中国科学技术大学
University of Science and Technology of China

Ambulance Emergency Response Optimization in Developing Countries

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Paper Information

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管理学院

0. Authors

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- Education
  - Postdoctoral associate, Massachusetts Institute of Technology
  - PhD, University of Toronto
  - Bachelor degree, Acadia University

- Publication
  - Operations Research (1)
  - Manufacturing & Service Operations Management (2)

- Research Areas
  - Combining Optimization and Machine Learning

Timothy Chan (Full Professor, *University of Toronto, QS 34*)

- Education
  - PhD, Massachusetts Institute of Technology, 2007
  - Bachelor degree, University of British Columbia, 2002

- Publication (4269 citations)
  - Operations Research (5)
  - Management Science (4)
  - Manufacturing & Service Operations Management (1)
  - INFORMS Journal on Computing (2)

- Research Areas
  - Operations Research
  - Applied Machine Learning

1. Background

- Key characteristics:
  - ✓ Low- and middle-income countries (LMICs)
  - ✓ Lack of data
    - **Demand**: Using census data and survey data to predict the demand
    - **Travel time**: Equipping five vehicles with custom-built GPS devices that recorded their time and location over a period of 30 days
    - **Robust optimization**: accounting for uncertainty in travel times and spatial demand characteristics of LMICs.
  - ✓ Van ambulances and Small ambulances
    - Patients use a variety of transportation modes to reach hospitals
    - Most traditional van ambulances lack advanced medical equipment

Research Problem

✓ **LMICs' ambulance emergency response optimization**

- "Small data" environments
- Field research

Research Gap

Related area	Research content	Published research	Research Gap
Demand prediction	• Predict only spatial demand • Predict Temporal-only demand • Predict spatiotemporal demand	Schuman et al. 1977; Matteson et al. 2011;Setzler et al. 2009	Rely on granular historical call data
Travel-time prediction	Focused on nonlinear relationships between travel time and distance	Kolesar et al. 1975; Budge et al. 2010	Depend on the availabile historical emergency transport data
Facility location	Demand uncertainty and travel-time uncertainty in the ambulance response optimization	Chen and Lin 1998; Vairaktarakis and Kouvelis 1999	Focused on the special case of the one-median problem

3. Models and solution algorithms

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■ Deterministic network flow formulation:

- Network Flow Formulation (NFF):

$$\begin{aligned} \text{NFF:}\quad \textbf{minimize}_{\mathbf{y},\mathbf{f}} \quad & \boldsymbol{c}'\mathbf{f} \\ \textbf{subject to} \quad & \boldsymbol{e}'\mathbf{y} = P, \\ & \boldsymbol{A}\mathbf{f} \geq \boldsymbol{\Omega}\mathbf{y} - \boldsymbol{d}, \\ & \boldsymbol{f} \geq 0, \\ & \boldsymbol{y} \in \{0,1\}^n. \end{aligned}$$

Travel time

P: Number of outposts

- The second constraint:

$$\sum_{j \in O(i)} f_{ij} - \sum_{j \in I(i)} f_{ji} \leq \alpha_i y_i - d_i, \forall i \in \mathcal{N},$$

Ensure all demand is met

- We do not consider queuing in our model.
- Later evaluate the tactical performance to queuing and system congestion.

Robust Optimization Model:

- Two-stage robust network flow formulation (R-NFF):

$$\begin{aligned} \mathbf{R-NFF:} \quad \min_{y} \max_{\mathbf{c}\in\mathfrak{C},\mathbf{d}\in\mathcal{D}} \min_{f} \quad & \boldsymbol{c}'\mathbf{f} \\ \textit{subject to} \quad & \boldsymbol{e}'\mathbf{y} = P, \\ & \boldsymbol{A}\mathbf{f} \geq \boldsymbol{\Omega}\mathbf{y} - \boldsymbol{d}, \\ & \boldsymbol{f} \geq 0, \\ & \boldsymbol{y} \in \{0,1\}^n. \end{aligned}$$

- Demand uncertainty set: Use a scenario based uncertainty set

$$\mathcal{D} = \{\mathbf{d}^1, \mathbf{d}^2, \ldots, \mathbf{d}^N\}$$

- Travel-time uncertainty set: Use an interdiction-based uncertainty set

$$\mathfrak{C} = \{c_{ij}, (i,j) \in \mathcal{E} | c_{ij} = \hat{c}_{ij} + w_{ij}, \sum_{(i,j)\in\mathcal{E}} w_{ij} \leq B, w_{ij} \geq 0, \forall (i,j) \in \mathcal{E}\}$$

3. Models and solution algorithms

Three Solution Algorithms:

✓ Equivalent Mixed-Integer Optimization Model:

- ***Theorem 2.*** R-NFF is equivalent to the mixed integer linear optimization problem.

✓ Scenario Generation:

- Consider a subset of the demand scenarios: $\mathcal{D}^{|S|} = \{\boldsymbol{d}^1, \boldsymbol{d}^2, \ldots, \boldsymbol{d}^{|S|}\} \subset \mathcal{D}$

✓ Master Problem Heuristic:

- ***Theorem 1.*** A solution is optimal for NFF if and only if it is optimal for the p-median problem.

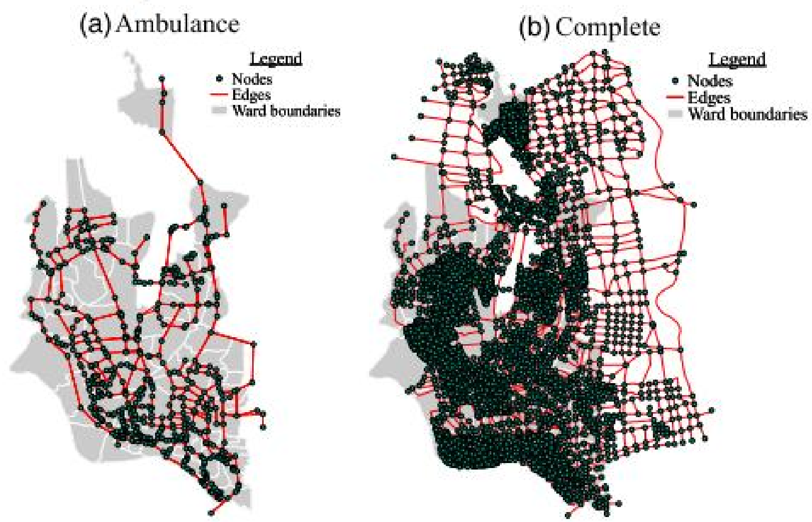
- Adapt the heuristic developed by Densham and Rushton (1992) for the classical p-median problem.

■ Road Network:

✓ Two different road networks on Dhaka's 92 wards:

- Ambulance network: 530 nodes and 1,280 edges
- Complete network: 5,358 nodes and 16,538 edges

Figure 1. (Color online) Two Road Networks Overlaid on a Ward Map of Dhaka



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■ Demand for Emergency Transportation:

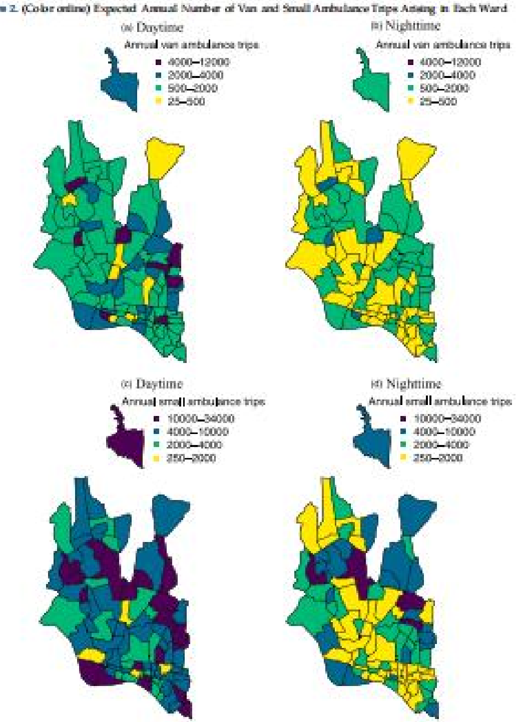
✓ Estimating the Annual Number of Emergency Trips:

- Do not have data on the total number of emergency transports.
- Two-step process that leverages the limited data (census data; survey data):

$$d_{w,\tau,m} = \xi n_{w,\tau} \delta_{w,m}$$

- Simulate scenarios for the uncertainty set $\mathcal{D}$: Assume ξ, $n_{w,\tau}$, $\delta_{w,m}$ obeys a given distribution, respectively.

Figure 2. (Color online) Expected Annual Number of Van and Small Ambulance Trips Arising in Each Ward



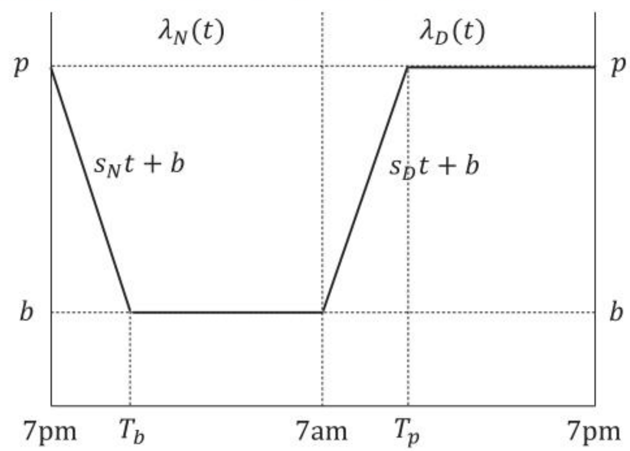
4. Application to Dhaka

■ Demand for Emergency Transportation:

✓ Simulating Spatiotemporal Emergency Trips:

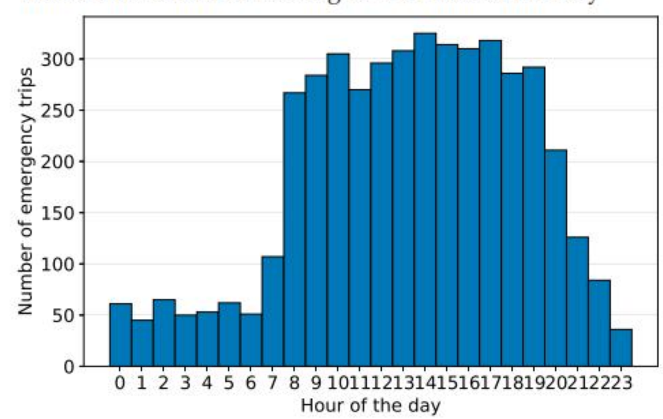
- Our simulation model, which evaluates the tactical performance of the optimization results
- Requires the exact time and node location for each emergency trip.

Figure 3. A Visualization of $\lambda_N(t)$ and $\lambda_D(t)$



Note. We drop the ward and mode indices.

Figure 4. (Color online) A Histogram Displaying One Week of Van Ambulance Emergency Calls Summed Across All Wards and Binned According to the Hour of the Day



4. Application to Dhaka

Travel-Time Prediction:

- Data set of vehicle trips collected by our custom-made GPS devices.
- Random forest model to estimate the baseline travel time $\hat{c}_{ij}$ for each edge.

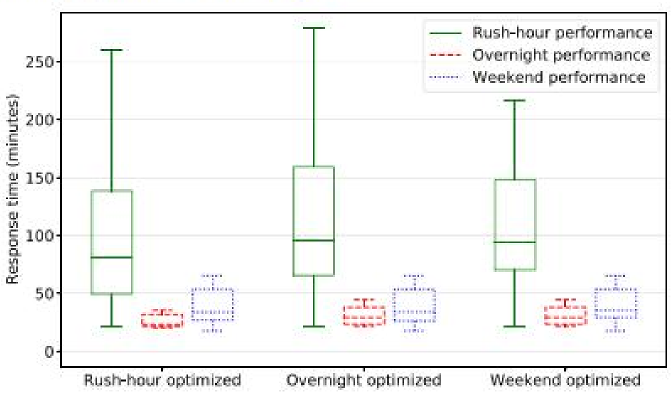
Tactical Simulation Model:

- The main focus of the simulation model is to capture the effects of congestion (i.e., waiting time) on overall response times.
- To evaluate its response time given a solution.

■ Should Different Outposts Be Used for Different Times of Day?

- During rush hour: 14.4 minutes (15.0%) and 12.5 minutes (13.4%) faster, respectively.
- During overnight and weekend: improved by 5.9 minutes (20%) and 0.2 minutes (0.5%), respectively.
- Our results suggest that ambulance providers in Dhaka do not need to optimize outpost locations by time of day or day of week.

Figure 5. (Color online) The Response Time Performance of Outpost Locations Optimized for One Specific Snapshot and Applied to Other Snapshots



5. Policy Experiments

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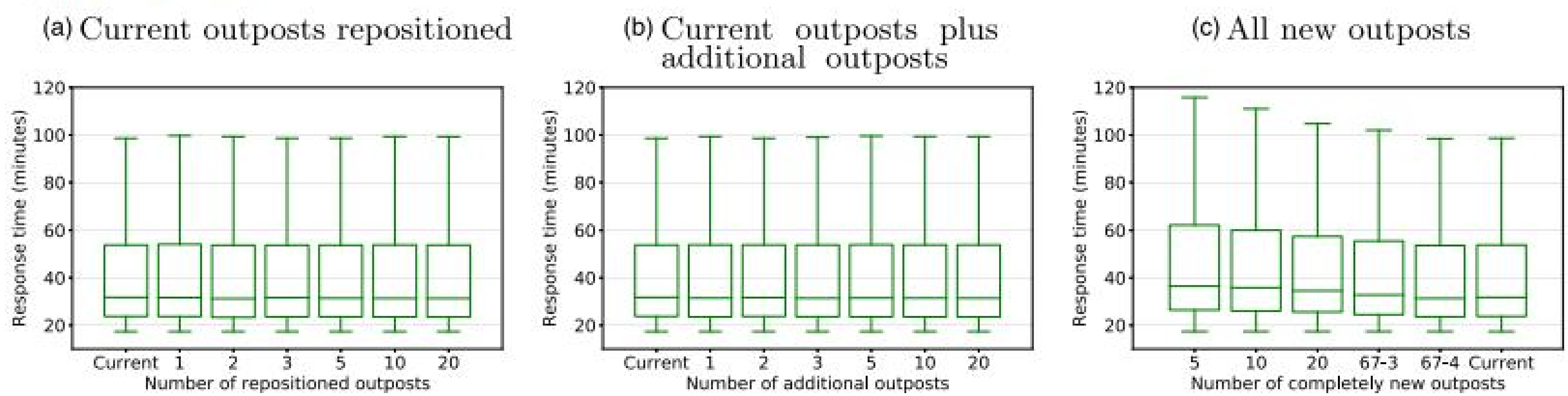
■ Performance Improvements by Optimizing Outpost Locations?

- Value of Repositioning Current Outpost Locations: Fig. 6(a)
- Value of Adding Outpost Locations to the Current Network: Fig. 6(b)
- Value of Designing a New Emergency Response Network: Fig. 6(c)

✓ This result suggests that some of the current outpost locations are contributing very little: Need complete redesign of the current system.

Figure 6. (Color online) Response Time Performance for Different Emergency Response Network Configurations for Day–Time Rush Hour



Note. The 67-3 and 67-4 labels in (c) correspond to 67 outposts with three and four ambulances per outpost, respectively.

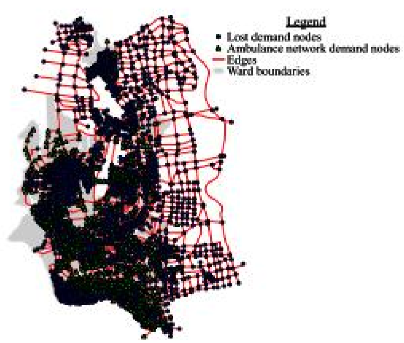
■ How Much Can the System Be Improved by Using Small Ambulances?

- Note that 23% of survey respondents indicated that traditional ambulance vans were either not available or too slow to reach their location.

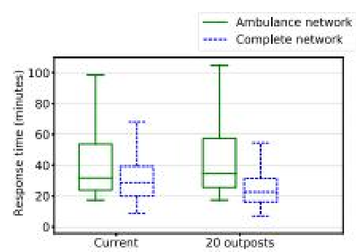
- In the ambulance road network, a potential loss of 544,231 ambulance (70.7%) trips (Fig. 8(a)).
- Figure 8(b) displays the response time performance.

Figure 8. (Color online) A Comparison of the Performance Between the Ambulance and Complete Road Network Outpost Locations

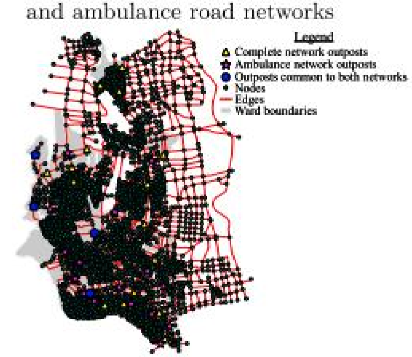
(a) Demand lost by the ambulance network



(b) A comparison of response time performance between the baseline and new locations



(c) Twenty all new outpost locations separately optimized for the complete and ambulance road networks

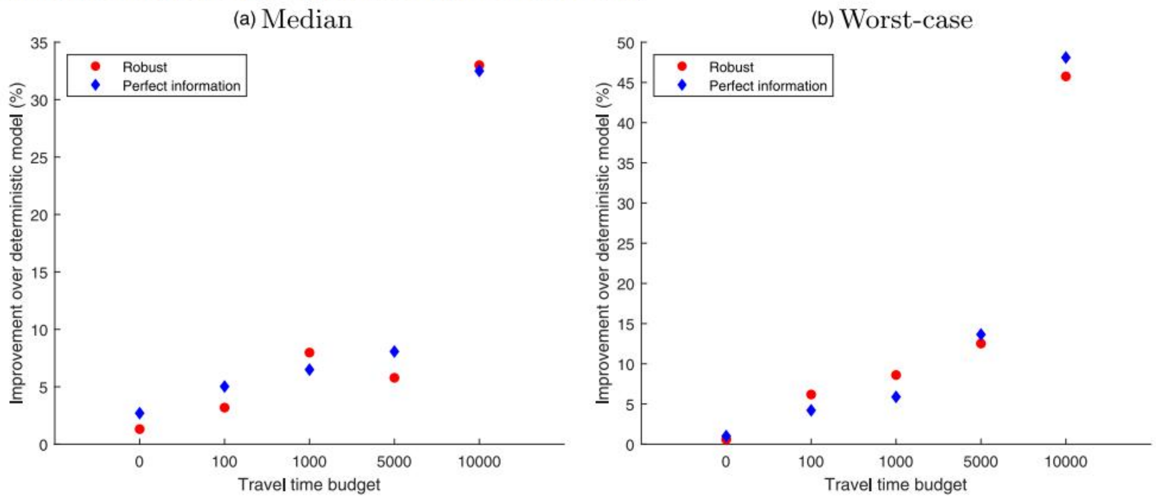


How Important Is It to Consider Uncertainty?

- Both models are solved using a heuristic, there are instances in which the robust solution slightly outperforms the perfect information solution.

- Robust solutions significantly outperform deterministic solutions.
- Robust solutions are comparable to those perfect information solutions.

Figure 9. (Color online) Response Time Improvement of the Robust and Perfect Information Formulations over the Deterministic Formulation as a Function of Travel Time Uncertainty



6. Comments

- Positive comments:
  - ✓ "Small data" environments: LMIC; Field research
  - ✓ Sophisticated numerical experiments
  - ✓ Fewer theoretical contributions but published in Operations Research

- Negative comments:
  - ✓ Data-driven paradigm

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Thank You!

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