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Judge's Commentary: The Outstanding Hurricane Evacuation Papers

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Introduction

Once again, Problem B proved to be quite challenging—both for the student teams and for the judges! The students were challenged by a multifaceted problem with several difficult questions posed, and the judges were challenged to sort through the wide range of approaches to find a small collection of the best papers. It is worth reminding participants and advisors that Outstanding papers are not without weaknesses and even mathematical or modeling errors. It is the nature of judging such a competition that we must trade off the strengths, both technical and expository, of a given paper with its weaknesses, and make comparisons between papers the same way.

The approaches taken by this year's teams can be divided into two general categories:

Macroscopic: Traffic on a particular highway or segment of highway was considered to be a stream, and a flow rate for the stream was characterized. Among the successful approaches in this category were fluid dynamics and network flow algorithms.

Microscopic: These can be considered car-following models, where the spacing between and the speeds of individual vehicles are used to determine the flow. Among the successful approaches were discrete event simulations (including cellular automata) and queuing systems.

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By far, the most common approach was to determine that the flow q, or flux, is a function of the density ρ of cars on a highway and the average speed v of those cars: $q = \rho v$. Successful approaches identified the following characteristics of the basic traffic flow problem:

- When the vehicle density on the highway is 0, the flow is also 0.
- As density increases, the flow also increases (up to a point).
- When the density reaches its maximum, or *jam density* ρ_0, the flow must be 0.
- Therefore, the flow initially increases, as density does, until it reaches some maximum value. Further increase in the density, up to the jam density, results in a reduction of the flow.

At this point, many teams either derived from first principles or used one of the many resources available on traffic modeling (such as Garber and Hoel [1999]) to find a relationship between the density and the average speed. Three of the common macroscopic models were:

- a linear model developed by Greenshield:

$$v = v_0 \left(1 - \frac{\rho}{\rho_0}\right), \qquad \text{so} \qquad q = \rho v_0 \left(1 - \frac{\rho}{\rho_0}\right);$$

- a fluid-flow model developed by Greenberg:

$$v = v_0 \log \frac{\rho}{\rho_0}, \qquad \text{so} \qquad q = \rho v_0 \log \frac{\rho}{\rho_0};$$

  or

- a higher-order model developed by Jayakrishnan:

$$v = v_0 \left(1 - \frac{\rho}{\rho_0}\right)^a, \qquad \text{so} \qquad q = \rho v_0 \left(1 - \frac{\rho}{\rho_0}\right)^a,$$

where v_0 represents the speed that a vehicle would travel in the absence of other traffic (the speed limit). By taking the derivative of the flow equation with respect to speed (or density), teams then found the optimal speed (or density) to maximize flow.

Many teams took the optimal flow from one of the macroscopic approaches and used it as the basis for a larger model. One of the more common models was simulation, to determine evacuation times under a variety of scenarios.

In order to make it beyond the Successful Participant category, teams had to find a way *realistically* to regulate traffic density to meet these optimality conditions. Many teams did this by stipulating that ramp metering systems (long term) or staggered evacuations (short term) could be used to control traffic density.

There were a number of mathematically rigorous papers that started with a partial differential equation, derived one of the macroscopic formulas, determined appropriate values for the constants, calculated the density giving the optimal flow, and incorporated this flow value into an algorithm for determining evacuation time. In spite of the impressive mathematics, if no plan was given to regulate traffic density, the team missed an important concept of the MCM: the realistic application of a mathematical solution to a real-world problem.

One key to successful model building is to adapt existing theory or models properly to the problem at hand, so judges see little difference between deriving these equations from first principles and researching them from a book. Whether derived or researched, it is imperative to demonstrate an understanding of the model you are using.

The Judging

No paper completely analyzed all 6 questions, so the judges were intrigued by what aspects of the problem that a team found most important and/or interesting. We were similarly interested in determining what aspects of the problem a team found least relevant and how they divided their effort among the remaining questions. To be considered Outstanding, a paper had to meet several minimum requirements:

- the paper must address all 6 questions,
- all required elements (e.g., the newspaper article) must be included, and
- some sort of validation of the model must be included.

We were also particularly interested in how teams modeled the I-26/I-95 interchange and the congestion problem in Columbia. Many teams chose to treat Columbia as the terminal point of their model and assumed that all cars arriving there would be absorbed without creating backups.

To survive the cut between Honorable Mention and Meritorious, a paper had to have a unique aspect on some portion of the problem. Two examples that come to mind are a unique modeling approach or some aspect of the problem analyzed particularly well. Thus, papers that failed to address all questions or had a fatal weakness that prevented their model from being extended could still be considered Meritorious. The Meritorious papers typically had very good insight into the problem, but deficiencies as minor as missing parameter descriptions or model implementation details prevented them from being considered Outstanding.

The Outstanding Papers

The six papers selected as Outstanding were recognized as the best of the submissions because they:

- developed a solid model which allowed them to address all six questions, and analyze at least one very thoroughly;
- made a set of clear recommendations;
- analyzed their recommendations within the context of the problem; and
- wrote a clear and coherent paper describing the problem, their model, and their recommendations.

Here is a brief summary of the highlights of the Outstanding papers.

The Bethel College team used a basic car-following model to determine an optimal density, which maximized flow, for individual road segments. They then formulated a maximum flow problem, with intersections and cities as vertices and road segments as arcs. The optimal densities were used as arc capacities, the numbers of vehicles to be evacuated from each city were used as the sources, and cities at least 50 miles inland were defined to be sinks. Each city was then assigned an optimal evacuation route, and total evacuation times under the different scenarios were examined.

The Duke team also used a basic car-following model from the traffic-modeling literature. This model provided the foundation of a one-dimensional cellular automata simulation. They did a particularly good job of defining evacuation performance measures—maximum traffic flow and minimum transit time, and analyzing traffic mergers and bottlenecks—aspects of the problem ignored by many other teams.

What discussion of Outstanding papers would be complete without a Harvey Mudd team? Of the teams that utilized literature-based models, this team did the best job of considering advanced parameters—including road grade, non-ideal drivers, and heavy-vehicle modification. They also did a very good job of comparing their model with the new South Carolina evacuation plan, recognizing the bottleneck problem in Columbia, and analyzing the impact of extra drivers from Florida and Georgia on I-95. Their entry was a nice example of a simple model that was well analyzed and thoroughly explained.

The Virginia Governor's School team began their analysis by reviewing the current South Carolina evacuation plan, a baseline to compare their model against. They researched the literature to find traffic-flow equations and then used a genetic algorithm to assign road orientation and evacuation start times for cities. They did an exceptionally good job of analyzing the sensitivity of their model to changes in parameter values.

The INFORMS prizewinner, from Lawrence Technical University, combined Greenshield's model with a discrete event simulation. The judges saw this entry as a solid paper with logical explanations and a good analysis. The team's model handled bottlenecks, and the team used a simulation of the actual 1999 evacuation to validate their model.

The MAA and SIAM winner, from Wake Forest University, derived a car-following model from first principles, which was then incorporated in a cellular automata type model. Like many of the best approaches, the parameters for their model came from the 1999 evacuation. They provided a thoughtful, not necessarily mathematical, analysis of intersections and I-95.

Advice

At the conclusion of our judging weekend, the judges as a whole offered the following comments:

Follow the instructions

- Answer all required parts.
- Make a precise recommendation.
- Don't just copy the original problem statement, but provide us with your interpretation.

Readability

- Make it clear in the paper where the answers are.
- Many judges find it helpful to include a table of contents.
- Pictures and graphs can help demonstrate ideas, results, and conclusions.
- Use discretion: If your paper is excessively long (we had a paper this year that was over 80 pp, not including computer program listing!), you should probably reconsider the relevance of all factors that you are discussing. Depending on what round of judging your paper is being read, judges typically have between 5 and 30 minutes to read it.

Computer Programs

- Make sure that all parameters are clearly defined and explained.
- When using simulation, you must run enough times to have statistically significant output. A single run isn't enough!
- Always include pseudocode and/or a clear verbal description.

Reality Check

- Why do you think your model is good? Against what baseline can you compare/validate it?
- How sensitive is your model to slight changes in the parameters you have chosen? (sensitivity analysis)

- Complete the analysis circle: Are your recommendations practical in the problem context?

Before the final judging of the MCM papers, a first (or triage) round of judging is held. During triage judging, each paper is skimmed by two or three judges, who spend between 5 and 10 minutes each reading the paper. Typically, when you send your paper off to COMAP, you have about a 43% chance of being ranked higher than Successful Participant. If, however, you survive the triage round, you have about an 80% chance of being ranked higher than Successful Participant. Head triage judge Paul Boisen offers the following advice to help you survive triage.

Triage Judge Tips

- Your summary is a key component of the paper; it needs to be clear and contain results. A long list of techniques can obscure your results; it is better to provide only a quick overview of your approach. The Lawrence Technical University paper is a good example of a clear and concise summary.
- Your paper needs to be well organized—can a triage judge understand the significance of your paper in 6 to 10 minutes?

Triage Judge Pet Peeves

- Tables with columns headed by Greek letters or acronyms that cannot be immediately understood.
- Definitions and notation buried in the middle of paragraphs of text. A bullet form is easier for the frantic triage judge!
- Equations without variables defined.
- Elaborate derivations of formulas taken directly from a text. It is better to cite the book and perhaps briefly explain how the formula is derived. It is most important to demonstrate that you know how to use the formulas properly.

Reference

Garber, Nicholas J., and Lester A. Hoel. 1999. *Traffic and Highway Engineering*. Pacific Grove, CA: Brooks/Cole Publishing Company.

About the Author

After receiving his B.A. in Mathematics and Computer Science in 1984, Mark Parker spent eight years working as a systems simulation and analysis engineer in the defense industry. After completing his Ph.D. in Applied Mathematics at the University of Colorado–Denver in 1995, he taught mathematics and computer science at Eastern Oregon University for two years. He then spent three years on the faculty at the U.S. Air Force Academy teaching mathematics and operations research courses. He now shares a teaching position with his wife, Holly Zullo, at Carroll College in Helena, MT, and spends as much time as he can with his three-year-old daughter Kira.