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System Dynamics Application in Air Traffic Management

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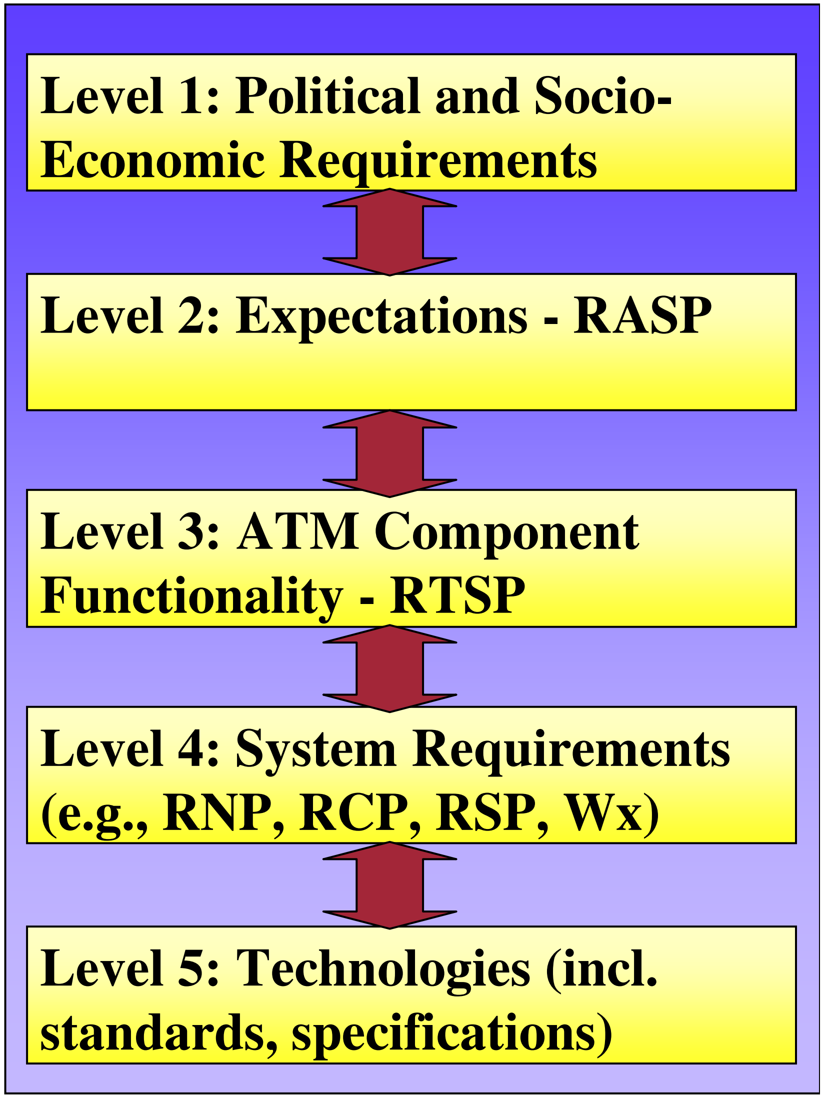
Overview

- **Performance-based modeling: ICAO 5-level hierarchy**
- **System Dynamics (SD) as a performance-based modeling methodology in CNS-ATM**
  - **What is System Dynamics?**
  - **Traditional applications of SD to CNS-ATM**
  - **Potential new applications**
- **Gulf of Mexico non-radar airspace (NRA): A case study**
- **Demo of SD model (Vensim)**
- **Conclusions and future work**

ICAO 5-level performance hierarchy

- **Initially defined in Global ATM Operational Concept Doc (ICAO 9854)**
  - Also: “Manual on Global Performance of the Air Navigation System”, ICAO Doc 9883 AN/468, Feb 2008
- **Layers represent different views of the CNS-ATM system**
- **Allows *tracing* of performance impact**
  - –Changes at lower levels affect next layer above (and vice-versa)
  - –Helps understand and communicate performance case



ICAO = International Civil Aviation Organization
RASP = Required ATM Service Performance
RTSP = Required Total System Performance
Wx = Weather prediction

ATM system feedback control perspective

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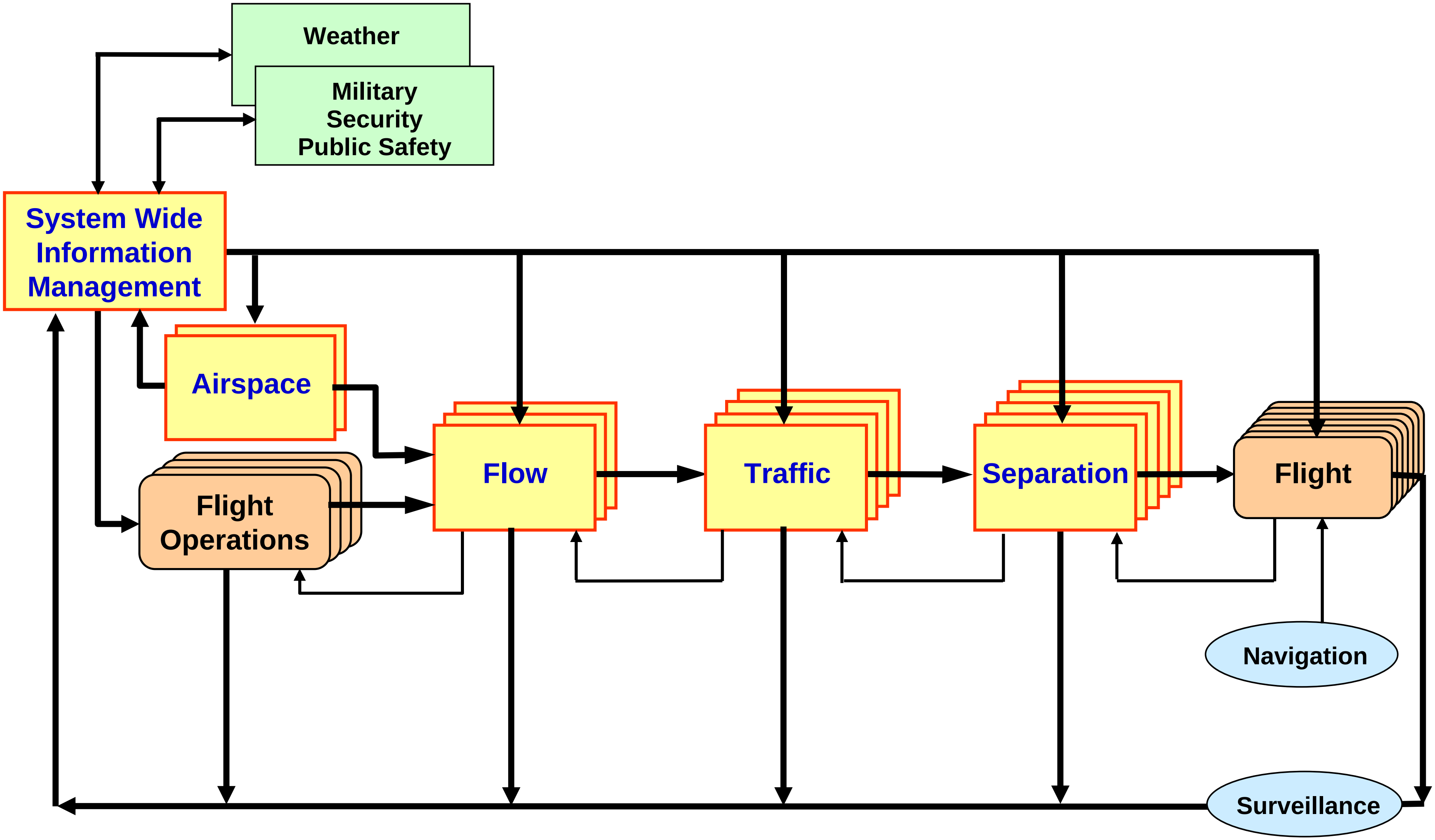
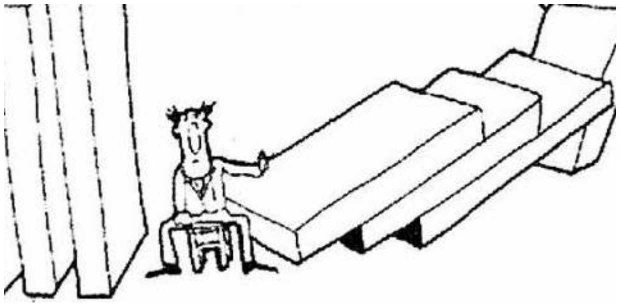
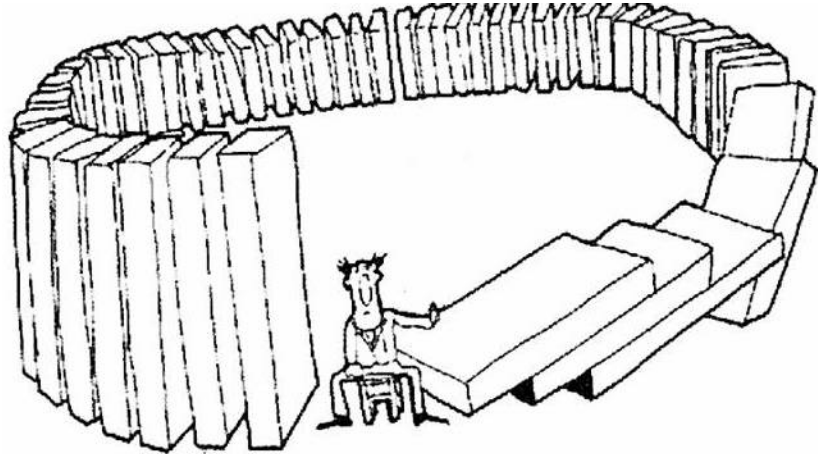


The Systems Thinking Viewpoint

Local Perspective

Feedback (systems) Perspective





Each action stands on its own as an event

Every decision for action is connected and over time will have multiple effects/impacts

The role of System Dynamics (SD) modeling

System Dynamics Model:

Why does the system behave this way?
Why and how do changes in one part of the system affect another?
How do uncertainties affect the output?
What areas need further, more detailed analysis?
How can we communicate system-level behaviors to a wide audience?

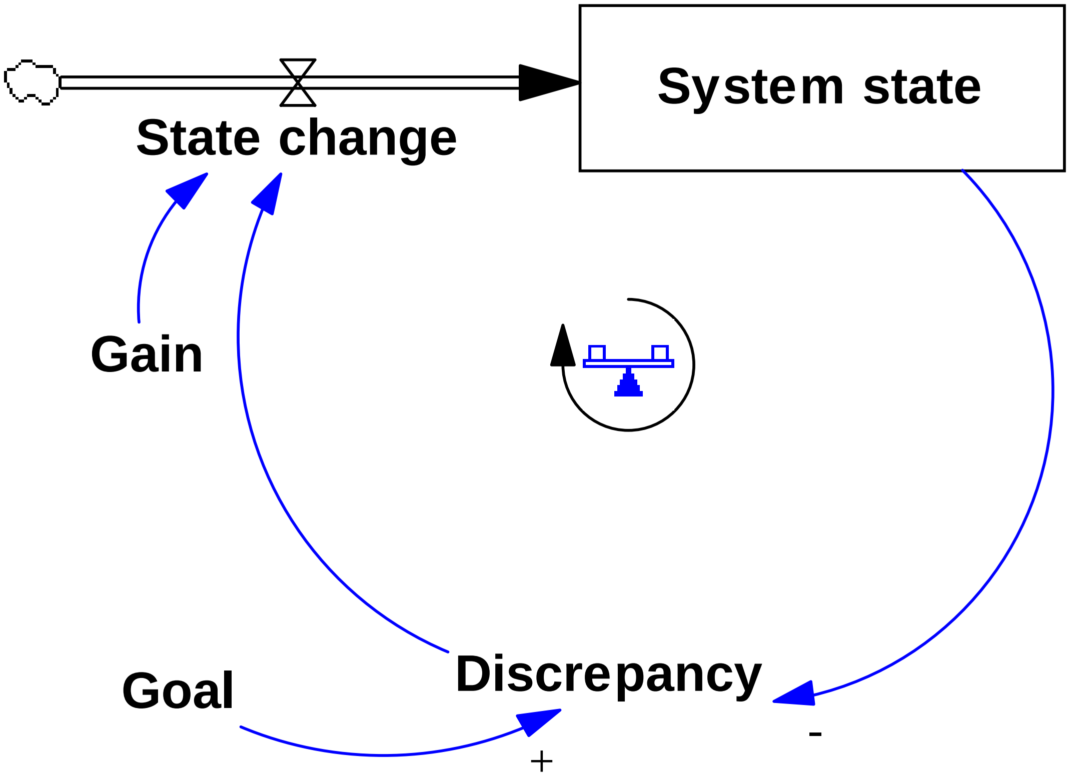
Process Models:

What are the latencies?
What are the queue wait times?
What is the mission timeline?
What are the right numbers of resources?

Physics-based and Human Factors Models:

How far can the radar see?
What is the communication delay?
What are the pilot and controller response times?
What is the cost of maintaining a radar?

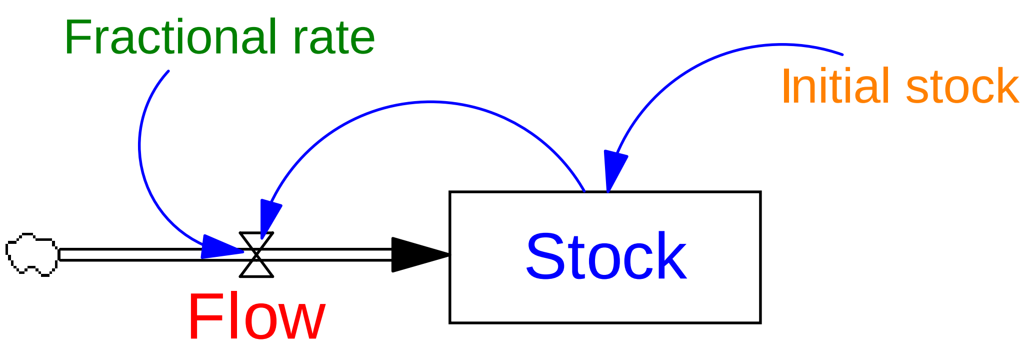
Feedback control (Vensim diagram)



Differential & integral equations & Stocks and Flows

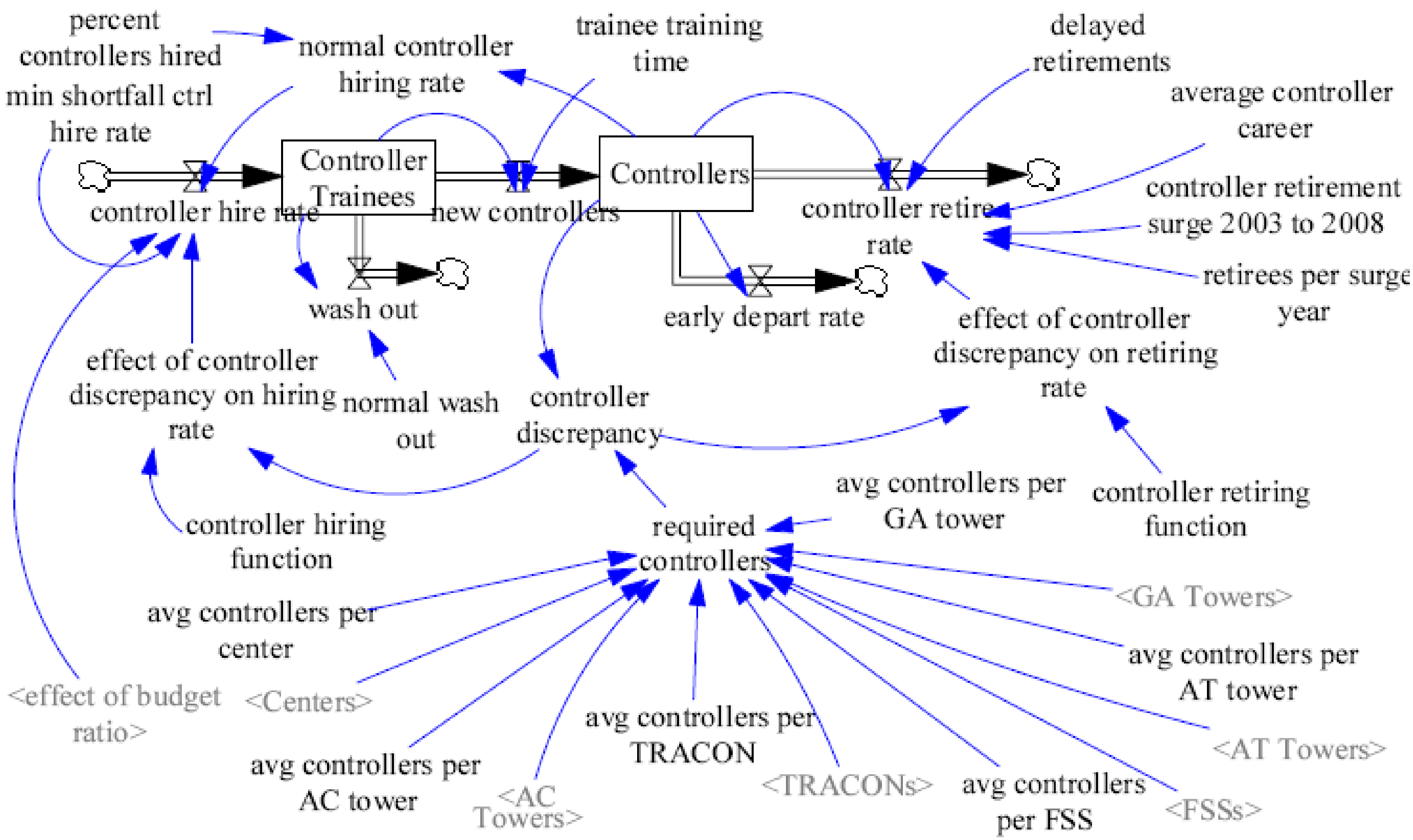
$$\frac{dx}{dt} = r\,x(t), \quad x(0) = x_0$$

$$x(t) = x_0 + r\int_0^t x(\tau)\,d\tau$$



$$x(t) = x_0 e^{rt}$$

Controller stock and flow diagram (Galvin 2002)



Examples of System Dynamics modeling in CNS-ATM

- *Overview of the FAA's NAS Strategy Simulator, (Sherry & Mezhepoglu (GMU/CATSR), Goldner (Ventana Systems), Yablonski & Knorr (FAA), 2005?)*
- *Air Traffic Control Resource Management Strategies and the Small Aircraft Transportation System: A System Dynamics Perspective*, (James J. Galvin, PhD thesis at Virginia Polytechnic Institute & State Univ, 2002)
- *Portfolio Analysis Of Air Transportation Infrastructure Investment*, (Lance Sherry & Bengi Mezhepoglu, Center of air Transportation and Systems Research, George Mason Univ, 2006)
- *A System Dynamics Tool for Economic Performance Assessment in Air Traffic Management, (Hustache, Gibellini, Leal-De-Matos, Eurocontrol, 2006)*
- *NAS Genomics: New Techniques and Initial Results for System-Level Understanding of NAS Behavior, (Klopfenstein et al (Metron Aviation) & James Weatherly (FAA) 2001?)*
- *The Pace or the Path? Resource Accumulation Strategies in the U.S. Airline Industry, (Salge & Milling, 22nd International Conference of SD Society, 2004)*

Modeling the performance hierarchy

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Level 1: Political and Socio-Economic Requirements

↕

Level 2: Service Level Expectations

↕

Level 3: ATM Component Functionality – (Required Total System Performance)

↕

Level 4: System Requirements (Comm, Nav, Surv, Wx))

↕

Level 5: Technologies (incl. standards, specifications)

Existing applications of System Dynamics (Levels 1–2)

Application described in this presentation (Levels 3–4)

GOMEX Non-Radar Airspace (NRA)

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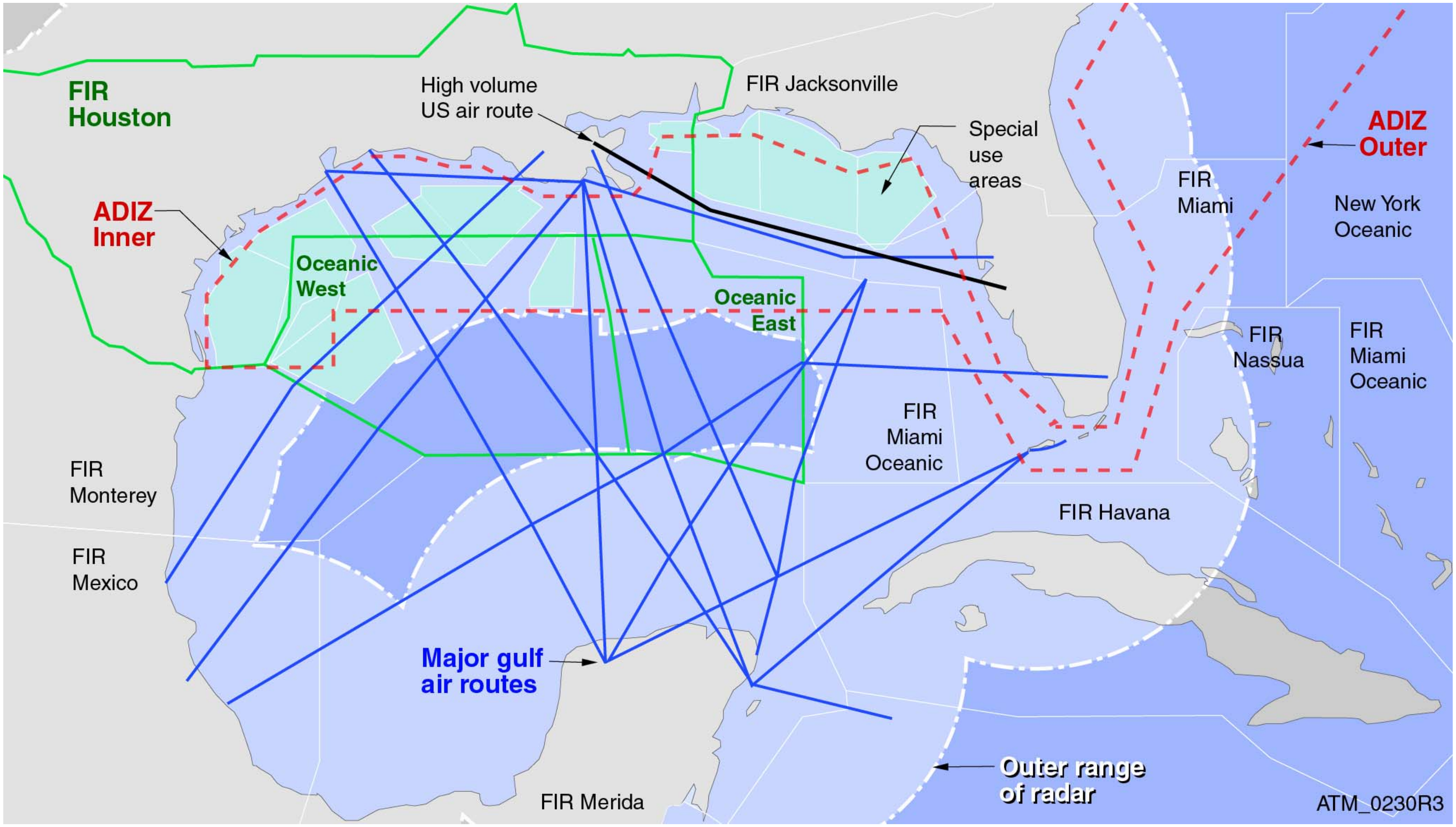


GOMEX questions directly related to 5-level hierarchy

- **How does use of ADS-B-out in the GOMEX improve ATM services (throughput and safety)?**
- **This is important to understanding the relationship of level 2 (service level) to level 3 (ATM component functionality) and level 4 (system requirements)** *(ADS-B = Automatic Dependent Surveillance – Broadcast)*

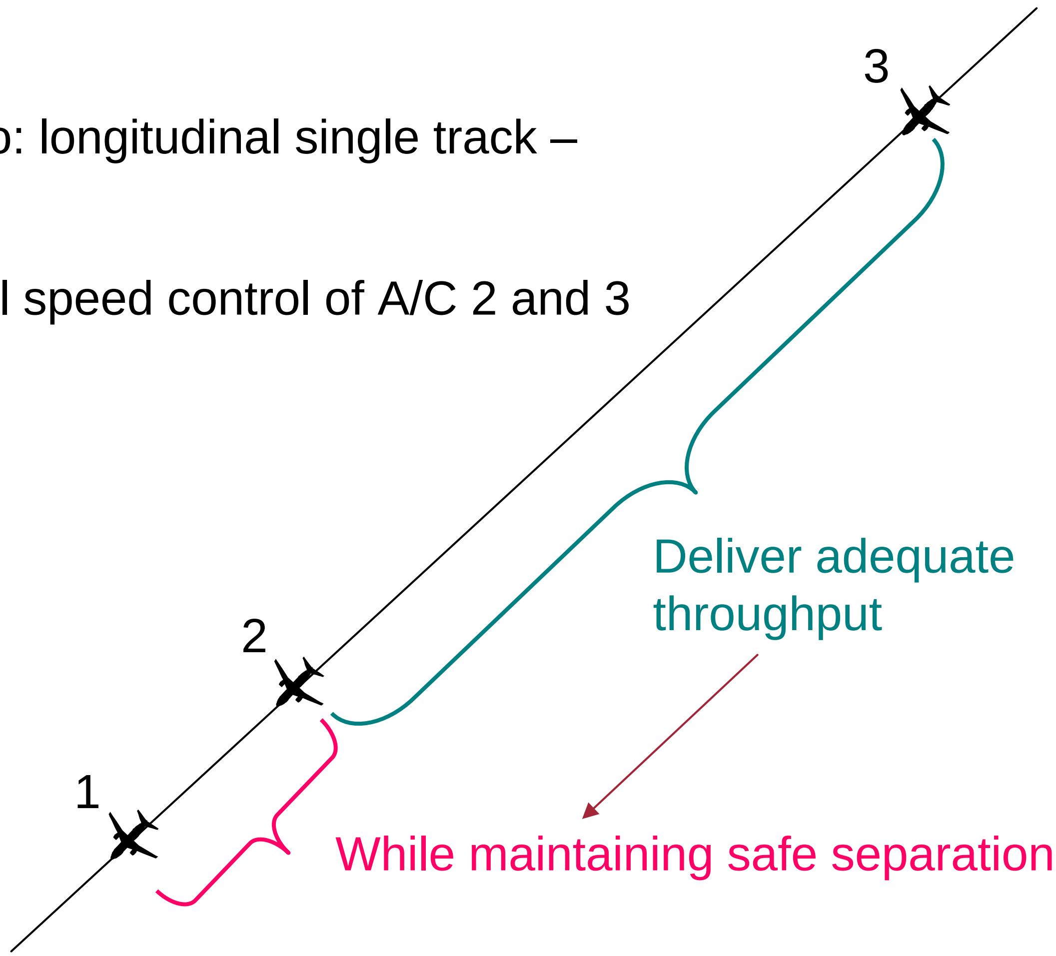
- **More generally, in a procedural environment, how do C, N, and S performance changes affect the throughput, safety, and cost? Related again to levels 2, 3, and 4, but in a more general context.**

- **Is improved navigation performance sufficient by itself to achieve the desired increases in throughput in the GOMEX?**
- **This question is motivated by the significant Boeing investment in RNP. This has implications for levels 2 through 5 (service level through total system performance, system requirements, and technological specifications)**

- **How do we take a technology enabler (such as ADS-B) and generate level 4 performance requirements?**
- **Direct effect on understanding the relationship between levels 4 and 5, but this is probably outside the scope of Vensim modeling.**

SD simulation model of the GOMEX scenario

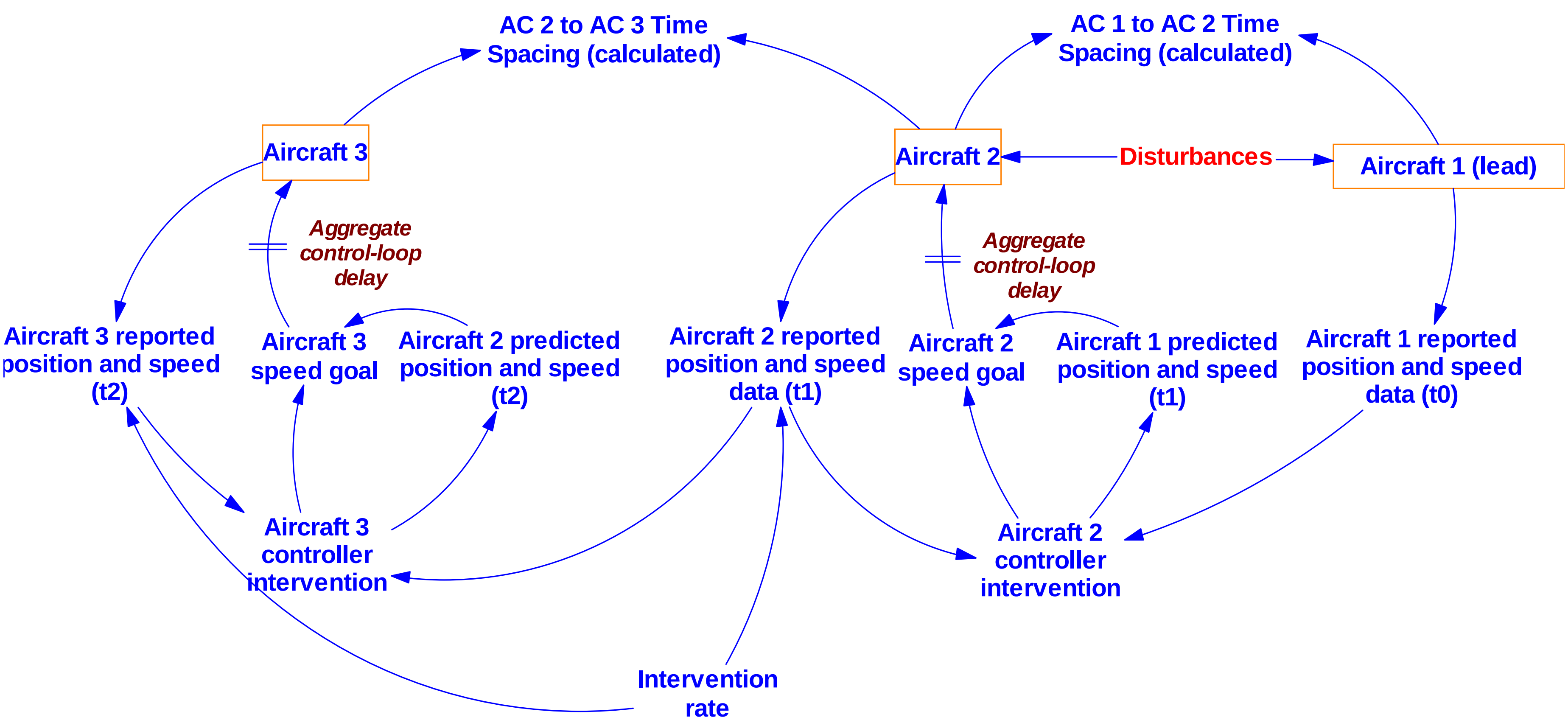
- Three-aircraft oceanic cruise scenario: longitudinal single track – no vertical or lateral motion
- Separation maintained by longitudinal speed control of A/C 2 and 3
- Track length 1000 nmi
- Simulation time 2 hours
- Nominal speed 480 knots
- Nominal separation 30 to 120 nmi
- Controller interventions nominally 10-15 minutes (80-120 nmi at 480 kts)
- Trade – procedural vs ADS-B out performance



Simplifying model assumptions

- **Each aircraft speed controlled based only on its state and the state of preceding aircraft**
  - **That is, no "optimization" over all aircraft in stream**
- **Aircraft acceleration/deceleration governed by same "speed adjustment time" (acceleration capability)**
- **Two representations of controller strategies**
- **Current procedure: Mach rule of 11**
- **ADS-B out procedure: Control to desired separation & speed**
  - **Two gains, one on position separation and one on speed difference**
  - **No gain scheduling or adaptive gains**
  - **Essentially a proportional-integral (PI) controller**

Longitudinal speed control model (Vensim)



Demo

Run Vensim

Summary and next steps

- **Accomplishments:**
- **Showed feasibility of SD approach in performance-based modeling**
- **Demonstrated use of SD on an application of interest: New operations in the GOMEX based on ADS-B out**
- **Next steps:**
- **Model validation: connect “slider” and output variables to operationally meaningful parameters**
- **Extend model to include lateral and/or vertical motion**
- **Integrate human-machine interfaces into model**

Boeing 7-Series Lineup

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Backup

Mach spacing "rule of 11"

Minutes behind	5	6	7	8	9	10	11 or above
Mach speed delta	.06	.05	.04	.03	.02	.01	Same speed or slower

Discriminators for the two operational scenarios

	Current procedure	ADS-B out
Control algorithm	Rule of 11	PI controller
Reporting interval	Long	Short
Control loop delay	Long	Short

Model attributes

Performance parameters	Control loop delay time	ATC intervention rate
Controlled variable	Individual aircraft speed(s)	
Output metrics	Throughput (1/total average spacing)	Safety (% of time that adjacent a/c spacing is below minimum)
Random variations	Aircraft track entry speed	Aircraft distance from preceding aircraft at track entry
Disturbances	Increase/decrease in aircraft speeds (via acceleration “spike”)	

Measures of throughput and safety

	Throughput	Safety
Measure	Average time-spacing over all adjacent pairs of aircraft and all Monte Carlo simulations	Percentage of time that time-spacing falls below a prescribed minimum, taken over all adjacent pairs of aircraft and all Monte Carlo simulations

Monte Carlo simulation parameter settings

Parameter	Current procedure	ADS-B procedure
Control algorithm	Mach rule of 11	PI controller
Aggregate control delay	360 sec	30 sec
Reporting interval (distance)	240 nmi	120 nmi
Nominal arrival spacing	30 nmi	30 nmi
Spacing goal	30 nmi	30 nmi
Lead AC initial speed	N(480,5) kts	N(480,5) kts
AC 2, 3 nominal arrival speed	480 kts	480 kts
AC 2, 3 arrival speed variation	N(0,2.5) kts	N(0,2.5) kts
AC 2, 3 arrival spacing variation	N(0,2) nmi	N(0,2) nmi
AC 1, 2 acceleration spike magnitude	N(0,2.5) kts/sec	N(0,2.5) kts/sec
AC 1 acceleration spike start	N(750,100) sec	N(750,100) sec
AC 2 acceleration spike start	N(600,100)	N(600,100)
AC 1, 2 acceleration spike duration	20 sec	20 sec
Position gain	NA	.001 (1/sec)
Speed gain	NA	.01 (dimensionless)

AC 1 & 2 separation (nmi) with current procedure

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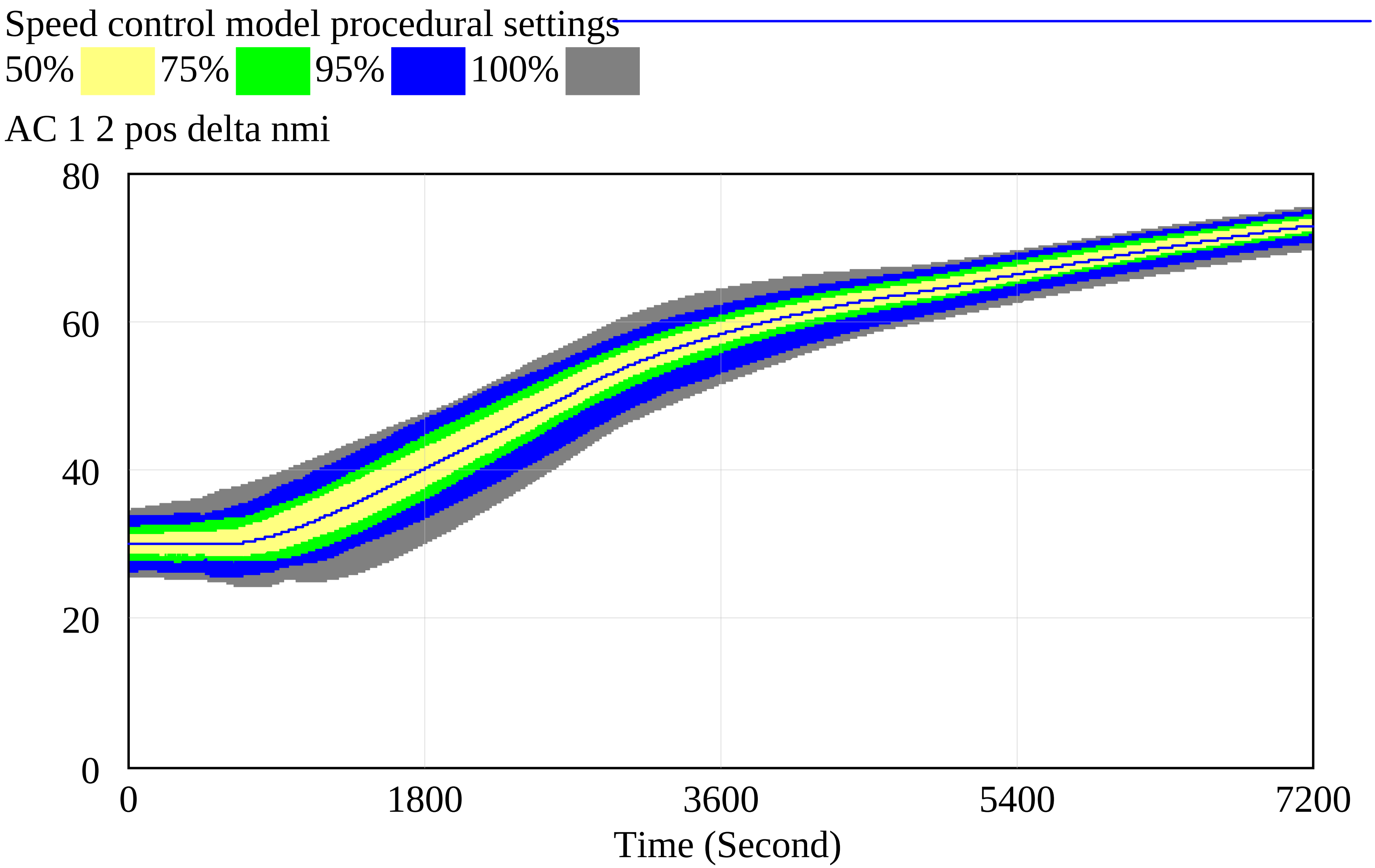

AC 1 & 2 separation (nmi) with ADS-B procedure

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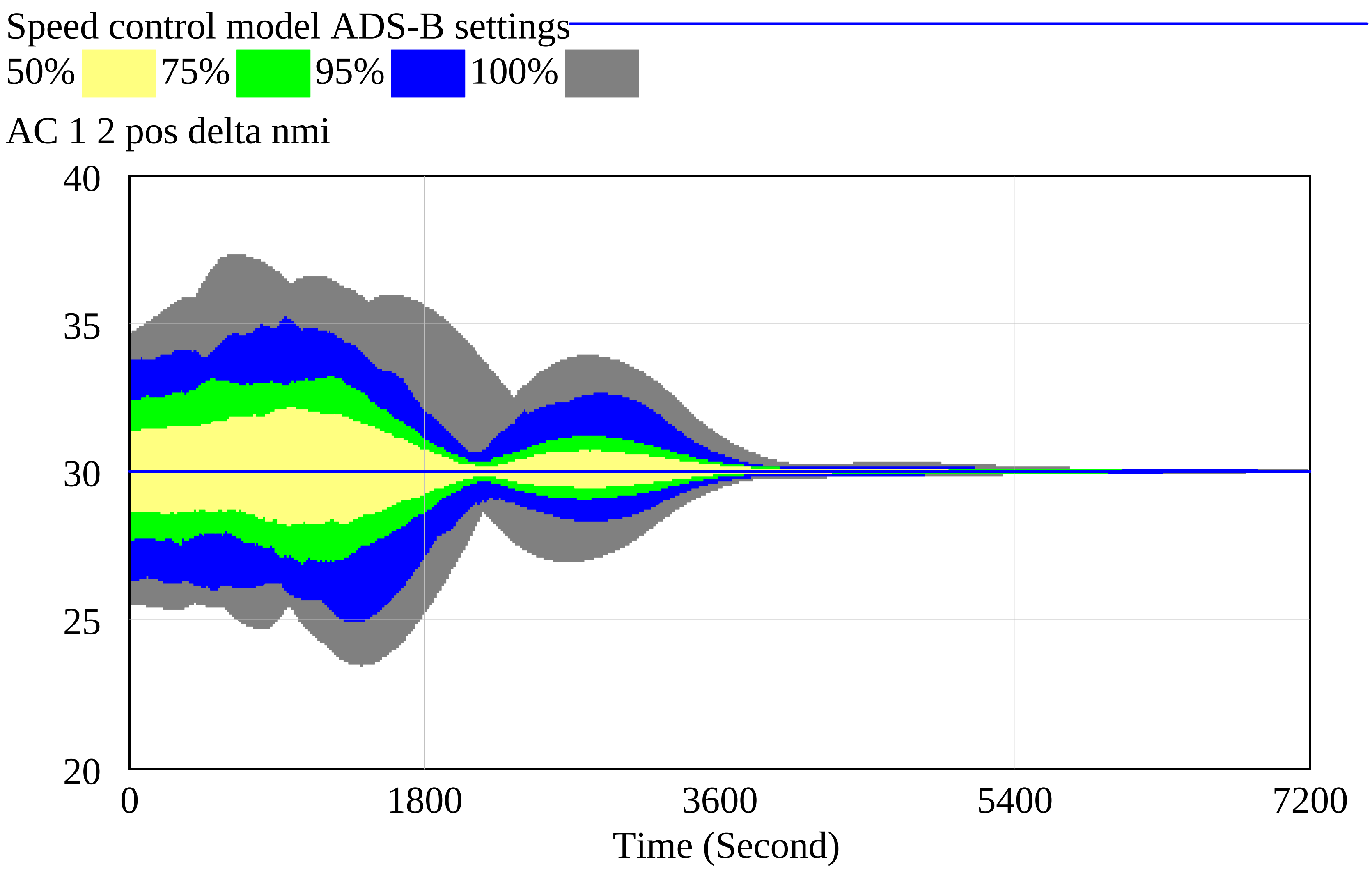
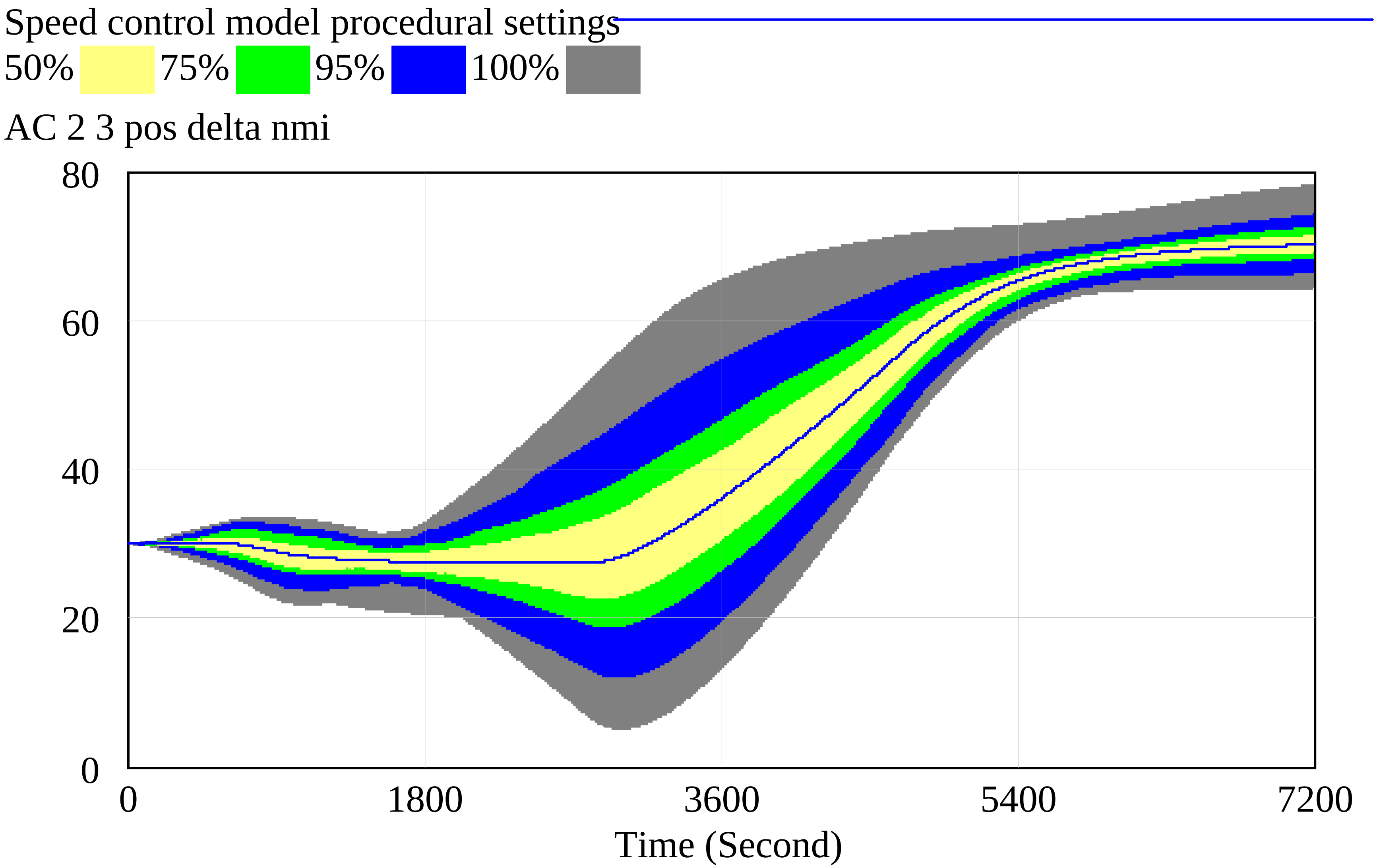


AC 2 & 3 separation (nmi) with current procedure



AC 2 & 3 separation (nmi) with ADS-B procedure

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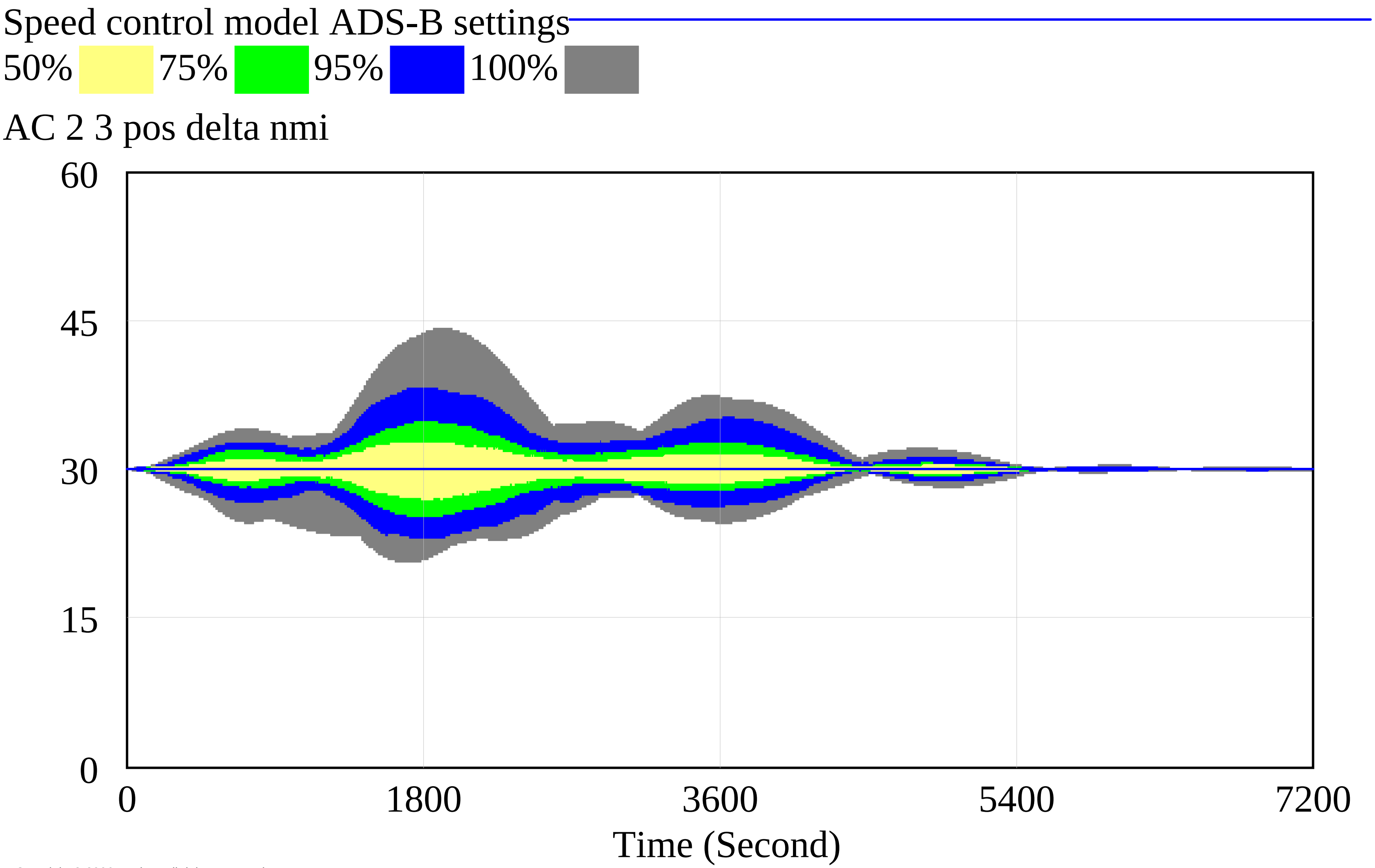
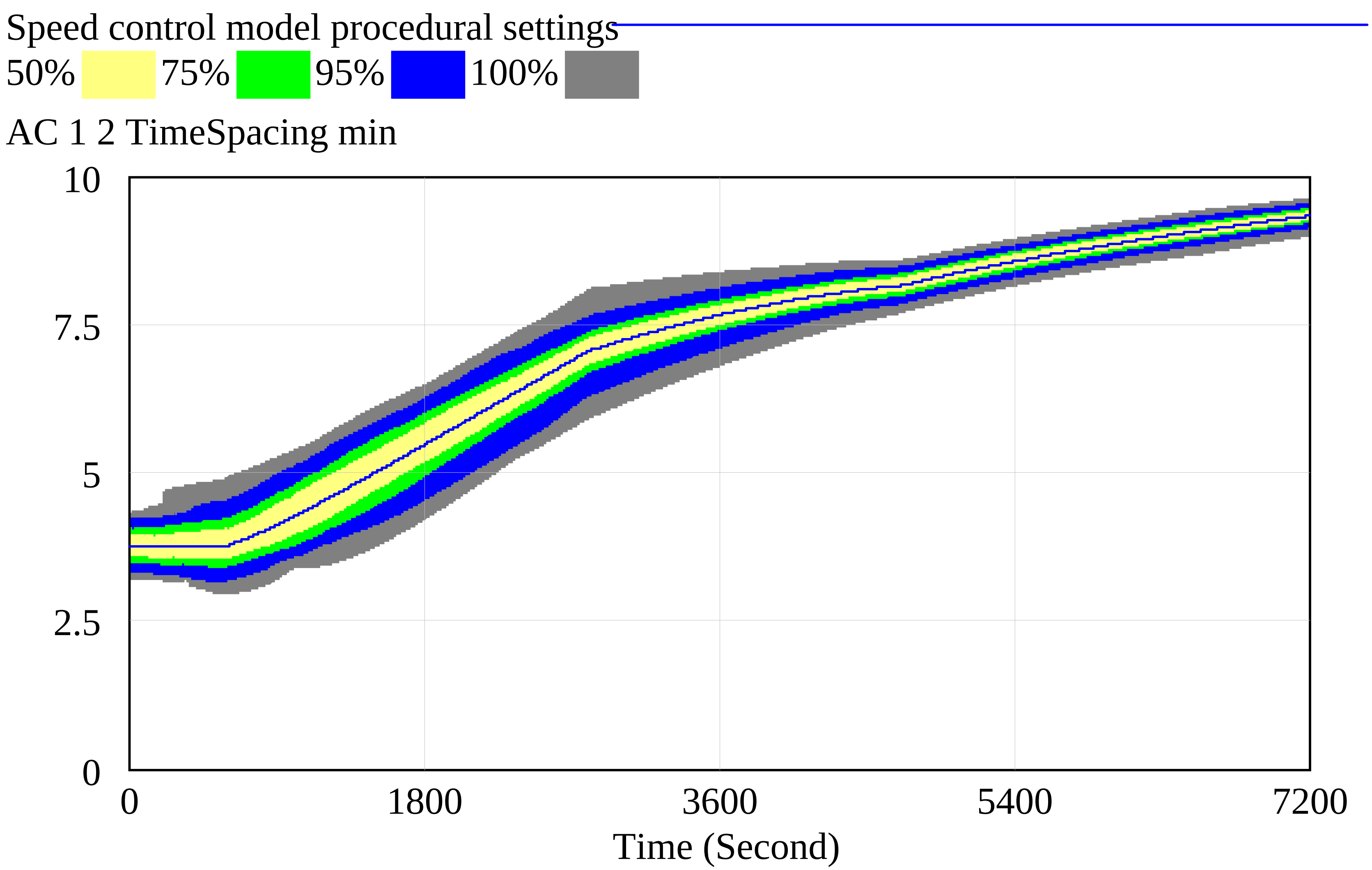


AC 1 & 2 time spacing (min) with current procedure



AC 1 & 2 time spacing (min) with ADS-B procedure

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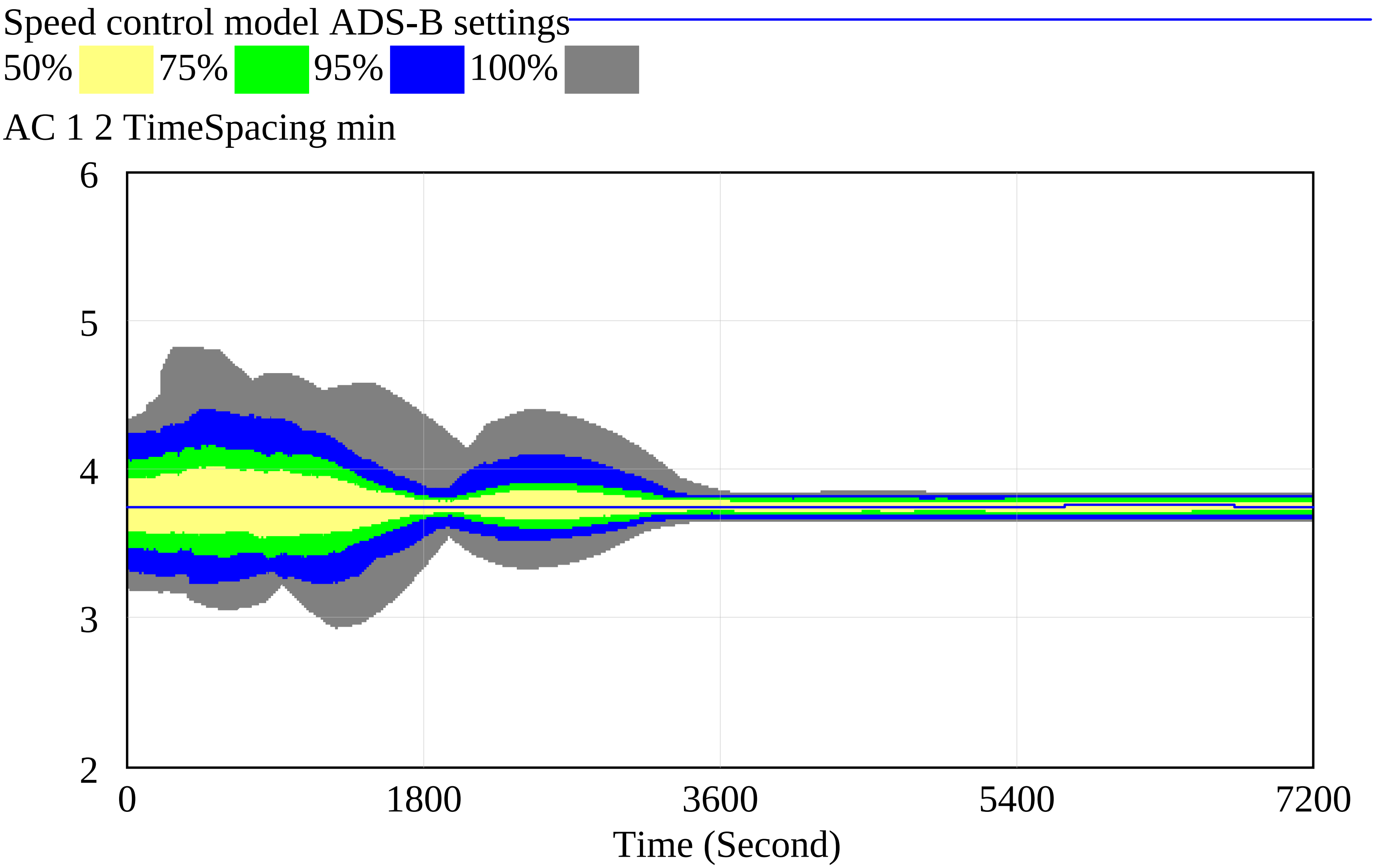

AC 2 & 3 time spacing (min) with current procedure

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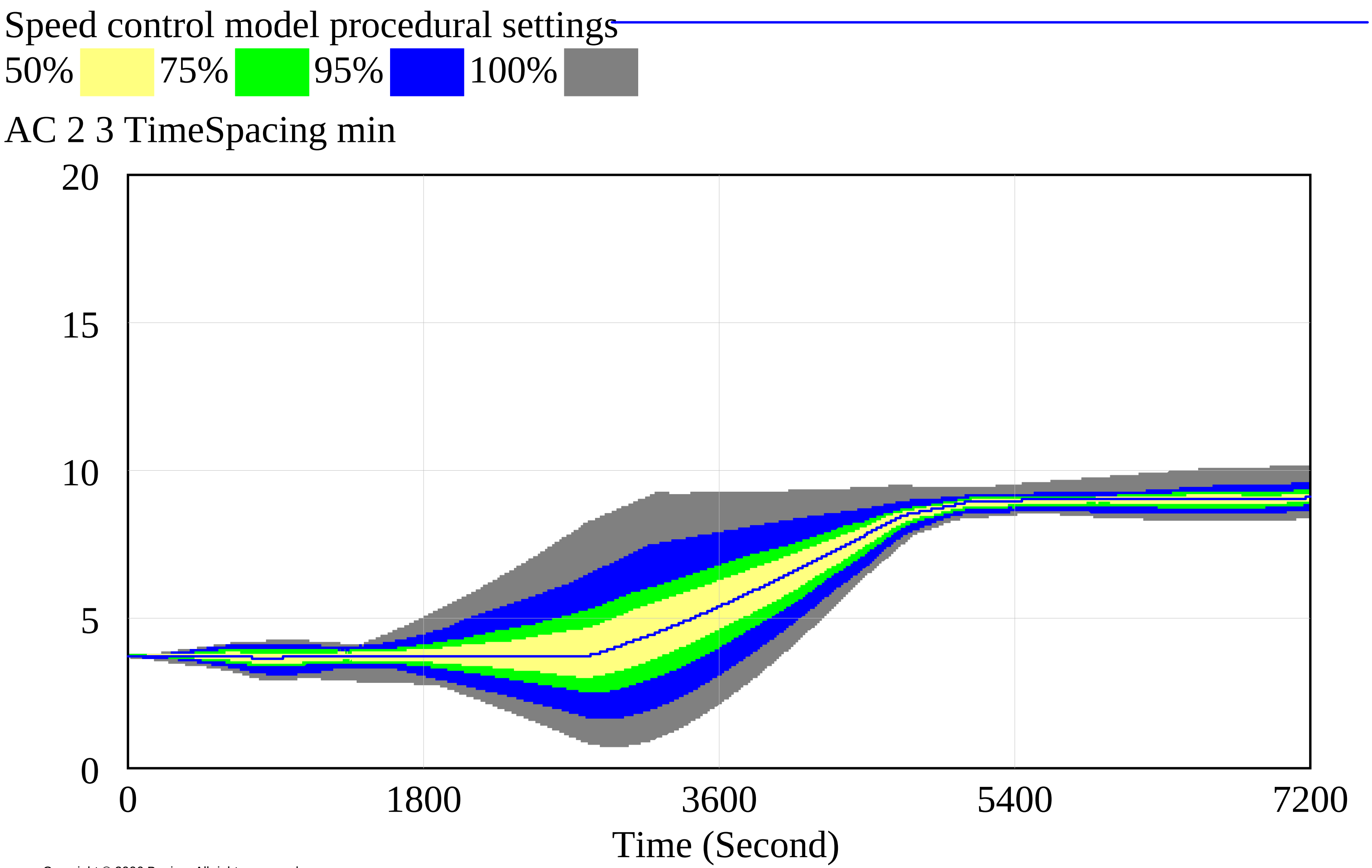

AC 2 & 3 time spacing (min) with ADS-B procedure

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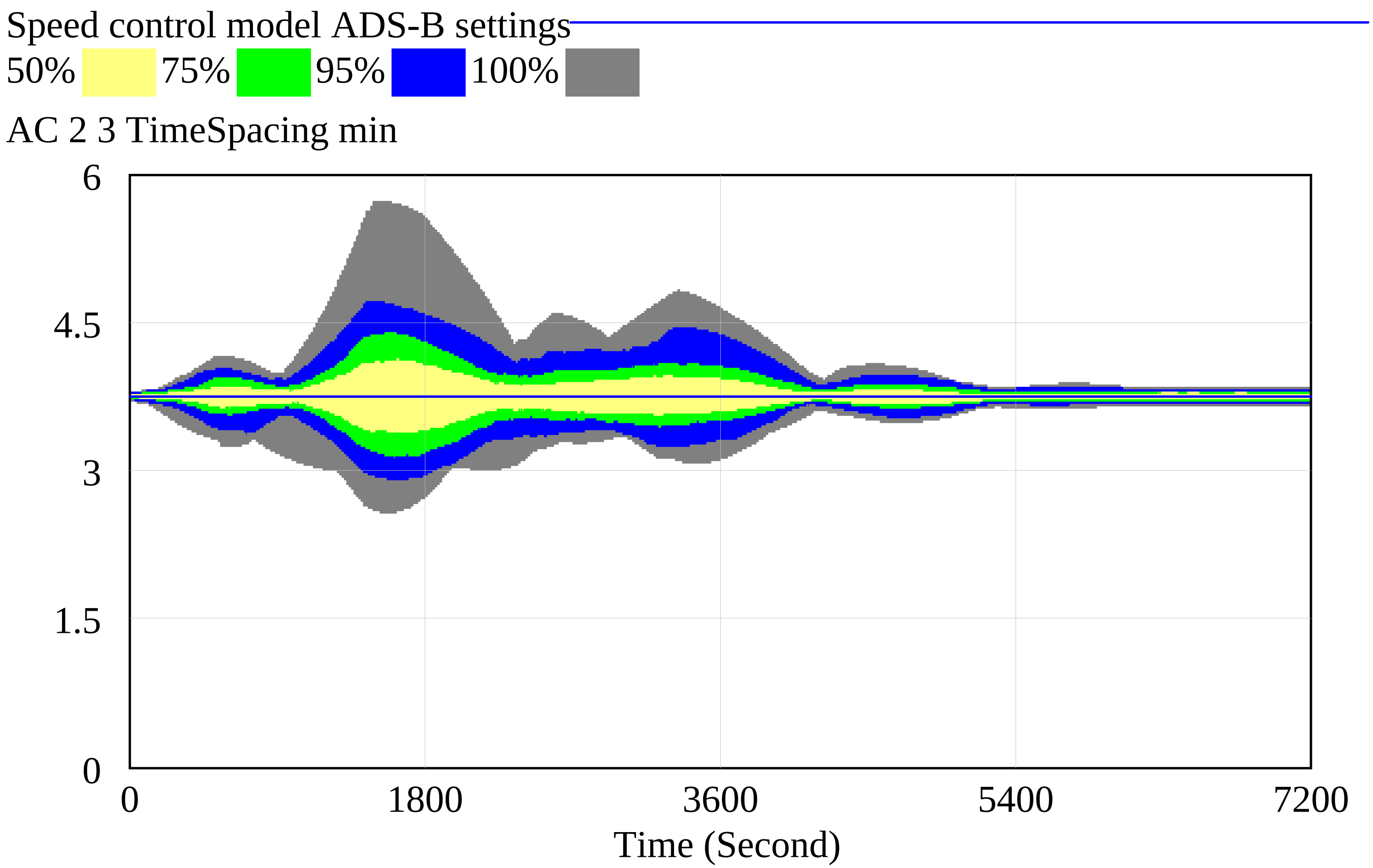
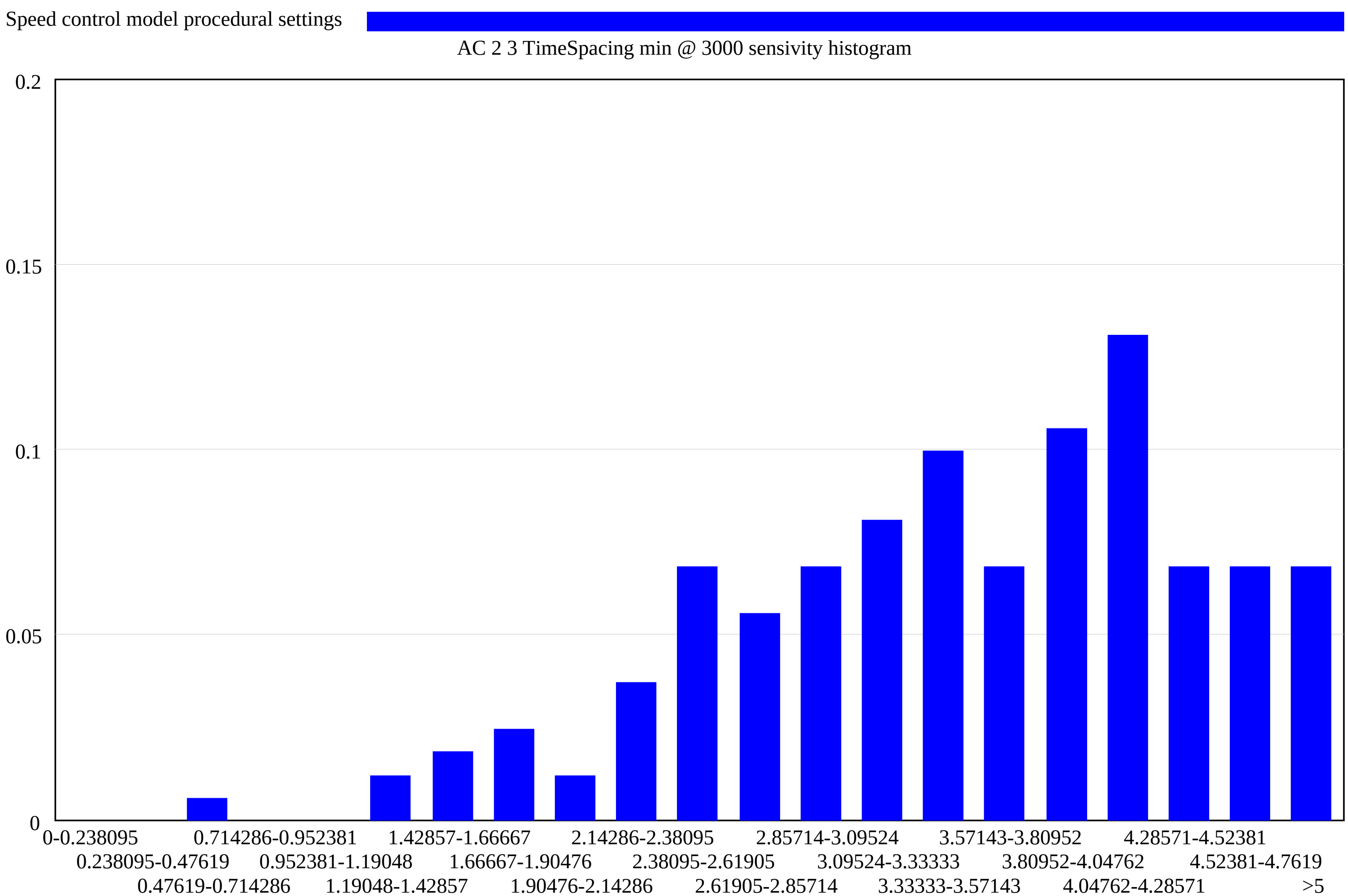


AC 2 & 3 time spacing distribution at simulation time t=3000 sec with current procedure



AC 2 & 3 time spacing distribution at simulation time t=1600 sec with ADS-B procedure

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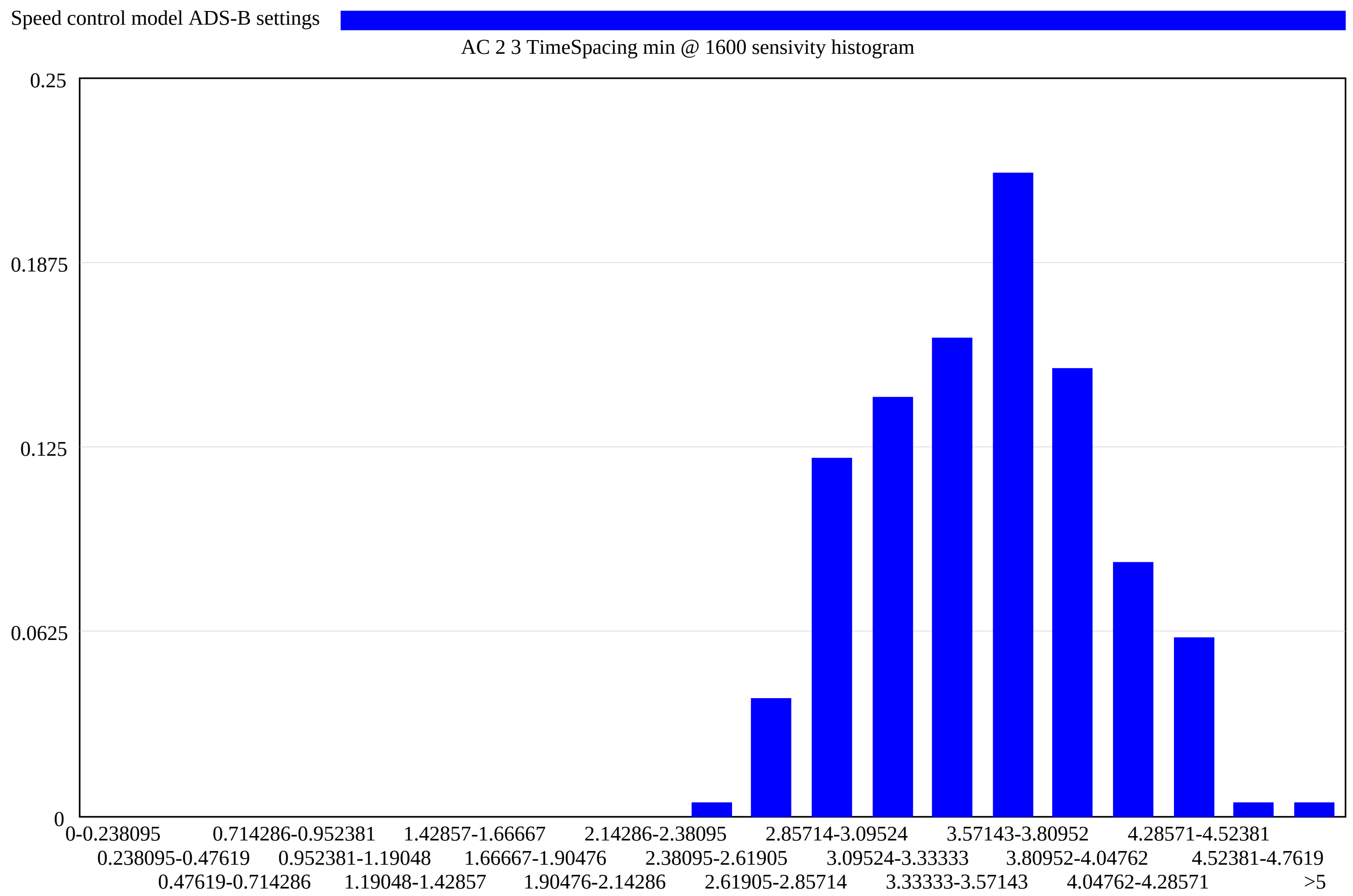

Time spacing statistics (minutes)

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	Current procedure	ADS-B procedure
Count	28801	28801
Min (min)	3.667	3.749
Max (min)	9.089	3.754
Mean (min)	6.112	3.750
Median (min)	5.392	3.750
Std Dev (min)	2.351	0.0011
Norm (min)	0.3847	0.000312309

The role of SD in modeling and simulation

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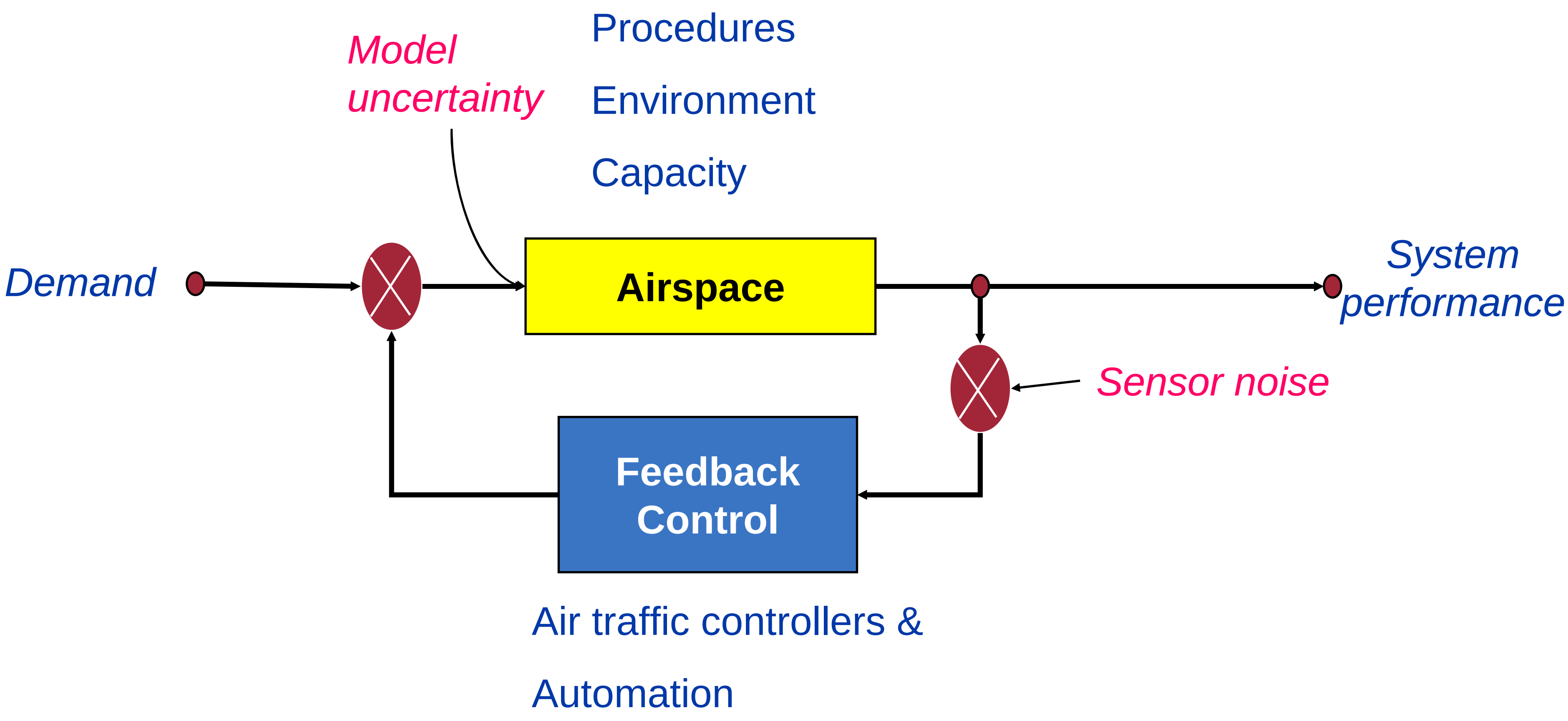
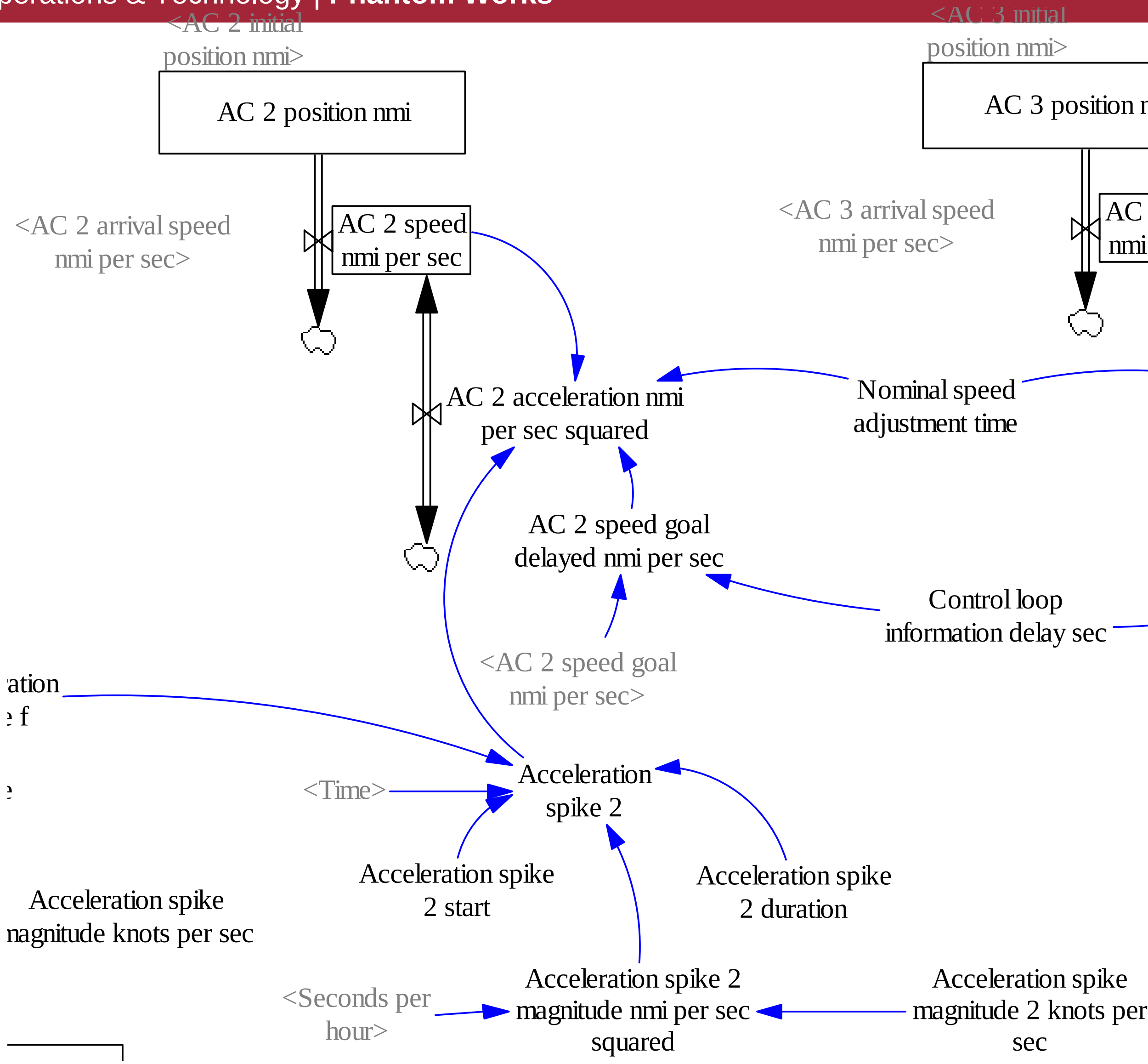
Degree of abstraction

Method	Types of Questions to Investigate	Typical Results
PowerPoint Engineering	What will sell and get $$ in the POM? What looks good with lightning bolts? How many buzzwords can we synergistically leverage in a value-added way?	Pre-determined solutions Impossible Architectures
System Dynamics Models	**Why does the system behave this way?** **Why do changes in one part of the system have an effect on another part of the system?** **What if projects have a lot of uncertainty?** **Why doesn't adding staff fix the schedule?**	**System level trends** **Identification of the relevant factors** **Insight into effects due to altering influence**
Process Models	What is the latency? What is the queue wait time? What is the mission timeline? What is the right number of resources? Where do bottlenecks form?	Timeline measures (seconds, minutes, etc) Throughput measures (bit/sec, bombs dropped/hr, etc) Resource utilization measures Queue length measures Insights into effects due to changing parameters
Physics-based Models	How far can the radar see? How much fuel can it carry? How accurate is the weapon? What is the cost per seat mile?	System performance prediction

The control system point-of-view in ATM



State variable representation (Vensim)



Speed goal calculation

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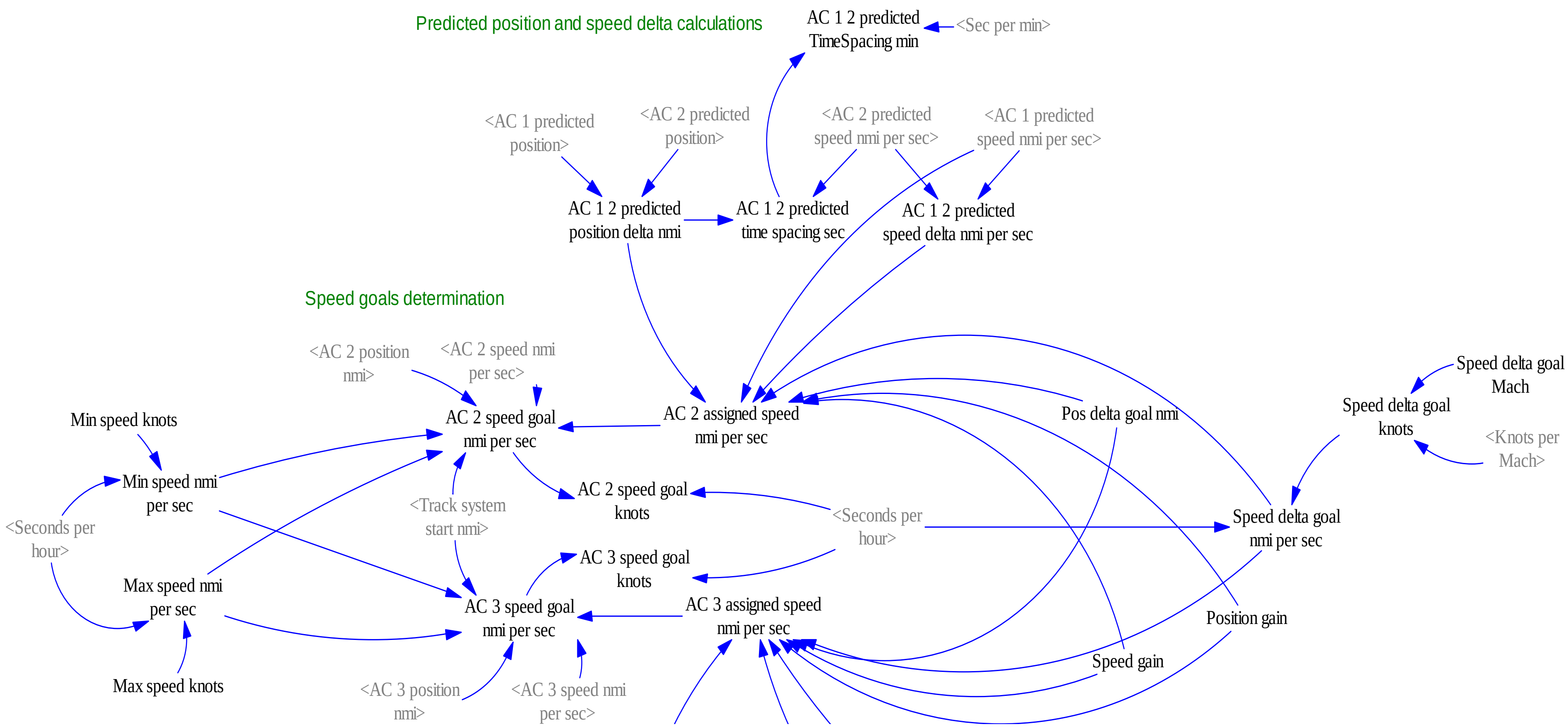

Examples of ATM-related SD Models

- ATC Resource Management Strategies and the Small Aircraft Transportation System: A System Dynamics Perspective
- The Pace or the Path? Resource Accumulation Strategies in the U.S. Airline Industry
- NAS Genomics: New Techniques and Initial Results for System-Level Understanding of NAS Behavior
- Air Traffic Controller Manpower Planning Model
- http://www.govtech.com/pcio/92101
- Making believers out of skeptics

Examples of ATM-related SD Models

- SD and ATM human factors
- SD and VLJ's
- SD and ATM economic performance
- SD safety-throughput sketch
- SD and Systems Thinking (generic)
- **NAS Strategy Simulator:** http://gltrs.grc.nasa.gov/reports/2005/CP-2005-213878/03-A1%20-%20Integrated%20CNS%20Systems%20and%20Architectures/A1-03-SherryPaper.pdf
- **NEXTOR NAS Strategy Simulator:**
- **http://nextor.org/Conferences/200601_Research_Seminar/2006_01_19_Trani.pdf**

System Thinking – A Way of Seeing

- **System thinking is a discipline for <u>seeing wholes</u>.**
- **It is a <u>framework for seeing</u>**
  - **inter-relationships rather than things**
  - **discerning high from low leverage actions (interventions)**
- **The most fundamental word in systems thinking is *feedback*.**
  - **In systems thinking, every influence is both cause and effect and the key to seeing reality systemically is to <u>see circles of influence</u> (dynamic thinking) instead of straight lines (linear thinking).**
  - **By tracing these flows of influence we can sometimes <u>see patterns</u> which repeat themselves, making situations better or worse.**

GOMEX oceanic track scenario

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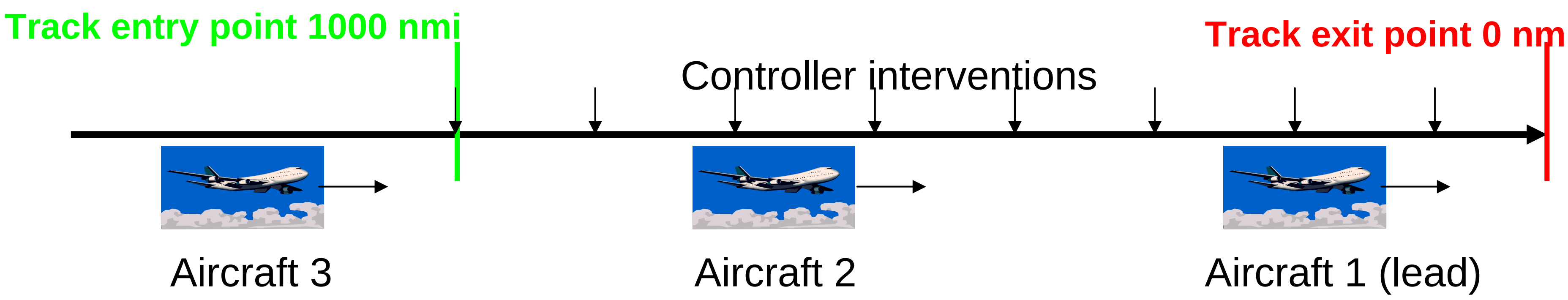

- Three-aircraft oceanic cruise scenario – procedural vs ADS-B out
- Longitudinal single track – no vertical or lateral motion
- Separation maintained by longitudinal speed control of A/C 2 and 3
- Track length 1000 nmi
- Simulation time 2 hours
- Nominal speed 480 knots
- Nominal separation 30 to 120 nmi
- Controller interventions nominally 10-15 minutes (80-120 nmi at 480 kts)

Vensim script

- **Open speed control model**
  - **Run name should be "Speed control"**
  - **Default settings are now procedural settings (although "Procedural settings.cin" can be read in at any time to reset)**
  - **Loaded dataset in Control Panel should be "Speed Control" (alone or at least first in list)**
    - **Remember only the graphs from the first dataset show up – if you want others you have to specify relevant parameters more than once according to each dataset you want to see (in the graph definition)**
- **Show different views and briefly explain model elements**
- **Go to Normal Performance page**
  - **Start simulation**
  - **Discuss response curves relative to procedural settings**
  - **Read in "ADS-B settings.cin" change file and discuss response curve differences**
  - **Show effect of changing Control Method from 0 to 1 (rule of 11 to PI controller)**
    - **No drift away from 30 nmi separation goal**
  - **Experiment with different settings for nominal speed adjustment time, reporting interval, and control loop delay. Show how reporting interval seems to have most effect, especially in the presence of slow down by lead aircraft or disturbances to ac 1 and/or 2**
- **To do a Monte Carlo run, enter "Speed control Monte Carlo" in the run mane box**
  - **Start the simulation with the Simulation Control icon (to the left of the "Set" button to the left of the Run Name box). Use Euler integration. Select "Sensitivity" button.**