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Route guidance: Bridging system and user optimization in traffic assignment

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ABSTRACT

In this paper we study the problem of the assignment of road paths to vehicles. Due to the assumption that a low percentage of vehicles follow the routes proposed by route guidance systems (RGS) and the increase of the use of the same, the conventional RGS might shortly result obsolete.

Assuming a complete road network information at the disposal of RGSs, their proposed paths are related with user optimization which in general can be arbitrarily more costly than the system optimum. However, the user optimum is fair for the drivers of the same Origin–Destination (O–D) pair but it does not guarantee fairness for different O–D pairs. Contrary, the system optimum can produce unfair assignments both for the vehicles of the same as of different O–D pairs. This is the reason why, in this paper, we propose an optimization model which bridges this gap between the user and system optimum, and propose a new mathematical programming formulation based on Nash Welfare optimization which results in a good egalitarian and utilitarian welfare for all O–D pairs. To avoid the issues with the lack of robustness related with the centralized implementation, the proposed model is highly distributed. We test the solution approach through simulation and compare it with the conventional user- and system-optimization.

1. Introduction

In this paper we treat the problem of the assignment of road network paths to vehicles depending on the momentary traffic situation on the road network. This problem is an open issue of present route guidance systems (RGS) whose strong assumption is that a low percentage of road users follow the proposed routes such that their influence on the change of traffic is insignificant.

Drivers' self-concerned behavior, together with the assumption that the complete road network information is at the disposal of everyone, is related to the user optimization and results in Wardrop equilibrium. The latter can be arbitrarily more costly than the globally optimal traffic assignment. However, assuming that all the vehicle drivers share the same objective function, the Wardrop equilibrium solution is fair for the drivers of the same Origin–Destination (O–D) pair, i.e., the used paths for the same O–D pair have the same value for a specific objective, e.g., minimizing total travel time. At the contrary, the solution might not be fair for different O–D pairs, i.e., the ratio of travel times between any two O–D pairs in the network of the same or similar travel durations in uncongested network can be arbitrarily high.

Furthermore, due to the increase of the use of the RGSs, the assumption on a low number of users is losing its legitimacy and the RGSs might shortly result in the same or worse traveling times than in the case when the RGS proposed path is not followed; the reason is that they direct all their users of the same O–D pair to the same route(s) without considering the dynamic component of an actual number of the drivers accepting to follow those routes. The drawback of the system optimum, on the other hand, which is calculated by minimizing total network cost, is that it can produce unfair assignments both for the vehicles of the same and of different O–D pairs.

In this paper, we study approaches that balance the requirements on equity and fairness both in the assignment of vehicles of the same O–D pair to available paths, but also in the assignment of paths to different O–D pairs. By considering different social welfare and fairness aspects in path assignment, we intend to bridge the system optimization which assumes collaborative road infrastructure users and user optimization which assumes selfish users in traffic assignment. In the usage of the road network infrastructure, we assume the existence of an interest group of rational agents whose presence in the network represents the majority of the users such that the users who do not follow the proposed RGS represent insignificant influence on the road congestion behavior. We try to optimize the behavior of the group members such as to produce maximum

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benefit for the interest group as a whole while not damaging individual group members. Furthermore, we propose an optimization model which bridges the gap between the user and system optimum, and propose a new mathematical programming formulation based on Nash Welfare optimization which results in a good egalitarian and utilitarian welfare.

To avoid the issues with the lack of robustness related with the centralized implementation, the proposed model is based on a highly distributed decision making between the geographically distributed road network intersection agents and road users (vehicles' drivers). In this way, we avoid the necessity of a central coordinator and the road network decision making structure represents well the network topology. The result is a light, distributed, geographically localized, and open multi-agent architecture such that it can seamlessly grow and reconfigure itself based on the transport network needs. Moreover, regarding the solution approach, dynamic traffic assignment problem is a non-convex optimization problem which is at present computationally tractable only for relatively small-scale examples. This is why we apply the static traffic assignment approach.

In the proposed optimization model, we assume that every driver within the interest group has at disposal all the network information regarding the travel time from his/her origin (O) to destination (D), as well as the travel times of other O–D pairs in real time. There is an assumption also that every driver has the information on the travel times which would result if he/she did not respect the route given by the system. However, there is an important drawback of this assumption due to the high unpredictability of future network behavior and related traffic congestion.

Once a vehicle driver is a member of the proposed route guidance system, his/her behavior can significantly influence the efficiency of the system, especially if the driver does not respect the route recommendations of the system. The developments of sensors and their integration on the roads allow for the implementation of a monitoring technology so that the system can identify the vehicles which behave contrary to the network traffic instructions performed a priori and perform corrective actions on those vehicles. One of the open issues is how to adapt to the changes of the vehicle self-concerned behavior, when to incentivize them and when to expel them from the system. We are aware of these issues but the treatment of this topic is out of scope of this work. Thus, for simplicity but without loss of generality, we assume that the users follow the system indications possibly incentivized by specific mechanisms, for example, available in the State-of-the-Art works which we mention in the following.

The rest of the paper is organized as follows. First, in Section 2 we discuss the State of the Art models in traffic coordination, their drawbacks, and the contribution of our work. In Section 3, we formally define the treated traffic assignment problem. In Section 4, we explain the main features of our multi-agent approach. The experiment setup description and results are presented in Section 5. The paper ends with the main conclusions and directions for future work in Section 6.

2. Related work and contribution of the paper

Various problem definitions, solution methods and models related to the optimized transportation networks have been studied intensively in different contexts, e.g., [1–3]. Traffic assignment models are usually based on two Wardrop's principles which state that at equilibrium vehicles travelling on the same O–D pair choose shortest paths such that the resulting (flow dependent) travelling time is the same for all and the paths that are not chosen by any vehicle provide equal or larger travelling times. The Wardrop equilibrium corresponds to the Nash equilibrium in a game with a large number of players [4].

Evaluating the worst-case ratio of Nash equilibria to the system optimum was first proposed in [5]. Papadimitriou in [6] introduces the notion of price of anarchy which measures the user optimum inefficiency in terms of total travel time, i.e., how bad is user-selfish with respect to the system-optimum solution. In [7], it was shown that for the uncapacitated problem, the total travel time associated to the user optimum is at most two times the minimum travel time. This ratio falls to 4/3 for linear travel time functions. Opposedly, in [8], Correa et al. present a family of instances with multiple sources and a single sink for which the price of anarchy is unbounded, even in networks with linear latencies. Furthermore, in [9], Correa et al. proved that, in the case of nondecreasing and differentiable travel time functions, the worst-case of user optimum inefficiency is independent of the network topology. Lin et al. [10] prove for two-commodity networks related with Fibonacci numbers, that the dynamics of the price of anarchy of selfish routing related to the maximum latency has an exponential behavior with the network size. This result indicates the importance of influencing and coordinating the drivers' behavior to reach higher system efficiency.

Some of the available State-of-the-Art theoretical models and methods for infrastructure resource assignment and coordination can be found in, e.g., [1,2,9,11,12]. One of the tools for mechanism design of agent systems are auctions [13]. The implementation usually requires solving a combinatorial non-linear optimization problem which is in general NP-hard and intractable for complex networks [14]. However, with certain relaxations, the latter can be modeled as a convex optimization problem [1,15]. Computational optimization auctions are methods that are similar to the Gauss-Seidel and Jacobii methods, see, e.g., [16]. This approach is well suited for massive parallelization where decisions are locally made based on the information interchanged among different decision makers (processors) [13].

For comparison, in the traffic management of Internet links, it is possible to substantially increase network throughput, limit link overloads, and make a network robust to resource failures by optimizing administrative weights of links [17,18]. Routers can compute shortest paths to each other and thus make routing tables by using the information on the topology of the network and the administrative weights of links. If there are several shortest path links for a specific O–D pair, the traffic is split equally according to the ECMP (equal-cost multi-path) principle.

In real-world transport networks on public roads, it is difficult to implement system-optimized network models since individual objective functions are usually contrary to one another and decision makers act frequently selfishly. The issue of incentives to align local vehicle and global infrastructure objectives is an actual topic, e.g., [19–21].

The tradeoff between efficiency and fairness was considered in [22]. Several managerial prescriptions were developed for the selection problem based on this trade-off. In [23], Jahn et al. consider the static traffic assignment problem and propose a route-guidance system model for system optimal routing of traffic flow with explicit integration of user constraints considering a fixed maximum deviation of the assigned paths costs with respect to the optimal ones. Additive constraints guarantee that user travel times of the system optimum are not so far away from user travel times obtained with the user optimum model. Simulations results show superior fairness compared to the pure system optimum. This model was further theoretically studied in [24]. A strong assumption is that the driver acceptance of paths is assumed for all the paths without considering any additional fairness issue.

Since the dynamic traffic assignment problem is at present computationally tractable only for relatively small-scale instances,