



Discrete Optimization

## Aggregate-level demand management in evacuation planning

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### ABSTRACT

Without successful large-scale regional evacuations, threats such as hurricanes and wild-fires can cause a large loss of life. In this context, automobiles are oftentimes an essential transportation mode for evacuations, but the ensuing traffic typically overwhelms the roadway capacity and causes congestion on a massive scale. Congestion leads to many problems including longer, costlier, and more stressful evacuations, lower compliance rates, and increased risk to the population. Supply-based strategies have traditionally been used in evacuation planning, but they have been proven to be insufficient to reduce congestion to acceptable levels. In this paper, we study the demand-based strategies of *aggregate-level staging and routing* to structure the evacuation demand, both with and without congestion. We provide a novel modeling framework that offers strategic flexibility and utilizes a lexicographic objective function that represents a hierarchy of relevant evacuation-based goals. We also provide insights into the nature and effect of network bottlenecks. We compare our model with and without congestion in relation to tractability, normative optimality, and robustness under demand uncertainty. We also show the effectiveness of using demand-based strategies as opposed to using the status quo that involves a non-staged or simultaneous evacuation process. Effective solution procedures are developed and tested using hypothetical problem instances as well as using a larger study based on a portion of coastal Virginia, USA.

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### 1. Introduction

In this paper, we study the use of *aggregate-level demand management*, specifically staging and routing, in planning for large-scale, automobile-based, *evacuations with notice*, i.e., evacuations in response to impending threats such as hurricanes, floods, and wild-fires, where such evacuations are ideally completed before there is substantial risk to the population. These evacuations differ from *no-notice evacuations*, where evacuees are immediately exposed to risk (e.g., nuclear incidents, chemical spills, or terrorist attacks). Usually, the evacuation demand is not well managed, which leads to congestion that can dramatically increase the time required to complete an evacuation. Congestion can also endanger evacuees by placing them in a vulnerable position, such as being trapped on the roadway when the disaster strikes, and moreover, it can actively discourage people from evacuating threatened areas. For example, in the survey by Blendon et al. (2005), 54% of households cite traffic congestion as a reason for not evacuating. Currently, evacuation plans use supply management tools such as contra-flow to increase the capacity of the evacuation routes (see Urbina and Wolshon, 2003, for instance), while the demand management status quo typically instructs all evacuees to leave the threatened region within a specified time-frame, e.g., in the next

24 hours, and provides a set of evacuation routes from which to select. The actual time when evacuees leave within this specified time-frame is a household-level decision. Congestion is a common occurrence under these strategies (see Blumenthal, 2005; Litman, 2006, for a discussion on Hurricane Rita, for instance). In contrast, the aggregate-level plans studied in this paper offer specific instructions to a group of evacuees, where the grouping is based on a geographic location, i.e., a neighborhood (see <http://www.hcoem.org/Documents/EvacuationMap.pdf>, where the hurricane evacuation plan for Texas has staging based on zip code-defined neighborhoods or zones). These staging and routing instructions include an evacuation time-window and an evacuation route for each group. Such demand management tools could greatly facilitate the evacuation process by better structuring the evacuation demand to reduce congestion. Many practitioners and policy-makers are considering demand management strategies of this type (see Dash and Morrow, 2001; Wolshon et al., 2006; Wolshon, 2009). This level of aggregation is a compromise between the status quo of instructions that apply for the whole evacuation region, which do not effectively manage demand, and disaggregate-level (i.e., household-level) instructions, which would potentially be very effective at managing the demand, but would be more difficult to disseminate, thus making the resulting evacuation process difficult to manage. An aggregate level plan of the type studied here could be disseminated using standard methods such as Web pages and broadcasts, and would still be effective in

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suitably structuring the demand. While we examine the modeling and strategic aspects of this problem, we note that several studies indicate that people tend to behave in a pro-social manner during times of disaster (Midlarsky, 1968; Barton, 1969; Lindell and Perry, 1992), although evacuees could further benefit from more specific instructions.

To study aggregate-level staging and routing, we introduce a time–space network flow model that optimizes an evacuation-specific lexicographic objective function using an evacuation plan that specifies an evacuation time-window and an evacuation route for each source, thus *staging* and *routing* the demand by source. Within the specified time-window, a predetermined *loading curve* models the aggregate-level behavior of evacuees leaving their residences. Such aggregate-level behavior is often modeled using an S-shaped loading curve (see Hobeika et al., 1985; Lewis, 1985; Liu et al., 2006; Fu et al., 2007). Hurricane evacuation assessments performed by the US Army Corps of Engineers (e.g., Opal and Hugo, see <http://chps.sam.usace.army.mil/USHESdata/heshome.htm>) have loading curves that are roughly S-shaped. Given the status quo, additional research is required to study loading curves in response to the more detailed instructions prompted by a staged evacuation plan, but this is beyond the scope of the present paper. Hence, although we assume a general S-shaped loading curve, we do not rely on any particular shape for deriving our results. This model relies on established traffic flow theory, using staging and routing to restrict congestion. In particular, we specifically study a model that keeps traffic flows within the free-flow regime, and which therefore uses staging and routing to optimize *structured* (based on the loading curve), *unsplittable* (based on the single evacuation time-window and evacuation route for each control group), *dynamic* (based on staging and on the loading curve) *network flows through time*. We compare this with solutions that allow congested flows, i.e., flows that are outside the free-flow regime.

In contrast to aggregate-level plans, disaggregate-level plans conceptually provide each evacuee with unique staging and routing instructions, and thus these plans represent *unstructured*, *splittable*, *dynamic network flows through time*. Disaggregate-level models are easier to formulate and solve than aggregate-level plans, for instance, many disaggregate-level models (e.g., Chalmet et al., 1982; Chiu et al., 2007; Yao et al., 2009; Bish et al., 2011b) are formulated as linear programs (LPs) because of the continuous nature of their network flows. On the other hand, aggregate-level models are combinatorial in nature, and thus require binary decision variables and are formulated as more difficult-to-solve integer programs. Aggregate-level plans are, however, easier to implement in practice.

We next discuss the disaggregate-level evacuation modeling literature. Chiu et al. (2007) examined a disaggregate-level staging and routing LP model for no-notice evacuations. Yao et al. (2009) studied disaggregate-level routing for evacuation planning, using a robust optimization based on an LP framework, to account for uncertainty in the population size. Bish et al. (2011b) analyzed general aspects of disaggregate-level staging and routing evacuation plans considering multiple evacuee-types. Similar models are used in building evacuations. For instance, Chalmet et al. (1982) formulated a disaggregate-level transshipment model on a capacitated network for analyzing the building evacuation problem. Hamacher and Tufekci (1987) studied minimum cost flows that lexicographically optimize multiple objectives and designed solution algorithms for these problems. For a review of the literature on evacuation models for buildings, see Hamacher and Tjandra (2001). Carey (1987) addressed disaggregate-level staging and routing in the context of a dynamic traffic assignment problem, while Ziliaskopoulos (2000) studied disaggregate-level routing in the same context. Hoppe and Tardos (2000) examined

the quickest transshipment problem, where a single commodity is transshipped from a set of sources to a set of sinks (with a specified demand for the commodity) in the shortest possible time. Disaggregate-level staging and routing is implicit in their model that controls discharge from the sources and that can split flows among various routes.

There are relatively fewer models that look at aggregate-level instructions. Liu et al. (2006) studied aggregate-level staging and disaggregate-level routing using a mixed-integer program to minimize a static and additive zonal risk parameter, which is appropriate for no-notice evacuations. The aggregate-level nature of the staging is somewhat counteracted because the traffic model used exhibits *traffic holding* (see Ziliaskopoulos, 2000; Peeta and Ziliaskopoulos, 2001, for a discussion), which unrealistically controls traffic flows, thus conceptually permitting a disaggregate-level staging of flow out of every roadway segment. We discuss this issue in more detail in Section 2 below. Andreas and Smith (2009) presented a model that considers aggregate-level routing where the evacuation routes for all sources combine to form a tree. Chen and Miller-Hooks (2008) introduced a building evacuation model that has both aggregate- and disaggregate-level aspects. At sources, evacuees enter the network based on an input parameter, and the model makes an aggregate-level routing decision at the node-interval level. Thus all evacuees on any particular node in any particular interval get the same directive, i.e., the flow from any node in any interval is not split among the outgoing arcs, which is different from our concept of unsplittable flows, which specifically refers to flows from any source following a designated route. The evacuation process we study herein is based on the unsplittable flow concept, which was introduced by Kleinberg (1996a,b) in the context of a single source supplying multiple sinks along specific routes to satisfy the corresponding demands. Unsplittable flows can be essentially thought of as aggregate-level routing. Martens (2007) examined a dynamic version of the unsplittable flow problem, but with *k*-splittable flows. This work differs significantly from our aggregate-level evacuation problem because it addresses a single commodity problem that does not consider staging or loading curves.

We believe that aggregate-level demand management will be a key strategy for evacuating large, highly-populated regions in a timely manner. To develop effective demand-based evacuation strategies, it is essential to understand how to stage and route structured, unsplittable, dynamic flows (based on behavioral loading curves) in an optimal fashion through a network. Manipulating these structured flows is far different than manipulating unstructured, splittable flows (the focus of the previous analytical work on evacuation), and is much more complex. This paper advances our understanding of this difficult management problem by making the following specific contributions:

- Structured, unsplittable, network flows through time are introduced. This is essential for understanding aggregate-level staging and routing, and for designing effective new strategies for evacuation management that minimize congestion. We compare these free-flow strategies with optimal strategies under congestion. The impact of congestion on model tractability, normative optimality, and robustness under uncertainty in demand is investigated in detail.
- A conceptually novel lexicographic objective function that represents a hierarchy of relevant evacuation-based goals is developed and tested.
- Differences between structured unsplittable flows through time, and the more traditional unstructured splittable flows through time (which are used extensively in the evacuation literature) are examined. Our findings identify important

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