A Novel Approach to Evacuation Route Planning

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The goal of evacuation route planning is to identify routes that can be used to minimize the time required to move vulnerable populations to safe destinations. Evacuation route planning is a key component of effective disaster emergency management and homeland defense preparation. As such, it is an important challenge facing the U.S. Army, which must be ready and able to assist in large-scale evacuations of civilians. Since evacuation planning is computation intensive, high performance computing is essential to meeting this challenge. Also, real-time solutions are needed to support evaluation of alternative scenarios (e.g. weather, change in transportation networks, or number of evacuees).

Traditional warning systems convey only the threat descriptions and the need for evacuation to the affected population. Such systems do not consider capacity constraints of the transportation network and, as a result, have proved inadequate during actual evacuation events. When Hurricane Andrew was approaching Florida in 1992, evacuation announcements led to tremendous traffic congestion, general confusion, and chaos. In very recent times, when Hurricane Rita approached Houston, evacuations resulted in congestion on Texas highways for tens of miles as seen in Figure 1.

Figure 1. Hurricane Rita evacuees from Houston clog I-45 (FEMA.gov).

It is now evident to planning authorities that to reduce congestion during large-scale evacuations at all levels, effective evacuation route planners are needed that take into account the capacity constraints of transportation networks. An overall framework of evacuation route planning is shown in Figure 2, using the example of another type of disaster — a bio-chemical attack. The base map and weather data are used as inputs in the analysis of the plume dispersion of the bio-chemicals. An evacuation route plan is generated from the analysis by incorporating the demographic information and transportation

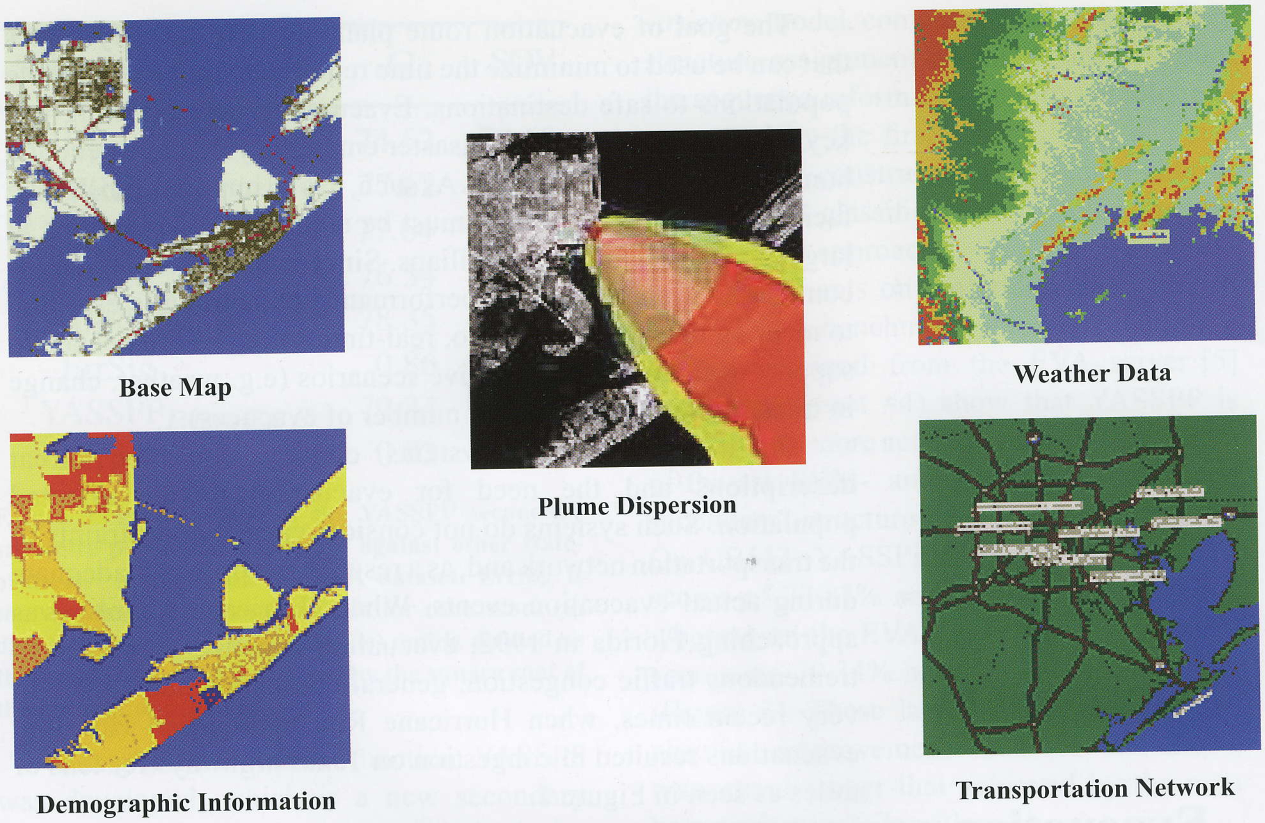


Figure 2. Bio-chemical Attack Analysis (images from www.fortune.com).

network. The evacuation route planning problem is formulated as follows:

Given: (1) A transportation network with non-negative integer capacity constraints on nodes and edges, (2) non-negative integer travel time on edges, (3) the total number of evacuees and their initial locations, and (4) locations of evacuation destinations.

Output: An evacuation plan consisting of a set of origin-destination routes and a scheduling of evacuees on each route. The scheduling of evacuees on each route should observe the capacity constraints of the nodes and edges on this route.

Objective: Minimize the evacuation egress time, which is the time elapsed from the start of the evacuation until the last evacuee reaches the evacuation destination.

Constraints: (1) Produce an evacuation plan in real-time (e.g. seconds), (2) edge travel time preserves the FIFO (First-In First-Out) property, (3) edge travel time affects delays at intersections, and (4) limited amount of computer memory.

Previous methods were based on a linear programming [1] and suffered from limitations. First, they did not scale up to large (e.g. >50,000 nodes) transportation networks in urban evacuation scenarios as shown in Table 1, because they used time-

Number of Nodes	50	500	5,000	50,000
Linear Programming Method Running Time	0.1 min	2.5 min	108 min	> 3 days

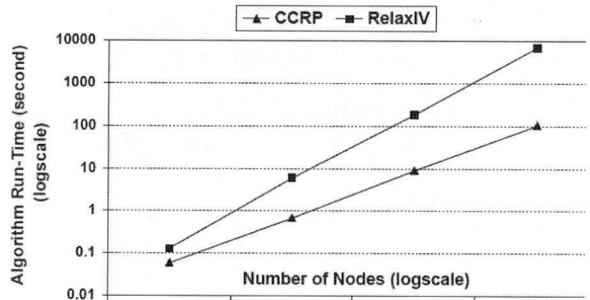
Table 1. High computational complexity of existing method, linear programming.

expanded networks requiring large amounts of computer storage and were aimed at computing optimal solutions that incurred exorbitant computational costs. Second, they required users to provide an estimate of the upper bound on the total evacuation time, and incorrect estimates of the upper bound led to failure.

To combat these limitations, a novel geo-spatial approach was developed, namely a Capacity Constrained Route Planner (CCRP) [2], which can be used to quickly identify feasible evacuation plans. This approach provides an efficient decision support tool for homeland security officials to evaluate existing evacuation plans. It also allows them to determine plausible evacuation plans for large transportation networks in an urban scenario when resource constraints or dynamic conditions make it infeasible or uninteresting to find the optimal plan.

This approach has two key ideas. First, it models the capacity and occupancy of each road segment as a time-series rather than fixed numbers because these attributes could change over time during an evacuation. Second, it repeatedly considers all pairs of sources and destinations. In each iteration, it schedules the evacuation of a group of evacuees across the closest source-destination pair. Special graph algorithms are used to eliminate redundant computation in this step. For smaller networks, where linear programming tools could be used, this approach produced high quality solutions with evacuation times comparable to those achieved by linear programming methods. In addition, this approach significantly reduced the computational cost by using much less computer memory.

Evaluation included experiments on synthetic scenarios. Figure 3 shows the performance superiority of the CCRP



	50	500	5000	50000
CCRP	0.06	0.69	9.38	108.16
RelaxIV	0.13	6.39	189.51	6971.05

Figure 3. Run-time (log-scale) with respect to network size.

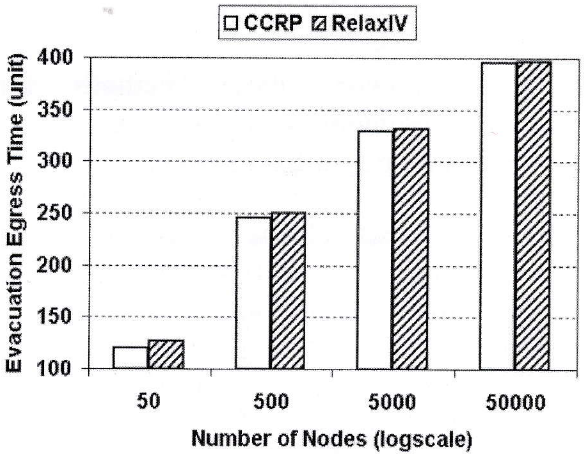


Figure 4. Quality of solution with respect to network size.

algorithm over one of the existing linear programming approaches named RelaxIV in a logarithmic scale. Even though the run-time of CCRP showed remarkable improvement in terms of scalability, CCRP produced high quality solutions (within 5 percent of the optimal evacuation time) close to the optimal solution produced by RelaxIV, as shown Figure 4.

Figure 5 shows the parallel formulation of the CCRP algorithm. It parallelizes step 1 of CCRP, which was a bottleneck step of the algorithm. The parallel strategy was to divide

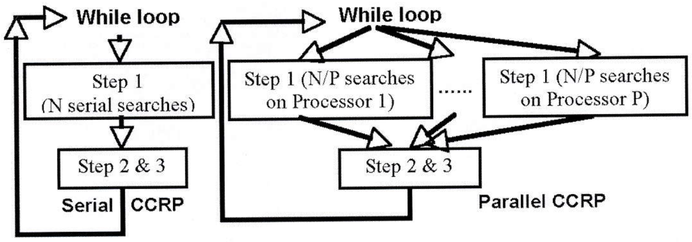


Figure 5. Parallel formulation of CCRP.

N shortest path searches among P processors, each processor thus having N/P searches. Figure 6 shows the results of a parallel version of CCRP for large problem sizes (50, 000 nodes). Speedup improved as the number of processors increased, with especially high speedup achieved by dynamic parallel load balancing.

Evaluation of these methods for evacuation planning included a real-world scenario around the Monticello nuclear power plant near the Minneapolis/St. Paul metropolitan area. The evacuation zone was a 10-mile radius around the nuclear power plant as defined by Minnesota Homeland Security and Emergency Management. An experiment was conducted using the road network around the evacuation zone provided by the Minnesota Department of Transportation, and the Census 2000 population data for each affected city. This case study showed that the approach could be used to improve existing evacuation plans by providing higher capacities near the destination and by choosing shorter routes. Due to the timelines of this case study, it was invited for presentation at a congressional breakfast [3] on GIS and Homeland Security.

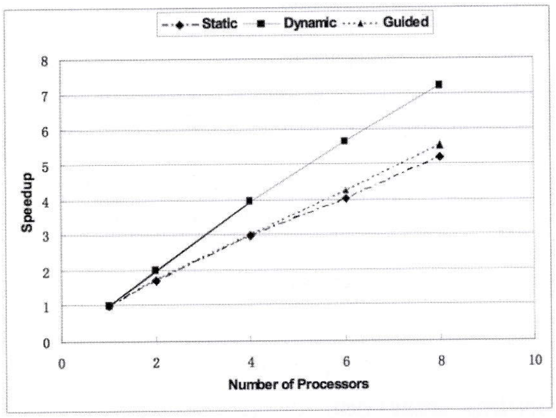


Figure 6. Parallel CCRP – experiment results.

The shortest path algorithm in this approach assumed that the edge travel times included traffic delays at intersections. It also assumed that the travel times were not time-dependent. Current plans are to incorporate existing work in this area to address those limitations. Another interesting possibility for future work is to integrate the CCRP approach with the traffic assignment-simulation approach to conduct stochastic simulation of traffic. As the complexity and scale of experiments increase, the computing power of the AHPCRC will play an important role in the effort to develop scalable evacuation route planners. ◆

References

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