Challenges in Evacuation Route Planning for Incident Management[1]

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The recent loss of lives and traffic jams (Figure 1) for tens of miles as hurricanes Rita and Katrina approached the Gulf coast demonstrate the enormous difficulty in evacuating urban areas [6]. Besides hurricanes, evacuation may be necessary due to other potential disasters, e.g., fire, terrorism, and nuclear or chemical plant accidents. Thus, the local emergency management community engages in evacuation route planning and required drills, e.g., fire-drills in schools and large office buildings.

Figure 1: *Hurricane Rita Evacuation* (Best viewed in color), Source: National Weather Service, Dallas News.

During emergency evacuation, transportation scientists, first responders and other stakeholders pose many questions requiring spatio-temporal computations, e.g., what are the best routes (or transportation modes, shelters, timeslots) to evacuate affected locations? How many evacuees are likely to use each route, shelter, and logistics facility? Challenges arise due to violation of key assumptions behind transportation planning tools, e.g. microscopic traffic simulators, and popular shortest path algorithms. For example, transportation planning tools (e.g. DYNASMART, TRANSIM) rely on game-theory-based Wardrop equilibrium [9] among selfish commuters, who may change routes between trips to/from work. However, evacuation traffic may not exhibit such behavior. In addition, common shortest path algorithms (e.g. Dijktra's, A*) are based on dynamic programming and thus assume a stationary ranking of alternative routes [1,8]. A community may prefer a freeway-based evacuation route during non-rush-hours, but a different route during rush-hours, since the ranking of alternative paths changes over time possibly due to congestion. In addition, these routing algorithms do not account for capacity constraints of transportation links, particularly when the number of evacuees is large.

Currently, evacuation route plans are often hand-crafted for selected scenarios, since algorithms methods [5] based on linear programming take unacceptably long time (e.g., hours or days) to recommend best evacuation routes for large metropolitan areas (e.g., Houston). These methods address time-varying ranking of routes by using the time-expanded graph (TEG) representation. As illustrated in Figure 2(B), TEG replicates a graph representing the transportation network across various time-points in the evacuation time-period. Additional edges are added to link network copies across time. Link capacity and travel-time constraints are modeled as linear constraints. Linear programming formulation is used to derive solutions. Post-processing is used to derive evacuation routes. While this approach is reasonable for small towns, it does not scale up to larger problems. Consider metropolitan transportation networks with millions of nodes and edges with evacuation lasting hours or days. TEG representation leads to excessive duplication of the transportation network across time-points and a very large set of linear constraints, which increase computational time to hours or days. In addition, this approach needs an estimate of upper bound on total evacuation time to determine the number of copies of transportation network needed in a TEG representation. Incorrect estimate of upper bound on total evacuation time may lead to either a failure to produce any solution or excessive computational costs.

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Our recent work on the Capacity Constrained Route Planner (CCRP) [7] introduced a novel representation, namely, Time-Aggregated Graph (TAG), which eliminates redundant information to yield a more compact representation than TEG. As shown in Figure 2(C), TAG models node/edge attributes as functions of time rather than fixed numbers. Thus node/edge capacities, node occupancies, etc. are modeled as time-series. Second, it iteratively considers all pairs of sources and destinations. Each iteration schedules evacuation of a group of evacuees across the closest source-destination pair. Special graphs construction is used eliminate redundant computation in this step. Non-stationary ranking of alternative routes during an evacuation is addressed by a linear-cost earliest-arrival-index on input TAG with travel-time-series [3,4].

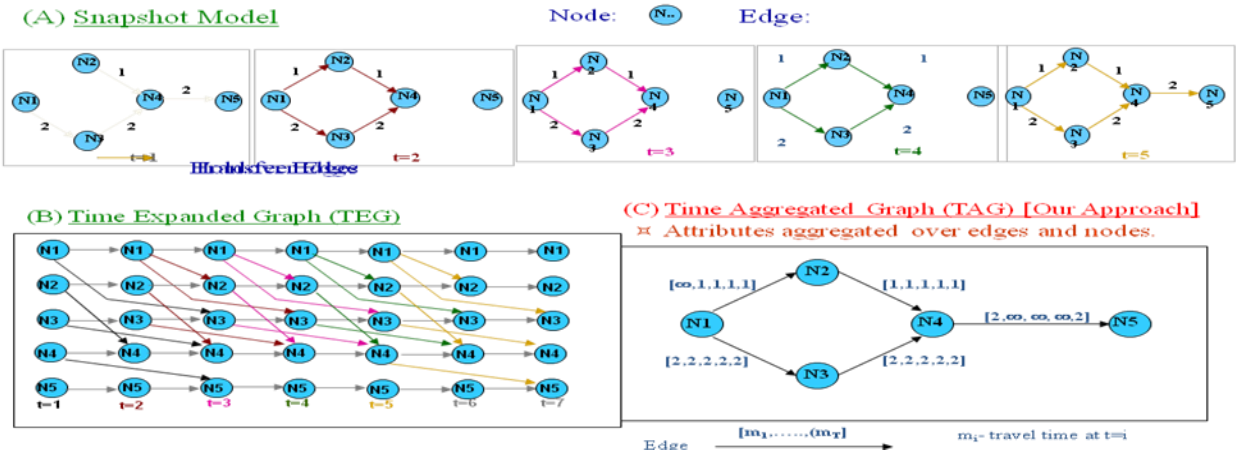
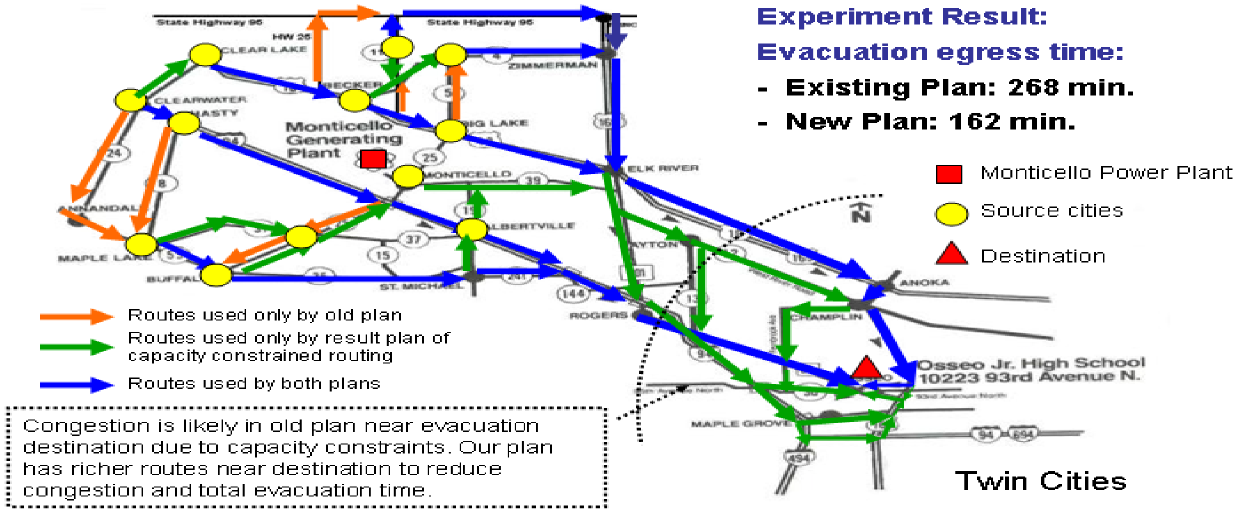


Figure 2: *Representations of Time-evolving Transportation Networks* (Best viewed in color)

Experimental results [7] with Minneapolis-St. Paul metropolitan scenarios show that CCRP is an order of magnitude faster than competing methods. Evaluation with the Monticello, MN, nuclear power plant scenarios (Figure 3) show that CCRP lowers evacuation time relative to existing hand-crafted plans by identifying and removing bottlenecks, by providing higher capacities near the destination and by choosing shorter routes. It was used to plan evacuation routes for many homeland security scenarios around multiple locations, time-of-the-day, and transportation modes. It facilitated a transportation science discovery that encouraging able-bodied evacuees to walk (instead of letting them drive) reduces evacuation time significantly (by a factor of 3) for small area (e.g., 1-mile radius) evacuations.


Experiment Result:

Evacuation egress time:

- **Existing Plan: 268 min.**
- **New Plan: 162 min.**

Congestion is likely in old plan near evacuation destination due to capacity constraints. Our plan has richer routes near destination to reduce congestion and total evacuation time.

Figure 3: *CCRP improved evacuation routes for Monticello Nuclear Power Plant* (Best viewed in color)

There are many interdisciplinary research challenges related to the evacuation planning problem for the following reasons. Recently, I was invited to deliver the annual Dangermond lecture at U.C. Santa Barbara, which accorded a unique opportunity to talk to evacuees of the recent Santa Barbara fires, and evaluate assumptions of CCRP in the context of forest-fire evacuations. CCRP assumes that individual evacuees will act independently. However, Santa Barbara evacuees preferred group evacuations of members of a household. For example, parents went to schools to pick-up children before leaving town. Third, CCRP looked for system-optimal evacuation routes, which may not be equitable for special-need groups (e.g., children). These insights beg the following question: “How do we develop computationally tractable evacuation planning models that honor the constraints of equity in evacuation, household requirements and the non-stationary route rankings?”

Modeling household cooperation and equitability are complex social science issues, which may not be amenable to computer algorithms. In collaboration with social scientists and policy makers, we need to characterize decision-support roles for computational methods. For example, computation may shortlist alternative evacuation plans along with relevant metrics (e.g., total evacuation time, equity, fairness) to reduce the enormous set of possibilities in front of decision makers and aid decision making process. Even to play such a role, current evacuation planning algorithms will need to be revised possibly as multi-objective optimizations. A novel approach may be based on eliminating solutions which are inferior to other solutions on all (or almost all) objectives. Recent computing literature is exploring skyline query processing for location based services to address similar problems. It may be useful to bring these approaches to evacuation route planning problem.

Of course, traditional optimization approaches may be considered using a total ranking of objectives, or simultaneous consideration of a weighted sum of different objectives. Under the former paradigm, transportation network and shelter capacities may first be divided among population segments in an equitable manner using preliminary models of equitability from policy makers and social science researchers. Then, households within each population segment may be assigned to appropriate shelters with available capacities for that segment. Finally, routes may be recommended for individuals within each household to reach a common shelter possibly by getting together at some place in between. If this paradigm of dealing with equitability first and household constraints later leads to unacceptable evacuation-routes, then one may investigate other ways, e.g., combining equitability and household constraints into a unified measure of solution quality, and exploring algorithms to improve the unified solution quality measure.

Other challenges include exploration of new ideas to expand transportation system capacity or to manage demand. For example, contra-flow [6] may be used to reverse direction of a majority of inbound lanes of a highway to increase outbound capacity. Governors of Texas and South Carolina asked for use of contra-flow during Hurricane Rita (2005) and Hurricane Floyd (1999). Hurricane evacuation plans in Florida and New Orleans include contra-flow plans. However, current contra-flow plans are hand-crafted and computational methods may improve those further [2] while meeting resource constraints. Phased evacuation [6], where more vulnerable areas are evacuated before less vulnerable ones, has the potential to reduce overall evacuation times by reducing congestion, which decreases highway capacity. New Orleans evacuation plans include phased evacuation. However, the plans are hand-crafted and computational methods may be helpful. For example, evacuation route planning methods may be generalized to recommend evacuation schedules taking into account conflicts among evacuation routes of various communities. Computer tools may allow concurrent evacuation of communities whose evacuation routes do not have conflicts. This may improve current phased evacuation plans.

It is important to improve modeling of other transportation modes such as public transportation by characterizing their capacities, speeds, etc. We also need to improve accuracy of input datasets related to numbers and locations of evacuees and available (rather than maximum) capacity of transportation networks possibly by using emerging datasets from cell-phones, global-position systems, and sensors on highways.

References

[1] T. H. Cormen, C. E. Leiserson, and R. L. Rivest. Introduction to algorithms. McGraw-Hill, 1990.

[2] S. Kim, S. Shekhar, M. Min, Contraflow Transportation Network Reconfiguration for Evacuation Route Planning, IEEE Transactions on Know. and Data Eng., 20(8), 2008. A summary in Proc. ACMGIS 2005.

[3] B. George, S. Shekhar, and S. Kim. Spatio-temporal network databases and routing algorithms. University of Minnesota. CSE Technical Report No. 08-039, 2008. (A summary of results appeared in Proc. Symposium on Spatial and Temporal Databases, Springer LNCS 4605, 2007). http://www.cs.umn.edu/research/technical_reports.php?page=report&report_id=08-039

[4] B. George, S. Shekhar, Time-Aggregated Graphs for Modeling Spatio-temporal Networks, Journal of Data Semantics, Volume 11, 2006 (Springer LNCS 5383, 2008). (Initial results Workshop on Conceptual Modeling for GIS in conjunction with Intl. Entity Relationship Conf., 2006).

[5] H. W. Hamacher and S. A. Tjandra. Mathematical modeling of evacuation problems: State of the art, Pedestrian and Evacuation Dynamics, Springer Verlag, 2001.

[6] T. Litman. Lessons from katrina and rita: What major disasters can teach transportation planners. Journal of Transportation Engineering, 132(1), American Society of Civil Engineers, 2006.

[7] Q. Lu, B. George, and S. Shekhar. Capacity constrained routing algorithms for evacuation planning: A summary of results, Proc. Intl. Symp. on Spatial and Temporal Databases, Springer LNCS 3633, 2005.

[8] A. Orda and R. Rom. Shortest-path and minimum-delay algorithms in networks with time-dependent edge-length. Journal of the ACM, 37(3):607–625, 1990.

[9] J. Wardrop, Some theoretical aspects of road traffic research, Proceeding of the Institution of the Institution of Civil Eng., 2(1), 1952.