A Robust, Scalable Transportation System Concept

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Why, What, and How:  
The Problem & Proposed Concept

• **Today’s System**
  – Limited growth in utility
  – Non-scalable and brittle
  – Marginal response to traveler needs

• **Intermediate Concepts**
  – Still under today’s tech limits
  – Incremental improvements in individual systems
  – “The Whole” is less than the sum of the parts?

• **Revolutionary System System-of-Systems Concept**
  – Higher-level, integrated transportation concept
  – Goals: Increases in . . .
    • Throughput & Accessibility
    • Robustness & Natural adaptation
  – But: there is no master architect

**How?: Generate Desired Transportation Sys-of-Sys’s**
Within sets of rules of an agent-based simulation, observe what mix of vehicles (air/ground), airspace networks, infrastructure, business strategies, and policies emerge as the agents seek to achieve the desired transportation traits (“new NAS”).
Scope, Assumptions, & Knowledge

• Scope:
  – Given cost, schedule, and purpose, simulation/concepts will be high-level
    • VAMS/ACES, etc. study lower level concepts & objectives with high fidelity
  – Understanding transportation concepts as Sys-of-Sys’s will be emphasized

• Assumptions
  – “Clean Sheet” study approach, meaning we will:
    • Allow innovative system concepts, but . . .
    • Not ignore realities like: legacy of current systems, market imperatives, etc.

• Knowns and Unknowns
  – Knowns
    • E.g. 95% of Cargo/People moved on Ground/Water, 5% by Air (BTS)
    • Transportation capital for “new NAS” will be shared with other modes of travel.
  – Known unknowns
    • E.g. Rate of growth/decline of economy; time to build in new technologies
    • Seek: Thresholds to overcome barriers (make improvement sensitivities known)
  – Unknown unknowns
    • E.g. The technology, policy, or disruption that will make the system invalid
    • Seek: Insight that turns these to known unknowns
# Our Study Language

## Categories & Descriptions

<table>
<thead>
<tr>
<th>Categories</th>
<th>Descriptions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resources</td>
<td>The entities (systems) that give physical manifestation to the system-of-systems</td>
</tr>
<tr>
<td>Economics</td>
<td>The non-physical entities (stakeholders) that give intent to the SoS operation</td>
</tr>
<tr>
<td>Operations</td>
<td>The application of intent to direct the activity of physical &amp; non-physical entities</td>
</tr>
<tr>
<td>Policies</td>
<td>The external forcing functions that impact the operation of physical &amp; non-physical entities</td>
</tr>
</tbody>
</table>

## Levels & Descriptions

<table>
<thead>
<tr>
<th>Levels</th>
<th>Descriptions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alpha (α)</td>
<td>The base level of entities, for which further decomposition will not take place. α-level components can be thought of as building blocks.</td>
</tr>
<tr>
<td>Beta (β)</td>
<td>Collections of α-level systems, organized in a network.</td>
</tr>
<tr>
<td>Gamma (γ)</td>
<td>Collections of β-level systems organized in a network.</td>
</tr>
<tr>
<td>Delta (δ)</td>
<td>Collections of γ-level systems organized in a network.</td>
</tr>
</tbody>
</table>

![Diagram of Levels and Components](image.png)

**Approach**
## Mapping to Transportation

<table>
<thead>
<tr>
<th>Level</th>
<th>Resources</th>
<th>Operations</th>
<th>Economics</th>
<th>Policy</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\alpha$ ($\approx 10^6$)</td>
<td>Vehicles &amp; Infrastructure (e.g. aircraft, truck, runway)</td>
<td>Operating a Resource (Aircraft, truck, etc.)</td>
<td>Economics of building/operating/buying/leasing a single resource</td>
<td>Policies relating to single resource use (e.g. type certification, flight procedures, etc.)</td>
</tr>
<tr>
<td>$\beta$ ($\approx 10^4$)</td>
<td>Collection of resources for a common function (an airport, etc)</td>
<td>Operating resource networks for common function (e.g. airline)</td>
<td>Economics of operating/buying/selling/leasing resource networks</td>
<td>Policies relating to multiple vehicle use (e.g. airport traffic mangt, noise policies, etc.)</td>
</tr>
<tr>
<td>$\gamma$ ($\approx 10^2$)</td>
<td>Resources in a Transport Sector (e.g. air transportation)</td>
<td>Operating collection of resource networks (e.g.; commercial air Ops)</td>
<td>Economics of a Business sector (e.g. Airline Industry)</td>
<td>Policies relating to sectors using multiple vehicles. (safety, accessibility, etc.)</td>
</tr>
<tr>
<td>$\delta$ ($\approx 10^1$)</td>
<td>Multiple, interwoven sectors (resources for a national transportation system)</td>
<td>Operations of Multiple Business Sectors (i.e. Operators of total national transportation system)</td>
<td>Economics of total national transportation system (All Transportation Companies)</td>
<td>Policies relating national transportation policy</td>
</tr>
<tr>
<td>$\varepsilon$ ($\approx 10^0$)</td>
<td>Global transportation system</td>
<td>Global Operations in the world transportation system</td>
<td>Global Economics of the world transportation system</td>
<td>Policies relating to the global transportation system</td>
</tr>
</tbody>
</table>

### Approach
Transportation Abstraction
Our Model and Guide for the Study

Disruptors:
- Causing delay and/or cancellation of transportation activities
  - Natural disruptors: weather related events that affect operational condition of resources
  - Artificial disruptors: accident, terrorism, pollution

Drivers:
- Determine overall demand profile for transportation activities
  - Economic factors: GDP, household income, fuel price
  - Societal factors: demographic characteristics, urbanization trend
  - Psychological factors: culture, perception of safe/secure system
Resource Entities: The Generic Trip

**Portal Entities**

<table>
<thead>
<tr>
<th>Element</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mode change</td>
<td>Required time to transfer from/to secondary mode</td>
</tr>
<tr>
<td>Wait-ahead</td>
<td>Required time for most scheduled services</td>
</tr>
<tr>
<td>Wait-in-line</td>
<td>Required time for processing ticketing, baggage claims and security check</td>
</tr>
<tr>
<td>Portal delay</td>
<td>Undesirable waiting time due to capacity limit, weather, etc.</td>
</tr>
</tbody>
</table>

**Enroute Entities**

<table>
<thead>
<tr>
<th>Item</th>
<th>Attributes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rudiment Items</td>
<td>Types of portals and vehicles</td>
</tr>
<tr>
<td>Attributes</td>
<td>Path-length parameter</td>
</tr>
<tr>
<td></td>
<td>Construction cost</td>
</tr>
<tr>
<td></td>
<td>Operation cost &amp; rule</td>
</tr>
<tr>
<td>Interfaces</td>
<td>Refueling/rest points</td>
</tr>
<tr>
<td></td>
<td>Enroute delay effect (inter- and intra-city)</td>
</tr>
<tr>
<td></td>
<td>Influence from weather effect</td>
</tr>
<tr>
<td></td>
<td>Throughput of vehicles</td>
</tr>
</tbody>
</table>

**Vehicle Entities**

<table>
<thead>
<tr>
<th>Category</th>
<th>Attributes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operational Performance</td>
<td>Cruise speed</td>
</tr>
<tr>
<td></td>
<td>Maximum range</td>
</tr>
<tr>
<td></td>
<td>License requirement</td>
</tr>
<tr>
<td></td>
<td>Payload capacity</td>
</tr>
<tr>
<td></td>
<td>Near all-weather operations</td>
</tr>
<tr>
<td>Economic Characteristics</td>
<td>Acquisition cost</td>
</tr>
<tr>
<td></td>
<td>Direct operation cost</td>
</tr>
<tr>
<td></td>
<td>Insurance/maintenance cost</td>
</tr>
<tr>
<td></td>
<td>Price/fee schedule</td>
</tr>
<tr>
<td>Infrastructure Compatibility</td>
<td>Types of portal</td>
</tr>
<tr>
<td></td>
<td>Types of enroute space</td>
</tr>
<tr>
<td></td>
<td>Dual mode capability</td>
</tr>
</tbody>
</table>

• Validate with (fixed) averages
• Simulate with (variable) values ... sensitivities
# Stakeholder Entities

<table>
<thead>
<tr>
<th>Stakeholders</th>
<th>Descriptions</th>
<th>Objectives</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Public</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Consumers</td>
<td>Individual travelers or shippers (for commercial goods) that are the end user for the transportation system.</td>
<td>min: travel time, expense, max: comfort, safety</td>
</tr>
<tr>
<td>Society</td>
<td>Represents the aggregated interests of citizens, from research agencies, to communities, to the national level.</td>
<td>min: noise, emission, max: quality of life</td>
</tr>
<tr>
<td><strong>Industry</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Service Providers</td>
<td>Owners of resources who sell transportation services to consumers.</td>
<td>max: profit, market share, consumers’ satisfaction</td>
</tr>
<tr>
<td>Manufacturers</td>
<td>Design, produce and sell transportation resources to service providers and/or consumers.</td>
<td>max: profit, market share, service providers’ satisfaction</td>
</tr>
<tr>
<td>Insurance Companies</td>
<td>Provide protections against mishap operation of transportation resources by collecting insurance fee.</td>
<td>max: profit, market share, customers’ satisfaction</td>
</tr>
<tr>
<td><strong>Government (Policymakers)</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Regulatory Agencies</td>
<td>Impose rules on the system that restrict stakeholder activity and resource characteristics.</td>
<td>max: safety, security</td>
</tr>
<tr>
<td>Infrastructure Providers</td>
<td>Plan and approve employment and enhancement of infrastructure resources.</td>
<td>max: capacity, min: delay</td>
</tr>
<tr>
<td><strong>Indirect Stakeholders</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Media</td>
<td>Report information, forecast and plan from/to the public.</td>
<td>Varied, but vague</td>
</tr>
<tr>
<td>Research Agencies</td>
<td>Develop and provide transportation related technologies.</td>
<td>Provide firm foundation for transportation development</td>
</tr>
</tbody>
</table>
Agent-Based Modeling (ABM)

- Instead of prescribing the behavior dynamics, in ABM, individual agents (guided by behavioral rules) interact within the environment & system-wide effects are observed.

- Two major agent classes:
  - Software agents and simulation agents (“Sims”)

- Some simulation agent types:
  - Reactive: Simple reactions based on fixed rules
  - Intelligent: The β-level entities are the intelligent agents in our case
    - They generate the resource network (α-level entities) and a new NAS emerges at the γ-level, hopefully with the desired traits (scalable, desirable, accessibility)
    - May impart levels of autonomy, “learning”, into the α-level units to satisfy objectives
  - Mobile: Vehicles, Travelers
ABM Demo

• Go to Boids Demo
What’s different about this modeling approach?

- **Emergence** -

  - Emergence
    - “Persistent patterns” that emerge from small set of well-chosen building blocks constrained by simple rules (from Holland, 1998)
    - These patterns obey “macrolaws” that do not make direct reference to underlying generators.

  - Predictive vs. Emergent
    - Linear vs. non-linear;
      - We (and our typical models) generally think in linear terms
    - Single layered vs. multi-level
    - Static vs. dynamic

  - Value Added:
    - Uncover *landmine* or *jackpot* patterns over time, instead of point predictions for single systems (which are hardly ever right)
What is an “Emergent NAS”? 

• Classic view: The NAS consists of … (Ref. Hansman, MIT)  
  – Airports, Air Traffic Management, Weather, Personnel, Cost  
    Recovery Mechanisms; True, but . . .  
• NAS is most simply a series of networks: nodes and links  
  – NAS networks are not designed, but generated  
  – No single network represents the always correct answer  
• Networks define connectivity (links) of packets (people)  
  between points A and B (nodes)  
  – Topologies “which nodes connected”  
  – Accessibility “how often connected”  
• The NAS networks are γ-level constructs; they arise based  
  on rules in both the Resource and Stakeholder realms  
  – The resource and stakeholder networks are intertwined  
  – New innovations stimulate improvement in old technologies

Approach
Summary Study Plan: 
Implement Abstract Model and Simulate

1. Build: initial agents, generate environment, calibrate
   a. Simple network model with constraints
   b. Volpe mode split data (and existing tools we have)
   c. Rough comparison cases (e.g. LMI-3X)
2. Create: “clean sheet” ABM that evolves concepts for:
   a. Aircraft & Network concepts (portal operations, airspace ops)
   b. Business and regulatory concepts
   c. Factors in other modes
3. Simulate & Observe: Let the β-level agents organize themselves to respond to demands, disruptions, and drivers & thus:
   a. Select the α-level entity traits that they desire to meet this objective
   b. Generate the “new, emergent NAS”, at the γ-level
4. Anticipated results: Answers to . . .
   a. What are the persistent patterns that emerge in the “new NAS” concepts?
   b. What are the simple agent rules that enable them?
   c. Where are the highest sensitivities & most significant barriers?
Study Plan/Schedule

Selection

Data Gathering, Model Construction

Funding/Contract
Start at Purdue

Calibration Studies

Mid-Study Review

System-of-Systems Concept generation runs & evaluation

Workshare:
Nearly all work performed at Purdue University; guidance from:
• Andy Hahn, LaRC SAB
• Small consultant effort (PIPS)

Simulation Interpretation & Description of Emergent Concepts

Reflection on Feedback; Preparation of Final Report

Final Report

Team (NASA/Purdue) monthly status reports/telecons

Jan
Feb
Mar
Apr
May
Jun
July
Aug
Sep
Oct
Nov
Dec

Final Presentation
Synopsis

• Key outcome: High-level simulation of “new NAS” Sys-of-Sys
• Desired objectives for “new NAS” concept(s)
  – Increased throughput and accessibility (e.g. “3X” increase)
  – Increased robustness (insensitivity to disruption: weather, resource, terrorism, traffic jams)
  – Increased “Natural”-ness
    • Minimal constraints and rules to get "good" behavior, naturally expressed
    • And, make money!
• The resulting set of concepts could be used to broadly guide both technology investment and regulatory direction of this complex Sys-of-Sys