. To avoid using only one direction we have to make sure that the optimization process stops if specific threshold values are reached; otherwise recalculating green times could easily set specific green times to 0 and never reset them again.

$$greenTimeIncrease = \begin{cases} 0;\ P < 33\%; \\ 15\ \%\ of\ green\ time;\ 33\% \le P < 66\%; \\ 30\%\ of\ green\ time;\ P \ge 66\%. \end{cases} \qquad (6)$$

The proposed methodology finds the optimal traffic balance for all directions in a single intersection. Continuous recalculation will naturally lead to a point in time when adapting green times is not possible anymore. In this context it may be useful to consider each intersection as part of a higher complexity structure, a network in which intersections communicate to each other to find a global traffic optimum. The algorithm was designed to be integrated into a system as the one proposed in the last chapter of this thesis.

Key intersections exchange parameter values in order to ensure a continuous traffic flow. Changing green times on a specific direction will influence directly connected intersections to change their green times too. The *coefficient_level* is introduced based on (7), to indicate the green time changes made on a particular direction and also notify the impacted intersections about the number of vehicles moving onto that specific direction, see Table III.

$$coefficient\_level = \begin{cases} +/- High; 30\%\ increase; \\ +/- Low; 15\%\ increase; \\ 0; 0\ time units. \end{cases} \qquad (7)$$

After determining the *MaximumOutput* and *LocalMinimum* values for an intersection, it must be checked if there was any coefficient sent along the impacted direction. If such is the case, the value of the coefficient must be added after recalculating the green times. The algorithm then adjusts the result with a predefined time unit value corresponding to a High or Low levels, which should be determined based on several simulation runs. In Table III, the predefined value is 3 time units; in order to keep the same cycle length this value is added to green phase 1 and subtracted from green phase 4. Each intersection may ignore the coefficient during certain cycles if the green time values have reached or passed their set boundaries during last cycle.

	Phase 1	Phase 2	Phase 3	Phase 4
Old Green Time	30	25	30	25
New Green Times	40	25	30	15
Coefficient_level	High	0	0	-High
New Green Times	43	0	0	12

Table III. New set of green times and coefficient level

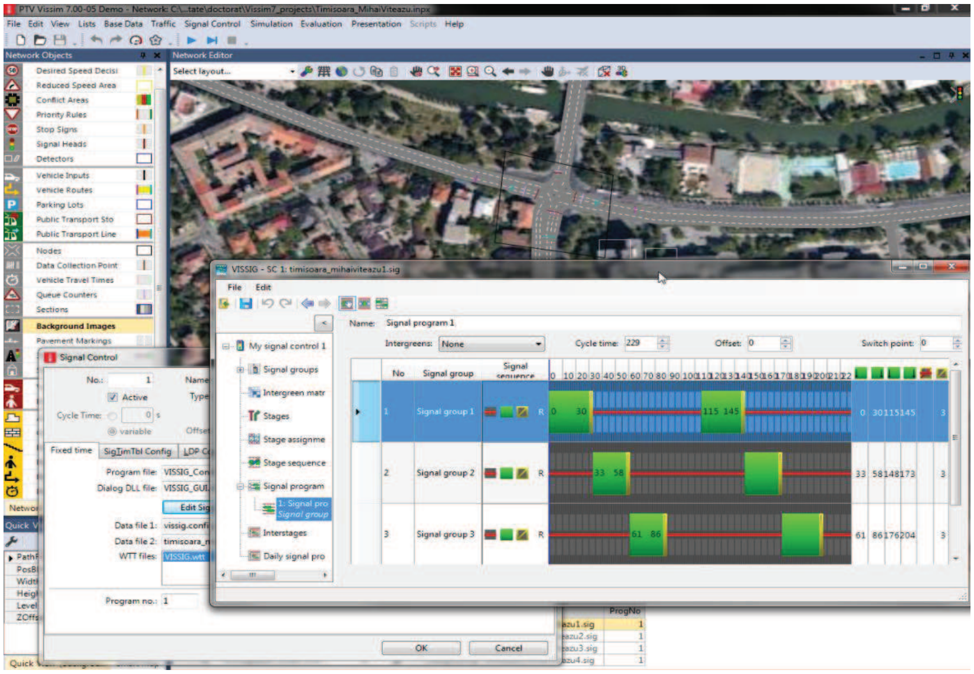
As opposed to [29], an essential aspect of the proposed methodology is considering the way the intersections are connected and influence each other by using a communication matrix C, defined in (8) based on the network defined by each city map. The line number represents the intersection sending information and the column number indicates the intersection receiving information. Take, for instance, element 3.1 from (8), which is located in line 1, column 2. This means that intersection 1 communicates with intersection 2, traffic exiting intersection 1 from direction 3 will enter intersection 2 on direction 1. Any implementation of Layer 2 requires a framework that will use the interconnection matrix data structure for the entire road network.

$$C = \begin{pmatrix} 0.0 & 3.1 & 4.1 & 0.0 \\ 1.3 & 0.0 & 3.2 & 2.4 \\ 1.4 & 2.3 & 0.0 & 0.0 \\ 0.0 & 4.2 & 0.0 & 0.0 \end{pmatrix} \qquad (8)$$

Using the above mentioned mechanism new green times are generated for the traffic signals in an intersection to respond to traffic changes. In order to test this solution using specialized tools, each of the formulas defined so far are implemented and computed separately. The results are used afterwards to generate new sets of green times for each specific intersection. The next section of this chapter presents the simulation results using the proposed methodology specific to layer 1 from traffic optimization stack in Figure 8.

3.4 Simulation Results

The proposed working model was evaluated using the VISSIM simulator, a microscopic simulation tool that provides conditions for testing different traffic scenarios in a realistic manner [42]. With VISSIM, the urban network was defined around the central part of Timisoara city and it implemented several groups of traffic lights working exactly like the real situation, see Figure 10 for the workspace screenshot.



Name: Signal program 1
Intergreens: None
Cycle time: 229
Offset: 0
Switch point: 0

No	Signal group	Signal sequence					
1	Signal group 1	R	0	30	115	145	3
2	Signal group 2	R	33	58	148	173	3
3	Signal group 3	R	61	86	176	204	3

Figure 10. VISSIM 7 workspace screenshot with signal controllers defined

Results present three traffic controlled intersections, subject to the adaptive traffic signal control, all in central area of Timisoara, see Figure 11. Using VISSIM, specific queue counters were set on each direction to monitor traffic flow. These counters record traffic data passing through during simulation time. Two parameters are of specific interest: average queue and maximum queue length. The center intersection adapts its green time phases dynamically, according to the described methodology. Traffic is injected into the urban network using VISSIM specific traffic data zone generators. During simulation, green times were adapted with five and ten time units, increasing green time for the directions heading north and decreasing south heading direction.

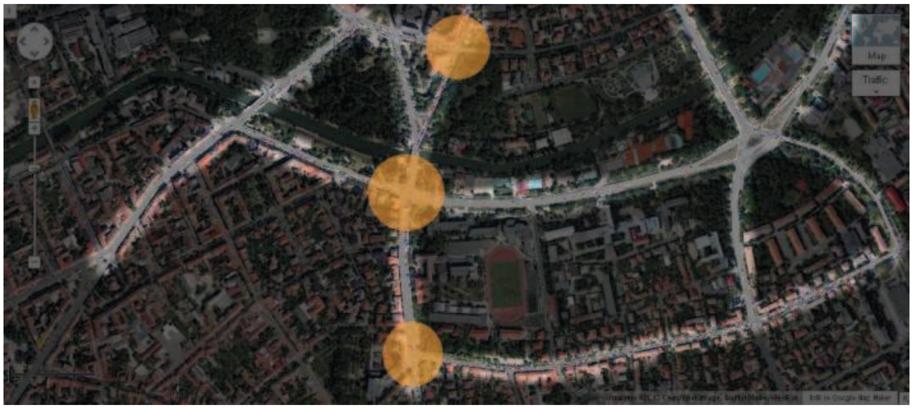


Figure 11. Case study map of Timisoara central area

To determine the impact over one of the studied intersections, traffic conditions were measured on all four exits, recording values before and after adaption of green times. The results show improvements at local intersection level for the intersection that adapts signal timings. In Figure 12 and Figure 13 the results show improvements in the overall evaluation of the parameters for the entire intersection. The green area shows the actual traffic flow after the optimization mechanism was applied. Compared with the initial value, there are moments in time when the improvements reach almost 40% percent for the Average Queue Length, see Figure 12. This parameter describes a more dynamic intersection, with shorter waiting times. Meanwhile, the Maximum Queue Length parameter shows an interest aspect when it reduces the pick the value, fact that is caused by the progressive response to the increasing traffic conditions. Because the algorithm responds to changing conditions, it is able to prevent a high queue from creating reducing this way the impact over drivers.

From the results plotted in Figure 12 and Figure 13, one can see a reduced average queue length value and a shorter maximum queue length compared with the initial values. But the most observation to see here is that traffic conditions are not perturbed on other directions, since the monitored parameters do not impact significantly the average values. Figure 14 and Figure 17 show the directions impacted by the adaption mechanism, on direction 1 the green time was increased, while for direction 4 it was decreased. The improvements for the first case are obvious and the results are the expected ones, but for direction which is reducing the green time values, the expected result would be to have an increase of queue length. As seen in Figure 17 the queue length is increasing, but as much as it has improved on the other direction. The reduced negative impact is the positive consequence of the applied optimization method.

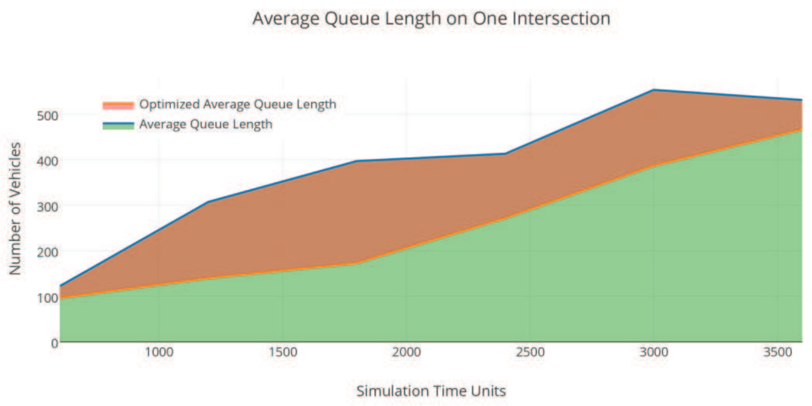


Figure 12. Average Queue Length for one intersection – VISSIM simulation results

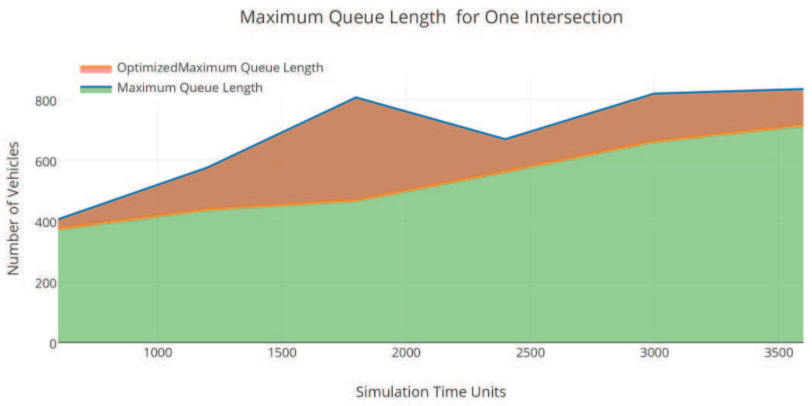


Figure 13. Maximum Queue Length – simulation results

Overall improvements are seen for the non optimized directions, where no negative impact is seen. Even though simulation traffic values were increased for the these directions, to have the algorithm changing the directions, Figure 15 and Figure 16 show good response to dynamic green adaption, by keeping the queue length close to the initial values.

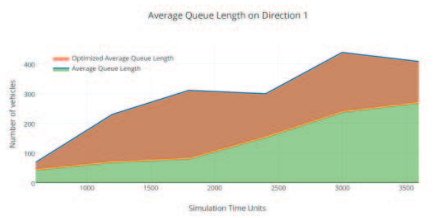


Figure 14. Average Queue Length on direction 1 of the studied intersection – VISSIM simulation results

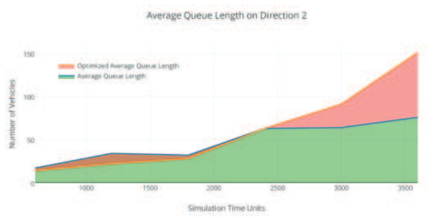


Figure 15. Average Queue Length on direction 2 of the studied intersection – VISSIM simulation results

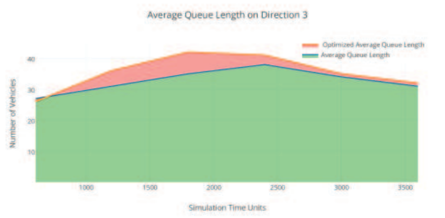


Figure 16. Average Queue Length on direction 3 of the studied intersection – VISSIM simulation results

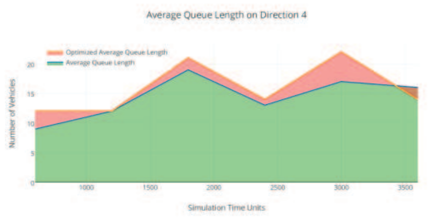


Figure 17. Average Queue Length on direction 4 of the studied intersection – VISSIM simulation results

An important aspect in Figure 18 and Figure 21 is the positive impact of the adaption mechanism over the maximum values which are reduced compared to non optimized data. Also, in Figure 19 and Figure 20 it is revealed the reduced negative impact on the other directions of the intersections.

Applying this method in a recursive manner could bring significant improvements in terms of the overall state of the intersection, results showed consistent values. But simulations also revealed that starting with the point where the injection rate of traffic flow is close to a value where all directions require a green time increase and a further communication with the directly connected intersections is needed.

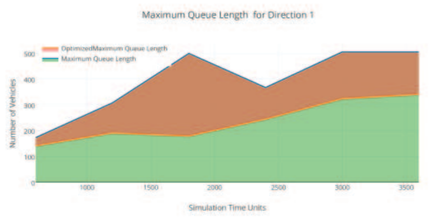


Figure 18. Maximum Queue Length on direction 1 of the studied intersection – VISSIM simulation results

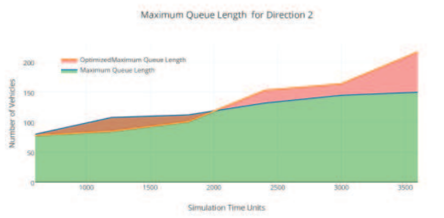


Figure 19. Maximum Queue Length on direction 2 of the studied intersection – VISSIM simulation results

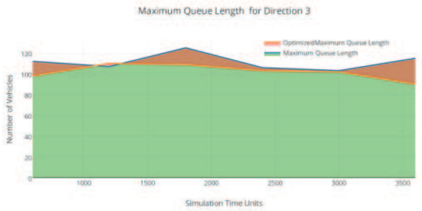


Figure 20. Maximum Queue Length on direction 3 of the studied intersection – VISSIM simulation results

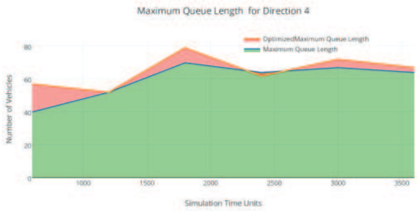


Figure 21. Maximum Queue Length on direction 4 of the studied intersection – VISSIM simulation results

I will summarize, that the local optimization reached its limitation, simulations revealed that these Level 1 operations could last for several minutes, but in the same time correlated decision is required. Next chapter will describe the next Level needed for these improvements to really count at network level.

4. ACHIEVING NETWORK ADAPTABILITY

4.1 Layer 2 - Traffic Controller Interconnection

Analyzing real traffic situations, one can observe that intersections behavior differ from one case to another and each has a unique queue forming pattern. There are intersections that have to deal with high values of traffic and others that not. This reveals that it is unnecessary to have them all communicating. An efficient way to deal with this aspect is to have the intersections act in a master-slave configuration, where only the ones with real problems exchange messages. The master will communicate with the adjacent masters about the changes that are performed locally, taking into consideration or not their response for the final computation of new green times. Slave intersections will be notified by the masters about the changes they need to adopt and about the new signal plans. This way is prevented the increase of network overhead. STiLO algorithm was developed to select master nodes, but it also proved to be an efficient method of deploying traffic lights onto a road traffic network.

In this section it is described the master selection mechanism (STiLO) which represents a novel approach in designing and deploying traffic light systems by identifying key intersections of the road network. Based on techniques borrowed from Complex Network Analysis, the described algorithm can be applied successively at different levels of granularity allowing a hierarchical clustering of the intersections and prioritization of the traffic lights, needed for Layer 2 operations.

Using the methodology described in the previous chapter, to optimize at intersection level, it is clear that it is not possible to generate improvements at network level. As described in the 3-layered stack definition provided in the previous chapter, layer 2 needs a specific mechanism to determine the role for each intersection. One can see that the intersections cannot work simultaneously and each adapt its own green times. In this context, intersections will be split in two categories, slave and master. In its acceptation, the master intersection must connect with other masters and communicate in order to take decisions that will influence also the slave intersections.

Designing traffic systems implies several decisions that need to be taken and one of the most important is where traffic lights should be installed. In this section, a complex topological approach is proposed for selecting a minimal number of intersections as key nodes. These are identified as key points where traffic lights are required based on the topological network analysis. At microscopic level this aspect may be less obvious, but changing the view to macroscopic level makes the algorithms from complex networking become applicable. By monitoring the complex distribution one can identify some key components in the network topology, such as the central intersection points [57].

4.1.1 Hierarchical Placement of Traffic Signals

The proposed working methodology is centered on topics from the CNA, presented in Chapter 2. The first step is the recursive division of each analyzed city map into topologically relevant communities. These communities contain key intersections, identified through computing the betweenness centrality metric for each community. The second step is represented by the hierarchical assignment of traffic light controller and the associated controllers to key intersections identified at the first step.

Each city network topology is defined as the set of interconnected nodes (intersections) in which possible optimizations are viewed as part of the three-layer stack [50]. From this point of view, each node may implement traffic lights controllers, or semaphores. These can generate local optima values in terms of traffic flow, building Layer 1 operations from the 3-layer optimization stack. However, not all traffic lights can communicate and coordinate their actions, but those who do generate Layer 2, which will consist of master and slave nodes.

Achieving Pareto optimality for the global traffic flow is linked to managing local traffic flow; however, combining local optima do not necessarily lead to a global optimum. Therefore, the proposed approach to optimize traffic flow, by maximizing or creating continuous flow wherever possible relies on managing communication and change of role between master and slave nodes. Master nodes are defined and uniquely chosen in their communities. They are responsible for any decision takes at community-level. Slave nodes are defined as nodes directly connected to master nodes. They are responsible for adapting their green phase durations based on their local conditions and on the instructions received from connected master nodes.

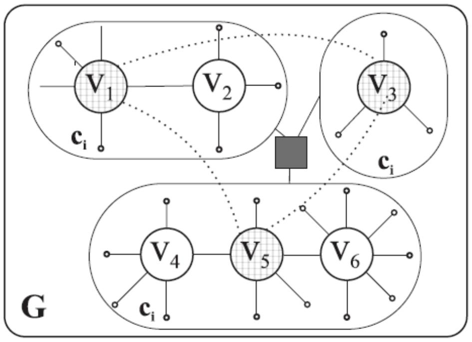


Figure 22. Hierarchical structuring of intelligently managed traffic light intersections

In Figure 22 a road network consisting of 3 communities is presented. The applied must run a selection mechanism to identify groups of master-slave nodes in order to advance from Layer 1 to Layer 2 and to change the approach from computing a global optimum to an adaptive mechanism. Grayed nodes represent (V_1; V_3; V_5) master type intersections organized at Layer 2. All other nodes in each community represent slave nodes. These are obtained after running the proposed methodology. Each identified master traffic controller has the authority of changing dynamically the green time on any of the traffic lights in its community (c_i) as long communication is possible. Nodes identified as masters will coordinate at Layer 2 traffic movements generated at Layer 2. From layer 3 point of view, each of the communities is clustered from a logical point of view exchanging information between master nodes of distinct communities so the grey square represents a logical connection between the communities identified in Figure 22.

In order to identify a set of master nodes to be used for a real road traffic network, the algorithm must be run at different resolutions, generating communities along with the corresponding master-slave nodes. This methodology has two possible applications. One is in the context of selecting the master node for the 3-layered stack proposed approach and a second one of efficient placing traffic lights into the road network. The resulting nodes determine where traffic controllers are required.

The following section describes how master and slave nodes should be chosen and how the communication should take place in order to increase traffic flow, as a specific Layer 2 operation. Since the road network supports dynamic changes in traffic conditions and control priorities, nodes could also react and change roles.

Communication between master nodes has to implement the following message exchange sequence. Once a master node makes adjustments on its timing plan, for a specific direction, it will send a message notifying the directly connected masters on that direction about the changes. Based on local traffic conditions, the receiving node decides if it can take into consideration or not the adjustment request to modify its timing plan based on the neighbor’s recommendation. The receiving node must acknowledge the message whether it is taking into consideration the changes or not. In case of a negative decision, the sending master node will not make any further changes on that direction until a positive one is received.

4.1.2 Community detection

For the methodology to be implemented, communities must be identified. They are defined as clusters of nodes that have similar structural characteristics, in this specific situation having a high density (connectivity) inside the community and a lower connectivity with other communities [55]. Gephi is an external tool used for large graph analysis and it has an implementation of the community detection algorithm as described in [86]. It uses a single parameter, the resolution, the lower the value, the larger the number of identified communities, each with fewer nodes, with a default value of 1.0. Therefore, a consistent methodology for choosing the resolution is required. Figure 23 identifies the number of communities against the resolution value after taking into consideration a set of major cities from Romania and Europe. The cities were chosen based on their variety in terms of surface and population density.

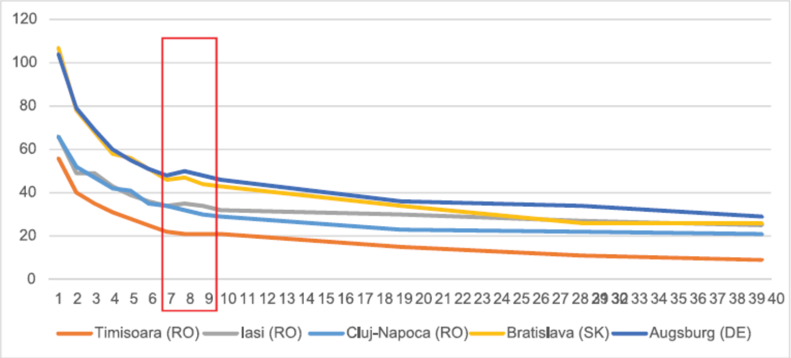


Figure 23. Dependence between the resolution and the number of communities

An almost exponential decay of the number of detected communities occurs in the left part of the chart, marked by the rectangle in Figure 23, an inflection point marking the area from where this becomes almost logarithmic. The user has to choose a suitable value for RES inside the marked area manually which is going to be used in the next step of the working methodology. The results show an approximate mapping onto the historical neighborhoods. This value is recommended to be chosen so that the number of resulting communities is closely to the one if the neighborhoods in the city. For example, for Timisoara case study, value 10 was chosen, which generated a close number of communities to the number of historical neighborhoods.

4.1.3 STiLO methodology

The topology of each city is defined by the graph G= $\{E,V\}$, where $E = \{\, e_{\,i} |\, i = \overline{1,n_e}\,\}$ is the set of all edges (streets), with n_e being equivalent to the number of streets and V= $\{\, v_{\,i} |\, i = \overline{1,n_v}\,\}$ is the set of vertices, with n_v being the number of intersections.

The proposed algorithm is called Social Traffic Light Optimization, STiLO, proposed in [87] . It uses two parameters, the resolution RES, previously determined and the threshold THRESH value for stopping the recursion, also chosen by the user. TRESH determines the number of nodes in a community, the larger the TRESH, the larger the community. The recursive process is implemented by function assignMaster(G,RES,TRESH), which runs the community detection algorithm as described in [86]. Subsequently, for each of the detected communities $(c_i \in C)$ the betweeness centrality is computed for each node v_i, as in [88]. The nodes are ranked and the master node is selected based on the maximum value of the betweenness. The hierarchical nature of the algorithm is implemented as a recursive process so the same methodology is applied for each of the "smaller" communities of c_i until the number of nodes in a community is less than the specified threshold value, TRESH.

Algorithm 1: Traffic Light Optimization (STiLO)

Input: city road road digraph $G = \{E, V\}$ with positional data (v_i, v_j). RES-resolution

```
input : $G = E,V$
define $RES = 10$
define $THRESH = \log_{10}|G|$
function assignMaster(G, RES, TRESH) {
        $C = detectCommunity(G,RES)$
        foreach $c_i$ in C do {
                foreach $v_i$ in $c_i$ do {
                        $betwenes s[i] \leftarrow computeBetweenes(c_i, v_i)$
                }
        $max\ Betweenes \leftarrow max(betweenes[\ ])$
        $v_{master} \leftarrow c_i[max\ Betweenes]$
        if($|c_i| > TRESH$)
                assignMaster($c_i$, RES, TRESH)
        }
}
```

Output: the list of master nodes

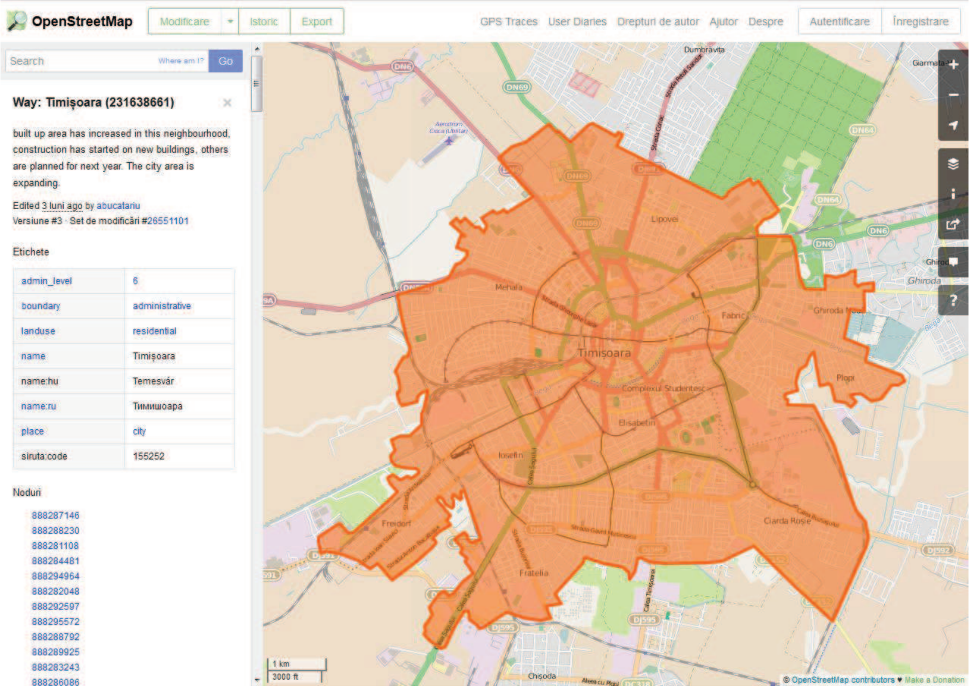
4.1.4 STiLO Applied over Timisoara - A Case Study

Studies were conducted on Timisoara, the second city in Romania in terms of both population and urban density, placed in the western part of the country. Founded during the medieval era, the city witnessed numerous changes in administration, from ottomans to Austria-Hungarians being transferred into Romanian administration in 1918. Each of the rulers influenced today's current city architecture and layout. Two almost disjoint sets of urban layouts are distinguished inside the same city. One is represented by the old city center organized during the Austria-Hungarian administration and clustered around a central public square with a radial-concentric topology and the other is more recently built, during the communist era, with wider boulevards and narrow maze like streets spanning between these boulevards. Moreover, the city is divided in two almost symmetric parts by the Bega canal, the two sides having 16 bridges, of which 10 are suitable for car passing and the rest are for pedestrians and bicycles.

Several external tools were used for the investigations. Gephi, version 0.8.2, which offers the tools to dynamically determine nodes and edges related characteristics based on graph theory notions, such as: average path length, modularity and betweenness distribution. Input graph data were obtained by parsing the OpenStreetMap (OSM – see Figure 24) export XML file via customized Python scripts. For each city, the data was stored in a flat database a bounding rectangle specified by the geographical coordinates of opposite corners. Shell scripts were used to parse the database and build appropriate queries for the Overpass API which provided raw XML with the semantics of OSM.

Resulting file contains relevant data for the investigation in the form of nodes(id,lon,lat) and ways(id, nd(nodeIs), tags(key,value)) represented as an ordered list of nodes from start to stop. The list of tags is used to specify various attributed for ways in a key-value format. The road type attribute was used to filter pedestrian lanes and the number of lanes attribute was used in order to associate weights to each edge. The graph representation of OSM was normalized by eliminating the intermediary nodes which were used in the original data set in order to represent curved roads. Consequently, the resulting data represent strictly the topology of the interconnections and not the shape. The filtered data set is written by the Python script in the proper form of a Gephi compatible GEFX file.

Table IV summarize some of the specific metrics that were established in the field of CNA applied on the Timisoara graph dataset using Gephi. The average node degree signifies that most of the intersections have at most two other connecting roads - classical T crossroads - which is specific for the block quarters. The network diameter is defined as the longest of the shortest paths in the graph and signifies the maximum number of intersections trough one has to cross in order to traverse the city. Together with the average path length this is considered as being some of the defining metrics for the quality of the urban road network.



Way: Timișoara (231638661)

built up area has increased in this neighbourhood, construction has started on new buildings, others are planned for next year. The city area is expanding.

Edited 3 luni ago by abucatariu
Versiune #3 · Set de modificări #26551101

Etichete

admin_level	6
boundary	administrative
landuse	residential
name	Timișoara
name:hu	Temesvár
name:ru	Тимишоара
place	city
siruta:code	155252

Noduri

888287146
888288230
888281108
888284481
888294964
888282048
888292597
888295572
888288792
888289925
888283243
888286086

Figure 24. OpenStreetMap view of Timisoara

Parameter	**Value**
Number of nodes	4070
Number of edges	5542
Average degree	1.434
Diameter	61
Average path length	42.916
Modularity (res = 10)	0.938

Table IV. Main topological parameters for Timisoara case study map

The urban structure of Timisoara is seen in Figure 25, in form of a graph where each "dot" represents an intersection. Each community is represented with a different color. As the algorithm is relaying on the concept of community as seen in the field of CNA the community detection was applied on the entire graph in order to obtain what is defined as first level communities. Of particular interest is the fact that topological communities map really well onto the traditional quarters of the city. Figure 26 shows traditional quarters of the city identified as complex network communities and the main topological metrics. Of particular importance for the quality of the urban road network is the average path length and the average degree. In each of the subfigures it is shown the value for these parameters and one can observe the fact that the Circumvalatiunii (Figure 26 – a) quarter is having the highest average degree (3.309) which corresponds to a large number of X crossroads. The low value of the average path length in Giroc and Chisoda villages (Figure 26 – d) is consistent with the almost bipartite structure of the two subgraphs.

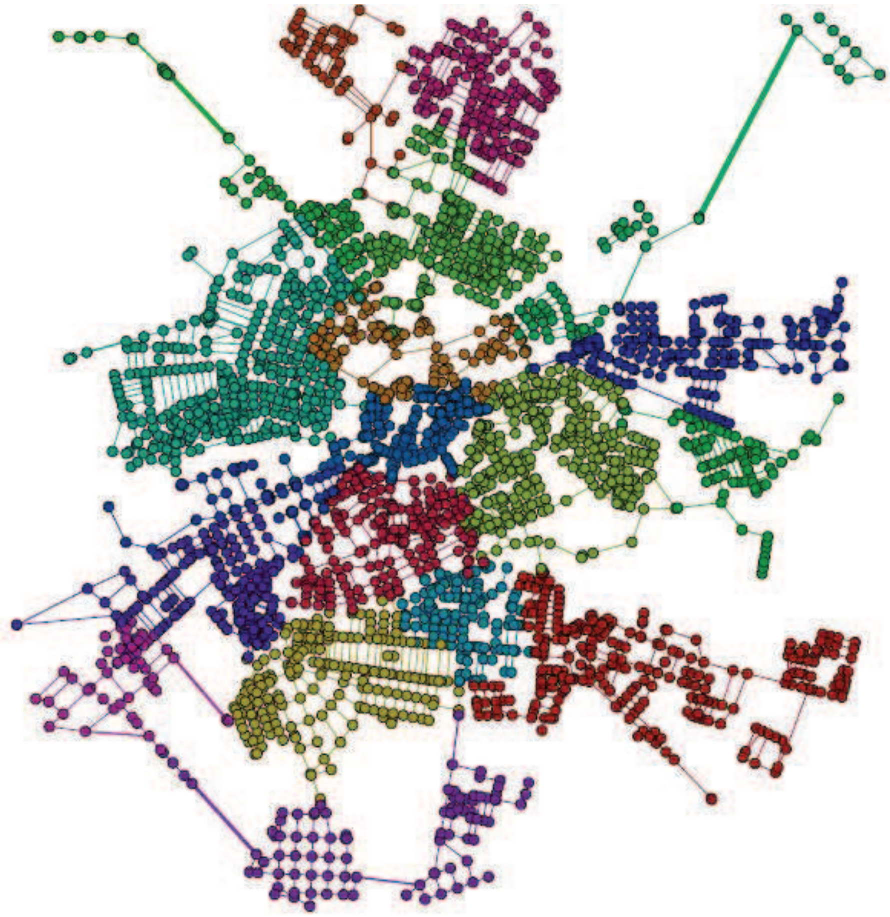


Figure 25. Timisoara's street infrastructure generated by Gephi, with communities colored distinctively

After applying STiLO methodology, a set of master nodes are obtained, indicated by the high value of betweenness metric. From traffic point of view, these nodes represent highly loaded nodes that could lead, in time, to significant traffic jams. These nodes could become key intersections for any traffic optimization process. Case study conducted over the city of Timisoara revealed a match between the nodes identified by STiLO and real intersections with significant traffic problems.

Figure 27 presents the application of the recursive process on a community detected in Timisoara. Smaller sets of nodes are obtained after each step of the methodology. Recursion was stopped at level 4 of recursion, but depending on THRESH value, even more granularity can be obtained if necessary. In subfigure (f), the partitioning of a community of 71 nodes is shown in subfigure (e) into 3 subcommunities. At each level the node with the highest betweenness was emphasized with a red circle, the one which is to be considered as a master, in the described mechanism (subfigures (a), (c), (e)).

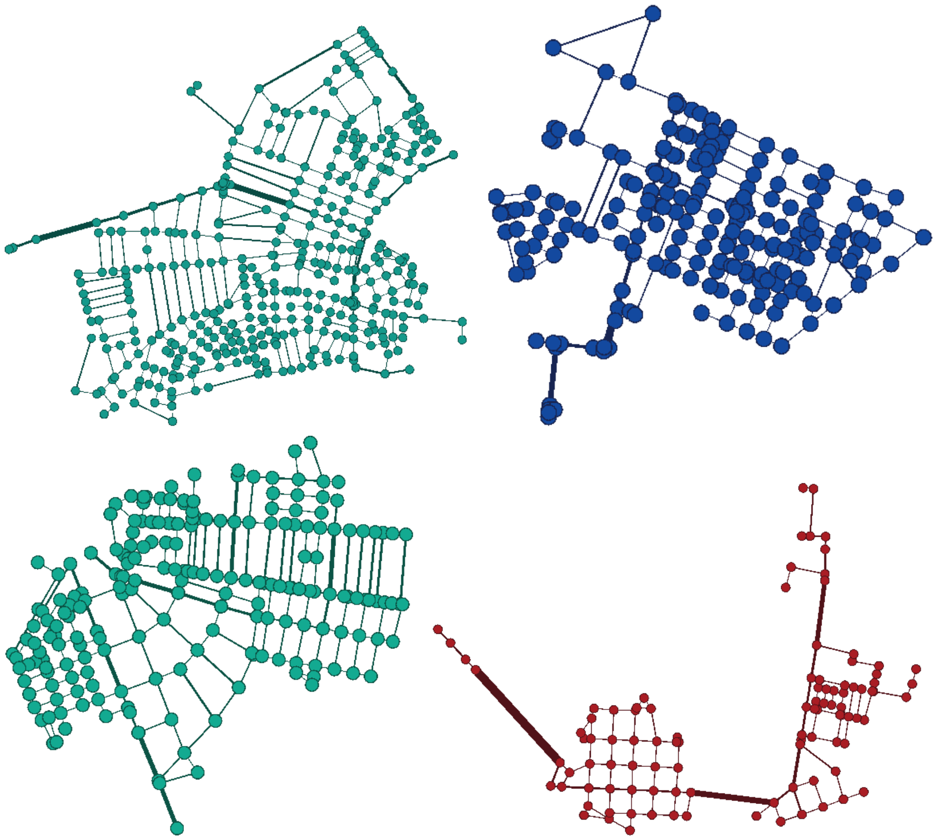


Figure 26. Detected communities and the corresponding quarters of the city (a) Circumvalatiunii 362 nodes, Avg.degree=3:309, Avg. path length=12:62, (b) Aradului: 297 nodes, Avg. degree: =2:863, Avg. path length:= 13:33, (c) Girocului quarter: 206 node, Avg.degree= 2:951, Avg. path length=10:589, (d) Girocului and Chisoda villages: 88 nodes, Avg. degree= 2:951, Avg. pathlength= 9:683

STiLO methodology applies the community detection and betweenness centrality algorithms, specific to complex network analysis into the field of urban transportation. The results emphasized that the proposed method identifies the hotspots in traffic based on the network topology. STiLO proved to be a suitable algorithm for hierarchical placement of traffic lights under the form of master and slave nodes, necessary for the Layer 2 and Layer 3 of the implementation of 3-Layer formalism proposed in Chapter 3. Furthermore, STiLO proposes an efficient method to identify the intersections in a city where traffic lights are required and where coordination is needed to improve traffic quality.

The case studies confirmed the correct identification of the master nodes as intersections where traffic jams usually happen.

Efficient placement of traffic lights is also an important aspect to take in consideration, if this method is combined with an already installed ITS. STiLO methodology also contributes to reducing deployment and maintenance costs for the infrastructure and also lowers the impact over the environment through low emission levels due to improved traffic flow.

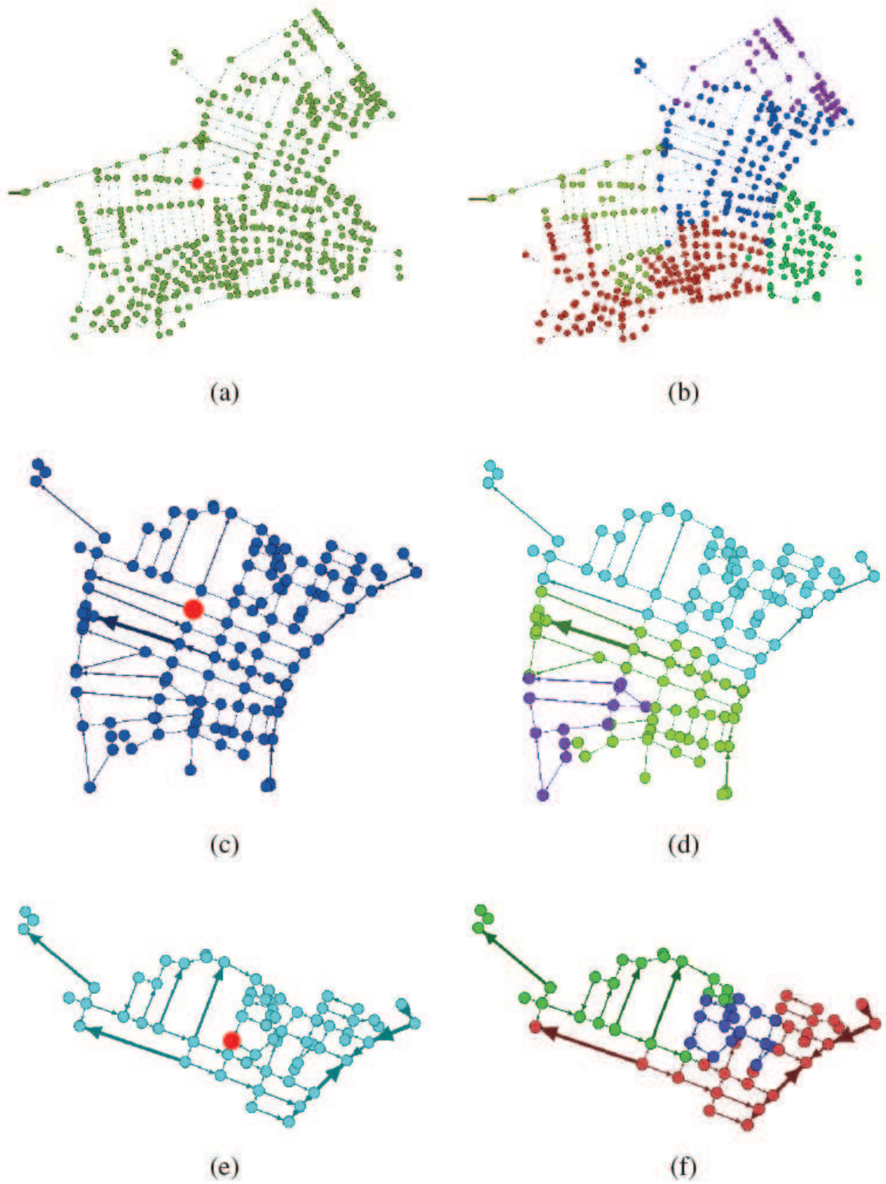


Figure 27. Recursive application of the STiLO algorithm for the community presented in Figure 6(a)

4.2 Layer 3 – A Bio-Inspired Redistribution of Traffic Flow

This chapter, describes an approach that revolves around finding congestions hotspots in a given road network, pointed by their high betweenness centrality value. After this first step, the algorithm will adapt the associated directions in order to level the distribution of the betweenness values. Since this approach is hard to implement on global scale, covering an entire city's road network, this will first apply at local scale, to sub-graphs, called communities. Having optimized these communities, it will turn out to a more balanced traffic flow at network level.

The comparison of the obtained results with real traffic data showed a correct identification of the hotspots for several case studies. This shows the potential of this algorithm to help adjacent intersections redistribute traffic flow leading to more balanced values for an entire network. Layer 3 can group other algorithms that target the same network improvements and work with changes on local community level.

4.2.1 Prerequisites

Road traffic network is analyzed using some basic network metrics, already presented in previous chapters: network size (nodes and edges), average path length, clustering coefficient, average degree, network diameter, density and modularity, and also the distributions of the degrees, betweenness, closeness and centrality. This network analysis will help leverage the street reorganization to better correlate communities to each other by using community detection and centrality algorithms.

A short walk through the concepts used, states that the average path length of a network represents the average of all path lengths over all paired nodes. The average degree of the network also defined as the average of all node degrees. Modularity measures how well a network can be split into different communities. The higher the modularity, the best-delimited are these communities. Betweenness centrality determines a node's influence into a graph. It is computed as the number of shortest paths passing through a specific node, divided by the total number of shortest paths.

Mapping specific metrics on to a road traffic network, nodes over intersections and edges over roads, it is true to state that a node with high betweenness maps onto a key intersection passing a high amount of traffic flow. Based on this definition and taking in consideration the usual driving habits of always choosing the shortest path, one can conclude that nodes with high betweenness in a city network are nodes which are, or may become congestion hotspots.

The proposed methodology relies on the concepts described above to describe the quality of traffic road network. This is why, the first step is to find the right communities so they present a good match between them and each city's neighborhood. In order to achieve this, fine tuning process has to be done, by adjusting the resolution parameter when identifying communities. There is a social aspect in is approach because the road network is the result of the human society and because neighborhoods tend to map very well onto communities, showing some local patterns of streets usage and traffic.

The second step of this methodology uses genetic optimization aspects to cope with traffic problem. The metric for the road quality is defined by the slope of the interpolation line of the betweenness distributions for each community. Further, a genetic algorithm is implemented that swaps random edges of the directed network, until it reaches the fitness function. Based on the common agreement that the better route to take is the shortest in time instead of shortest in distance, the decision is to increase the betweenness values of the nodes having the lowest values in order to redistribute traffic to segments that can support more.

A simpler approach was proposed in [89], where the authors had the redistribution of traffic flow done only by changing one random direction. This proved to be not enough, as the impact of only one way modification did not had consistent improvements on different case studies.

Because of the social aspects present in this approach and also of the bio-inspired, genetic algorithm implemented for redistribution of traffic flow at local intersection level, this methodology is named Social Intersection Genetic Shuffler (SIGS) and it is proposed in [90].

4.2.2 SIGS Methodology

The same approach described in the previous chapter is used to extract road traffic infrastructure information and reducing it to a manageable graph. Using the same tools, from the OpenStreetMap exported maps to the import of customized files into Gephi software, the input data for this methodology is obtained.

Consider G= $\{E, V\}$ be the graph representing the topology of the city, where $E = \{\, e_i \mid i = \overline{1, n_e}\,\}$ is the set of edges and V= $\{\, v_i \mid i = \overline{1, n_v}\,\}$ is the set of vertices, with n_e and n_v being the number of streets and number of intersections. Also, each node contains information about its position in the form of (n_i , n_j) pairs, needed for the application of GeoLayout plugin used by Gephi to map the entire graph onto the city layout. Using the same information, the position of the obtained hotspot is mapped onto a real intersection.

First stage of this methodology will be represented by the recursive breakdown of the road graph into smaller communities, c_i considered as relevant. As described in [86], communities are detected, and for each of them, the following values are computed: the initial betweenness distribution, B, and the slope of its linear distribution, m_0.

The next stage is related to the analysis and optimization of the distribution values, and this is being performed by the geneticShuffle() procedure, shown in Algorithm 2. After applying this above mentioned procedure, a new population is generated, representing the newly generated community, c_i ‘. This shuffle randomly selects pairs of two communities with betweenness in the defined interval of (LowThresh, HighThresh). The limits can vary and are empirically determined based on size of each community and also on the value of betweenness distribution. For the current implementation, the values represent 20% and 80% from the maximum value of the initial betweenness. At the next step, the new population is generated, as the new Set of nodes, obtained from the crossing of two random before selected, Set1 and Set2.

The mutation is applied on this new Set by changing the direction of the adjacent nodes. In this manner, the new generation will have modified directions and therefore will change the betweenness distribution. Using this new distribution, the new slope is computed, m1, and the fitness function is defined. The fitness is calculated for each community and it represents the absolute difference between the slopes of the initial population and of the newly generated population. The threshold for this fitness function is set to $\varepsilon = 10^{-2}$, considering this value as a consistent value for this slope change.

Algorithm 2: Social Intersection Genetic Shuffler (SIGS)

```
Input: city road road digraph $G = \{N, R\}$ with positional data $(n_i, n_j)$. res-resolution

A: Core algorithm
$C \leftarrow detectCommunities(G, res)$
foreach $c_i \in C$ do :
    do
        $B[] \leftarrow computeBetweeness(c_i)$
        $m_0 \leftarrow slope(linearInterpolate(B))$
        $c_i' \leftarrow geneticShuffle(c_i, B[])$
        $B'[] \leftarrow computeBetweeness(c_i')$
        $m_1 \leftarrow slope(linearInterpolate(B'))$
    while $(|m_1 - m_0| > \varepsilon)$

B: GeneticShuffle procedure
$geneticShuffle(c_i, B[])\{$
    $Set_1 \leftarrow randomSet(c_i, B[i] > HIGHTRESH)$
    $Set_2 \leftarrow randonSet(c_i, B[i] < LOWTRESH)$
    $Set \leftarrow Set_1 \cup Set_2$
    foreach $(n_i \in Set)$ do
        foreach $(n_j'$ adjacent $n_j)$ do
            $mutateEdge(n_j, n_j') \Leftrightarrow swap(n_j, n_j') \leftrightarrow (n_j', n_j)$

Output:road network $G$ with normalized betweenes distribution
```

4.2.3 SIGS Applied over Timisoara – A Case Study

The first conducted case study was applied over the city of Timisoara, because some of the results were already confirmed by reality after using STiLO methodology. Other reasons to choose Timisioara were the relative mapping of communities over the historical neighborhoods of the city and the correct identification of traffic hotspots in traffic obtained in the previous chapter. The input data was the same as for STiLO methodology, making the results more consistent. The only drawback in using Timisoara as a case study is the lack of traffic information that is not provided by Google Traffic Layer for this specific region. The confirmation of results is done through my personal experience with traffic conditions in this city.

Figure 25 shows the city map generated by Gephi with the communities identified after running the community detection plugin. SIGS iss applied on different communities identified within the city. The following figures show the results obtained after running the proposed algorithm on several neighborhoods, selected to be in different parts of the city.

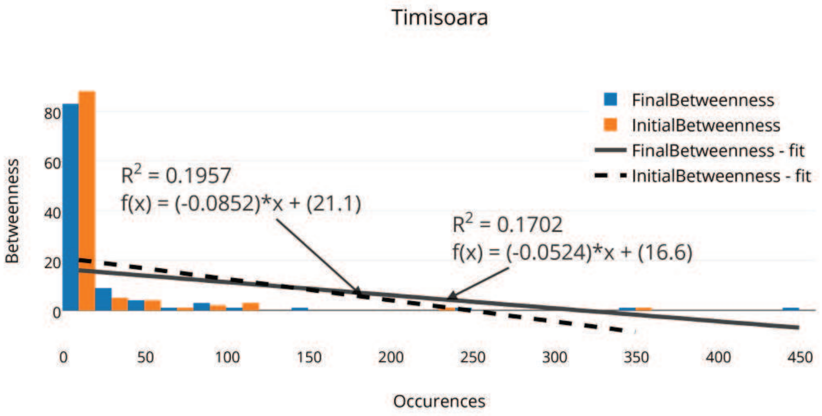


Figure 28. Timisoara around "Cetatii Boulevard"

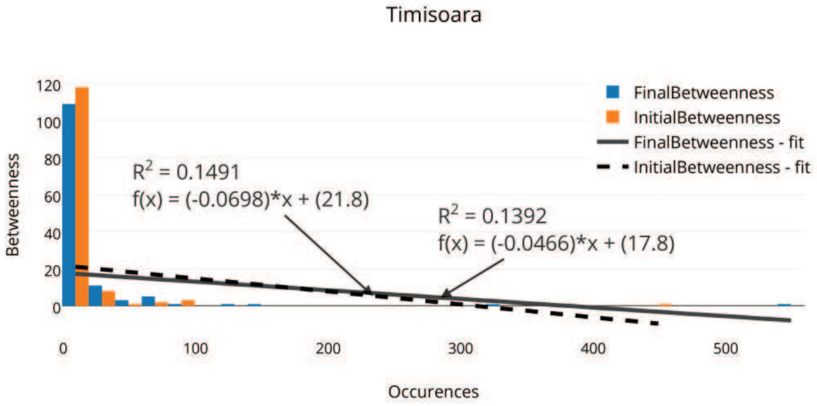
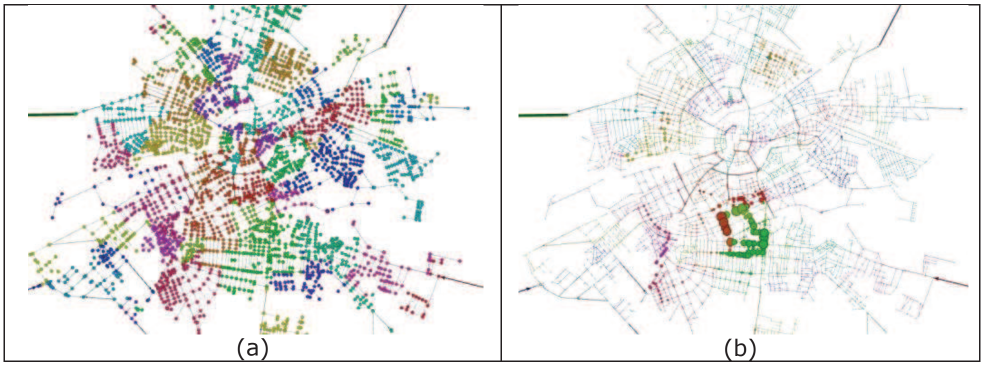


Figure 29. Timisoara, central city area, around "Mihai Viteazu Street"

An interesting remark after running this algorithm is pointed in Figure 30. In subfigure (b) the identified backbone for the city displayed in subfigure (a) is displayed based on the value of betweenness metric. This topological analysis of Timisoara road network identifies the backbone, but with major traffic hotspots in one part of the city. But in this particular case study, personal experience shows that in our city there are more traffic hotspots concentrated in several different parts of the city. So, this could lead to the conclusion that what we experience in Timisoara is mainly caused by a non optimal traffic signaling. It also points the influence of social life over traffic conditions. An important aspect is that social activities in Timisoara are concentrated in the north part of city, where the city mall offers all that facilitates social interaction: coffee shops, cinemas, food courts and even a hypermarket.

This only explains the failure in managing inbound traffic using the current road infrastructure without any intelligent solution deployed. The next simulations show an almost perfect match between real traffic hotspots and the ones identified in reality.



(a) (b)

Figure 30. Timisoara case study map; Subfigure (a) shows communities identified after running first step of SIGS; Subfigure (b) displays the identified "backbone" of the city where the highlighted nodes have the highest betweenness

4.2.4 More Simulation Results for SIGS

This methodology was applied over different cities, selected to cover different continents, different city layouts, from radial to grid topologies, and each with specific geographical and/or social characteristics, either divided by rivers, others on seaside. For the sake of clarity and better understanding, only three case studies will be detailed further. These cities are Budapest in Europe, Los Angeles from North America and Sendai from Asia. Another aspect was taken into consideration when selecting cities for simulations, naming the online availability of real traffic information which will be used to compare with the obtained results.

Table V summarizes key topological properties of the studied road networks, correlated with the demographic characteristics for each analyzed graph: initial number of nodes, edges, number of communities and also the number of neighborhoods resulting after applying SIGS. The similar average degree is specific for transportation network, because they are inherently flat, while the average path length is in close relationship with the size of the road network. The high modularity values show how well defined is the community structure. A first observation is related to the small number of communities in Los Angeles. This is due to the regular grid type topology it presents, which generates larger communities.

City	**Budapest, Hungary**	**Los Angeles, USA**	**Sendai, Japan**
No. of nodes	12308	29759	42807
No. of edges	17309	44226	59224
No. of communities	147	122	336
Modularity	0.979	0.972	0.983
Average path length	30.175	73.044	47.094
Average degree	1.428	1.486	1.384
Population density	3.31	3.2	1.31

Table V. Static topological characteristics of presented study

One aspect to follow in this table is the number of communities. This provides the initial data set of the genetic algorithm and from the urban point of view it roughly maps onto the neighborhoods of each analyzed city. Using the resolution parameter, it is possible to influence the number of obtained communities. In these simulations, the fixed value of 1 is used, but the higher the value, the higher the number of communities.

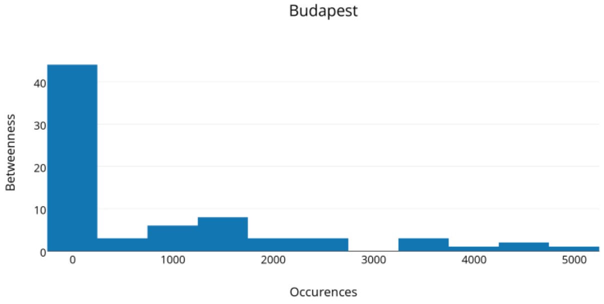


Figure 31. Betweenness distribution for nodes in Budapest

Recursively the community detection algorithm is applied on the entire input graph, the city network, and on each of the described methodology is described. The investigation is started on the city of Budapest, because of the geographic reason of being close to Timisoara, author’s hometown. The initial input graph consists in 12038 nodes and 17309 edges and these are divided into communities of 500 to 1000 nodes. Figure 31 shows the power-law betweenness distribution of the intersections in Budapest. The high betweenness nodes have to handle large amount of traffic and susceptible to congestion phenomenon. This distribution is typical for social networks, where high influencing persons are in the center of the relations network. But this is not a desired distribution in a city traffic infrastructure. This would mean that there are intersections through which most of the drivers would pass regardless their route and destination. SIGS, balances this distribution towards a more uniform one, reducing the number of nodes with high values, while slightly increasing the ones with lower values.

Figure 32. Case study data sets regarding traffic hotspots in three cities taken into consideration: Budapest, Downtown Los Angeles and Sendai; Subfigures (a), (b), (c) show the identified communities after applying the first step in SIGS; Subfigures (d), (e), (f) display the identified "backbone" of the city, the nodes with high betweenness have larger size; Subfigures (g), (h), (i) represent data captures from Google Traffic Layer showing traffic conditions in the areas of interest

Budapest is the capital of Hungary, an old city which combines also elements of modern urban planning. It has large boulevards, good subway infrastructure which supports major traffic flow through the city and offers an efficient alternative for the road infrastructure. One specific aspect is the fact that it is divided by Danube river and it has seven major bridges crossing it, which, as expected, introduce bottlenecks in traffic flow. Its topology is depicted in Figure 32 (a). After running SIGS algorithm the obtained network is presented in Figure 32 (d), in which one can perceive the distribution of the most crowded intersections. Figure 32 (g) sets the Google Traffic Layer which shows a good correlation with the results obtained before.

The next city analyzed is Los Angeles. Because of its great metropolitan area size, a sample containing a large part of the city is taken into consideration and not the entire one, Figure 32 (b). Of interest are two particularities of this city. One is the complex infrastructure, consisting in highways that crisscross the metropolitan area and act as long links over the graph and providing a more uniform distribution. This is seen in one dataset which consists in of an area having almost 20% of the network covered only by highways. In this case traffic is taking the high speed links and there is no overcrowding on local level. Another dataset represented a typical downtown area with a grid street layout. For this case, improvements are seen and come from providing two-way routes in some of the crowded areas. Google Traffic Layer offers significant information for this city and because of that, a large time window was used for finding peek intervals (morning, evening rush hours). The correlation between the SIGS generated data and the online traffic data can be seen in Figure 32 (e) and Figure 32 (h).

The third city to take in consideration is Sendai, Figure 32 (c). Placed on the ocean-side, it has also a well developed infrastructure being a major transportation hub in that area. Because of the known efficient public transportation system, there are no major problems reported. But, from the algorithm’s point of view, a limit case can be imagined and possible hotspots will map over the smaller ones, Figure 32 (f) and Figure 32 (i).

In sub-figures from Figure 32, one can perceive the good correlation between the areas identified with SIGS methodology and the roads affected by high traffic values, pointed by the captures from the Google Traffic Layer showing historical traffic conditions. Subfigures (d), (e), (f) offer an overview of traffic “backbone” of the city.

Based on the datasets used to generate subfigures in Figure 32, betweenness distribution slopes are computed for several communities in the analyzed cities. Table VI shows the initial and final slope value of the interpolation of betweenness distribution along with the improvement obtained after running SIGS. The improvement percentage is determined by dividing the increase or decrease to the original slope value. For example, for BUD1, the improvement is computed as follows: (m0-m1)/m0 *100.

Data set	**m_0**	**m_1**	**Improvement [%]**
BUD1	0.0778	0.0458	41.13
BUD2	0.2198	0.0533	75.7
LA1	0.0070	0.0064	8.57
LA2	0.0277	0.0142	48.74
SEN1	0.184	0.145	21.2
SEN2	0.0172	0.074	-41.2

Table VI. Initial and final distribution slopes, showing obtained improvement

Comparative analysis of the betweenness distribution before and after running SIGS algorithm is presented in the following figures. Each area of interest is presented in a figure with the linear interpolation of the optimized and non optimized betweenness. Figure 33 shows improvements over a community detected in the city of Budapest. The initial slope m0 is reduced from 0.112 to 0.061 which represents an improvement in the redistribution of node betweenness from the analyzed community. The variations of slope values presented in the community in Sendai city, see Figure 34, show small differences, from an initial m0=0.184 to m1=0.145. The positive in this case is that there is no degradation of this network.

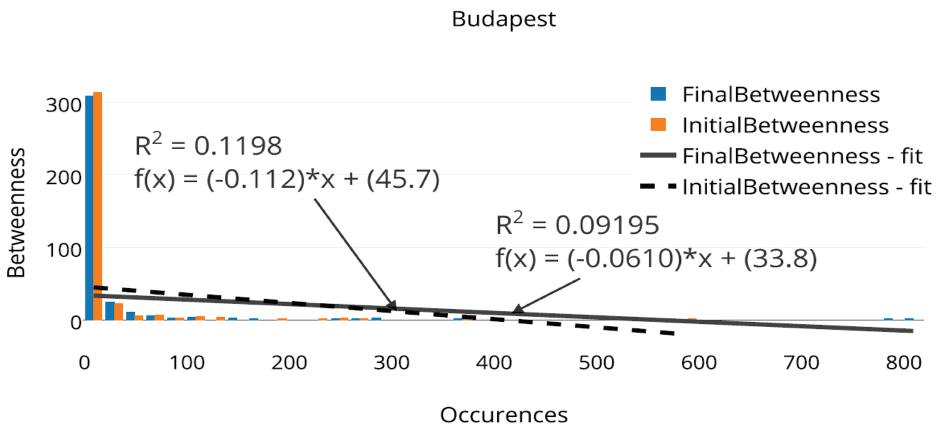


Figure 33. Analyzed community in the city of Budapest

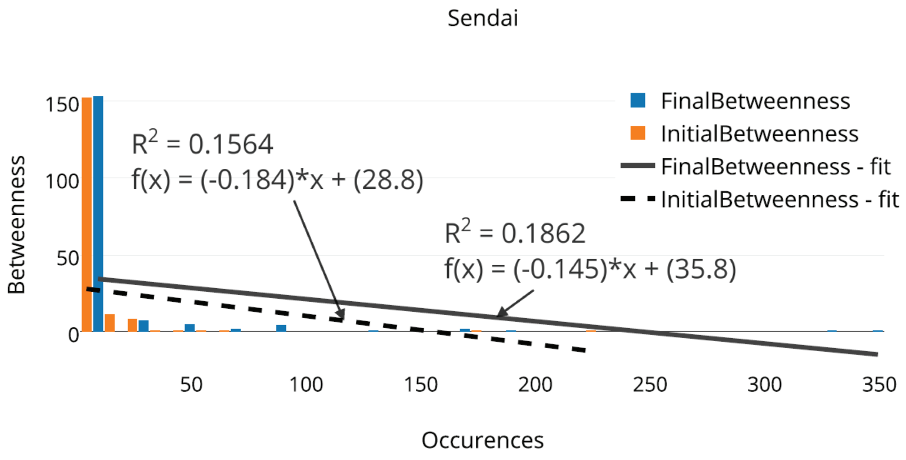


Figure 34. Analyzed community in the city of Sendai

Some extreme cases are presented in the following figures. In Figure 35, BUD1 represents a central historical area from Budapest and the slope of the initial betweenness is m0=0.22. The dotted trend-line represents the linear interpolation of the optimized betweenness after running SIGS, with the new slope value of m1=0.053. The improvement obtained in this case is almost 75%.

In Figure 36 a special case can be seen, a large community, covering 32% percent of the total Los Angeles analyzed graph. In this situation, a worsening of the initial measured parameters values occurs, due to the already steady traffic because of the highways present in it.

Sendai has large number of small communities and the algorithm reaches its limitations because there is no community optimization possible. For this type of communities the random shuffle procedure does not have enough data to sample and the result is less than expected. Still, one can see in Figure 37 that there is no degradation of the metrics, there is only a shifting of the interpolation line, but with a negligible variation of slope. An observation is to be made here, that this way, the algorithm can work as a good estimator of the current quality of traffic in the city, meaning that there are no big problems to be solved.

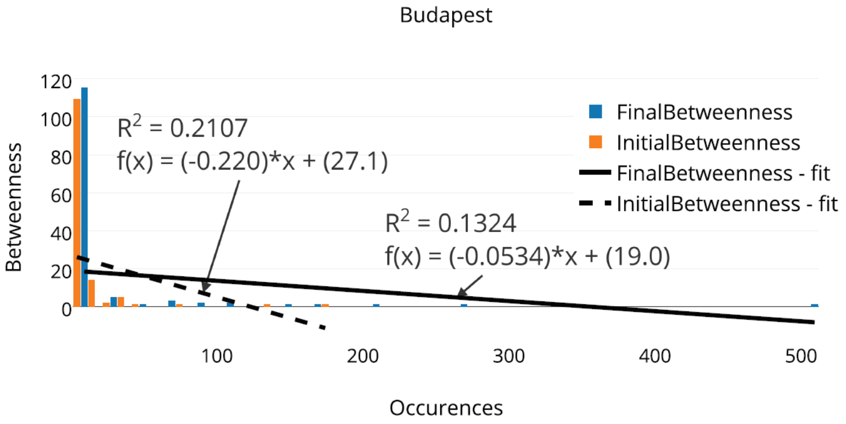


Figure 35. Central historic area in Budapest

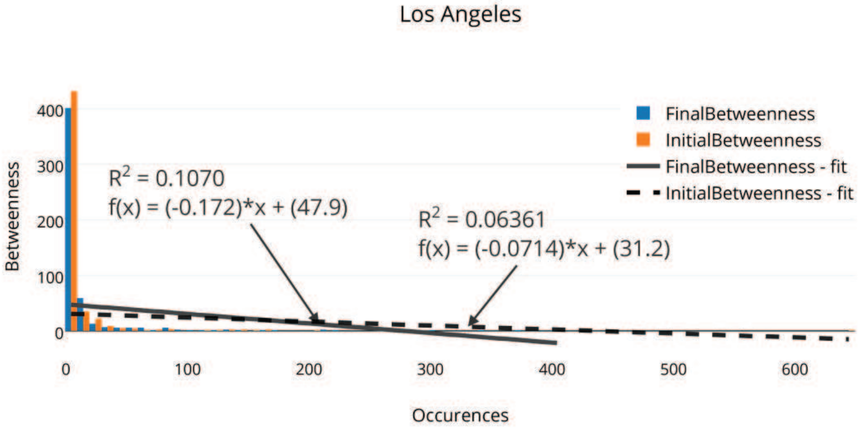


Figure 36. Los Angeles macro community

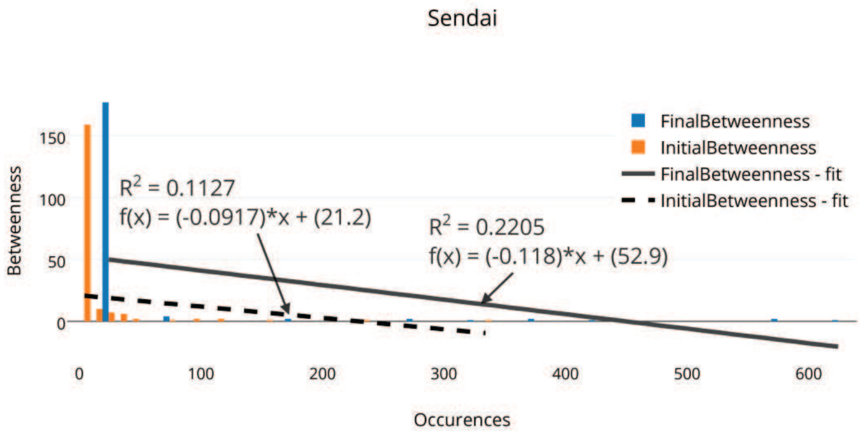


Figure 37. Sendai small community

The smaller improvements obtained in LA1 dataset is due to the high percentage of highways that provide an already more uniform betweenness distribution. As a remark for this area is that congestion is not an affecting problem.

So far, this work represents a novel approach in redesigning the road infrastructure of a city. Combining concepts from the area of network analysis with the efficiency of genetic algorithms and mapping them to road networks, SIGS algorithm is obtained. As there no such similar approach to road infrastructure optimization, the discussion of the results remains theoretical, as solution can be implemented at much lower costs not requiring new streets to be constructed.

This approach shows that using techniques from the field of complex and social networks analysis communities can be identified in the road graph. Moreover, they match neighborhoods in real life and a further analysis of the high betweenness nodes show the relation with the most important intersections in terms of increased traffic value through it.

Balancing the traffic flow means leveling the distribution of the betweenness, allowing less important intersections to support additional traffic. In this way, congestion through major intersections will be decreased. SIGS algorithm recreates an optimized road network by changing lane directions in a genetic inspired manor to improve traffic flow.

The case study concentrated in taking three different cities, each with specific topology, from three different continents with substantial improvements in most cases. The solution given through heuristics by SIGS is of particular importance for the increasing traffic demand of modern cities with larger street networks. This method can be integrated further by a framework for a more detailed physical and economic analysis.

From a complex network point of view, of high importance is the proposed method that points out the congestion paths using betweenness centrality and the redistributed load for the identified hotspots. Results showed that the redistribution of betweenness can reduce the load in specific points up to 4 times, which can be considered consistent if the results are obtained on a city with high population and a complex traffic system, like Budapest. Besides shortening the average travel times there are the advantages of lowering pollution and reducing noise levels in urban environments.

Limitations exist for SIGS methodology. Some extreme limits of data sets, like a large number of small communities lead to insignificant improvements, because slope analyzed has negligible variations. Another extreme case is the small number of large communities where exists the possibility of degrading the actual conditions, results showed an increase of the slope value. These cases can both be approached and avoided by fine tuning the resolution parameter to generate well balanced communities, maybe in correlation with the real existing ones.

More insightful analysis need to be performed using proven simulation tools on real-world testing to check the functional requirements of SIGS algorithm. A theoretical analysis shows that better results can be obtained by using a further optimization step in which each of the identified methodologies represent nodes in a higher level network. Implementing the methodology in a hierarchical, multi-level manner could improve more the results at global network level. Future work should focus towards implementing this heuristic algorithm using the local traffic light signaling proposed for layer 1 in order to provide real time dynamic adaption of the topology using lane reallocation in correlation with actual traffic conditions.

4.3 TACTICS – A Fault Tolerant Adaptive Control TraffIc Cyber-Physical System

TACTICS is the adaptive traffic framework envisioned to respond to continuous traffic changes in a network that implements the three layered formalism proposed in this thesis. The main actuators of this framework are the intelligent traffic lights which will run adaptive green time algorithm. The hardware deployment of TACTICS is done without affecting the current infrastructure, no need for new roads to be built or heavy road works implied. A new hardware that uses only video camera detection and communication module will be used, without the need of installing pavement sensors where they are not already installed. The proposed workflow was partially tested as described in Chapter 3, using the VISSIM simulator and correlated with results generated with Gephi software. Improvements were obtained in terms of reducing waiting times and queue lengths over the currently deployed solution based on fixed time plans.

4.3.1 A Cyber-Physical System for Transport Control

The field of *Cyber-Physical Systems* (CPS) emerged in 2006, integrating the fields of computation and controlling of physical entities. Opposed to traditional embedded systems, CPS is typically designed as a network of interacting elements with physical input and output instead of as standalone devices. The notion is closely related to concepts of sensor networks.

From the beginning, complex, distributed and dynamic systems like the ones providing air and road traffic control, and smart cities have been discussed in the

CPS community, concluding the need for an inter-disciplinary combination of diverse engineering fields. Several common goals and requirements in large-scale CPS have been identified so far, concurrency, real-time capability, distributed control, self-adaption, self-organization, reliability and fault tolerance [91].

Time is a physical phenomenon, so software implementations of real-world processes must provide measures to model concurrent relations between communicating entities. All entities must use the same concept of time and delay is not allowed in the concurrent software processes. Closely related to time concept is the real-time requirement, meaning that information processing must happen before critical information is outdated or overwritten by new information.

Classical engineered solutions focus on centralized approaches relying on global information. Such solutions usually lack the dynamic dependencies, which make them easy to understand and manage. Centralized approaches, however, assume that collecting data and its processing meet real-time requirements. In large and complex systems, this usually is not the case since the period of collecting and processing data is longer than entities can wait for a response. Traffic in large road networks is one example of a situation where centralized optimization is almost impossible: continuously collecting dynamic traffic information from all roads, optimizing traffic flows with respect to minimal global travel times and disseminating the resulting routing recommendations takes too long to be practically deployed in real world networks. New approaches must at least self-adapt to changing demand and loads in the network to route vehicles to their destinations [91].

Self-organization implies previously described self-adaption and also explores new strategies to reach other objectives. Physical environments and conditions may change frequently, requiring methods that detect changes without external request or modification. As a main desiderate for any system is a high reliability and an increased fault tolerance. Because a CPS usually interacts with physical domain which can be unpredictable, in mission-critical or highly dangerous situations such as: collision avoidance, robotic surgery, nano-level manufacturing and it has to be very reliable even self-organizing if possible.[91]

CPS brings together specific engineering methods and computer science research on embedded systems, scheduling and distributed algorithms, emphasizing the mapping of processes and physical features. A good example of CPS domain is the control of vehicle flows with the goal of reducing congestion and travel times in a road network.

4.3.2 TACTICS – Architecture Description

TACTICS defines the framework for the physical implementation of the three layered stack proposed in Chapter 3. As described earlier in this thesis, the first layer runs local adaption mechanisms that change green time values at intersection level based on the detected traffic flow. But, running this algorithm on each intersection is not an optimal solution because of the high number of intersections a city can have. To address this situation, each intersection is considered part of a higher complex structure, a network in which they communicate each other to reach correlated decisions and find a global traffic optimum. The layout of this framework can use the algorithm described in [92] to deploy the system in a real world situation. Because local intersection’s behavior must be seen as part of a traffic network, central loading points in terms of traffic load must be selected. STiLO methodology identifies such "hot points" and selects the most relevant to work in a master-slave configuration to reach correlated decisions.

TACTICS implements the characteristics of a cyber-physical system to create a fault tolerant framework for the adaptive control of traffic movements. This system consist in several customized Intersection Controller Units, each of them handles an entire intersection, covering all the signal controllers in that physical location. For each direction a Queue Detector (QD) is installed to determine the queue length for that specific direction. Their results act as input for each Signal Controller (SC) which is responsible for the new green time changes. All the SCs in the intersection are interconnected (Wireless or not) creating the so called Intersection Controller Unit (ICU), see Figure 39. This is responsible for the behavior and the adaption of the entire intersection to traffic changes. In Figure 38 the city, or a large portion of it, is reduced to several independent ICUs which are all interconnected, but with no centralized control center. On each of these units, STiLO methodology is applied to define if it is running in a master or a slave configuration.

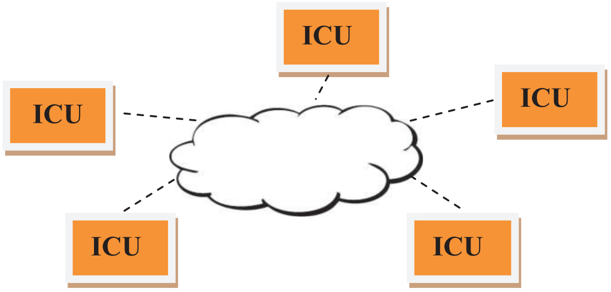


Figure 38. Traffic network for a city using TACTICS understanding

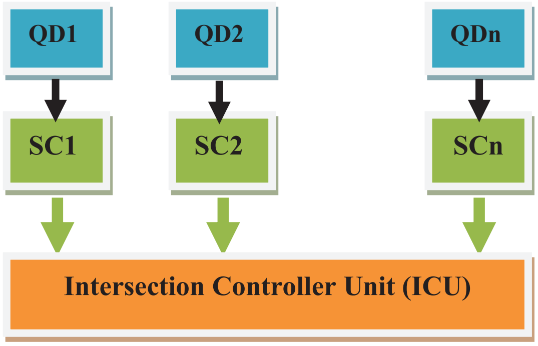


Figure 39. Intersection Controller Unit (ICU)

Figure 40 shows the working flow diagram for each ICU. The literature gives different solutions for real traffic data gathering [93], ranging from license plate recognition to roadside sensors that log in real time traffic data. Each QD reads the queue length using of-the-shelf car detectors and classification tools. Otherwise, a hardware module capable of estimating the length and dynamics of a queue must be implemented and used for queue detection. All data collected is feed into the Traffic Data Acquisition System which creates the modified Origin Destination table and the traffic density/flow (Td) matrix of the intersection. Using the rules described in the previous chapters these structures provide input for the Adjustment Mechanism working at the SC level. This performs all the computations necessary for the new green times. The new computed values along with the parameters and messages are ready to be sent to the interconnected intersections via Communication Controller. The Feedback Controller also receives these values and it decides to wait or not for an external response. The Communication Controller is responsible for sending the messages to the interconnected intersections and also receiving the corresponding responses. These are parsed and sent to the Feedback Controller which will take them into consideration or not before setting the new green times in the ICU.

One can see that the Communication Controller could be missing and in this case the adjustment works only at intersection level. This happens if the intersection that is being optimized is isolated and it works as standalone or if the communication is offline.

TACTICS uses no redundancy since it can work offline without any centralized control. If the master nodes are to implement the hardware redundancy it will be a cost increase in order to protect of a failure that is not a real threat to the system, since each signal controller can take the role of ICU. Several solutions are to be further studied, like the need of a failure detection module can be implemented to monitor the state of ICU.

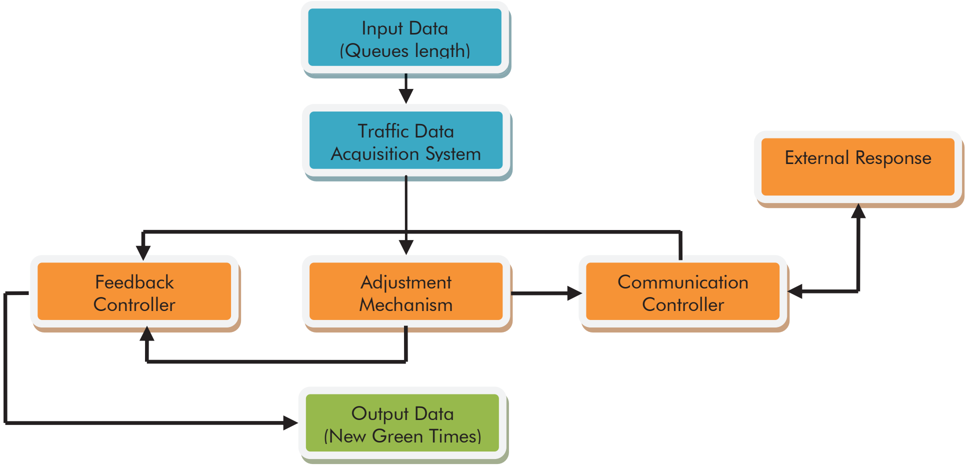


Figure 40. Functional block diagram of an ICU of TACTICS

TACTICS proposes a framework to implement the described three layered optimization stack, the communication procedure and the specific messages that are defined so that the entire system responds and adapts to continuous traffic changes. Each node uniquely identified by a traffic light is dynamically controlled to act as a virtual traffic officer. For this framework to be operational, the network topology will have to be defined at deployment time. A procedure for a new node insertion, corresponding to a new traffic signal installation is needed and it will be defined. Following this mechanism, each node is capable of positioning itself into the network, by knowing his neighbors and it is able to find its role, either as a slave or master. STiLO must be run for the new deployed node to determine its role.

The adaptive green time mechanism is the core of this algorithm, because it is determines and sends the new green times to the traffic signals operating in intersections. As already mentioned in the previous chapters, the dynamic of each traffic light-controlled intersection is defined using a set of only three parameters and new green time values are derived based on their values. These are, green time value (Gt), meaning the time which allows traffic to flow through an intersection, traffic flow (td), representing the number of vehicles passing on a specific direction and cycle length (Cl), which is the timeframe between two consecutive green times.

Several steps are performed for changing traffic signal timings, according to the algorithm described in Chapter 3. First step is to determine whether a local intersection has a problem in managing passing traffic flow through it. Next step is to determine if it is possible to make changes locally or not, based on the input values read. If the intersection can respond to traffic changes by changing its own green time values then it will determine the changing coefficient that will be sent to the interconnected ones. In case the current intersection is identified using STiLO as master than it communicates to the slaves the changes made on the impacted directions. It also notifies the other interconnected masters about the changes. Using the methodology described in Chapter 3, the *greenTimeIncrease* (see greenTimeIncrease formula (7)) and the *coefficient_level* (see coefficient_level formula (6)) are computed and sent to the connected intersection. The response is expected during the same cycle in order to know if changes are accepted or not. The algorithm starts over and reads traffic data after each cycle is over.

Two types of messages are defined: requests and reports. These are exchanged between master and slave intersections. Their format is defined in Figure 41 and has a minimal format in order to be easily implemented regarding the transmission method used (TCP/IP, Bluetooth etc).

Message ID	Message Type	Source	Target	Payload

Figure 41. Message format used by TACTICS

Based on the resulting coefficient values and on the adaptive green time methodology, several Message IDs are defined:

REQ_INC_LOW – Request Increase green time with a Low value
REQ_INC_HIGH – Request Increase green time with a Higher value
REQ_DEC_LOW – Request Decrease green time with Low value
REQ_DEC_HIGH – Request Decrease green time with a Higher value
REP_YES – Reply Yes to each of the above message
REP_NO – Reply No to each of the above message
ACK – Acknowledge message can be used with all the other messages, depending on the intersection load and overhead.

A bidirectional communication is proposed to exchange information using a simple request-reply report, where each intersection notifies the interconnected one about the changes that is going to perform. Each intersection will also take into consideration the incoming requests only if its local conditions permit it. When the other intersection acknowledges the message, it means that the information will be used for the next timing adjustments and a negative answer means the information cannot be used because of the already calculated green times. Time aspect is important in this phase as there is no synchronization of traffic signals.

Each semaphore has its own working time: cycle length, number of phases, changing order and the list could continue. Because of this aspect, rules must be described, so the communication between the intersections is optimal and also to avoid unnecessary overhead inside ICU. First, all the computations are done during the first red time period after a cycle is completed. In this interval, the new green times and coefficient levels are to be determined based on each specific methodology. All other requests coming from slave intersections in the next period will be taken into account only in the next cycle.

Second rule is that no answer is kept more than one cycle. Several cases are to be identified: one is when the green time of the slave intersections overlaps the master green time value and the second is the case when the response from the slave is received during maser's green time. In the first case the request from the master is not reaching the slave in the current cycle which means no response from the slave. This is the specific case in which the master will adapt its green time without any change from the slave. The adaption will still take place for the slave intersection during the next cycle following the response to master. Another case is when the request from the master is not reaching the slave, because of a larger cycle length and in this case, the master is always changing its values and sending new requests until it gets a response. The third rule is that if the communication is lost, each intersection acts as master without sending any message. Statistically, acting as master an intersection could improve locally for short time, and because any congestion is limited in time it could cover the time needed to pass that situation.

The proposed methodology finds the optimal traffic balance for all directions in a single intersection and communicates its results with the interconnected ones in order to achieve a more balanced network. But, continuous recalculation will naturally lead to a point in time when adapting green times is not possible anymore.

5. CONCLUSIONS

This thesis is the result of a personal interest in the area of traffic movement optimization since we are all influenced by traffic changes, either as pedestrians, as passengers in public transportation or as drivers. Regardless the case, we are all influenced and we have an active contribution to continuous changes of traffic conditions. Traffic congestion problem is approached because it is the cause of time loss, money spent on fuel due to a great amount of time spent waiting in queues, air pollution and crowded intersections at peak hours.

In this chapter I will try to consider and argue upon the proposed three layer formalism and how the new proposed methodologies, described in Chapter 3 and Chapter 4, apply in a real world implementation to improve traffic quality at network level. The described formalism identifies the layers that define traffic optimization problem. The local green time methodology finds the optimal timings to cope with dynamic changes in traffic. STiLO algorithm proposes an innovative method for optimal traffic signal placement and identification of possible congestion hotspots. SIGS describes a new bio inspired method to balance traffic flow in an urban network. This algorithm performs a topological analysis based on aspects specific to social network analysis. It also uses a bio-inspired approach to redirect traffic to less crowded intersections. All the original contributions will be separately discussed, based on the obtained results. Future work will be presented in the last part of this chapter along with a new proposed traffic optimization platform, TACTICS, and the challenges to implement it.

5.1 A Retrospective Analysis

The main goal of this thesis was to propose a new approach to the field of traffic movement optimization over an existing road network, without physical changing it. Modern approaches such as Intelligent Traffic Systems and Adaptive Traffic Control Systems combine elements from different area of expertise to offer solutions to the dynamic changes of traffic conditions in urban environments. In the last years, this quest for new solutions has moved beyond the domain of transportation and has borrowed methods and tools specific to Computer Science. The increase of traffic data and the high availability of online information create the perfect framework for a new approach to optimize traffic conditions.

New network science represents the new interdisciplinary field which studies complex networks such as computer networks, biological networks, telecommunication networks or social networks. This field combines theories and methods from different domains like mathematics, physics, computer science, statistics and sociology. They are combining also graph theories, statistical mechanics, information visualization and social structure to generate a new perspective over network analysis. In this context, transportation field uses a fresh and less explored methodology that gathers all these concepts and apply them in the quest for traffic flow optimization.

Bio inspired computing has been in use for several years now. It uses computer science to model real life phenomenon, mainly exploring the area of genetic algorithms. This heuristic search mimics the process of natural selection that is mainly used to generate solutions to optimization and search problems. The search for a traffic optimum fit the description of bio-inspired algorithms and applies them to generate different responses to traffic values.

The general debate of whether centralized or decentralized control is better has not come yet to a common conclusion. It is my conviction that for managing traffic changes in our high speed moving era, decentralized control systems are the answer because the megacity structures are becoming a reality and the centralized control of such systems will be almost impossible. This is the reason I proposed decentralized control scheme, based on a three layer formalism to respond to the unpredictable character of traffic flow. Using concepts borrowed from the complex network analysis and combining them with specific traffic analyzer tools, there were encouraging results that kept the personal interest alive for all this time. From one method to the other, from simulation to simulation, enthusiasm increased, gathering more people from one year to another. The proposed "3-layered stack" formalism became the spine of this rapidly growing traffic control system that kept me motivated.

5.2 Original Contributions

This thesis gathers around several original contributions:

- The three layer formalism proposed to split the problem of traffic flow optimization into distinct levels that can be addressed independent, with specific methods.
- Mixing concepts from complex and social network analysis with urban networks problems to identify hotspots in traffic using static analysis of the layout of city maps.
- STiLO methodology is developed as the method for optimal placement of nodes which are identified with intersections from a real traffic network.
- SIGS algorithm proposes a high level method to reorganize traffic movements inside a road network, relying on bio-inspired computing to give a fast and optimal solution to reduce the load in crowded intersections.
- Simulations performed on real traffic networks, generated an unique workflow, that uses external tools and customized scripts to parse the imported data available online (via OpenStreetMap), so that it is integrated by different simulators, from the one specific to road traffic analysis (VISSIM) to the one that is specialized in network analysis (Gephi);

The decentralized control scheme based on the three layer formalism was proposed in the first part of this thesis. Described in Chapter 3, this optimization flow splits the problem into three different layers, each with specific methods developed to use as input the data provided by the previous level and generate output useful for the next layer. The common goal is to improve conditions at network level using collaboration between each layer. As there is no description of such formalism, to the best of my knowledge, I consider that traffic control needs its own "OSI model". This will guide each traffic optimization processes through each layer, starting with the first intersection level.

Chapter 3 describes the method specific to work at Layer 1, which creates the foundation for the next two layers. Local heuristics are developed to quickly react to traffic changes by adapting traffic signal times instead of using static signal plans. Simulations were performed using VISSIM Simulator software tool and they used as input data, real traffic values recorded by hand. Further results were generated after access to VISSIM Simulator license was granted, thanks to PTV Group. The proposed solution showed a decrease in terms of waiting times and in queue lengths at local intersection level, but with no major perspectives at network level, as these were only isolated quick reactions to changes of traffic values. This leads to the need for an upper layer capable of correlating these results.

Since for Layer 1 only local improvements were obtained, without any indication on how they will contribute to the conditions at network level, the next step was to switch focus to develop Layer 2 specific algorithms. It is obvious that there is a need for a methodology to use Layer 1 changes and propagate them to the upper Layer 2 and Layer 3. Further, the investigation was geared towards finding a suitable algorithm for hierarchical placement of Layer 1 controllers, in a master slave configuration, so one can influence the behavior of interconnected intersections and create the foundation for Layer 2 specific methods.

All these factors, led to a research through the field of complex network analysis, in the quest for specific methods to deal with large urban networks. Social TraffIc Light Optimization algorithm emerged after mapping concepts specific to the field of complex network analysis (CNA) and more specific social network analysis (SNA) onto road infrastructure topology. Key aspects borrowed from SNA are the community detection and betweenness centrality metrics. By combing them, Social Traffic Light Optimization (STiLO) methodology was defined. Findings in different case studies show that STiLO is an efficient method to identify intersections where traffic lights deployment is necessary creating a method that optimizes hardware installation. It is also the method used to identify and define master-slave roles for traffic signals. Gephi tool is used along with VISSIM Simulator because it offers the possibility to perform large network analysis by running specific algorithms on the imported traffic network. Several case studies were analyzed with confirmation of correct identification of master nodes over the city of Timisoara.

With the focus changed to Layer 2 and the next network level, a novel bio-inspired methodology is born as a response to the social aspects influencing every day traffic conditions. Social network analysis concepts, such as betweenness and community, prove to be of interest applied for real world networks. Graph data analysis showed that communities match the neighborhoods in real life and key intersections were identified using the interpretation of high betweenness values.

The analysis of betweenness distribution opened the path for a method to redistribute traffic flow and to reduce the number of hotspots in traffic. This new algorithm levels the power-law distribution of these values. It translates into obtaining a balance in traffic flow for some intersections allowing other less crowded to support additional traffic. This congestion decreases in major intersections, while it grows on the less loaded ones. Social Intersection Genetic Shuffler (SIGS) methodology proposes to level the distribution of betweenness using a bio-inspired approach. Briefly, SIGS recreates an optimized network, based on the original one, by changing lanes directions. Case studies were conducted on several cities from different continents and compared their results with data provided by Google Traffic Layer. This comparison showed that the congestions paths pointed out using betweennes centrality analysis match the ones reflected in real traffic conditions. This proves that a topological analysis on the urban network can point the problems that are waiting to happen in traffic networks.

Significant improvements on this topic would yield besides reducing the average travel times also decreasing the pollution coping with today's interest for environment protection. Improvements are envisioned based on results so far, but this research has to be backed up with real traffic data and deployments. This research has to work as a framework for future implementation for real traffic control system.

Therefore, previous mentioned algorithms, network aspects and physical processes described in the previous chapters created the perfect context to define a future cyber-physical system. Part of my future work plans, this fault Tolerant Adaptive Control TraffIc Cyber-Physical System (TACTICS) sets the framework for the hardware implementation of all the methodologies proposed so far, following the three layer formalism. Described in more details later in this chapter, TACTICS will integrate concepts of concurrency, real-time capability, distributed control, self-organization and reliability to improve traffic conditions in urban traffic networks.

Literature review shows that vast majority of traffic systems approach the traffic control on smaller regions. On the other side, a global optimization requires high amount of hardware and human resources. In this thesis I have introduced a set of tools that work on different layers, as defined by the three layer formalism proposed in Chapter 3 to improve traffic flow conditions at network level. Following this formalism I introduced a method to adapt traffic signal times to respond to traffic changes. Next using specific methods borrowed from complex network analysis, two new methodologies were proposed, STiLO and SIGS. STiLO proves to be an efficient method to deploy traffic signals into a traffic network and to select the roles for intersections in a master-slave configuration. SIGS is an algorithm that uses a bio-inspired optimization method to redistribute traffic flow for highly loaded intersections. These methods are covering specific operations for each layer from the three layered stack, without reaching a global network optimum. What I have proposed with my research was to get as close as possible to a network improvement and also to take into consideration the social characteristic of traffic.

5.3 Present and Future

This thesis addresses the problem of optimizing traffic flow through an urban network using a distributed control at local intersection level. Even though many see this strictly as a transportation problem, recent developments in Information Technology changed this field of research. The advances in mobile technologies and communications increased the availability of data and led to the development of real smart infrastructures. As the reader went through the chapters of this thesis, was able to see the view of computer engineering applied into this domain. A lot is still to be done on the described issues, but this thesis opens the road for using the social network analysis to solve the problem of transportation, placing itself at the crossroad of computation research.

The proposed optimization process ensures a continuous traffic flow between key intersections from an urban traffic network. This is the reason why future work focuses towards implementing the heuristic algorithm for the intelligent traffic light signaling, that works for Layer 1 to have a real time dynamic adaption of the topology as a response to traffic continuous changes in road demand. The investigation continues on proposing new methods for dynamic layout changes and traffic flow redistribution on the existing infrastructure. Also, more simulation testing must be performed based on real data collected from traffic.

Designed as a network of interconnected smart traffic signal, TACTICS is envisioned to implement the three layered formalism and the methods that define each level. This system has to provide real-time capability, distributed control, self organization and fault tolerance that a transport control systems requires. The hardware deployment of TACTICS in the real world is the next objective in sight. Traffic is influencing the well being of the entire community, so people should benefit from the implementation of the proposed algorithms that prove to bring improvements. While classical solutions focus on centralized control and global information, TACTICS will use dynamic data collected in real time to control traffic movements.

The importance of fault tolerance is widely recognized and many projects take into consideration this aspect. But traditional fault detection solutions, usually fail to work properly in the context of large scale distributed systems. This is the consequence of the large number of processes involved, the high number of messages being delivered and the dynamic nature of the underlying topologies.

More research has to be done towards finding fault tolerance strategies at local intersection level. Possible intersection attacks must be addressed and defense mechanisms need to be implemented. But the most challenging aspect is to be able to define an attack. How can one define if sensors installed in an intersection are subject to a malicious attack or if the sensors are physically damaged? How can a node identify a security breach? Defining the problem is as interesting as finding the solution and this can be subject for a future standalone research.

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