6 Disequilibrium Network Design: A New Paradigm for Transportation Planning and Control

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6.1 Introduction

In a very broad sense, the network design problem (NDP) is a topic that has captured the attention of many researchers. This is mainly due to the immense importance of strategic capital investment decisions involving transportation infrastructure. For the purposes of this paper we limit the scope of the network design problem to highway systems. Design related decisions relevant to highways include a rich and wide variety of strategic (e.g., new right of way), tactical (one way street assignment, HOV assignment) and operational (traffic signalization, ramp metering) decisions that typically arise in transportation planning.

The equilibrium network design problem is to find an optimal network design in terms of additional facilities or capacity enhancements, when the network flow pattern is constrained to be an equilibrium. The much reported occurrence of Braess' paradox (Murchland, 1970) requires that design models have Wardropian user equilibrium (Wardrop, 1952) constraints. The transportation research literature includes many such equilibrium design models wherein equilibrium constraints are generally articulated as an equivalent optimization problem (Abdulaal and LeBlanc, 1979; LeBlanc,1975) or as an equivalent variational inequality problem (Friesz et al., 1990; 1992; 1993b; Marcotte, 1986). Unfortunately such equilibrium network design models presuppose a static environment and completely ignore the impacts of potential disequilibria which can arise due to perturbations in the capacity of the network infrastructure. Such a static perspective may lead to the occurrence of a temporal version of Braess' Paradox. The “temporal Braess’ Paradox” does not yet enjoy a standard definition, but in the context of the present discussion can be viewed as occurring when a capacity altering action lowers (or leaves unchanged) overall delay in the present and near future but increases overall delay at some more distant time. Such outcomes are possible when the present value of disequilibrium impacts is substantially negative, as can occur when the immediate disequilibrium response is a sharp congestion increase or when the disequilibrium response is a mild congestion increase of relatively long duration. An example is provided by a highway construction project intended to enhance capacity but which produces traffic congestion for weeks or months prior to its completion; in this case, the present value of construction impacts may be sufficiently negative to eradicate all positive benefits in the post-construction period. This is particularly true in standard cost benefit kind of analyses, wherein near term benefits are more heavily discounted than long term

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In light of the above remarks, we wish to present a "disequilibrium network design" paradigm. This new paradigm differs from the historical static one in the sense that it takes into account both the underlying time varying nature of the network and the disequilibrating effects that capacity enhancements to the network may produce. Below we articulate such a disequilibrium network design paradigm model for selecting optimal capacity enhancement trajectories for network arcs, with the time evolution of flows and minimum path costs are described by an appropriate disequilibrium adjustment process. In this control theoretic formulation we employ the concept of a network traffic disequilibrium, by which is meant a flow pattern which may fail to satisfy flow conservation (transportation market clearing) constraints and for which network users may experience clear advantages from changing their paths, but which evolves from a previously realized (dis)equilibrium in accordance with some plausible behavioral laws.

The aforementioned disequilibrium network design paradigm depends on a valid description of the disequilibrium adjustment process which guides the network of interest from one disequilibrium state to another, eventually settling down to a conventional steady state (static) equilibrium. Friesz et al. (1994) and Friesz et al. (1996) have developed models of this type based on realizable network generalizations of the traditional aspatial tatonnement models reported in the economics literature. These models consider day-to-day adjustments of flows and costs. Because of their central importance to disequilibrium design, a brief introduction to disequilibrium adjustment processes is presented below. Throughout all the subsequent sections, the notation introduced by Friesz et al. (1994) to describe dynamic traffic disequilibria is employed. This notation, which is similar to that traditionally employed for static equilibria is summarized in the Appendix.

### 6.2 Disequilibrium Dynamics for Urban Network

This section is adapted from the presentation in Friesz et al. (1996) of a tatonnement model used to describe disequilibrium dynamics representing highway passenger traffic.

Friesz et al. (1994) have described the time rates of change of path flows, represented by the vector $h$, and perceived origin-destination costs, represented by the vector $u$, as a tatonnement process\(^1\) whose disequilibrium dynamics have the following form:

\[
\frac{dh}{dt} = \eta F(ETC) \tag{1}
\]
\[
\frac{du}{dt} = \kappa G(ETD) \tag{2}
\]

\(^1\) A tatonnement process is a trading process among all agents (sellers and buyers) in an economy which is conducted by a super-auctioneer. Specifically, in the trading process the auctioneer calls out a set of prices and receives transaction offers from the agents. If these offers do not match (amount demanded is not equal to amount supplied), he calls another set of prices by following some rules and the process continues without any transaction being allowed to take place until transaction offers match.