On the Resilience of Transportation Systems to Flooding in Coastal Cities: A Game-Theoretic Perspective

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***Abstract*—Instilling resilience in transportation systems is a major challenge for our cities and communities. In this paper, the problem of studying the resilience of transportation networks in face of flooding in coastal cities is addressed. An analytical framework, based on the game-theoretic concept of Wardrop equilibrium, is introduced to model the network before and after flooding. The proposed solution seeks to shift capacity, either totally or partially, between road sides to decrease the travel time of some flow demands while slightly increasing the travel time of other flow demands. Preliminary results show that the average travel time is shown to be better than the case of flooding.**

I. Introduction

Resilience is a term used to describe a system's performance under disruptive events such as natural disasters or planned attacks. It is defined as the ability of a system or a critical infrastructure (CI) to adapt to or rapidly recover from potentially disruptive events [1]. Critical infrastructure are those physical and cyber systems that are vital to the functioning of our modern economic and societies. In the United States, Transportation systems are one of the main CIs according to the Department of Homeland Security (DHS) [2]. Transportation systems help move people and goods across the country therefore their functionality and reliability should be maintained especially at emergency times.

Transportation systems are prone to natural disasters such as earthquakes and flooding. Earthquakes usually have a higher effect on transportation systems especially on roads and bridges [3]. Several approaches studied the problem of restoring the transportation networks after natural disasters, especially earthquakes, such that minimizing the restoration time and/or cost [3]–[5]. As earthquakes can cause physical damage to roads or bridges, restoration techniques usually focus on restoring specific roads/bridges, under a limited budget, to achieve the most traffic flow in the least restoration time. On the other hand, the problem of studying the transportation network in case of flooding did not get much attention in literature. This is because, the effect of flooding in most cases is temporary and the problem affects mostly coastal cities not any city like earthquakes. Recently [6], [7] studied the effect of flooding on traffic flow. The authors in [6], proposed to direct drivers to use alternative routes based on the expected flood severity. The model is mainly empirical that directs drivers away from roads that are high likely to have low traveling speeds due to flooding. In [7], introduced the integration of flooding models into traffic simulators to measure the effect of flooding on planed trips that need to be canceled or rerouted.

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The main contribution of this paper is to develop an analytical framework to study and improve the resilience of transportation systems in face of flooding in coastal cities. In particular, we are interested in improving the total system's travel time for drivers in case of flooding by partially or totally changing some roads traffic direction. We use game theory to model the transportation network and calculate the total system's travel time under equilibrium. We propose to calculate the increased travel time under flooding based on flooding severity and roads' preparedness. A bi-level problem is introduced to determine changes in roads' directions to maximize the traffic flow under flooding. This change is constrained by the available budget and should be temporary and ends once the flooding is over.

II. System Model

We consider a transportation network defined by a directed graph $G = (\mathcal{V}, \mathcal{E})$, where $\mathcal{E}$ represents the directed edges or roads and $\mathcal{V}$ represents the intersection points which can be sources, destinations, or intermediate points. Bi-directional roads are modeled as two different edges, an edge for each direction. We will refer to edges as links in the following.

Flow based travel time function for a link a is given by:

$$t_a = t_{a,0} \cdot (1 + \alpha \cdot (\frac{x_a}{C_a})^{\beta}), \tag{1}$$

where $t_{a,0}$ is the free flow travel time for link a determined by the maximum speed allowed on link a, x_a is the amount of flow on the link, C_a is the capacity of the link determined by the road condition and its number of lanes. α and β are two parameters that are typically set to 0.15 and 4 respectively [8].

We propose to model the flooding effect as a decrease in the speed with which cars can use the link. This results in an increase in the free flow travel time for the link at the time of flooding $t_{a,f}$ as follows:

$$t_{a,f} = t_{a,0} \cdot (1 + \frac{\gamma}{P}), \tag{2}$$

where γ is the flooding severity and $\gamma \geq 0$, P is the road preparedness which depends on how the link is well prepared by drainage systems or pumps to withstand flooding and $p \geq 1$. Both γ, P take values based on predefined categories.

To study the traffic equilibrium, flow demands are given between certain origin-destination (O-D) pairs in the network. We consider all the possible paths between every (O-D) pair. At equilibrium, all different used paths between any (O-D) pair, should have the same travel time according to Wardrop equilibrium. Wardrop equilibrium is calculated as follows for the network:

$$\min\ Z(x) = \sum_a \int_0^{x_a} t_a(w)dw \tag{3}$$

$$\text{s.t.} \quad \sum_k f_k^{rs} = q_{rs}, \quad \forall r, s$$

$$f_k^{rs} \geq 0 \quad \forall k, r, s$$

$$\text{where} \quad x_a = \sum_r \sum_s \sum_k f_k^{rs} \delta_{a,k}^{rs} \quad \forall a,$$

where f_k^{rs} is the flow on path k that belongs to the (O-D) pair (r, s), q_{rs} is the total demand between (O-D) pair (r, s). The first constraint is called the flow reservation rule as it ensures that the amount of flow on all paths between any (O-D) pair equals the total flow demand between this pair. The second constraint, is the non-negativity as there is no negative flow. Finally, $\delta_{a,k}^{rs}$ is an indicator that equals 1 if the link a is part of the path k between the (0-D) pair (r, s), and 0 otherwise.

The solution to (3), gives the equilibrium flow assignment for each path int the network. The amount of flow on each link is the summation of the flow of all the paths this link is part of. The travel time of each link can then be calculated from (1) by substituting the optimal flow assignment. Finally, the total system's travel time is the time between each (O-D) pair multiplied by the total flow on this path.

The problem in (3) is considered again after updating the free flow travel time as in (2). This gives the increased total travel time in case of flooding. The proposed approach is then applied to derive the optimal change in links direction that can achieve the maximum possible travel time. The proposed approach works as follows: links that share the same road but opposite directions are couple together. A capacity shift can occur between coupled links which is either full or partial shift. In full shift, both links are assumed to have the same direction, which means the capacity of one link is transfered to the other link. This is proposed to occur in practical situations by declaring any road as a one-way road in times of flooding. In partial shift, a fixed number of lanes from one direction are assumed to serve as the opposite direction. This means partial capacity from one direction is transferred to the other direction. In practical, this can occur by using temporary separators between lanes and signals to indicate the change.

III. Preliminary Results

We applied the proposed framework to the network in Fig. 1. Link capacities are as shown in the figure. There are two (O-D) pairs (1,4) and (3,4) with the demand values $80, 60$ respectively. Free-flow link travel times are assumed to be $30, 20, 20, 30, 30$ for links $1-5, 6-10$ respectively. The solution of the proposed framework was to shift the whole capacity from link 6 to link 1. This resulted in an increase in the travel flow time on path 2 but a significant decrease in path 1 travel time. Travel time for both paths and their average are shown in Fig. 2.

IV. Plan for The Full Paper

In the full paper, we will derive the analytical optimal solution for the problem of capacity shifting. We want to solve the problem under budget constraint where shifting the whole capacity is assumed to cost less than shifting part of the capacity as the later requires more physical resources to be used. Finally, we want to consider the coupling effect between edges representing the same road but with the different directions. This coupling will appear in (1) as an extra term pertaining link $x_{\bar{a}}$, where $\bar{a}$ is the opposite direction as in link a. This coupling effect, while being small, can result in different analysis.

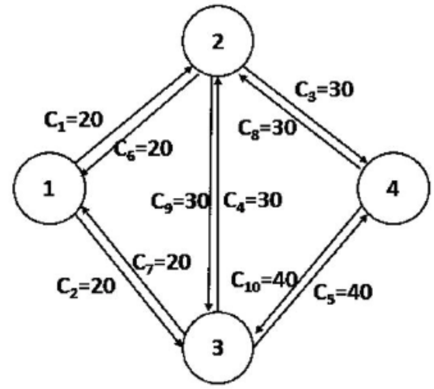

Fig. 1: A sample transportation network to test the proposed framework.

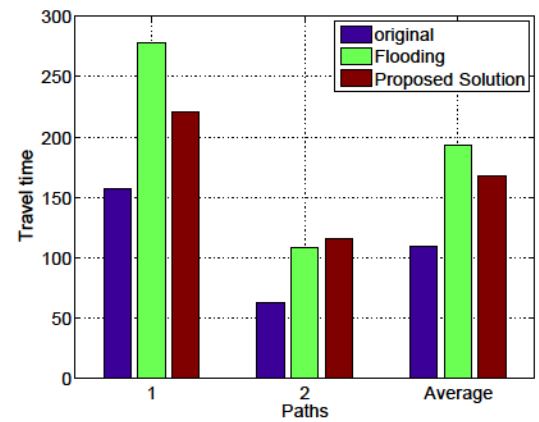

Fig. 2: Total System's travel time.

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