An Algorithmic Approach for Environmentally-Friendly Traffic Control in Smart Cities[*]

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ABSTRACT

Traditionally, vehicular traffic control has focused primarily on easing congestion on public roads and thereby reducing the end to end trip delay for drivers. We consider how traffic control could be optimized to additionally address environmental impact, for instance by reducing the amount of traffic in areas of the city with higher residential population. We model the corresponding optimization as a combinatorial graph problem, with an objective incorporates both the average end to end delay for commuters as well as penalties on traffic for each road segment. We present a fully distributed algorithm with a guaranteed constant-factor approximation ratio with respect to the optimal solution. We evaluate the proposed algorithm through numerical simulations.

Categories and Subject Descriptors

H.4.m [**Information Systems Applications**]: Miscellaneous; I.6.4 [**Simulation and Modeling**]: Model Validation and Analysis

Keywords

Smart Cities, Urban Traffic Control, Heuristic Algorithm

1. INTRODUCTION

With the constant development and urbanization of human society in recent years, the density of urban residential areas is increasing all over the world. Currently, according to The World Bank urbanization indicators, close to 80% of the world population are living in urban areas and more than 20% are living in cities with population more than 1 million [1]. To serve these increasingly high density urban populations, governments everywhere seek sustainable development approaches [13] that balance commercial and personal needs with environmental protection.

One of the key components of the civil infrastructure that needs to be considered and carefully controlled to provide an urban environment that is not only functional and efficient, but also sustainable is the vehicular traffic infrastructure. Indeed, while transportation is the key facilitating aspect of any urban area, it is also, at the same time, a major contributing factor affecting the natural environment. In light of this, the transportation network needs to be designed and operated in order to meet not only the human and commercial needs of the city (by minimizing traffic jams and enabling the rapid movement of people for work and personal reasons) but also to reduce air pollution and sound pollution particularly in the most sensitive areas (such as residential areas, open-air pedestrian-heavy shopping areas, parks, urban wilderness, hospital and other healthcare provider locations).

As the first step to have a measure of transportation needs of dwellers and commercial entities in a city, the concept of Origin-Destination(OD) matrix is typically used [3]. An OD matrix is a matrix with rows correspond to common origin regions (at some arbitrary level of granularity - ranging from streets to districts) of the commuters and commercial vehicles in the corresponding city and columns correspond to destinations of the vehicles. Each element of the matrix then represents the density of vehicles for a given time period traveling between the given source and destination regions. OD matrices for any city can be estimated via many different approaches from taking surveys to more modern approaches relying on the use of deployed sensors to automatically gather traffic counts of highway as well as arterial road segments [10].

In the long run, the information provided by the OD matrix, which gives an indication of the traffic demand, can be used as a basis for planning and developing the transportation infrastructure for the city — from new light rail lines to new roads or additional highway lanes. However, in the short-run, keeping in mind that the transportation network development is costly and slow in practice compared to more dynamic and rapidly changing needs of urban population, other forms of traffic regulation and control are needed to adapt to these high frequency changes. Examples of these regulation and control mechanisms may include traffic light duration change, speed limits, stop signs, congestion-priced tolls, etc. By deliberately changing the expected end to end delay of different paths, these controls aim steer the traffic in the city towards desirable operating points.

Traditionally, traffic engineering has focused primarily on easing traffic condition and minimizing the average end to

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end delays for drivers on the roads. Our contribution in this work is to consider how traffic optimization could also address the environmental impact to enable more livable, greener, sustainable cities. We incorporate this concern by introducing different penalties or costs, here referred to as environmental costs, associated with unit traffic volume for different regions of the city. Higher costs would be associated with parts of the city where residents or the natural surroundings are more likely to be impacted adversely by air and noise pollution. The costs could also be designed to take into account micro-climatic conditions, e.g., as certain regions such as valleys may be more susceptible to pollution due to lack of air circulation or temperature inversion effects, these regions may have a higher cost associated with them. On the contrary, lower cost locations may correspond to sparsely populated industrial sections, or regions with better air circulation. We incorporate these costs into the optimization objective, aiming to steer traffic away from high cost locations as much as possible, while balancing this environmental concern with the traditional concern of minimizing end to end trip times.

We introduce a fully distributed algorithm that accounts for these different regional priorities as well as for aggregate travel time of the commuters. The algorithm is fully distributed and does not need to be aware of the OD matrix of the city. It is also proved that the algorithm returns a solution that is guaranteed to be within a constant factor of the optimal solution.

The rest of this paper is organized as follows. Section 2 touches upon works that have been done in similar areas. Section 3 models the setting with a combinatorial graph problem. In continuation, an algorithmic distributed approach is discussed in section 4 with a guaranteed bound and some simulation results are presented in section 5. At the end, section 6 concludes the paper by addressing the future paths of this work.

2. RELATED WORK

Urban traffic control was first addressed in the literature to manage congestion and reduce average end to end trip delay of commuters [7, 11]. Later on, by constant increase of city densities, environmental and urban design standards are set to be considered as other important factors in sustainable city growth and as a result in traffic control [9, 8].

Some works in this context, rely on origin-destination estimation to achieve a figure of demands for a given urban areas [3]. This allows them to centrally use traffic control means such as signalling and ramp meters to reach a desirable traffic dynamics. Others take a more on-line approach to dynamically respond somewhat locally to the traffic demands or develop solutions for a wide range of traffic regimes. As an example of this, authors in [4] introduce a real time algorithm for the optimal control of traffic signals named as CORONS. It is real time and responsive to the traffic flow by directly controlling the number of traffic light switches in a given period of time. It will minimize the sum of the number of vehicles on the controlled links through which to control the congestion and end to end trip delay. Another work [5] uses a Hybrid Petri nets in which urban intersection traffic signalization is modelled through a hybrid system. In this model vehicle flows are modeled as a time driven event and the traffic signals behaviour are described by discrete events. The goal is more focused on certain urban standards, more specifically the travel time of emergency vehicles. Demand uncertainty is considered in [12] where authors introduce a bi-level heuristic approach for transportation network design and regulation in order to meet certain emission constraints as well as demands. Another example [2] takes a microscopic approach to investigate the effect of different toll road policies on emission in New Jersey Turnpike.

Traffic control in essence can be also seen as an optimization or optimal control problem wherein the given probed data of the transportation network aims at minimizing aggregate end to end delay [6] or other objectives. Other works like [8] use the same approach and consider both environmental (in particular, emission reduction) as well as travel time optimization, taking a multi-objective approach using model predictive control.

3. PROBLEM STATEMENT

We investigate a general transportation network under a light or medium traffic demand. The network is modelled by a directed graph $G = (\mathcal{V}, \mathcal{E})$ where $\mathcal{V}$ is the set of all intersections and $\mathcal{E}$ is the set of directed edges. Each edge corresponds to a road segment stretched from one intersection to another without any other intersection in the middle. The direction of each edge identifies the direction in which traffic can flow in the corresponding road segment. We also assume a fully greedy approach for the drivers behaviour such that each driver chooses the path that drives him or her in the shortest time to the destination. Under our assumed traffic regimes, the drivers can fairly easily choose the shortest path to their destinations without much error.

Having a network of roads with given intersections each indexed by say $i \in \{1, ..., I\} \in \mathcal{V}$, and naming each segment of each road between two consecutive intersections i and j as $s_{ij} \in \mathcal{E}S$, we define two set of variables associated with this structure. There is an environmental cost (penalty cost), c_i, assigned to each intersection i showing how undesirable it is to have traffic passing that intersection. Second, there is a delay stamp, d_{ij} for each edge $s_{i,j} \in \mathcal{E}$ which determines how long in expectation it takes a car to traverse the corresponding road segment. This delay is assumed to be the controllable design parameter. It may be directly set in the form of speed limits set dynamically using electronic signage, or indirectly via the control of traffic lights, ramp metering, even tolls.

We define the problem as follows: assuming that we are given the weight for each intersection, and the OD matrix, how can we choose the delay for each road segment in such a way that the traffic load (determined by drivers greedily responding to these signals by choosing shortest-delay routes) such that a combination of the average trip delay of the commuters and the weighted environmental cost is kept low. More formally: What is the optimum way of delay assignment to the road segments of the traffic network, such that $d_{ij} \geq d_{ij}^{min}$ and the following term is minimized:

$$C(G, \mathcal{D}, \mathcal{F}) = \sum_{k,l \in I} \sum_{s_{ij} \in P_{k,l}} f_{kl}(\alpha c_i + d_{ij}) \qquad (1)$$

where d_{ij}^{min} is the lowest delay that can be assigned to the edge i, j, i.e. in absence of traffic lights and stop signs it will take the vehicles at least this much time to travel this edge. Also, $\mathcal{F}$ is the set of all traffic flows in the road network consisting of flows $f_{kl}, \forall k, l \in I$ originating form intersection k and destining to l. As mentioned before, it is assumed that cars always pick shortest paths which is a set of road segments and $P_{k,l}$ represents such a set for the shortest path from k to l. α is a weighting factor decided by policy makers to adjust the relative importance of minimizing environmental impact vis-a-vis reducing commuter trip delays.

4. SOLUTION APPROACH

Given the problem statement in the previous section we are interested in a solution that can be easily implemented for a general wide range of traffic regimes. More specifically, we are looking for an optimum delay assignment $d^*_{ij} \geq d^{min}_{ij}$ for any road segment $s_{ij} \in \mathcal{E}$ such that we can minimize objective in 1. Having all the knowledge about the transportation network layout and traffic OD matrix (traffic demand) of the area and assuming a central control system, this is a mixed integer optimization problem over $\mathcal{D}$ Though we do not present a formal proof here, we conjecture that this problem is NP-hard. On the other hand, we are interested in a fully distributed approach that does not have the knowledge about the transportation layer and traffic demand. In the following theorem we show a simple assignment that leads to a bounded result.

THEOREM 1. *An assignment of delays as follows:* $d^H_{ij} = \max(\alpha c_i, d^{min}_{ij})$ *on any given road network results in an objective which is less than* 4 *times of the optimum value.*

PROOF. Let d^*_{ij} be the optimum assignment of delays for a given road network.In this case, any driver and as result each flow f_{kl} act selfishly and chooses the shortest path based on the minimum delay assignment. Let's denote the optimal path for f_{kl} by P^*_{kl} for the optimal assignment. Also we show the optimum cost function by C^* and the amount f_{kl} contributes into it by C^*_{kl}.

In our heuristic the assigned delay to segment s_{ij} is shown by d^H_{ij}. In the first step, assume that each traffic flow f_{kl} traverse the same path as the optimum solution (not the shortest) but with the new assigned delays. As a result, the contribution of f_{kl} to the objective in this scenario is:

$$C'_{kl} = \sum_{s_{ij} \in P^*_{kl}} f_{kl}(\alpha c_i + d^H_{ij}) \tag{2}$$

Where C'_{kl} denotes the contribution. We can also write:

$$\begin{aligned} &\alpha c_{ij} \leq d^H_{ij} \\ \Rightarrow &\alpha c_{ij} + d^H_{ij} \leq 2d^H_{ij} \\ \leq &2(d_{min} + \alpha c_{ij}) \leq 2(d^*_{ij} + \alpha c_{ij}) \end{aligned} \tag{3}$$

Substituting this into what we have before, we get:

$$C'_{kl} \leq 2C^*_{kl} \Rightarrow C' \leq 2C^* \tag{4}$$

However with the mentioned assigned delay the path that each flow takes will not be the same as the optimum. Let's denote the actual greedy path for each flow f_{kl} with P^H_{kl} and its associate cost as C^H_{kl}. We have:

$$C^H_{kl} = \sum_{s_{ij} \in P^H_{kl}} f_{kl}(\alpha c_i + d^H_{ij}) \tag{5}$$

Region ID	9	10	12	13	14	20	21	22	25
Costs	1.7	0.2	0.1	1.5	1.5	0.1	0.5	0.3	0.1

Table 1: Environmental Costs for different sections of the targeted urban area.

Incorporating the fact that the sum of the delays on P^H_{kl} is smallest compared to any other path including the P^*_{kl} we can write:

$$\begin{aligned} &\sum_{ij \in P^H_{kl}} d^H_{ij} \leq \sum_{ij \in P^*_{kl}} d^H_{ij} \\ &\Rightarrow C^H_{kl}/f_{kl} = \sum_{ij \in P^H_{kl}} d^H_{ij} + \sum_{ij \in P^H_{kl}} \alpha c_i \\ &\leq \sum_{ij \in P^*_{kl}} d^H_{ij} + \sum_{ij \in P^*_{kl}} \alpha c_i - \sum_{ij \in P^*_{kl}} \alpha c_i + \sum_{ij \in P^H_{kl}} \alpha c_i \\ &\leq \sum_{ij \in P^*_{kl}} d^H_{ij} + \sum_{ij \in P^*_{kl}} \alpha c_i + \sum_{ij \in P^H_{kl}} \alpha c_i \\ &\leq C'_{kl}/f_{kl} + \sum_{ij \in P^H_{kl}} d^H_{ij} \\ &\leq C'_{kl}/f_{kl} + \sum_{ij \in P^*_{kl}} d^H_{ij} \\ &\leq C'_{kl}/f_{kl} + \sum_{ij \in P^*_{kl}} d^H_{ij} + \sum_{ij \in P^*_{kl}} \alpha c_i \\ &= C'_{kl}/f_{kl} + C'_{kl}/f_{kl} = 2C'_{kl}/f_{kl} \end{aligned}$$

Wubstituting the result in Eq. 4 we have:

$$C^H_{kl} \leq 4C^*_{kl} \tag{6}$$

Summing over all $f_{kl} \in F$ completes the proof. ☐

It is important to note that this result holds for any transportation network without the need to incorporate global or local knowledge about the current state of traffic demand. However, the choice of α and the environmental cost terms is exogenous to our optimization and assumed to be determined based on the city's unique circumstances and needs as determined by policy-makers. A limiting case will be when $\alpha \to \infty$ where assignment as simple as $d^H_{ij} = \max(w_i, d^{min}_{ij})$ will give the optimum. As a matter of fact, our heuristic will perform worst when the contribution of delays and environmental impact are of the same order in the objective. And it performs better when one contribution dominates the other.

5. RESULTS

This section presents a few simulation results to investigate the performance of our heuristic algorithm mentioned in Theorem 1 in practice. For that we consider a part of transportation network of city of Los Angeles. The traffic demands are generated based on estimated OD matrix for that region [10]. The routing matrix is calculated and the area of focus is dissected into 35 region. Certain environmental costs are assigned to the intersections in each region some of which are noted in table 1.

Some of the results are presented in figures 1 and 2. Figure 1 shows the density of traffic in certain sections of the

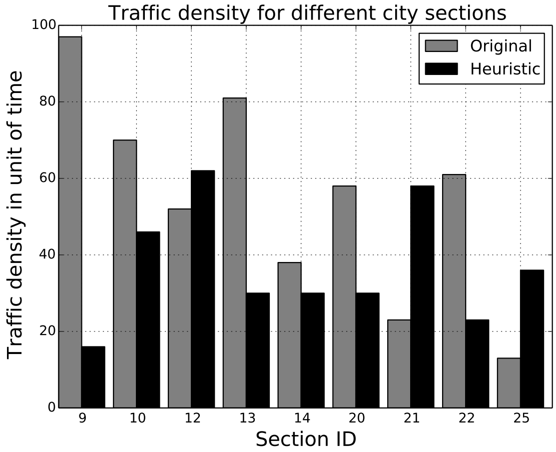

Figure 1: Traffic Density in unit of time, $\alpha = 2$.

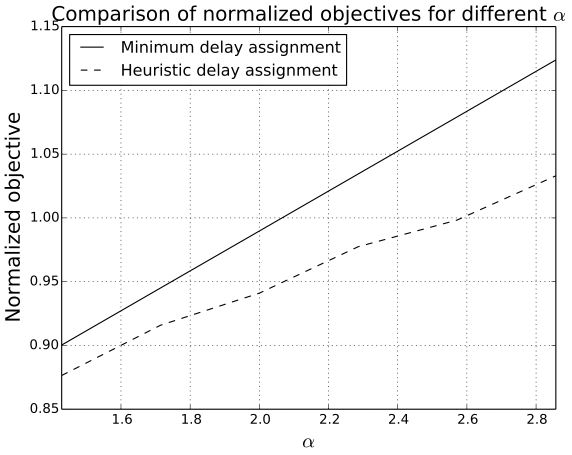

Figure 2: The graph representing a part of Los Angeles transportation network.

targeted area with original traffic settings compared to the scenario with delay assignments to road segments according to our proposed algorithm. As it can be seen sections with higher environmental costs witness a decrease in traffic density and the ones with lower environmental costs are used more frequently with the vehicles. The amount of increase or decrease in traffic density of each section is not only a function of their relative costs, but also affected by the underlying transportation network and their relative geographical positions.

Figure 2 shows the normalized objective of the transportation network under the generated traffic demand. The solid line represents the normalized objective under the current expected delays of the traffic network and the dashed line represents the normalized objective assuming the heuristic delay assignment to road segments for different weighting factors (α). while the original case objective linearly increase with increasing α the heuristic objective performs better and as α increases finds a more significant gap with the original case.

6. CONCLUSION

Here, we discussed a fully distributed heuristic for traffic control that takes both commuter trip delays and sustainable city measures into account. We discussed that a fully central optimum solution is likely to be NP-hard and showed our fully distributed algorithm has a bounded performance. For future work, we suggest to continue the work on the dynamic and congested traffic networks where a simple locally aware algorithm may have acceptable results.

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