Smart Mobility by Optimizing the Traffic Lights: A New Tool for Traffic Control Centers

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Abstract. Urban traffic planning is a fertile area of Smart Cities to improve efficiency, environmental care, and safety, since the traffic jams and congestion are one of the biggest sources of pollution and noise. Traffic lights play an important role in solving these problems since they control the flow of the vehicular network at the city. However, the increasing number of vehicles makes necessary to go from a local control at one single intersection to a holistic approach considering a large urban area, only possible using advanced computational resources and techniques. Here we propose HITUL, a system that supports the decisions of the traffic control managers in a large urban area. HITUL takes the real traffic conditions and compute optimal traffic lights plans using bio-inspired techniques and micro-simulations. We compare our system against plans provided by experts. Our solutions not only enable continuous traffic flows but reduce the pollution. A case study of Málaga city allows us to validate the approach and show its benefits for other cities as well.

Keywords: Traffic lights planning · Multi-objective optimization · Smart mobility

1 Introduction

Traffic lights are increasingly important elements for the efficiency, environmental care, and safety of our cities. These devices were initially positioned at road intersections, pedestrian crossings, and other locations to control conflicting flows of traffic and avoid possible accidents. At each intersection, all traffic lights are synchronized to carry out a sequence of valid phases periodically. Each phase consists of a combination of color's states and has a time span that vehicles are allowed to use a roadway. The assignment of the time span for each phase in the phase sequence of all intersections at an urban area is what we call a Traffic Lights Plan (TLP).

Finding the best TLP is crucial for reducing the number of stops for red lights thus minimizing the travel time of vehicles through the road network. Intuitive examples are the well-known green waves, which facilitate a continuous traffic flow in one main direction. Reducing the travel time of drivers prevents them from losing time and arriving late to their destination. As a side effect, this

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also helps reducing the fuel consumption and CO_2 emissions while the vehicle is stopped for red lights.

Nowadays, the large number of vehicles and citizens moving around rises the inefficiency of current traffic control systems, designed to set local control policies but unable to optimize a global, real city scenario. In this article we present HITUL, a decision support system that helps traffic managers to generate optimal TLPs for actual cities, leading to above-mentioned potential benefits in terms of energy consumption, traffic flow management, pedestrian safety, and environmental issues. Unlike decentralized self-regulated lights, or traditional queue based systems, the use of metaheuristic algorithms [6,10] to find successful TLPs is still an open issue. The ability of metaheuristics and Nature inspired techniques [1,15] to solve very large problems with many restrictions and in competitive running times make them unique to build HITUL.

In addition, we use the well-known SUMO (Simulator of Urban Mobility) traffic simulator [4,14], which offers a detailed source of information about the vehicle's flow (velocity, fuel consumption, emissions, journey time, etc.), giving rise to configurations of realistic scenarios according to real patterns of mobility of the target city. This is a key difference from our systems to other solutions: not only the large dimension of the zones considered (previous works go for a street or a corner while we go for a city), but also the level of details and reality in our studies (e.g. real maps, driving regulations, car and driver individual analysis, times, pollution, etc.).

The remainder of this article is as follows. In Sect. 2 we mention some related works which have addressed this problem. Then, we introduce the HITUL system in Sect. 3. The Sect. 4 describes the practical case of Málaga city to validate our approach. Finally, Sect. 5 states conclusions and the future work.

2 Related Work

This problem has been tackled by both industry and academia, showing the importance and the impact of having an appropriate TLP to alleviating traffic jams which also allows to reduce hazardous substances emitted with car exhaust gas.

On the one hand, the industry has proposed several solutions (for example, SPROUT [17], Cross Zlin [7], or ATC [2]) but in general are focused on the real-time configuration of a single traffic light junction and they make use of some additional infrastructure which provides online information of the changing traffic situations. For example, the SPROUT System [17] proposes the utilization of ultrasonic detectors and optical beacons on the road to detect cars, thus determining the movement of cars on the road. Using this information, it predicts in real time when cars will arrive at streets corners, and estimates the number of times a car stops and the time of each stoppage, then it calculates and implements an appropriate traffic signal pattern.

On the other hand, in the academia this problem has been divided into two separate (but related) phases: the first one is about how real-time information of the current traffic can be gathered; while the second one focuses on the design of systems which provide optimized TLP using that previous information. In the first research domain, we can mention DATLCES [18], GLOSA [5] or POVA [19]. These works analyze the utilization of different technologies to gather the data (from classical detectors or cameras to recent communication systems such as RFID, VANET communications, ...). The second research domain focuses on the optimization of the TLPs using existing traffic information. The most common search engines used are queueing theory [18], fuzzy systems [12], and metaheuristics [9].

As it can be observed in the previous paragraph, this problem has been tackled in very different ways and with different objectives, but we have detected some topics which can be improved:

- Most current approaches are based on a limited number of traffic elements (roads, traffic lights, urban areas).
- Take a single goal (e.g., reduce the number of stops) and do not take into account other metrics such as emissions, travel time, ...
- Even when dealing with it, they will not quantify the benefits on emissions and other indicators.

Our proposed tool will solve these issues by addressing a large urban area (a complete city), with both mono- and multi-objetive optimization, and using real and open data to provide solutions to real scenarios.

3 The HITUL System

HITUL is a support tool for decision-making regarding the planning of the city traffic light network, one of the ways to deal with congestion and traffic jams. Figure 1 illustrates this relationship between our proposed HITUL system and the external components or actors in the system.

In the context of a metropolitan area, the HITUL system takes advantage of open traffic data and information services to provide its functionality. These data sources are available to everyone without copyright restrictions or licensing fees. An example is OpenStreetMap [13], a free repository of geographic information supported by over 1.6 million users around the world, who collect data using manual survey. HITUL also uses information publicly provided by the city Traffic Control Center (TCC), such as the traffic intensity measured in specific locations of the road network.

In the following, the main functionalities implemented are listed. Next, the proposed design according to these software requirements is discussed, including the underlying functional architecture and the planning algorithm. Finally, the optimization strategy used to implement the system is described. Let us start with the main system functionalities.

3.1 Main Features

The HITUL system aims at supporting the decision-making of an officer at the TCC. Its main feature is the automatic generation of optimized TLPs (see

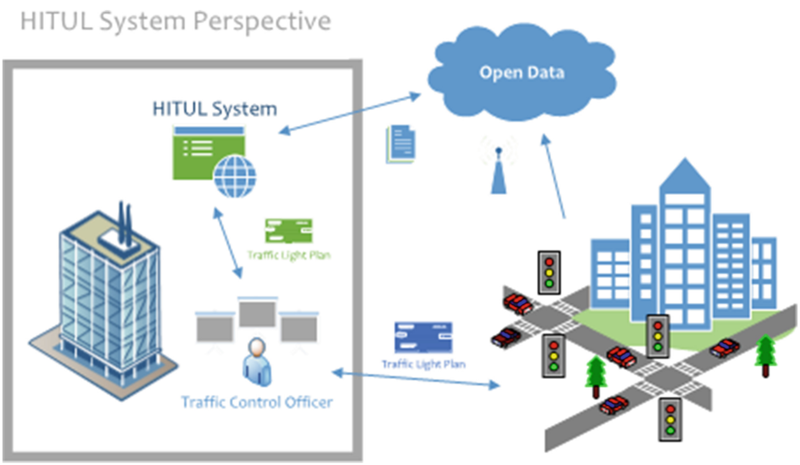

Fig. 1. Perspective of the HITUL system.

Sect. 3.3 for more details). But it also includes some additional characteristics in order to interact with the traffic center manager and make easy the utilization of our generated plans. The following list briefly outlines the major features that the system provides:

1. **Combine different objectives.** HITUL generates optimal plans based on a selection of different objectives at the same time: *waiting time*, *number of stops*, or *carbon footprint*. This functionality is intended to search for more stable TLPs according to multiple, possibly conflicting criteria, instead of satisfying one single requirement. Multi-criteria decision making is an important and hot issue in research not yet well exploited in final real applications.
2. **Consider different traffic profiles.** Adapt to the real behavior of the road traffic according to the time of the day, the day itself, and the moment of the year. Our system provides a list of available options: working day, rush hour working day, Saturday, Sunday, Saturday rush hour, and Sunday city return hours.
3. **Select an urban zone or optimize the whole city traffic.** This functionality allows to select a zone, a single district or the whole city, whose traffic lights are required to be optimized. The remainder city signals are configured according to a TLP provided by the traffic manager or by our system. This is a very practical feature for the traffic manager, since it helps them implementing temporal, localized traffic control policies.
4. **Comparisons between TLPs.** The system allows to compare obtained TLP among them, as well as compare a plan obtained by the system with another plan provided by an expert in a standard format. The plan selected to compare with is named *base plan*. As a result, the main differences will be drawn in a visual representation so that the officer can easily identify those traffic lights which differ more with respect to the base plan.

5. **Export/Import optimal TLPs.** The system supports the export of each TLP obtained using the XML standard format. At the same time, the system allows to load the base plan to compare with as far as it satisfies the aforementioned file format. This functionality enables the integration with other present and future TCC systems.

3.2 Architecture Overview

In this section we provide a technical overview of our proposed HITUL system. It is structured in three layers, each one grouping close related software components. First, a front-end server provides a single page application (SPA) exposing the traffic optimization dashboard, as well as the interfaces to take useful open data coming out from the software package.

Also, the system has a back-end numerical server running data processing and optimization tools in a Java EE platform that provides a high level of availability, reliability, and scalability. Implemented algorithms for computing optimized TLPs are based on bio-inspired techniques and some multi-objective versions based on crowding and using numerical archives for non-dominated solutions whose core intelligence is regulated mainly by the Non-Dominated Sorting Genetic Algorithm (NSGA-II) [8].

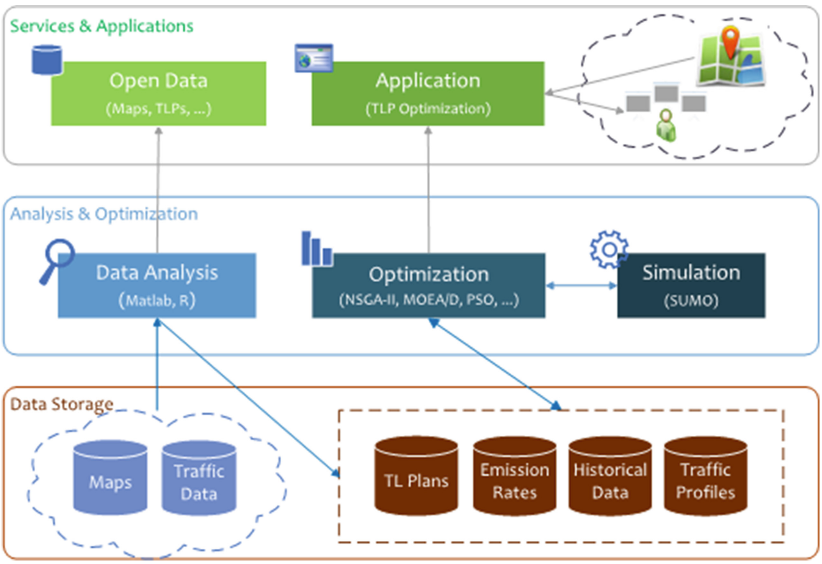

Fig. 2. Overview of the HITUL system Architecture.

Finally, the HITUL architecture involves a database server, comprising the data collections and the interfaces to manage them. We use a regular relational database since we have not relevant reasons to go for a non-relational data storage and access.

Figure 2 summarizes the main components at each layer as well as their interaction with other components in our software package. This flexible architecture will allow to develop future extensions of the HITUL service. A Client/Server utilization is amenable both for a truly remote internet access, or an in-house utilization, where users are in a room (floor, building) and the actual computational servers are in a cold room or computer facilities center, with data always flowing inside the premises, respecting the standard security measures of the TCC. This is highly dependent on the city, hence our decisions have been taken to help new scenarios of use in different cities.

3.3 Optimization Strategy

The objective of optimizing TLPs is to find cycle (timing) programs for all the traffic lights located in a given urban area with the aim of reducing the global journey time, emissions, and fuel consumption. Consequently, the solution is represented with a tuple of positive integer numbers $\mathbb{Z}^+$ within the time interval $[30, 120]$[1] meaning the phase duration of the different states in all the traffic lights of the studied area. We have also added an integer value associated to each intersection that is called offset within the time interval $[-30, 30]$. The offset of a signal is the delay of the beginning of the initial phase of the intersection. When offset is used it is possible to get green waves, which occurs when a series of traffic lights are coordinated to allow continuous traffic flow over several intersections in one main direction.

The proposed algorithm sets a value in the time interval $[30, 120]$ in each position of the vector solution that represents a phase and a value in the interval $[-30, 30]$ in the positions of the offset of each intersection. Let us say our largest instance has 3800 phases and 961 offsets, the problem search space would consist of $91^{3800} \times 61^{961}$ candidate solutions. Therefore, efficient automated approaches are required to tackle it. Evolutionary algorithms [3] have shown to be very effective in solving hard optimization tasks. For this reason, in the case of mono-objective optimization we used the so-called Genetic Algorithm (GA) [11]. Our implementation of the genetic algorithm in this paper typically uses a ranking method for parent selection and elitist replacement for the next population, that is, the best individual of the current population is included in the next one. The operators used are single point crossover and integer polynomial mutation. Note that the search algorithms used have been implemented using jMetal 5.0 [16], a Java framework aimed at the development, experimentation, and study of metaheuristics for solving optimization problems. The source code of the algorithms used in this tool are publicly available at GitHub[2].

[1] Recommended interval by the Mobility Delegation of the Málaga's City Council.
[2] https://github.com/jMetal/jMetal.

On the other hand, when more than one objective must be optimized at the same time and are considered as equally important, we used the Non-Dominated Sorting Genetic Algorithm (NSGA-II) [8]. NSGA-II is a genetic algorithm which is the reference algorithm in multi-objective optimization. Its main characteristic is the use of a ranking procedure and a density estimator known as crowding distance to sort the resulting population. The solution obtained by means of NSGA-II is not a single solution, but a number of them called *non-dominated solution set*. This is a set composed by solutions which are not worse than any other solution for all objectives. The representation of this set of solutions in the objective space is known as Pareto front.

As above noted, the evaluation of the generated TLP is performed by means of the well-known SUMO [14] traffic simulator, which offers a continuous source of information about the vehicle's flow (velocity, fuel consumption, emissions, journey time, etc.), giving rise to configurations of realistic scenarios according to real patterns of mobility. The output of a SUMO simulation is registered in a journey information file that contains data about each vehicle's departure time, the time the vehicle waited to set off (offset), the time the vehicle arrived, the duration of its journey, and the number of steps in which the vehicle speed was below 0.1 m/s (temporal stops in driving). Other output files gather information about emission traces in vehicles (CO_2, NO_x, PM, etc.) and hydrocarbon consumption. This information is used to evaluate the quality of alternative traffic light cycle programs.

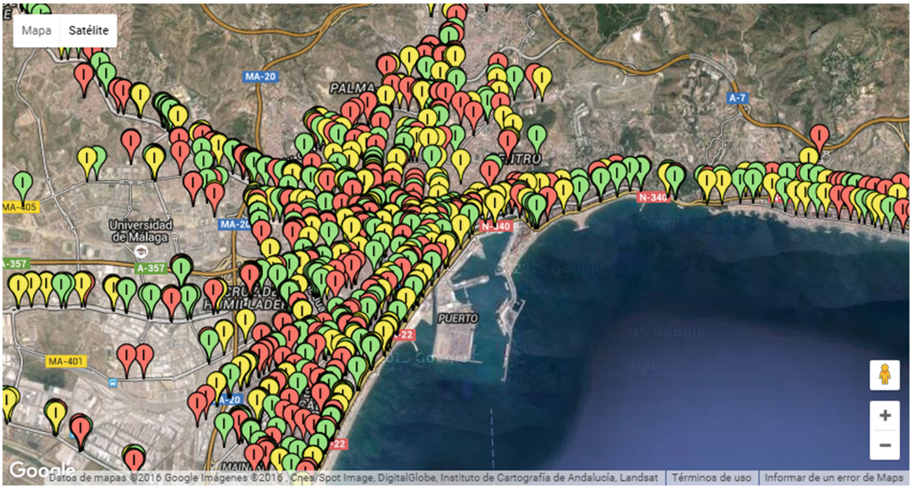

Fig. 3. Differences between base plan and the optimized traffic lights in whole Málaga city map (with 961 intersections). Red color indicates a big difference, yellow a medium one, and green a small one. (Color figure online)

4 Practical Use and Benefits: Case Study of Málaga

Since we are interested in developing an optimization tool capable of dealing with close-to-reality and generic urban areas, we have generated an instance by extracting actual information from real maps of Málaga, obtained from the Mobility Delegation of the City Council. To illustrate this case of study, we created 11 digital maps representing ten different districts and the whole city. In Fig. 3 is shown the traffic lights of a selected area of Málaga city. In the whole city, there are 961 intersections, composed by multiple traffic lights (from 4 to 16) each. Therefore, the optimization of the phases time span of each intersection is a great challenge for the optimization solver, and even more challenging for the team in charge of the Mobility in the city.

In Fig. 3 can be seen the result of the traffic light optimization of the entire city. Our tool generates a sequence of optimal TLPs, that is the result of optimizing the current plan continuously. This search process stops when the algorithm is unable to find more accurate plans or by demand of the operator.

Every time the user selects an optimized plan, the application shows the differences with respect to a base plan, also selected by the user. As this tool is aimed at helping to make changes in the traffic light phase duration that benefit the traffic flow, the differences between the base plan and the optimized plan are highlighted in different colors. When there are big differences between the phase time of an intersection, the marker which represents the intersection is colored in red, a medium difference is represented in yellow, and a small or null difference is represented in green color. This color scale might help decision makers to focus on a subset of intersections looking for possible problems in the programming of those traffic lights, in which differences in time were longer.

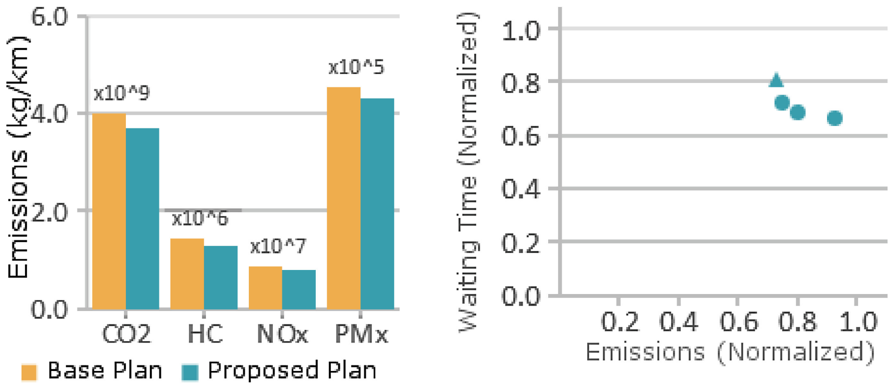

Fig. 4. Results of the execution of HITUL. On the left, the comparison between the based plan and the selected optimal plan, for several pollution indicators (*CO2*, *HC*, *NOx*, and *PMx*). On the right, the set of optimized plans proposed is shown, using a triangle mark to highlight the plan selected for the comparison with the base plan.

Using HITUL, the decision maker could generate traffic light schedules to minimize waiting time, journey time, and emissions. The improvement achieved with HITUL in solution quality with respect to the expert's solution is remarkable. In Fig. 4 left, it can be seen a comparison of the emissions of the base plan generated by the expert's algorithm and an optimized solution using HITUL. This optimized solution is highlighted in Fig. 4 right by using a triangle mark. In this case, it represents the plan that produces less pollution to the environment at the expense of a longer waiting time for drivers. Finally, the HITUL system allows the user to select the non-dominated solutions to compare with, which is a very useful functionality for decision-makers to match occasional traffic needs in terms of the two optimization criteria selected.

The TLP problem is, in fact, a multi-objective problem since the drivers want to minimize the waiting time and journey time, meanwhile the municipality wants lower gas emissions. For this reason, HITUL is able to run a multi-objective algorithm which provides a Pareto front with non-dominated solutions considering two objectives at the same time. In Fig. 4 right, it is shown a Pareto front taking into account waiting time and gas emissions as equally important objectives. Then, the decision-maker could pick one non-dominated solution up from the generated Pareto front.

5 Conclusions

In this paper, we present a decision support system, named HITUL, that helps traffic managers to generate optimal TLPs for actual cities, leading to high potential benefits in terms of energy consumption, traffic flow management, pedestrian safety, and environmental issues.

The proposed system addresses most of the drawbacks of current existing systems considering very large zones and realistic information. Also the system provides some facilities for making easier the decisions of the traffic managers, such as allowing the comparison between traffic plans, highlighting the importance of each individual traffic light in the final plan, or allowing to restrict the zone to be considered, the traffic profile used or even the main goal that s/he wants to optimize. The validation of the system in Málaga, a medium-large spanish city, has demonstrated that HITUL is able to provide real support for decision makers regarding the planning of the city traffic light network.

As future work, we plan to extend the study to other cities, aiming to address different types of network topologies and traffic densities. Also, new optimization algorithms will be applied, as well as hybrid approaches built for selecting the algorithm that best solves the traffic problem for the real city characteristics. Finally, we plan to integrate our tool with other systems that provide us with more city data in real time (e.g., based on sensors) for more accurate solutions.

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