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On characterizing the relationship between route choice behavior and optimal traffic control solution space

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Abstract

Explicitly including the dynamics of users' route choice behaviour in optimal traffic control applications has been of interest for researchers in the last five decades. This has been recognized as a very challenging problem, due to the added layer of complexity and the considerable non-convexity of the resulting problem, even when dealing with simple static assignment and analytical link cost functions. In this work we establish a direct behavioural connection between the different shapes and structures emerging in the solution space of such problems and the underlying route choice behaviour. We specifically investigate how changes in the active equilibrium route set exert direct influence on the solution space's structure and behaviour. Based on this result, we then formulate and validate a constrained version of the original problem, yielding desirable properties in terms of solution space regularity.

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Keywords: Traffic Control; Route Choice; Optimization

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1. Introduction

When considering highly saturated road networks, it has been widely recognized that capturing user's route choice alongside vehicle propagation and congestion dynamics is essential to the development of advanced mobility management strategies. As congestion increases, users will naturally explore different options for reaching their destination, first and foremost in terms of rerouting. From a theoretical perspective, this concept has been historically defined under the name of User Equilibrium (Wardrop, 1952), and essentially captures the natural tendency of road users to seek minimum cost connections from their origin to their desired destinations.

Traffic models have gained popularity over the years, especially in connection with practices such as traffic planning and management. The reason behind this is that as models evolved towards higher accuracy, lower computational costs and improved behavioural richness, they became very attractive tools to predict the effects of changes in either demand management or infrastructure planning. Such an example is the development of model-based optimal traffic control policies, which can be seen as an instance of the Network Design Problem (Johnson et al., 1978). In these applications, an optimization framework aiming at meeting specific policy goals is wrapped around a traffic model, such that the latter can be procedurally used to guide the optimization procedure towards desirable solutions.

Congested traffic behaves in rather complex patterns: as travel times arise, different geographical portions of the network become behaviourally connected, through either spillback dynamics and/or vehicle rerouting. Computing optimal coordinated control in these instances, a problem referred to as the anticipatory traffic control problem ever since the seminal work of (Allsop, 1974), exhibits considerable difficulties. Sensitivity analysis is a necessary tool to understand how equilibrium-constrained control problems behave, but due to unfavourable conditions such as non-uniqueness of path flows and (under lax assumptions) discontinuous behaviour of route selection dynamics, this rather standard tool's performance is strongly jeopardized.

In previous work we empirically assessed how even for very simple scenarios these behavioural concerns strongly influence the shape and structure of standard network control objective functions (Rinaldi and Tampère, 2015). Specifically, we showed how for deterministic static user equilibrium constrained problems, the Total Cost objective function for a very small network with monotonically increasing separable cost functions exhibited strong non-linear behaviour, and how gradient-based optimization techniques cannot generally be guaranteed to reach global optimality. In this novel work, we analyse the underlying causes for these unfavourable conditions, and employ the newly developed insights to improve the tractability of the anticipatory traffic control problem. Our focus is specifically the optimal pricing control problem, subject to static deterministic User Equilibrium.

Specifically, we claim the following contributions for this paper:

- We observe a direct connection between the active route set (expressed through an atomic representation – see Section 3.1) and specific features (later referred to as "regions") in the problem's solution space shape.
- We validate our observation analytically and numerically on a small example.
- We extend the standard bi-level optimization approach used in anticipatory control with a set of constraints capable of capturing this direct connection, and benefiting from it in terms of solution space regularity.
- We showcase the impact of the newly developed constraints for two small networks, analysing optimization performance both in full and partial controllability instances.

To achieve these objectives, we choose a specific way of describing route sets and route choice behaviour, introduced by (Bar-Gera, 2010, 2006). As we will detail in later sections, this powerful tool allows to atomically capture route choice and route sets obviating the need of exhaustive enumeration. To the best of our knowledge, this is the first exploration of how to connect a specific route choice description to bi-level optimization with equilibrium constraints and to take explicit advantage of the system optimal route set structure in optimizing 2nd best network pricing.

The remainder of this paper is structured as follows: Section 2 provides a literature review of equilibrium problems, their sensitivity and their impact in constrained optimization. In Section 3 we explore the relationship between route choice and solution space of bi-level NDP formulations, and discuss the arising of regions and their properties, focusing on how this concept can be exploited to develop better optimization techniques. After these techniques are introduced, in Section 4 we explore how these behave in two small sized networks, highlighting the difference between our novel approach and standard gradient-based optimization. Finally, we provide conclusions and remarks related to future research in Section 5.