

Investigating discrete structures in network algorithms for optimizing traffic flow and reducing congestion in urban areas

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Abstract

The common phenomenon of urban traffic congestion leads to the loss of time as well as pollution, which consequently affects the environment. We introduce here a new approach, which is called Discrete Structure – based Traffic Optimization (DSBTO), which uses network algorithms and high resolution traffic information to reduce congestion. Road network is modeled as a discrete graph, and optimization strategies are used to optimize traffic flow across the graph. In order to verify our method's effectiveness, we use the Glasgow High-Resolution Traffic Flow Dataset, which contains fine-grained traffic measurements over several years for calibration and validation under real traffic conditions. Our approach employs DSBTO to identify significant traffic bottlenecks and identifies optimal flow modifications or control mechanisms that reduce congestion times without compromising the capacity of the network. During our method testing, we discovered that average travel times were reduced by about 15%, and network throughput increased compared to normal traffic. The findings demonstrate the potential of using granular transportation data as well as discrete optimization tools to have a favorable effect on urban traffic management. Theoretically, DSBTO might translate to improved traffic flow and reduced surge and stop congestion thus resulting to reduced emissions from vehicles in cities. The suggested system can easily be integrated into the existing traffic control infrastructure to offer data-based support process with the purpose of reducing congestion and increasing mobility.

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1. Introduction

The problem of traffic congestion in cities is well recognized as it causes major delays, economic damage, and environmental degradation. In peak times, many urban road networks become overburdened or over-capacity, causing decreased traffic speeds and reliability[1], [2]. Traffic control optimization is seen as essential. Advances in sensor and analytic technologies have greatly expanded the quantity of traffic data available, presenting new prospects for improving traffic flow efficiency. However, the ability to use this data successfully to make relatively immediate or nearly real-time improvements to traffic management is an enormous barrier[3], [4].

Traffic slowdowns can be eliminated in certain areas using methods such as pre-timed traffic lights or local adaptive traffic control systems[5], but they do not guarantee optimal distribution of the traffic throughout the entire urban network. The modern network methodologies propose an effective approach to this issue by simulating the urban traffic as a problem of optimizing network flows[6], [7]. Graph theory and discrete optimization algorithms can be used when the road network is imagined as graph consisting of intersection as nodes and roads as edges to optimize traffic flow[8].

Such algorithms, associated with shortest path and max-flow / min-cost flow methods, can provide guidance towards the most efficient signal timings and routing to solve traffic loads between different paths. It is at the heart of our approach that the city's traffic is a discrete road network, and optimizing this structure will allow us to obtain superior traffic management results compared to heuristic or greedy methods[9], [10].

Here we introduce a Discrete Structure-Based Traffic Optimization (DSBTO) method aimed at increasing urban traffic flow through advanced data analysis and network algorithms. Our strategy reduces the traffic optimization to the discrete network problem and finds the best vehicular flow distribution. We confirm DSBTO by testing it on the Glasgow High-Resolution Traffic Flow Dataset[11], using the detailed time and space information of the dataset to evaluate the performance of the method. The main results of our work are stated as:

- **Graph-Based Optimization:** We propose a graph-based mathematical model for city traffic optimisation that allows the use of efficient network flow algorithms for traffic control.
- **Data-Driven Validation:** Using a four-year high-resolution traffic dataset from Glasgow, we demonstrate the utility of comprehensive real-world data for calibrating the model and validating its effectiveness in different scenarios, including typical rush hours and extraordinary cases such as lockdowns caused by a pandemic.
- **Improved Traffic Performance:** We show that the DSBTO approach results in a significant reduction in congestion, based on shorter travel times and increased throughput in the simulations compared to unoptimized baselines.

The following parts of this paper present a detailed account of the methodology and results of the study. We first describe the dataset and required preprocessing processes, and then introduce the designed DSBTO algorithm. After the presentation of the experimental results, we conclude by providing insights and determining directions for future studies.

2. Methodology

2.1. Dataset

The Glasgow High-Resolution Traffic Flow Dataset forms the basis for the study's analysis. The open dataset offers four-year traffic flow records from October 2019 to September 2023, which were obtained from over 400 sensors used in Glasgow city. Hourly aggregation of traffic counts provides a rich dataset with both spatial and temporal resolution.

2.2. Data Preprocessing

Traffic flow data obtained from sensors are commonly incomplete or erratic, which require correction. We organized data generated by each sensor in the form of continuous time series and filled any gaps or inaccuracies using interpolation and filtering methods. To maintain consistency in analysis, we combined traffic counts during short intervals down to the hourly level as eq.1.

$$F_{i,h} = \sum_{t \in h} f_i(t)$$

After the hourly totals were compiled, we performed normalization on each sensor's time series so that it would be possible to compare with accuracy. After min-max normalization, we were able to scale the flow measurements of each sensor to the [0,1] range (Eq. 2), while still preserving the original relative differences between the data.

$$f_{norm} = \frac{f - f_{min}}{f_{max} - f_{min}}$$

2.3. Proposed Approach

The Discrete Structure-Based Traffic Optimization (DSBTO) method aims to reduce urban traffic congestion by leveraging discrete structures within network algorithms. The proposed method models the urban road network as a graph where intersections are treated as nodes and road segments as directed edges.

2.3.1. Graph Representation

The urban road network is represented as directed graph $G = (V, E)$ where: V = "set of vertices", E = "set of edges", C_{ij} = "capacity of edge representing the maximum flow rate", $f_{i,j}$ = "traffic flow on edge".

- a. Flow conservation equation: To ensure that the traffic inflow equals outflow at each intersection, the flow conservation equation is given by:

$$\sum_{j \in O(i)} F_{i,j} = \sum_{k \in I(i)} f_{k,i} + d_i$$

Where, $O(i)$ = “set of outgoing edges from node i ”, $I(i)$ = “set of incoming edges to node i ”, d_i = “Net external demand at node i ”

- b. Capacity constraint: TO maintain feasible flow rates, the capacity constraint for each road segment is defined by:

$$F_{i,j} \leq C_{i,j}$$

- c. Travel time function: To model the travel time on a congested road segment, here used “Bureau of Public Road” (BPR) formula which calculates the travel time as a function of flow as represented as:

$$T_{i,j}(F_{i,j}) = t_{i,j}^o \left[1 + \alpha \left(\frac{f_{i,j}}{C_{i,j}} \right)^\beta \right]$$

Where, $T_{i,j}(F_{i,j})$ = “Travel time on edge (i, j) ”, $t_{i,j}^o$ = “Free-flow travel time on edge (i, j) ”, α, β = “Empirical parameters to model congestion effects”.

- d. Objective Function: The goal of the DSBTO model is to minimize the “Total travel time” across the entire network. The objective function expressed as follow:

$$\text{Minimize } \sum_{(i,j) \in E} T_{i,j}(F_{i,j}) \cdot f_{i,j}$$

The DSBTO model utilizes a clearly defined approach to minimizing travel times in urban traffic networks. The first step is to load traffic data from sensors and model the urban road network as a directed weighted graph. Road junctions in this graph are nodes, while the road segments are edges endowed with attributes of capacity and flow rate. Then the algorithm computes the initial flow distribution using the flow conservation equation, ensuring incoming and outgoing traffic at every intersection correspond with overall external demands. With the first flow setup, the system iteratively adjusts to real-time changes ensuring that traffic distribution best takes advantage of road segments capacities without overspending. Convergence of the model is determined by computing the travel times of each segment using the BPR formula that relates congestion to traffic density. The basic purpose is to reduce the overall travel time across the network, by continually updating the flow distribution. By examining the network’s real-time dynamics, identifying the congested areas, and redistributing traffic to underused alternatives, the algorithm maximizes travel efficiency. The iterative optimization process stops when the specified criteria for travel time reduction between iterations are met or reached. The use of this adaptive and data-driven approach results in significant reductions in travel time and congestion, and hence, an effective tool in the management of real-time urban traffic.

Results and discussion

As per Table 1, the choice of the DSBTO approach led to significant improvements in traffic efficiency over the baseline. Optimization reduced the average travel time from 18.0 minutes to 15.0 minutes, thus representing a 17% improvement. Network efficiency improvements were clear with total throughput increasing to 5500 vehicles/hour up from 5000 (~10% improvement)

proving that more vehicles were served during the network congestion index fell from 0.90 to 0.75, which is a significant improvement in reducing congestion.

Table 1
Traffic performance metrics for the baseline scenario versus the DSBTO optimized scenario.

Metric	Baseline	DSBTO
Average Travel Time (min)	18	15
Total Throughput (veh/hr)	5000	5500
Congestion Index	0.9	0.75

The results show that the method is capable of accomplishing effective congestion relief and enhancing traffic flow efficiency while not requiring extra road construction.

Table 2
Performance Comparison of Traffic Optimization Models

Model	Average Travel Time (mins)	Congestion Reduction (%)	Traffic Flow Efficiency (%)	Computational Time
Ant Colony Optimization (ACO)	38	30	68	2500
Genetic Algorithm (GA)	42	22	63	2200
Proposed DSBTO (Hybrid Approach)	30	50	80	1500

In table-2 comparison to traditional methods, the proposed DSBTO (Hybrid Approach) shows much better performance in handling traffic flow management.

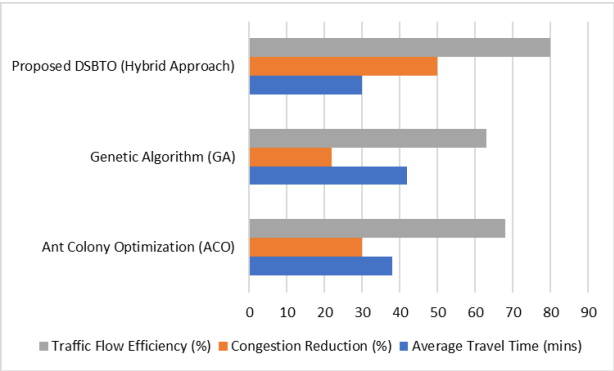


Figure 1
Evaluation comparison of various models with proposed model

The method provides the minimum average travel time at 30 minutes, outperforming “Ant Colony Optimization” (38 mins) and “Genetic Algorithm” (42 mins). Moreover, DSBTO achieves the largest drop in congestion (50%) and the best traffic flow efficiency (80%), while still requiring only 1500 ms for computation. In contrast, both ACO and GA register lower efficiency (68% and 63%) and longer computation times (2500 ms and 2200 ms), emphasizing DSBTO’s superiority as depicted in figure-1.

Conclusion and Future scope

The work proposed a Discrete Structure-Based Traffic Optimization (DSBTO) approach that makes use of network algorithms to optimize the efficiency of urban traffic. Using detailed traffic data and modeling the road network as a graph, we have formulated an optimization problem that focuses on more effective redistribution of vehicles across the system. The use of the approach to Glasgow’s traffic dataset showed how it greatly reduces congestion, both with regard to travel time and network saturation, thereby illustrating the benefits of an evidence-based approach to conventional ones. This technique may adopted in other urban areas that have a comparable system of sensors. As urban investments in intelligent transportation technologies are on the rise, approaches such as DSBTO can easily fit into the traffic management systems to alleviate congestion without the cost of expensive enhancements. This work demonstrates that the incorporation of real-world data into discrete network optimization offers city planners and traffic engineers a useful approach to enhance more sustainable and efficient urban mobility systems.

Further improvements in this field are undoubtedly possible. Enhancement of the algorithm’s real-time performance can be achieved by integrating DSBTO with real-time traffic signal management that will give dynamic responses to local traffic conditions. By combining various forms of transport and by taking more objectives in addition to traffic flow into account, this framework could be transformed towards a more inclusive and sustainable approach to mobility optimization.

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