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Controlling road congestion via a low-complexity route reservation approach ☆

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ABSTRACT

This work introduces a novel route reservation architecture to manage road traffic within an urban area. The developed routing architecture decomposes the road infrastructure into slots in the spatial and temporal domains and for every vehicle, it makes the appropriate route reservations to avoid traffic congestion while minimizing the traveling time. Under this architecture, any road segment is admissible to be traversed only during time-slots when the accumulated reservations do not exceed its critical density. A road-side unit keeps track of all reservations which are subsequently used to solve the routing problem for each vehicle. Through this routing mechanism, vehicles can either be delayed at their origin or are routed through longer but non-congested routes such that their traveling time is minimized. In this work, the proposed architecture is presented and the resulting route reservation problem is mathematically formulated. Through a complexity analysis of the routing problem, it is shown that for certain cases, the problem reduces to an NP-complete problem. A heuristic solution to the problem is also proposed and is used to conduct realistic simulations across a particular region of the San Francisco area, demonstrating the promising gains of the proposed solution to alleviate traffic congestion.

1. Introduction

Traffic congestion constitutes an ever growing problem in modern cities resulting in multiple adverse effects including driver frustration, environmental pollution while fuel cost and lost of productive hours are the economic downside. The leading cause of congestion is that during certain periods, the number of vehicles that request to simultaneously traverse specific road segments increases to the point where it approaches or even exceeds their critical capacity. This problem does not necessarily occur due to lack of overall network capacity but due to the absence of mechanisms that can achieve an efficient network utilization (Chen et al., 2001).

Interestingly, offering real-time traffic state information to drivers has shown to create additional side effects to the overall utilization since all rational drivers would try to follow less congested road segments instead of following the shortest distance paths. This selfish behavior, as demonstrated in Çolak et al. (2016), gives rise to network state oscillations and exacerbates road congestion. Moreover, the problem becomes even greater when the unpredictability of driving behavior is taken

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into account. Thus, the objective of this work is to develop a novel architecture which will provide the means to better utilize the network capacity, both spatially and temporally such that the effects of congestion are minimized.

The Macroscopic Fundamental Diagram (MFD) (Geroliminis and Sun, 2011) explains the macroscopic relationship between the three main mobility factors, i.e., speed, flow, and density. From studying the MFD two distinct regimes can be identified: (1) the free-flow regime and (2) the congested regime (Immers and Logghe, 2003) which are separated according to each region's accumulated density. The MFD indicates that an increase in a region's density within the congested regime, results to a decrease in the vehicle speed with the possibility of a gridlock occurrence. On the other hand, the possibility of a gridlock diminishes within the free-flow regime where free-flow speed conditions are observed and both driver and network dynamics are well approximated (Daganzo, 2007). These macroscopic relations are also present when autonomous vehicle features are assumed (Roncoli et al., 2015). Furthermore, as indicated in Geroliminis and Sun (2011), an MFD is well-defined within a homogeneous region (i.e., within the particular region, all links have similar traffic characteristics and insignificant variance across their densities). Guided by the MFD analysis, we know that for every road segment, there exists a critical capacity and while the vehicle density in the segment is below this critical capacity, vehicle flows and speeds are high and more or less predictable. On the other hand, if the critical capacity is reached (congested regime) then capacity is dropped and vehicle flows and speeds become unpredictable. Thus, a key objective of the proposed architecture is to prevent the vehicle density in any road segment to exceed its critical capacity. For the purposes of this paper, we assume that the critical density of each road segment is known (e.g., through the MFD analysis) however, even if these are not known they can be computed through extensive simulations or other tools like perturbation analysis (Ho et al., 1991).

This work introduces a novel route-reservation architecture and a routing algorithm that utilizes the obtained reservations in order to determine the best possible path subject to avoiding road segments that are expected to be at their capacity. In the proposed architecture, a Road Side Unit (RSU) decomposes the road network spatially and temporarily. Given past requests, the RSU has an estimate of the number of vehicles that are expected in each road segment, during any interval from the current time and into the future. Based on these reservations, the RSU knows which road segments are expected to be below their critical capacity and thus available to more vehicles and which segments are unavailable. When a vehicle is about to begin its journey (or even earlier if "pre-bookings" will be allowed), it sends a request to the RSU with its origin and destination. The RSU then computes the best possible path for the vehicle such that any road segment that is near its critical capacity is avoided and taking into consideration that it may be best for a vehicle to wait at the origin until certain road segments become available. Once the RSU determines the best path, it assumes the vehicle will move with the speed at capacity of each segment in order to update the number of vehicles in each segment and each future time slot.

Note that the proposed architecture, has a number of benefits that are worth emphasizing. Obviously vehicles are routed through non-congested paths which is a benefit for the individual vehicle. In addition, by not allowing vehicles to go through segments that are near their capacity, it "protects" other vehicles that have already reserved those segments and it guarantees that they will not experience congestion either, thus the approach has also a more social benefit. Finally, by allowing the RSU to suggest delayed departures, it keeps vehicles and their drivers away from the road minimizing their travel time and the cost associated with lost productivity and environmental impact. On the other hand, the proposed approach admittedly faces certain implementation challenges. First is the communication and computation aspects involved in the implementation. Given the recent developments in the information and communication domain, the Internet of Things (IoT) technology and the proliferation of connected vehicles, these challenges will be addressed in the near future. We also point out that distributed versions of the architecture which are more scalable are feasible and is the topic of our current research. Another major challenge is driver compliance. This challenge can be easily addressed in the context of autonomous vehicles by enforcing that the vehicles will follow the paths provided by the RSU. Even in the case of human drivers, there are some possible solution by monitoring the actual path followed (e.g., using the vehicle's GPS) and by providing incentives to compliant drivers or penalties to non-compliant ones.

Once the RSU receives a request for finding a route for a vehicle, it needs to solve the routing problem and the objective is to determine the path that will allow the vehicle to reach its destination at the earliest possible time while avoiding unavailable segments and possibly delaying its departure. It turns out, that this is a difficult problem to solve and as demonstrated in the sequel certain instances of the problem are NP-complete. Thus, some heuristic algorithms are needed to solve this problem one of which is proposed in this work and is compared to other approaches through extensive simulation.

In summary, the contribution of this paper includes a reservation-based novel architecture for achieving congestion free routing, in the context of Intelligent Transportation Systems (ITS). Given the obtained reservations, the vehicle routing problem is formulated and is shown to be NP-complete while an efficient heuristic algorithm is proposed that provides good solutions. Furthermore, the benefits of the entire approach are demonstrated through extensive simulations on realistic networks.

The rest of the paper is organized as follows. Section 2 describes the related work, while Section 3 introduces the architecture of the proposed solution. Section 4 mathematically formulates the proposed route reservation problem and performs a complexity analysis of the problem. Section 5 presents a solution approach based on "Time Expansion", while Section 6 presents a heuristic greedy solution based on Dijkstra's algorithm called Route Reservation Algorithm (RRA). Extensive simulation results are included in Section 7 that demonstrate the benefits of the proposed solution in realistic scenarios. Finally Section 8 concludes this work.