National Aeronautics and Space Administration

A Minimax Network Flow Model for Assessing Global Impacts of Congestion Management in Transport Systems

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Motivation

The U.S. National Airspace System (NAS) is becoming increasingly congested, particularly at our major airports

Congestion is a NETWORK problem, not just an airport-by-airport problem:

- Many participants with different goals (policymakers, airlines, airports, passengers, etc.)
- Actions taken by one participant at one location has wide-ranging impacts for all of the NAS

Understanding the global impacts of the actions of NAS participants is necessary for understanding effective controls for managing air traffic and congestion

Potential Regulatory Action: Airport Slot Restrictions

Limit on total landings/takeoffs at an airport in some period of time (usually an hour)

In the U.S., primarily exercised at a select few of the busiest airports, most notably the NYC Metroplex airports (EWR, JFK, LGA), where delays have been reduced

However, not a sufficient amount of attention to the network effects of slot restrictions

What tools/methods are available to analyze these effects?

The Minimax Node Load Problem (MNLP)

Minimax multicommodity flow model whose objective is to minimize, for a given input network, the worst-case load on any node which is not flow-constrained

$$
\begin{aligned}
&\min_{x,z} z \\
&s.t. \quad \sum_{k\in K}\sum_{j\in O(i)} x_{ijk} \le z, \quad \forall i \in N \setminus SC \\
&\qquad \sum_{k\in K}\sum_{j\in O(i)} x_{ijk} \le u_i, \quad \forall i \in SC \\
&\qquad \mathcal{N} x_k = d_k, \quad k \in K \\
&\qquad x_{ijk} \ge 0, \quad \forall (i,j) \in A, \ \forall k \in K
\end{aligned}
$$

N = node set
SC = flow-constrained node set
A = arc set
K = commodity set
x = flow allocation
u = flow upper bound
$\mathcal{N}$ = node-arc incidence matrix
i, j = node indices
k = commodity index

For an air transportation application:
Nodes = airports
Arcs = available flights
Flow = aircraft trips
Commodities = aircraft O-D itineraries
Flow constraints = slot restrictions

MNLP characterizes basic effects of congestion management strategies at the level of flow and network topology. The model is complementary to higher fidelity approaches and provides “starting points” for further evaluation of some out of a wide range of slot restriction scenarios

Questions under study:

How do slot restrictions affect the flow of aircraft through unconstrained nodes, and the minimax node load?

Do increases in the severity and extent of the slot restrictions increase these effects significantly?

A NAS-like MNLP Example

The input network above consists of 30 of the FAA’s OEP airports, with five hubs:

ATL (grey lines, referred to as H4)
DEN (blue lines, referred to as H3)
DFW (red lines, referred to as H2)
MSP (green lines, referred to as H1)
ORD (black lines, referred to as H5)

The remaining airports in this network are spokes. Commodities are associated with unique spoke pairs, each of which has a unit demand. (Note: Airport roles here are not meant to correspond to those in the actual NAS)

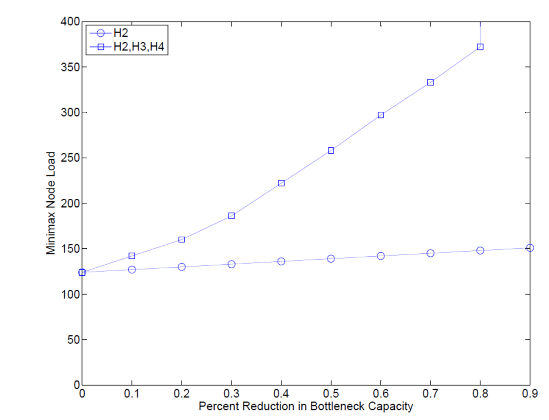
Numerical Experiments

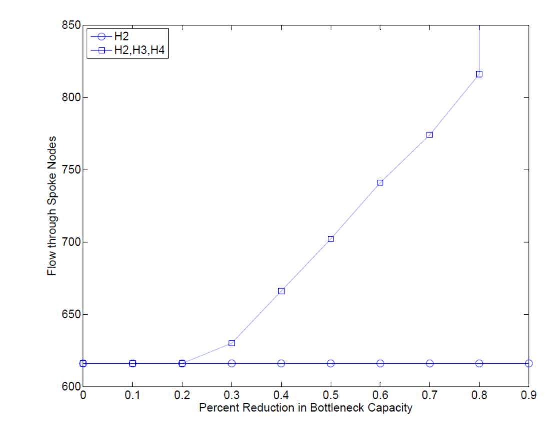
1) Solve unconstrained MNLP for input network, identify bottleneck hub (break ties arbitrarily)
2) Apply slot restriction to bottleneck hub (H2) in 10% decrements from unconstrained level of operation
3) Repeat 2 with same slot restrictions applied to H2, H3 and H4

Results

When only H2 is restricted, the minimax node load increases at a small linear rate (see below left). With restrictions on H2, H3, and H4, the increase is greater and nonlinear until the restrictions are so great that MNLP becomes infeasible

The aggregate flow on spokes (below right) stays zero no matter the reduction In capacity on H2, while increasing substantially when H2, H3, and H4 are restricted.





Conclusions

MNLP is a promising step in assessing global impacts of congestion management strategies, as demonstrated on a moderate-sized hub-spoke network

Stricter slot restrictions increase minimum worst-case operation over all airports and the load on all unconstrained hub airports. When more hubs are constrained, these increases are greater and extend to non-hubs

Current results are only a proof of concept , but are realistic and can complement and guide higher fidelity approaches

Future work includes incorporating airline actions and economic considerations