NETWORK DESIGN FOR EVACUATION PLANNING

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Abstract: Security threats and natural disasters (such as hurricanes and cyclones) are events that have historically led to large scale evacuations. Evacuation operations are strongly characterized by traffic volumes that substantially exceed the network capacity. This paper focuses on the planning aspects of evacuation by identifying contra-flow mechanisms integrated with the appropriate traffic signal control pattern, at the network level, that minimize the network clearance time. The study formulates the capacity addition problem as a mixed-integer network design problem. The cell transmission model is used to simulate the propagation of traffic flow

Keywords: Networks, traffic control, dynamics, queueing network models, integer programming.

1. INTRODUCTION

Security threats and natural disasters (such as hurricanes and cyclones) are events that have historically led to large scale evacuations. Evacuation operations are strongly characterized by traffic volumes that substantially exceed the network capacity, and consequently, the potential for severely degraded network performance. The efficient management of evacuations entails long-term planning and real-time operational paradigms that are, ideally, integrated. In the current paper, the focus is on the minimization of the total travel time by capacity re-allocation in the form of contra-flow operations and handling of intersecting flows in signalized intersections by the selection of the most appropriate traffic signal control strategy.

The cell transmission model (CTM), developed by Daganzo (1994), is a simple approach for modeling traffic flow consistent with the hydrodynamic theory (Lighthill and Whitham, 1955; Richards, 1956). It assumes a piecewise linear relationship between flow and density at the cell level. The modeling elements for a traffic network are the cell and the cell connector. The cell is a homogeneous section of a road. Its length is equal to the distance traveled in one time interval under light traffic conditions. The cell connectors link sequential cells and are responsible for advancing the flow to the next cell(s). The CTM was extended for network flow (Daganzo, 1995).

Kwon and Pitt (2004) highlight the significance of capacity addition to urban networks for enhancing network performance under evacuation. Traditionally, capacity is added to a traffic network through the construction of new lanes as part of a long-term planning process. For short-term large scale events like evacuation, contra-flow operations are an attractive low budget capacity relocation option.

Tuydes and Ziliaskopoulos (2005) formulate the network re-design problem that addresses contra-flow operations using the CTM as the underlying traffic flow model (Ziliaskopoulos, 2000). The concept of coupled cells is introduced, where capacity is shared between opposite cells. The capacity is split according to a continuous variable, the lane reversibility factor. No capacity is lost in the sum of opposite cells. It is just rearranged. This makes the formulation computationally efficient, since it retains the system optimum linear format. Wolshon (2005) presents evidence that the sum of flow on opposite links is reduced under contra-flow operations. The reversed-flow lanes have a significantly decreased capacity when routing flow to the opposite direction. This is because flow interaction exists between the two opposite physically non-separated flows, and drivers routed in the contra-flow lanes are unfamiliar with contra-flow driving (signage faced opposite; turn exits are not intuitive). Contra-flow operations

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are lane-based discretized network design options with option-specific planning characteristics. Hence, linear variables cannot represent them with adequate realism. Moreover, these linear variables cannot allow the formulation to efficiently account for option-specific budget and trained personnel constraints. Further, no constraints exist for handling crossing flows at intersections, which can be problematic in moving traffic under extremely congested situations. This implies an overestimation of the evacuation capabilities. Traffic control at intersections under evacuation is a challenging issue as most traffic delays during an evacuation occur at intersections (Southworth, 1991).

Cova and Johnson (2002) proposed a lane-based evacuation strategy for eliminating intersecting flows and minimizing merging flows. They organized routing in terms of non-intersecting lanes which can either merge or diverge.

Lo (1999) used the CTM for developing a dynamic traffic control formulation designated as dynamic intersection signal control optimization. A drawback of the formulation for network applications is that the objective used for the model - minimizing total delay in the system - cannot address networks with spatial loops. When the total number of vehicles that advance to the next cell(s) equals the vehicles in the starting cell (free-low speed), no delay is counted. This implies that vehicles are allowed to travel at free-flow speeds in network loops without ever exiting the evacuation and routed to safety.

2. PROBLEM STATEMENT AND FORMULATION

The evacuation network design problem (ENDP) is stated here. It seeks to identify the links whose capacities ought to be augmented through contra-flow mechanism and the traffic signal control pattern, so as to minimize the total time spent in the network over all evacuees subject to budget constraints on costs and personnel. It further assumes that cross-directional flows are not permitted under evacuation. There are two key components of the ENDP: (i) the routing of the evacuees to the network, and (ii) the determination of the exact contra-flow options and traffic signal priority assignments. The first component is addressed using dynamic traffic assignment, due to the time-dependency of the network conditions. The second component is a network design problem which determines where the capacity should be augmented (that is on which network links) so as to achieve some system-wide objective subject to a constraint on the total number of contra-flow options exercised. Also, priority is assigned to at most one flow in every pair of crossing flows by assigning for the whole study period a single traffic signal phase. This traffic signal control policy is consistent with the lane-based approach of Cova and Johnson (2002) since it eliminates intersecting flows allowing only for merging and diverging movements. The two components are addressed simultaneously using an optimization framework, where traffic flow is propagated using the cell transmission model. The augmented sub-network is defined to be the Evacuation Network.

The formulation is a mixed-integer mathematical model. The integrality is due to the modeling of contra-flow operations as well as the priority assignment at intersecting flows. Contra-flow operations are formulated as binary variables (options) that assign the exact expected capacity to a link when those contra-flow options are selected. Priority assignment is also a binary variable (option) controlling whether a link is allowed or not to forward flow for the whole planning period, and therefore it is called a static traffic signal control pattern. A time-dependent or dynamic traffic control pattern that assigns phases in each time interval is theoretically expected to reduce the network clearance time more effectively. However, it may be less effective in practice due to the unpredictability of human behavior as well as the computational costs involved. The variables responsible for the propagation of traffic are linear due to the macroscopic nature of the CTM.

The parameters of the formulation are:

$i \in C$	The set of all cells.
$C_R \subset C$	The subset of source cells (origin cells).
$C_S \subset C$	The subset of destination cells.
$C_G \subset C$	The subset of intermediate cells.
$j \in E$	The set of cell connectors.
$\Gamma(i)$	The set of the successor cells of cell $i \in C$.
$\Gamma^{-1}(i)$	The set of the predecessor cells to cell $i \in C$.
$t \in T$	The set of discrete and constant time intervals.
$m \in M$	The set of network design options.
a_i^m	The binary indicator showing if the network design option m is associated with the cell $i \in C$.
N_i^0	The initial maximum number of vehicles in cell $i \in C$.
N_i^m	The maximum number of vehicles in cell $i \in C \setminus (C_R \cup C_S)$, if network design option $m \in M$ is implemented.
Q_i^0	The initial maximum number of vehicles that can flow into or out of cell.
Q_i^m	The maximum number of vehicles that can flow into or out of cell $i \in C \setminus (C_R \cup C_S)$, if network design option $m \in M$ is implemented.
v_i	The free flow speed for cell $i \in C$.
w_i	The traffic wave's backward propagation speed for cell $i \in C$.
δ_i	The ratio w_i / v_i for each cell $i \in C$.
τ	The constant discrete time interval length.
c_m	The cost of implementing contra-flow option $m \in M$.