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Stability of Transportation Networks Under Adaptive Routing Policies

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Abstract

Growing concerns regarding urban congestion, and the recent explosion of mobile devices able to provide real-time information to traffic users have motivated increasing reliance on real-time route guidance for the online management of traffic networks. However, while the theory of traffic equilibria is very well-known, much fewer results exist on the stability of such equilibria, especially in the context of adaptive routing policy. In this work, we consider the problem of characterizing the stability properties of traffic equilibria in the context of online adaptive route choice induced by GPS-based decision making. We first extend the recent framework of “Markovian Traffic Equilibria” (MTE), in which users update their route choice at each intersection of the road network based on traffic conditions, to the case of non-equilibrium conditions, while preserving consistency with known existence and uniqueness results on MTE. We then exhibit sufficient conditions on the network topology and the latency functions for those MTEs to be stable in the sense of Lyapunov for a single destination problem. For various more restricted classes of network topologies motivated by the observed properties of travel patterns in the Singapore network, under certain assumptions we prove local exponential stability of the MTE, and derive analytical results on the sensitivity of the characteristic time of convergence on network and traffic parameters. The results proposed in this work are illustrated and validated on synthetic toy problems as well as on the full Singapore road network with real demand and traffic data, and the applicability of our results for online road network analysis, pricing and control is discussed.

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1. Introduction

The analysis of traffic network optima and equilibria under specific route choice models has historically motivated sustained research in the transportation community. The pioneering work of Wardrop (1952) has been foundational in that regard, and has been extended in a number of theoretical, numerical and experimental studies considering specific network topologies, path choice models, information model, rationality assumptions, optimality conditions (see for instance Arnott et al. (1991), Dafermos and Sparrow (1969), Ben-Akiva et al. (2002)).

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Efficient mathematical programming models for solving traffic equilibria have also been proposed, starting from the seminal work of Beckmann et al. (1956), who formulated the computation of the user equilibrium as a convex optimization problem. An associated variational formulation was later introduced in Dafermos and Sparrow (1969). For day-to-day dynamics, Hazelton and Watling (2004) present a method to compute the equilibrium in a Markov Chain framework. For a recent comprehensive description of theoretical results, algorithms and computational methods for the user equilibrium problem, we refer the reader to Marcotte and Patriksson (2007).

However traffic networks are not always at equilibrium. Dynamical models of non-equilibria conditions date back to the 1980's with the pioneer work of Smith (1984), leveraging Lyapunov theory to analyze dynamical properties of a path choice model. In Nagurney and Zhang (1997), the authors present detailed sufficient conditions for the stability of such path choice model (see also Cantarella and Cascetta (1995), Cominetti et al. (2010)). Recent results from Karafyllis and Papageorgiou (2014) exhibit conditions for asymptotic and exponential stability when the dynamics is modeled by a scalar conservation law. Lovisari et al. (2014) present a comprehensive stability and controllability analysis for a similar model. For day-to-day dynamics, Jha et al. (1998) provide results based on experimental simulations of drivers.

With the recent explosion in the number of GPS routing devices, recent work on shortest path and vehicle routing have been proposed for so-called *adaptive routing models*, in which the user may update his route choice at any node of the road network depending on traffic conditions. Real-time information is now common in traffic information systems, see Bayen et al. (2011) Fawcett and Robinson (2000). Algorithms to compute the optimal shortest path of a user using such real time information along the route are also of significant interest, see Nie and Fan (2006), Samaranayake et al. (2011), Samaranayake et al. (2012), Flajolet et al. (2014), Gao and Chabini (2006).

On the other hand, the question of the stability of traffic networks under adaptive route choice, in which users may update their decision at any node of the network, has received much less attention. Concerns about the time variability of traffic under such adaptive routing policies motivated Como et al. (2013), which analyses a dynamical evolution of traffic when users take into account real time information about the local congestion of roads only. In particular, the authors showed that an approximate Wardrop equilibrium is approached over time providing that the global preferences of path choice is slowly updated. Controlled traffic with adaptive routing is studied in Anderson and Anderson (2003) in which the authors prove that a certain category of algorithms (those minimizing the maximum volume) are stable.

In this article we study the stability of network equilibria under a realistic adaptive routing model, in which users consider global alternatives at each node of the network. We consider the framework of “Markovian Traffic Equilibria” (MTE) introduced in Baillon and Cominetti (2008), which is consistent with the decision model developed in the routing community, see Samaranayake et al. (2011). In a MTE framework, users leverage real time global information to choose the “best” path from each node of their current route. Imperfect information as well as the population heterogeneity are also assumed, leading to a stochastic perception of link travel-times.

We focus our analysis on the case of exponential stability of MTE, i.e. we exhibit conditions under which a network subjected to a disturbance of sudden variation creating non-equilibria conditions, returns very fast to its equilibrium characterized by a MTE. To the best of our knowledge, even though most simulation studies implicitly require weaker stability conditions, namely the asymptotic stability of equilibria (meaning that a disturbed network returns eventually to its equilibrium), very few studies have considered the stronger result of exponential stability of transportation networks. However exponential stability, and more generally knowledge (and possibly control) of the time to return to stability is a very important property for real-time operations, which should inform the design of decision support solutions and traffic control methods.

The main contributions of the work presented in this article are the following.

- We formulate a dynamical model of traffic flow in the framework of “Markovian Traffic Equilibria” in which users update their route choice at each node of the network depending on traffic conditions. The model proposed describes traffic dynamics outside of equilibrium.
- We propose a Lyapunov function candidate and prove that several of the technical conditions required for exponential stability can be obtained for any network type. We also prove exponential stability of the MTE for a class of homogeneous tree networks consistent with empirical observations on real traffic networks, which represents one of the first results of exponential stability of an adaptive route choice model. We also derive

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