Investigation of Airspace Metrics for Design and Evaluation of New ATM Concepts

Arash Yousefi
George L. Donohue, Ph.D.
Chun-Hung Chen, Ph.D.

Air Transportation Systems Lab
George Mason University

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Motivation

- 85 percent of U.S. air traffic controllers (14,000) will be eligible for retirement over the next decade *(Bureau of Labor Statistics)* and lack of replacing workforce may result to future crises.
- Available radio spectrum for controller-pilot communication is limited.
- Current airspace sectorization is not the most efficient design. *(NAR MITRE CAASD)*
- Establishment of baseline airspace metrics is inevitable for evaluating any changes resulting from new ATC systems or procedures.

Background

- Lack of intrinsic metrics for airspace capacity and complexity:
  - Number of aircraft passing through a sector does not capture the real airspace complexity, *(Sridhar et al. 1998)*.
  - Complexity of the mental workload is related to the number of aircraft in a sector but there are many other factors contribute in the control process.
- ATC workload depends of many qualitative and quantitative parameters.
  - It is extremely difficult to develop mathematical models of ATC workload.
- Different approaches have been established to model the ATC workload and measure the airspace complexity.

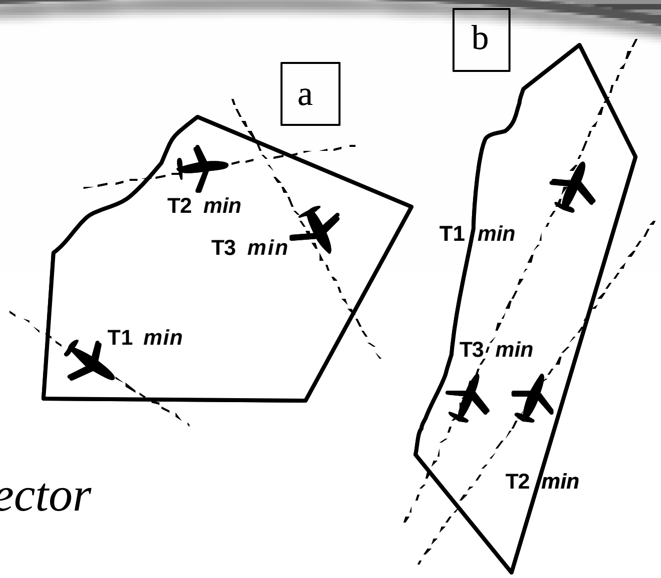
Recent Related Work

- Perceived complexity of an air traffic situation, (Wyndemere Inc., 96).
  - Related to the cognitive ATC workload with or without the knowledge of aircraft intent.
  - Human oriented and very subjective.
- Dynamic Density (Laudeman et al, NASA ARC, 1998)
  - More quantitative and based on the flow characteristics.
  - B.Sridhar et al., 1998, developed a model to predict the evolution of this metric in the near future.
- Delahaye et al., 2000:
  1. Geometric approach: Based on the properties of aircraft relevant position and speed.
  2. Airspace system as a dynamic system: model the history of air traffic as the evolution of a hidden dynamic system over time.
- Impact of structure on cognitive complexity, (Histon et al., 2002).
- Much more ...

Airspace Complexity

- Aircraft in each sector based on the sector complexity produce different workload levels for controllers.
- Critical factors contribute to sector complexity(assuming good weather conditions):
  - **Coordination factors:** required coordination actions for conflict resolution, level of aircraft intend knowledge, …
  - **Geometrical and geographical factors:** sectors geometry & volume, airports, proximity of SUAs, # of neighboring sectors, # of hand in/off points, …
  - **Traffic factors:** # of altitude changes, # of crossing altitude profiles, # of intersecting routes, sector transit time, fleet mix, …
  - **Encounter factors:** conflict convergence angle, conflicting aircraft relative speed, separation requirements, flight phases, …
- A fundamental question: ***"Is there any metric that reflects all critical factors contribute to the sector complexity"***

Airspace Density & Transit Time



- Total Transit time $= \sum_{i=1}^{n} T_i \Big/ Sector$ [minute/sector]

Where:
T_i = *Transit time for aircraft i in the sector.*
n = Total number of aircraft passing through the sector during any given time interval.

$$\begin{cases} den_a = den_b = 3 \\ Trans_a \neq Trans_b \end{cases}$$

- *Density = Number of aircraft passing through a sector during any given time interval [aircraft/sector]*

a: More conflicts due to route intersection

b: More control time due to longer routes

Neither of these metrics, alone, adequately estimates the level of controller activity.

ATC Workload Simulation

- Similar to simulations of other systems containing human and machine interaction, simulating controller workload is a very challenging task. One approach could be:
  - Total workload consists of 4 parameters:
    1. Horizontal Movement Workload (WL_{HM})
    2. Conflict Detection and Resolution Workload (WL_{CDR})
    3. Coordination Workload (WL_{C})
    4. Altitude-Change Workload (WL_{AC})
  - In each sector or group of sectors, the summation of these four parameters gives the total workload.

$$\text{Total WL} = \sum (\text{WL}_{\text{HM}} + \text{WL}_{\text{CDR}} + \text{WL}_{\text{C}} + \text{WL}_{\text{AC}})$$

ATC Workload Simulation *(cont.)*

- **Movement or basic workload (*WL_{HM}*)** is determined by the number of aircraft in a sector (sector density) and average transit time.

$$WL_{HM} = F_{HM} \times (N_{HM} \times T) \quad \text{where:}$$
$$F_{HM} = \text{Adjustment factor for horizontal movement}$$
$$N_{HM} = \text{Number of aircraft passing through the sector}$$
$$T = \text{Average Flight Time}$$

- **The altitude-change workload *(WL_{AC})*** is determined by the type of sector altitude clearance request for level off, commence climb and commence descent.

$$WL_{AC} = F_{AC} \times N_{AC} \quad \text{where:}$$
$$F_{AC} = \text{Altitude clearance factor}$$
$$N_{AC} = \text{Number of aircraft with this clearance}$$

ATC Workload Simulation *(cont.)*

- **The conflict detection & resolution workload (*WL_{CDR}*)** is based on conflict detection using the conflict type and conflict severity.
  - The ***conflict type*** is determined by the tracks of the aircraft (succeeding, crossing or opposite) and the flight phases (climbing, cruising, or descending). For each type there is an adjustment factor F_{CDR}.
  - The ***conflict severity*** is the percentage of available separation. For example if 100-120% or 80-100% of minimum separation is available. For each conflict severity, there is an associated adjustment factor defined as T_{CS}.

$$WL_{CDR} = F_{CDR} \times (T_{CT} \times N_{CDR}) \quad \text{where:}$$

F_{CDR} = Adjustment factor based on conflict type

T_{CS} = Conflict severity factor

N_{CDR} = Number of aircraft with this conflict type and severity

ATC Workload Simulation *(cont.)*

- **The coordination workload (*WL_C*)** is determined by the type of coordination action including:
  - Voice Call
  - Clearance issue
  - Inter facility transfer
  - Silent transfer
  - Intra facility transfer
  - Tower transfer
- For each of them there is a factor that reflects the complexity of that action

$$WL_C = F_C \times N_{CA} \qquad \text{where :}$$

$$F_C = \text{Cordinatio n action factor}$$

$$N_C = \text{Number of aircraft with this coordination action}$$

Simulation

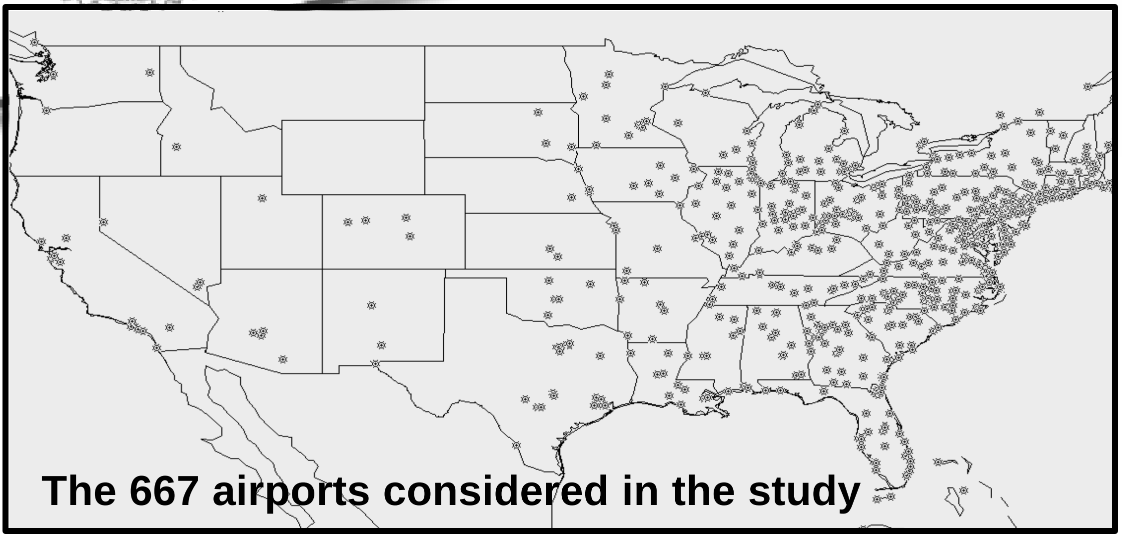
- Use of TAAM:
  - Airspace: 5 ARTCCs in NE of US (ZDC, ZID, ZNY, ZBW and ZAU) ~ 162 sectors.
  - Airports: 667 airports sending/receiving flights from the 5 mentioned ARTCCs.
  - Schedule: Time table for full daily GA and commercial flights (VFR & IFR).
- TAAM outputs are used to quantify the ATC workload.

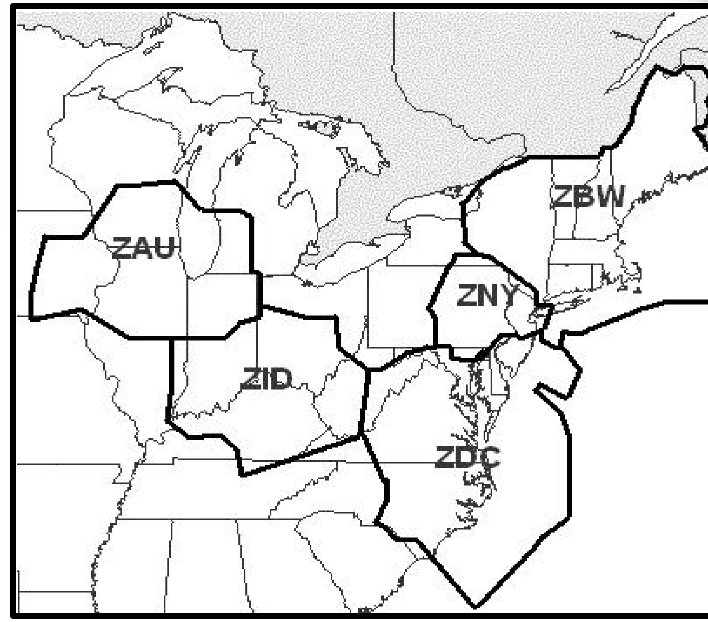
Controller's Complexity rating

Virtual Air Traffic (VATUSA) www.vatusa.org

ARTCC	Airspace Complexity [scale 5-13, 5 easiest, 13 hardest]
Albuquerque	8
Anchorage	9
Atlanta	9
Boston	10
Chicago	10
Cleveland	7
Denver	8
Fort Worth	9
Honolulu	5
Houston	9
Indianapolis	6
Jacksonville	8
Kansas City	8
Los Angeles	12
Memphis	7
Miami	7
Minneapolis	6
New York	12
Oakland	11
Salt Lake City	9
Seattle	9
Washington	10

Simulation *(cont.)*


The 667 airports considered in the study

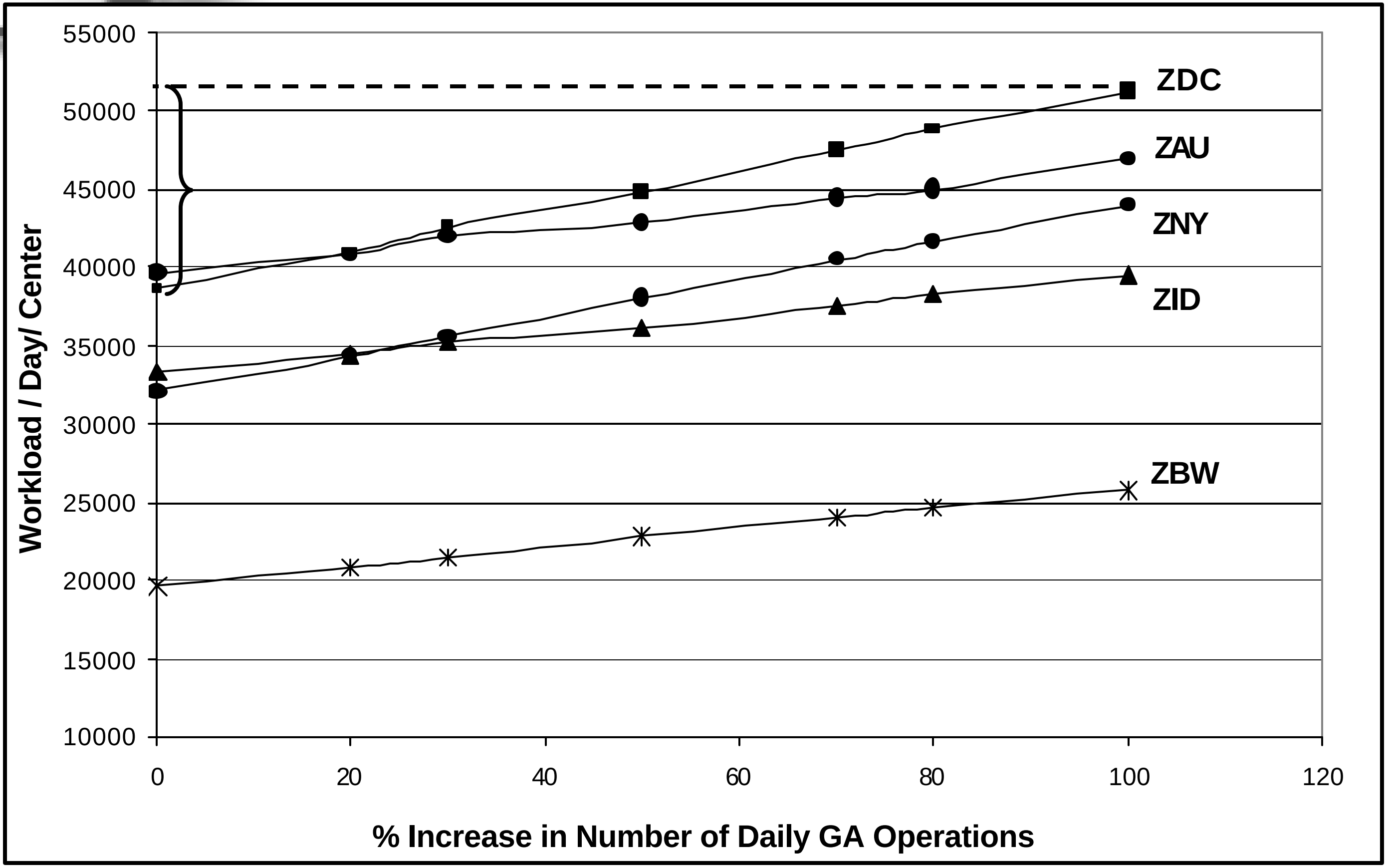


Market segment	Number of daily flights
- Non-GA including Commercial, GA and Cargo (IFR) extracted from the Flight Explorer	22764
- General Aviation traffic (IFR and VFR) generated using economic activities between OD	7051
Total	29815

ARTCC	Number of Sectors
ZDC	43
ZNY	25
ZID	34
ZBW	19
ZAU	41

Total daily flights used in the simulation

Impact of GA Operations Growth



- Relevant to research on projected growth of GA activities on ATC workload.
- Workload increase rate varies for each center.
  - i.e in ZDC ~ 25% increase in daily workload if GA operation doubles

Airspace Complexity Quantification

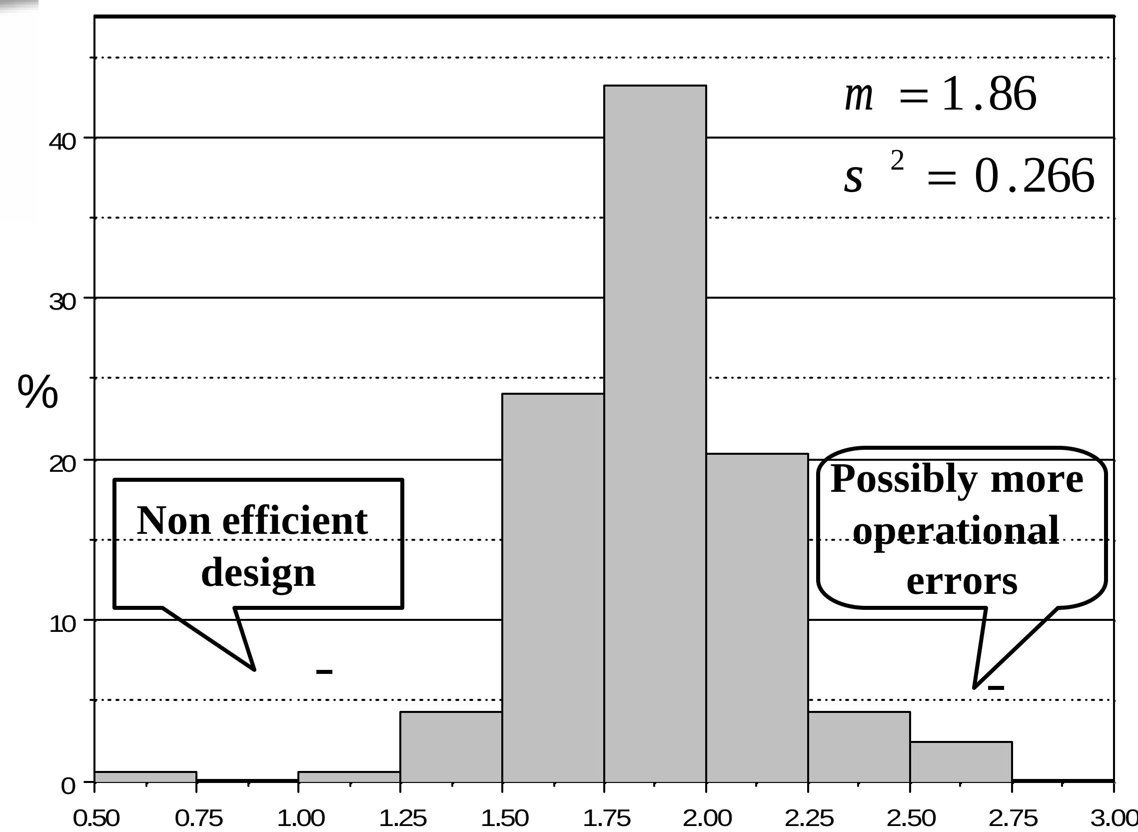
- Aircraft in each sector, based on the sector complexity, create different workload levels.
- For each sector, *Complexity Index (CI)* is defined as the average workload per each aircraft.
  - For a given time epoch:

$$\mathrm{CI} = \frac{\text{Total Workload}}{\text{Total Number of Aircraft}} = \frac{\sum (WL_{HM} + WL_{CDR} + WL_{C} + WL_{AC})}{\text{Total Number of Aircraft}}$$

- CI reflects critical factors contribute to the sector complexity.

CI Distribution for 5 NE Centers

- Large variation for CI among all sectors
- Non-efficiency in sectors with low complexity
- More operational errors may occur in high complex sectors

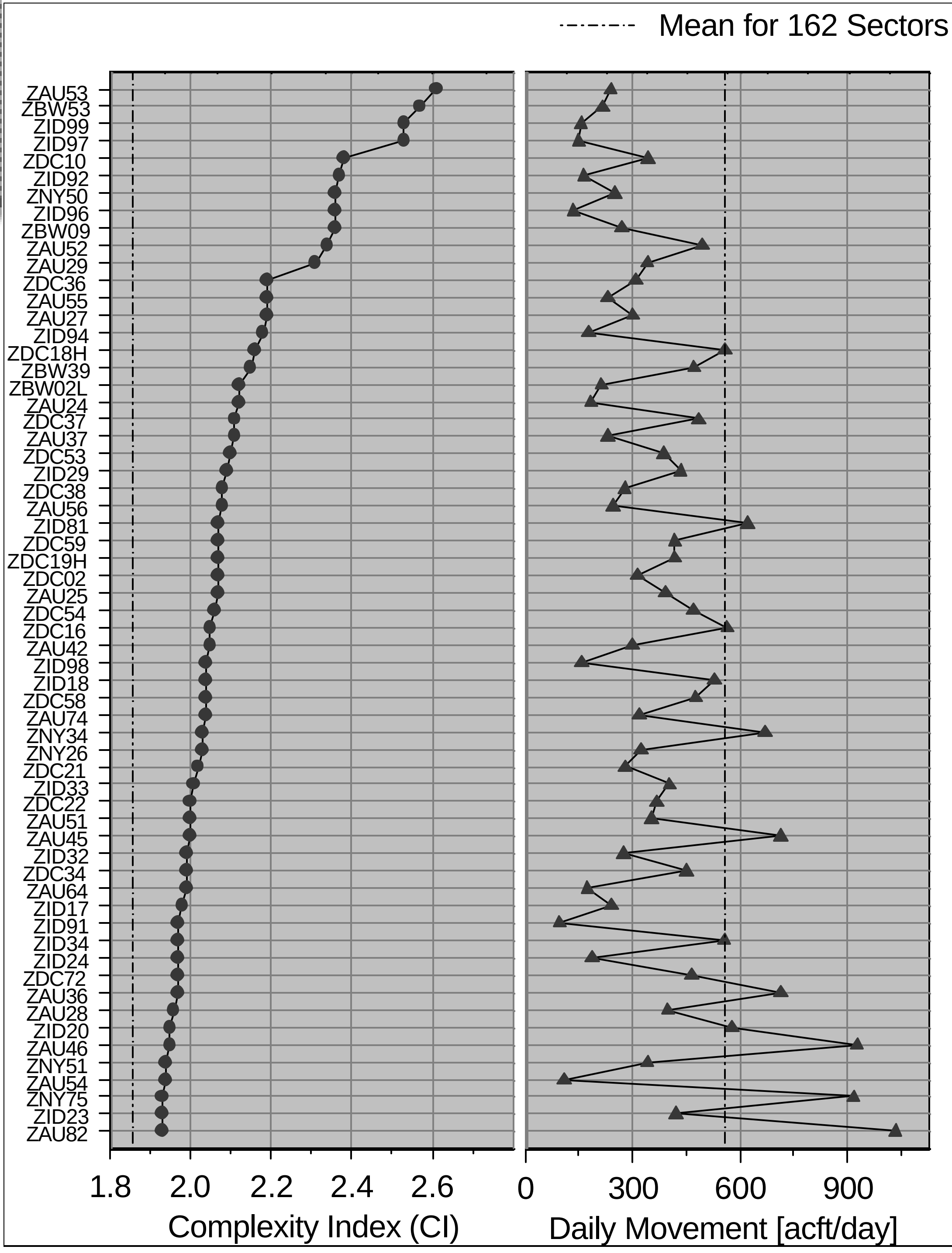


Complexity Index (CI) for 162 simulated sectors

***Hypothesis: An efficient airspace sectorization should uniformly distribute the complexity among all sectors*.**

CI Distribution *(cont.)*

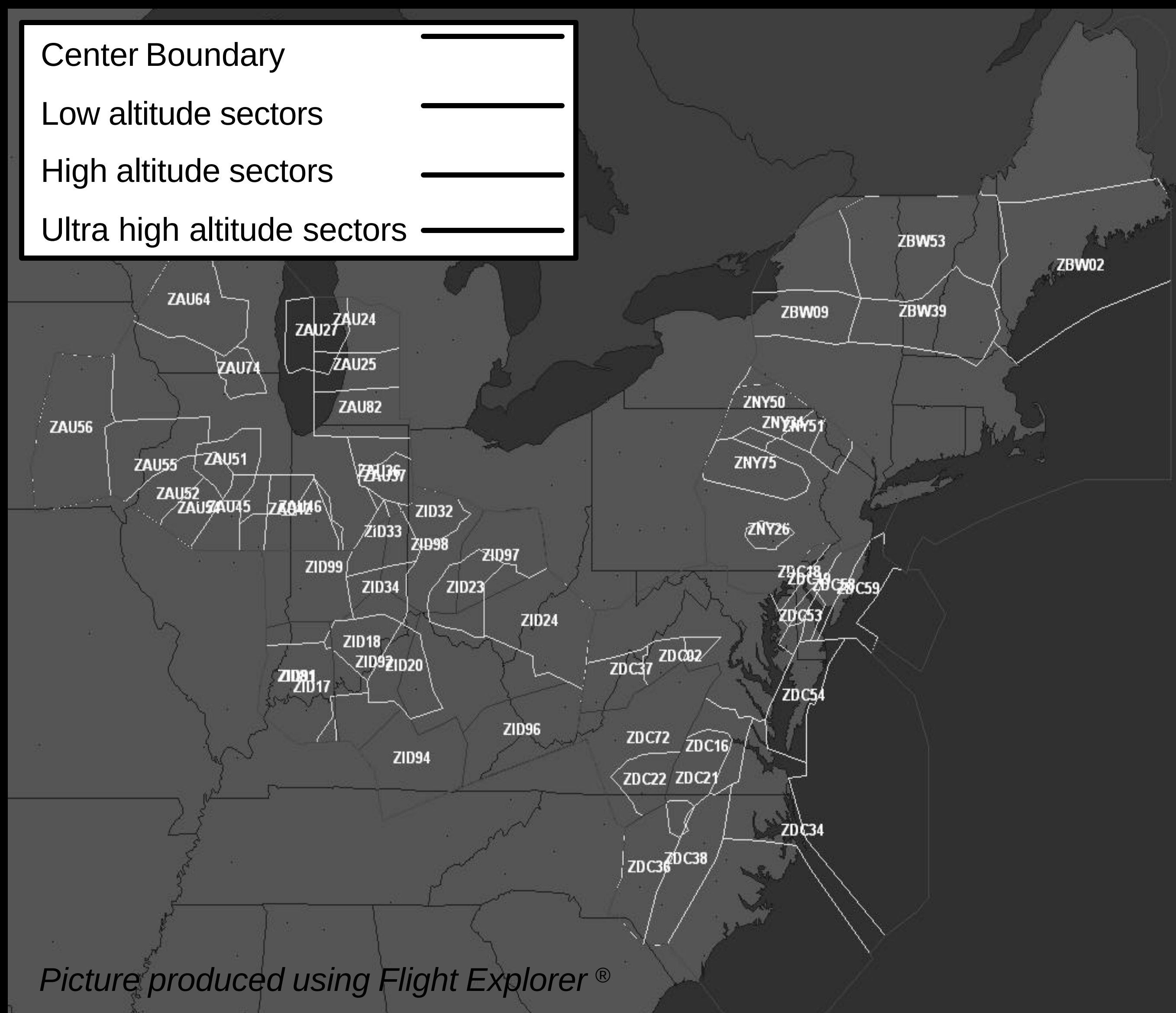
- 50 (out of 162) most complex sectors in NE corridor
  - Although not rigorous, overall, less complex sectors have higher traffic volume.
  - Intuitively it can be interpreted as a good design (less complex sectors are capable to accommodate more aircraft without exceeding the controller workload thresholds).



50 Most Complex Sectors

- Most of the complex sectors are located next to the center boundaries

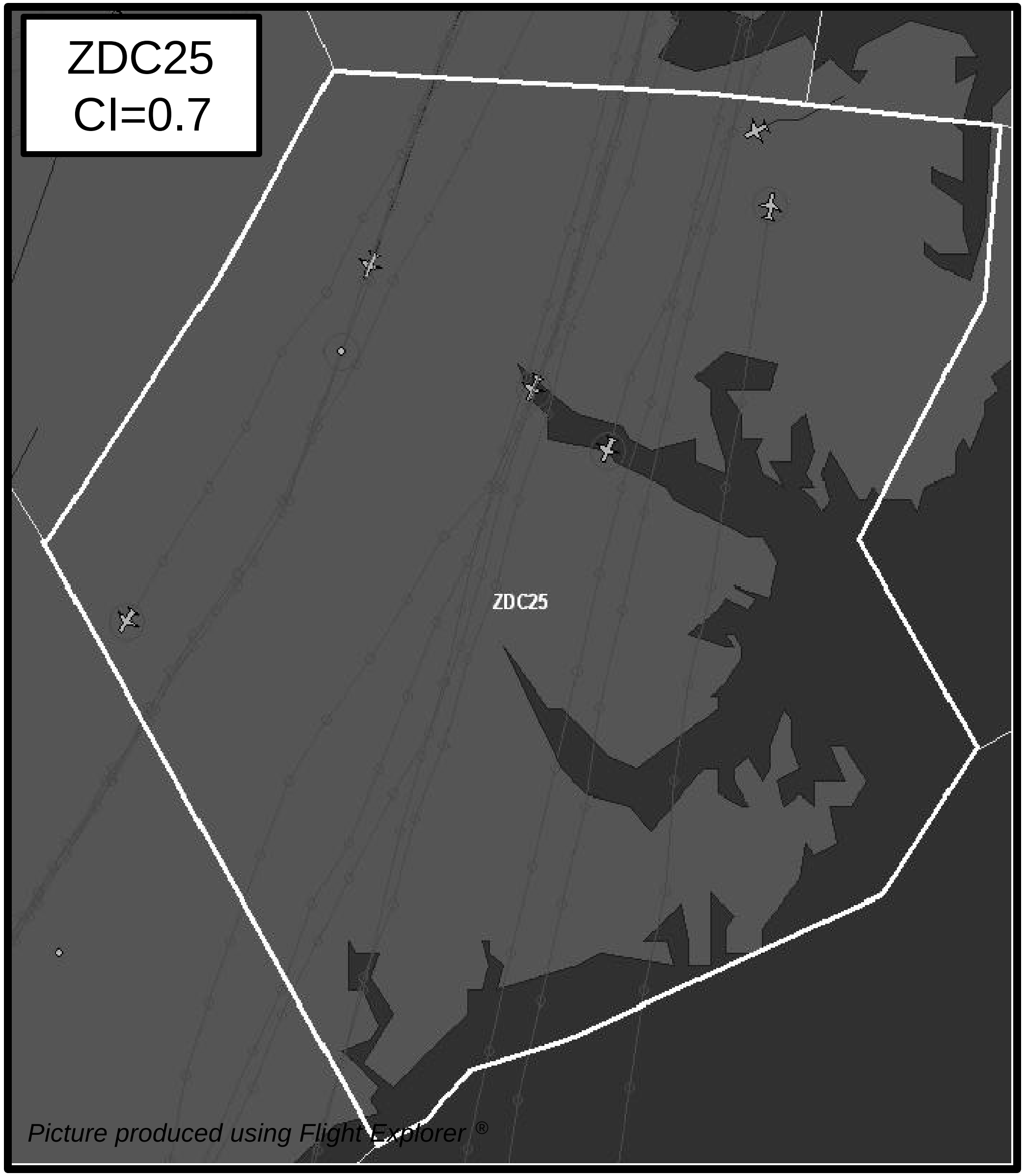
- Includes all altitude ranges



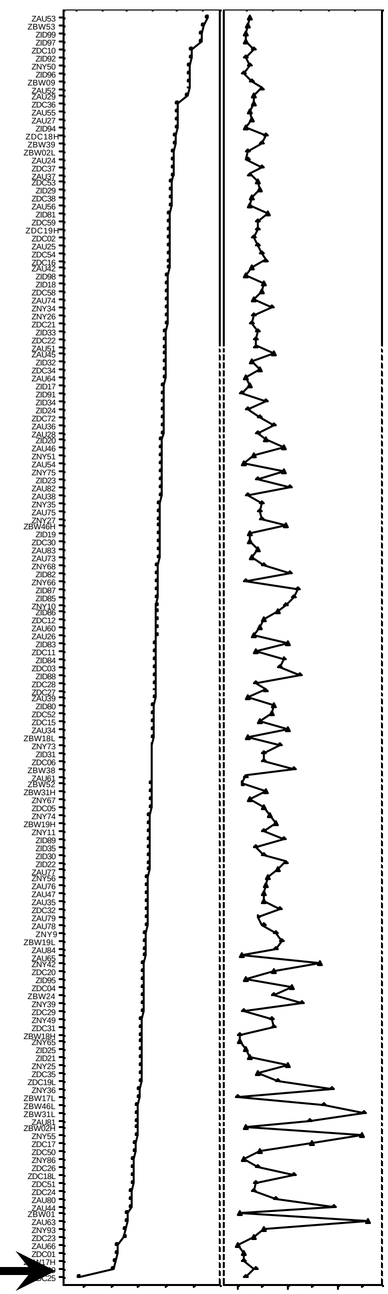
Picture produced using Flight Explorer ®

Daily movement

CI: mean=1.86, max=2.61, min=0.7



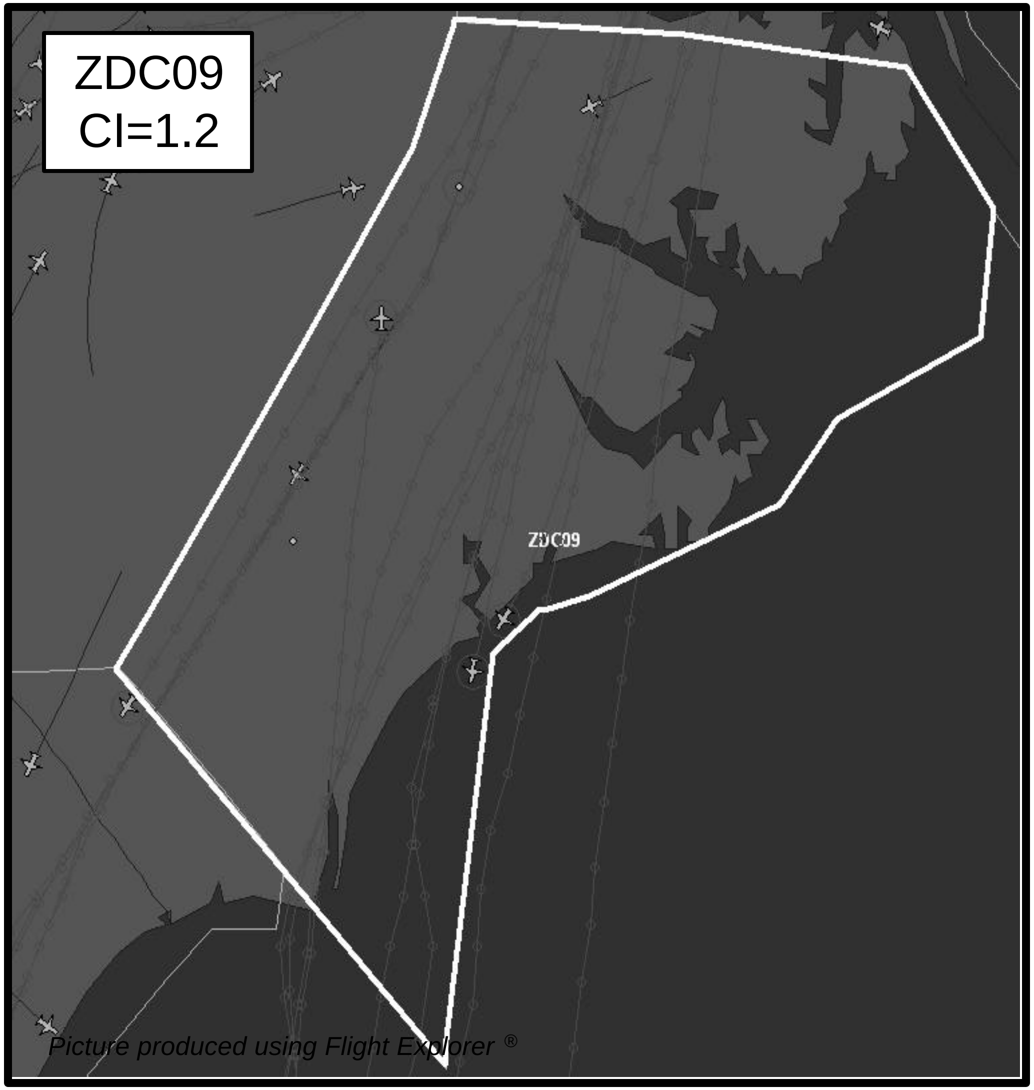
- Low altitude
- Structured traffic
- Low density
- Next to non-controlled airspace
- No airport
- No SUA



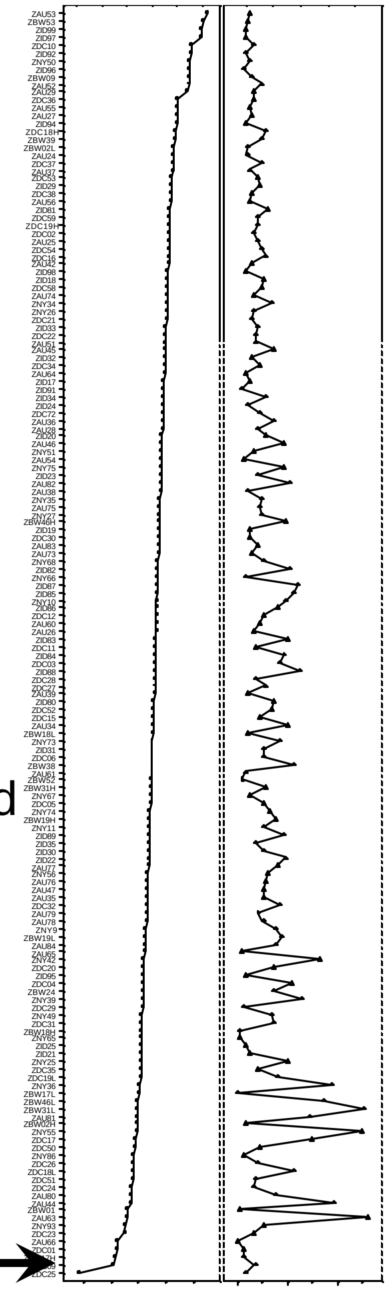
Complexity order: 162/162

Daily movement

CI: mean=1.86, max=2.61, min=0.7



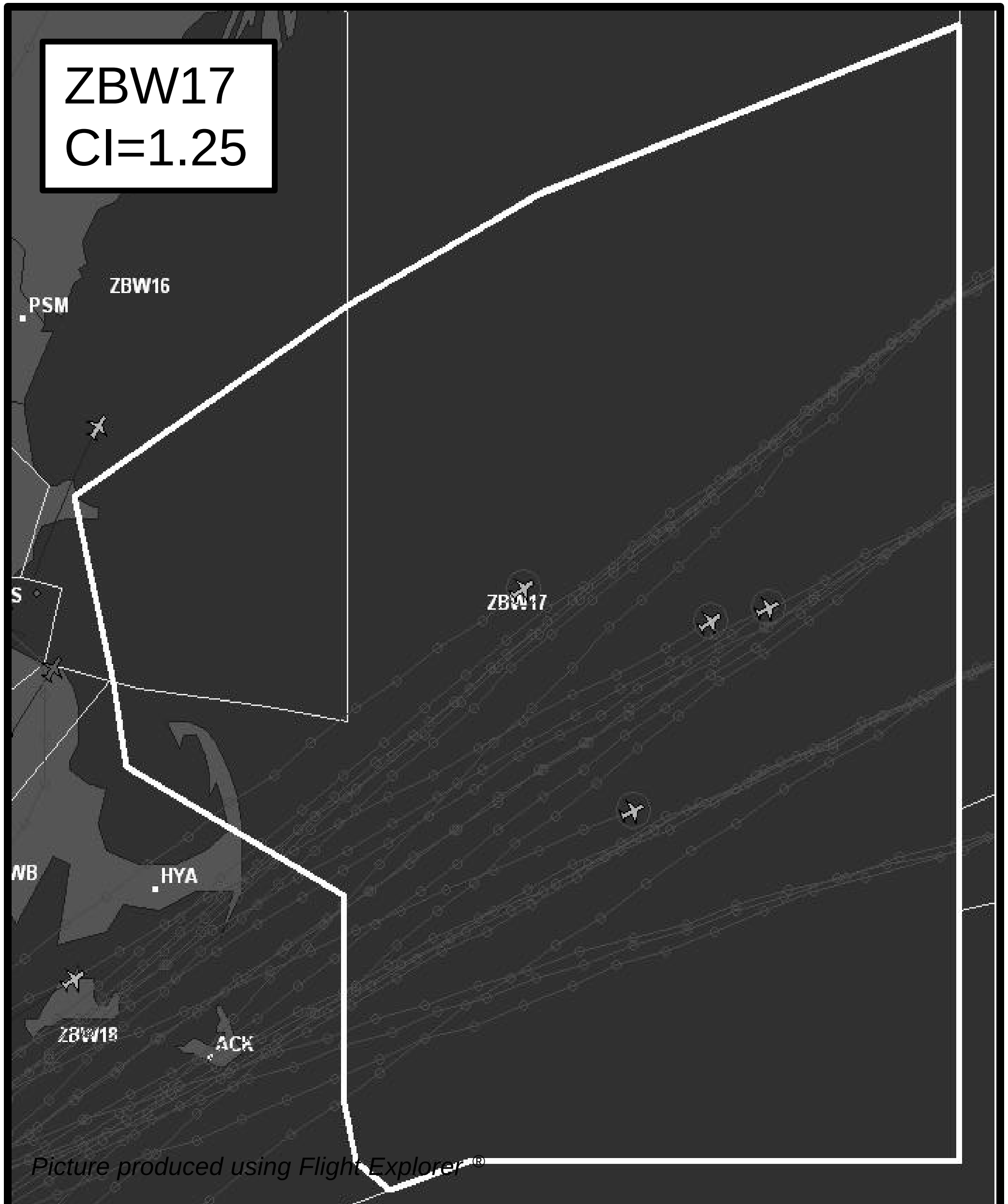
- Ultra high
- Structured traffic
- Low density
- Next to non-controlled airspace
- No SUA
- Inter-sector handoff points are concentrated



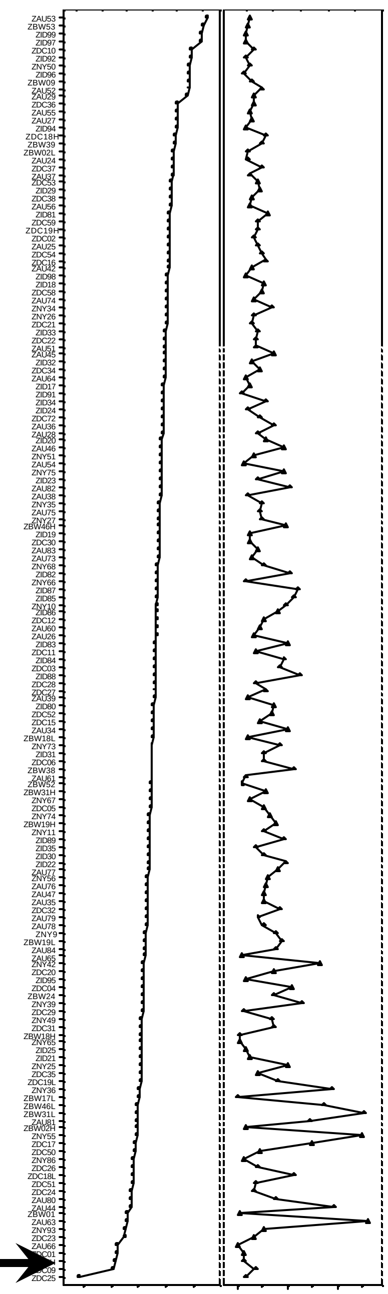
Complexity order: 161/162

Daily movement

CI: mean=1.86, max=2.61, min=0.7

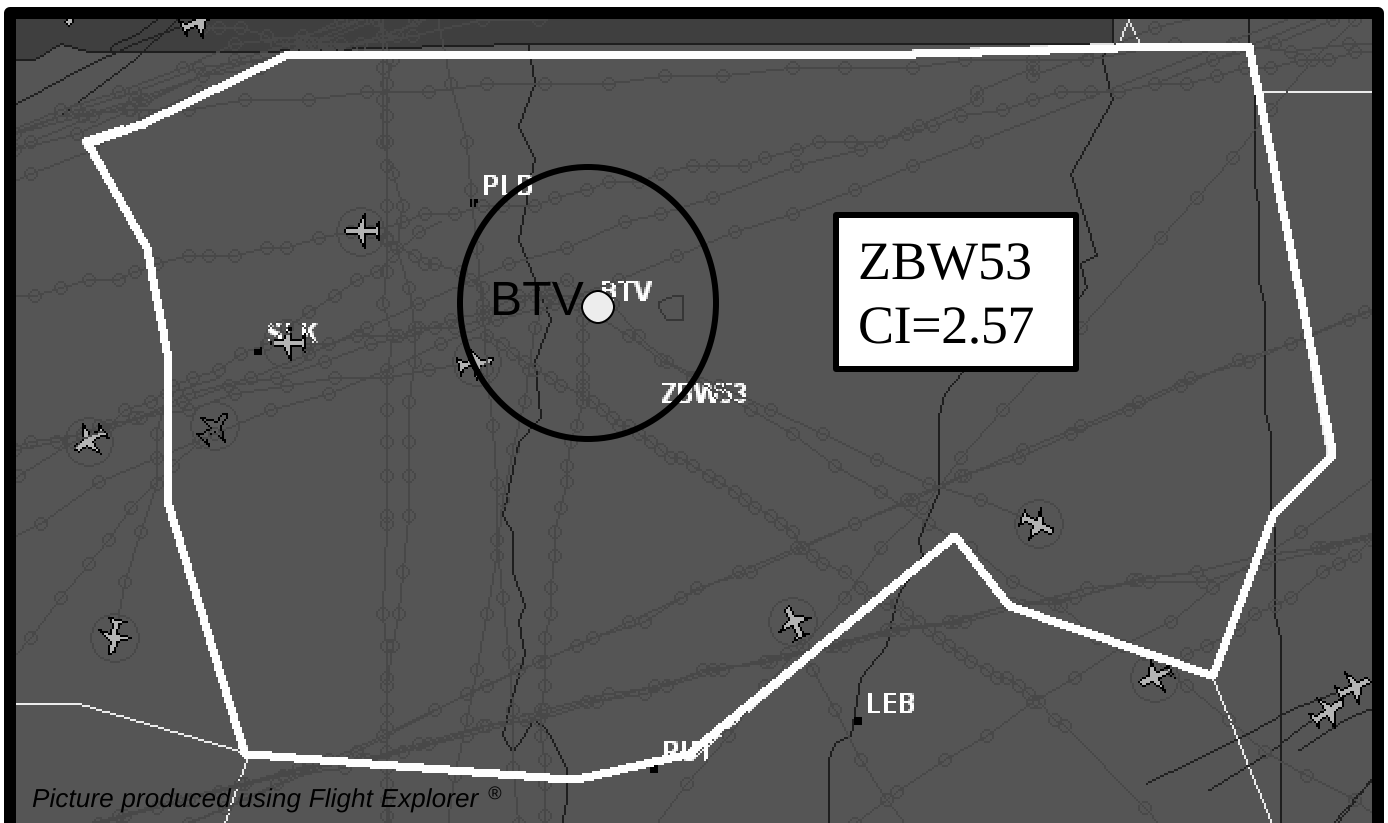


- ➢High altitude
- ➢Highly structured
- ➢Inter-sector handoff points are concentrated



Complexity order: 160/162

- Low altitude
- Non-structured traffic
- Many track intersections
- Many inter-sector handoff points
- Burlington INTL Airport
- Many level changes for flights operating out of BTV
- Short sector transit times at the edges



Daily movement

CI: mean=1.86, max=2.61, min=0.7

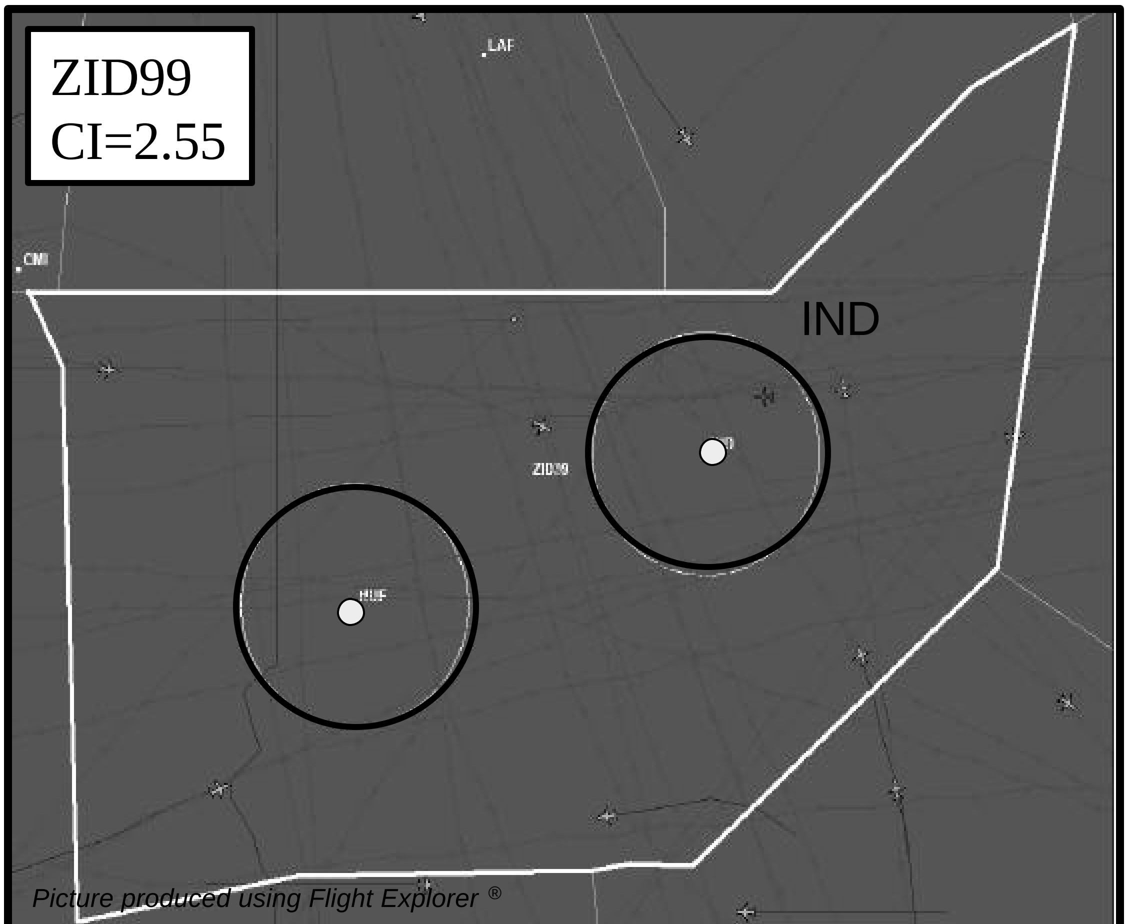
Complexity order: 2/162

- High altitude
- Non-structured traffic
- Many track intersections
- Many inter-sector handoff points
- Indianapolis INTL & Terre Haute INTL Airports
- Many level change for flights operating out of IND

Daily movement

CI: mean=1.86, max=2.61, min=0.7

Complexity order: 3/162



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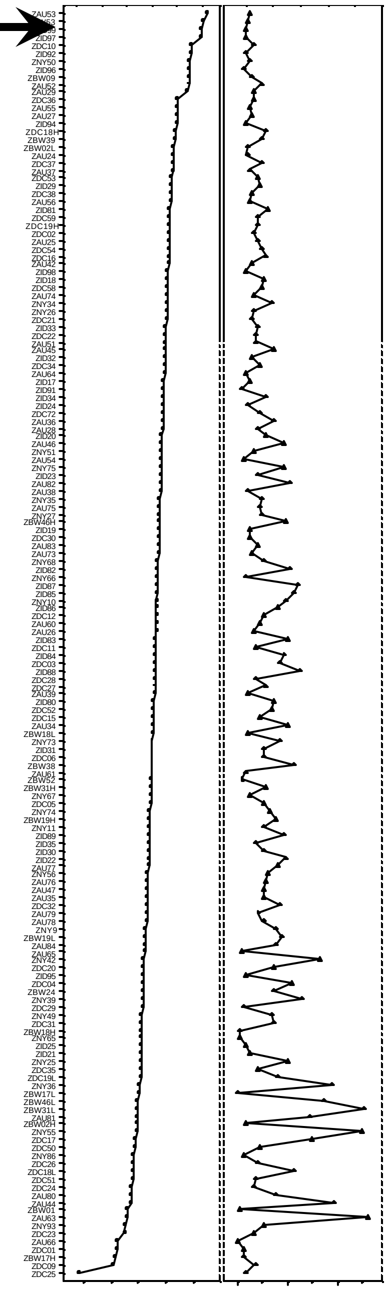
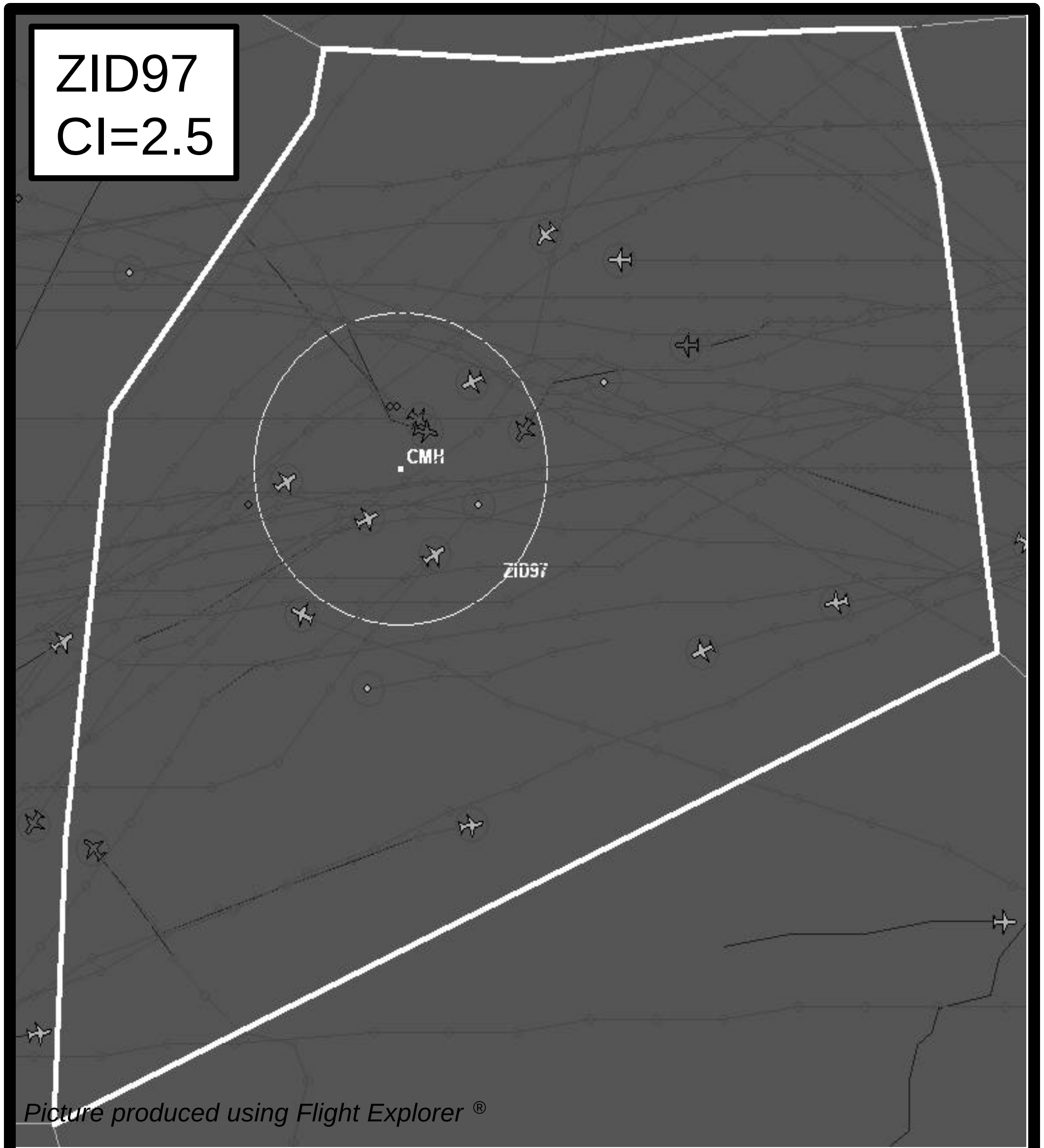


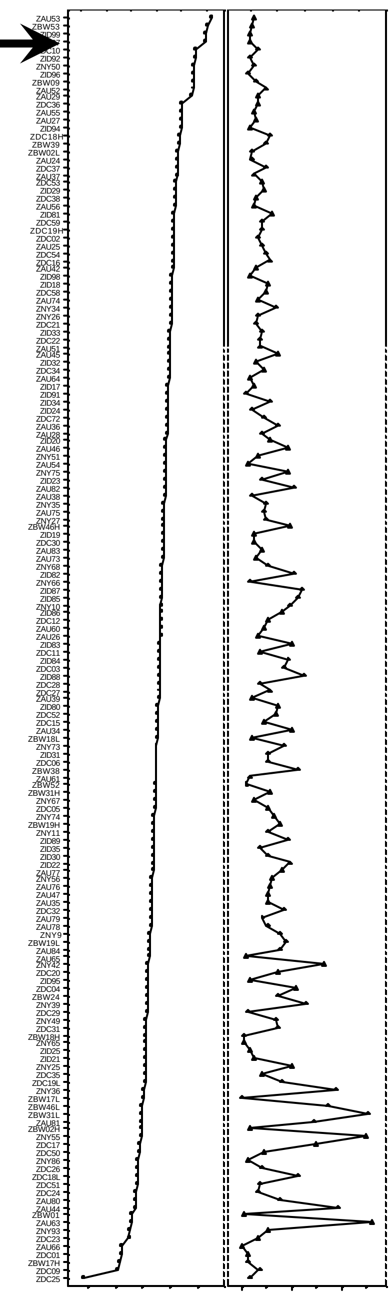
Daily movement

CI: mean=1.86, max=2.61, min=0.7

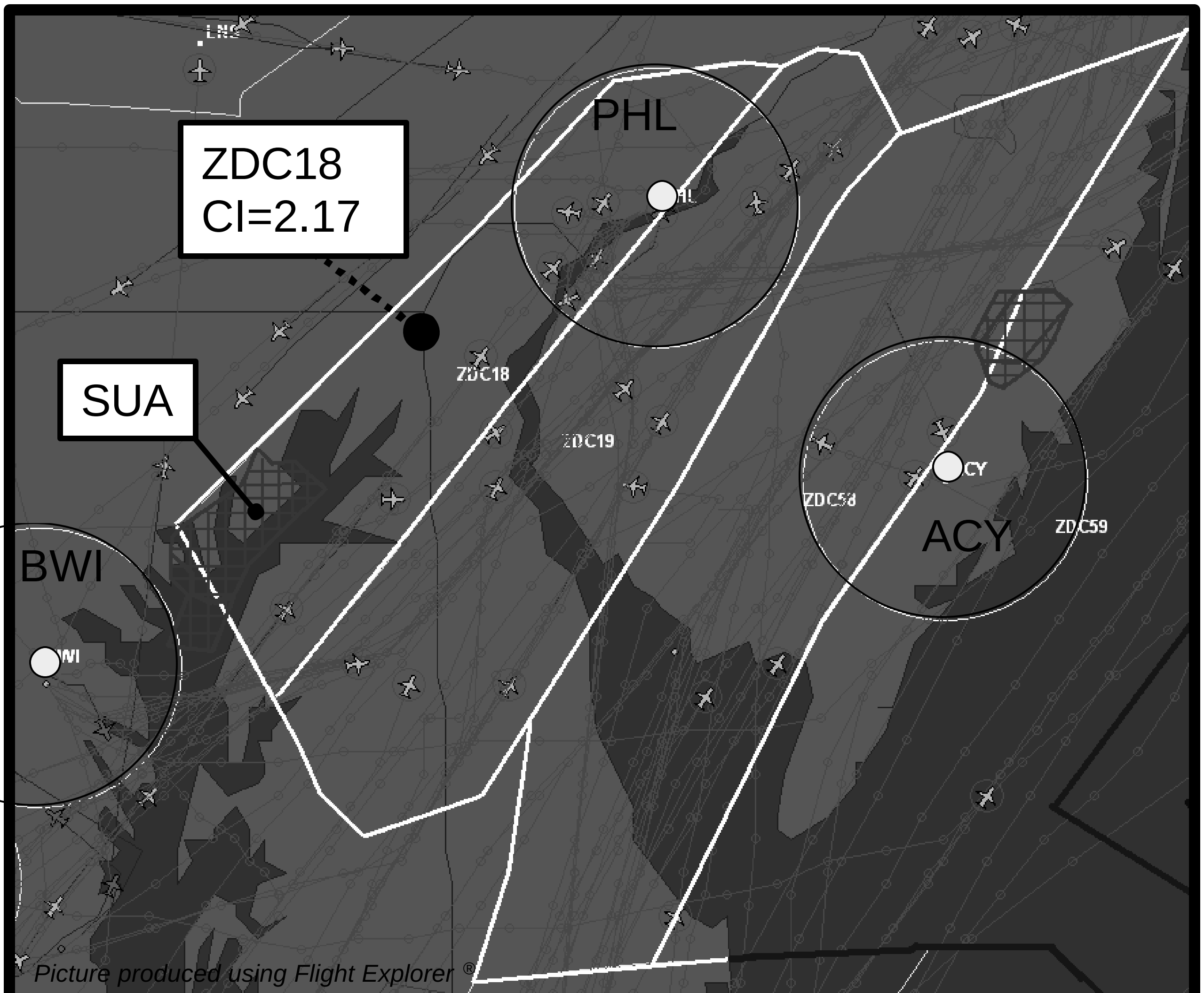
Complexity order:
4/162



- Ultra high
- Non-structured traffic
- Many inter-sector handoff points
- Many track intersections



- ➢Low altitude and small
- ➢SUA blocks sector entrance
- ➢Proximity of two large airports (BWI and PHL)
- ➢Many altitude changes
- ➢Almost structured but also many crossing traffic
- ➢Short sector transit times at the edges



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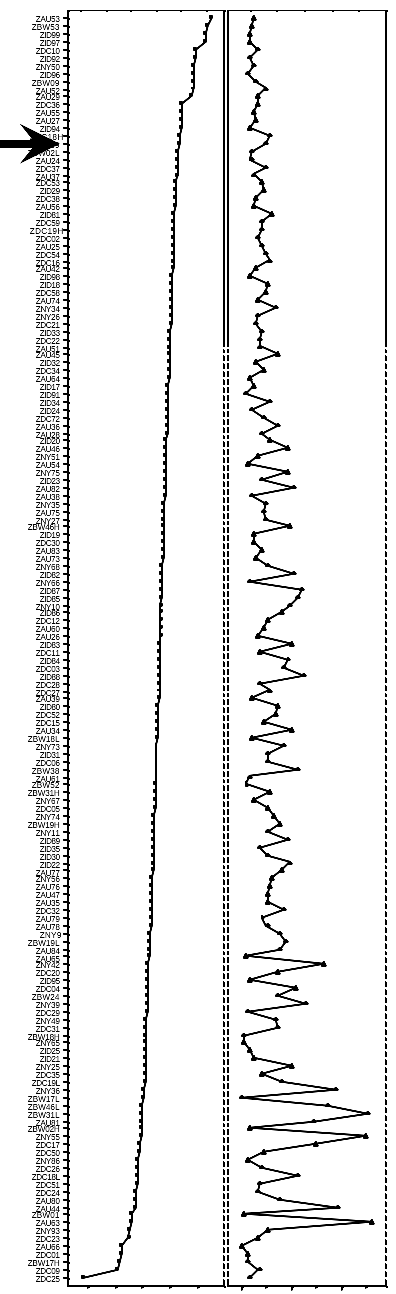
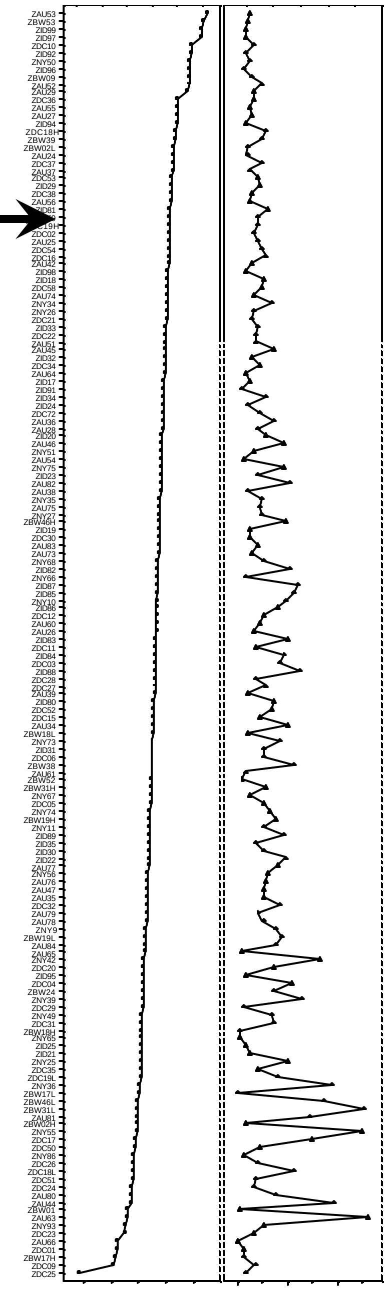


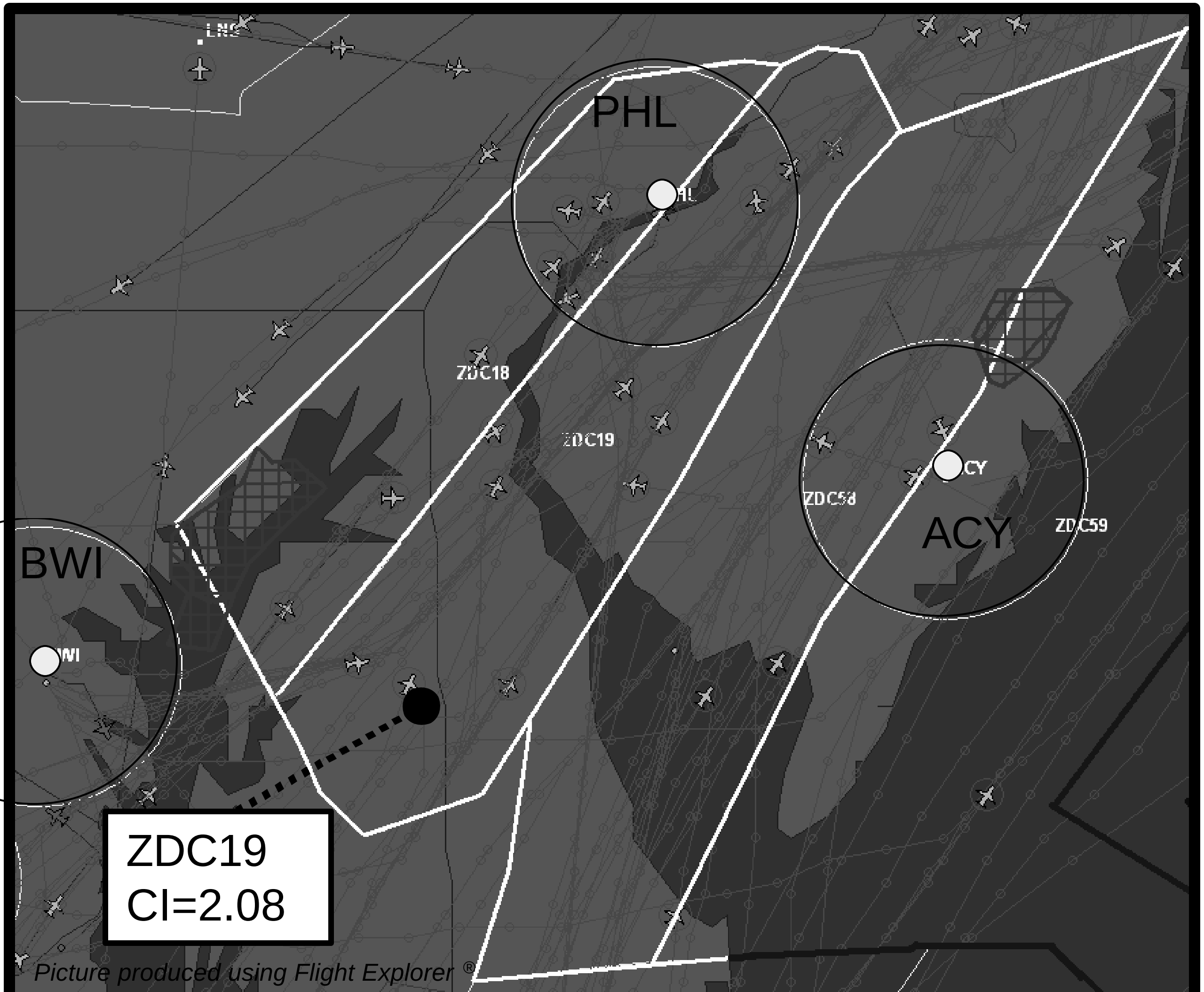
- Low altitude and small
- Structured but also many crossing traffic
- Proximity of three airports (BWI, PHL & ACY)
- Many altitude changes

Daily movement

CI: mean=1.86, max=2.61, min=0.7

Complexity order:
28/162



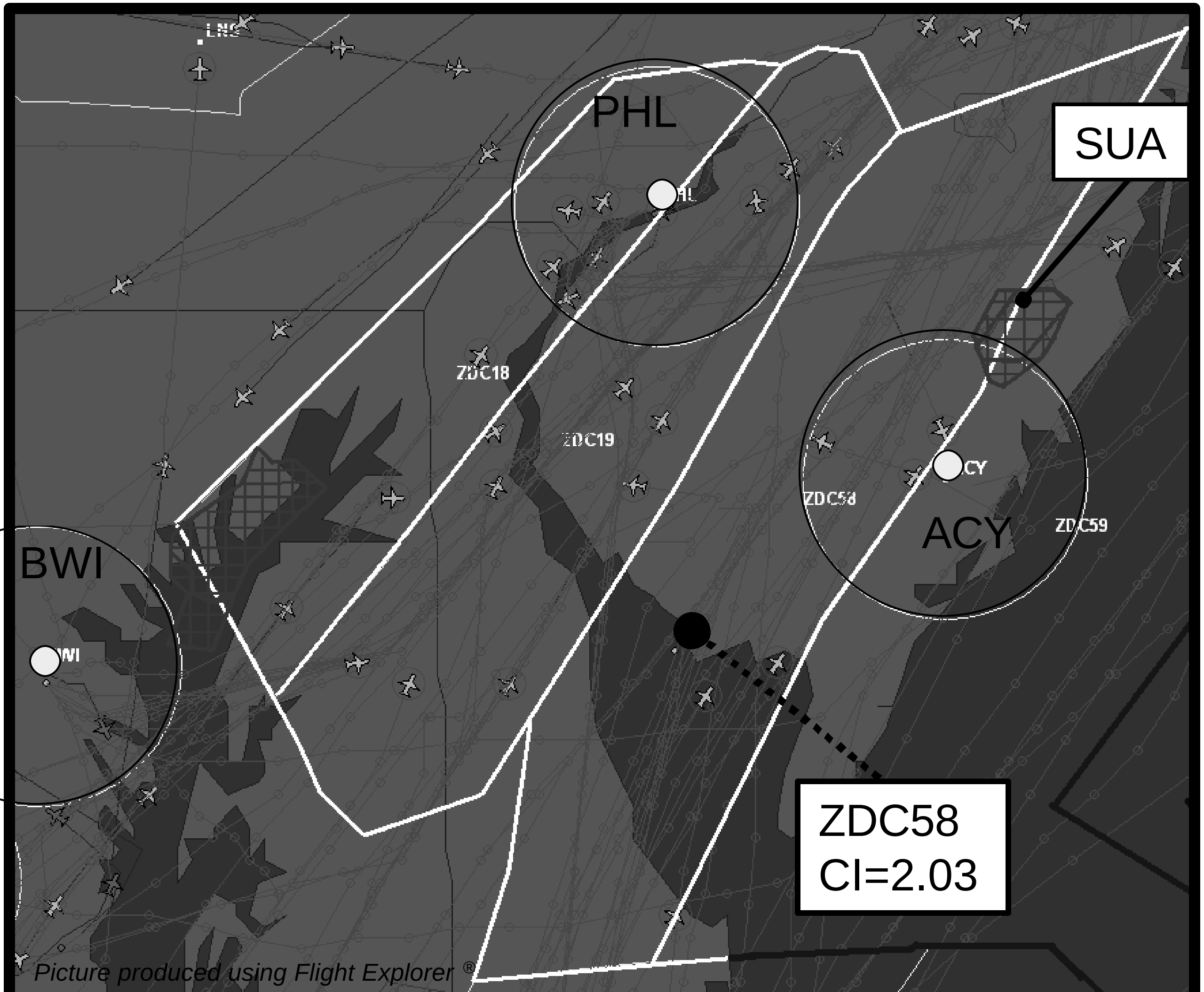


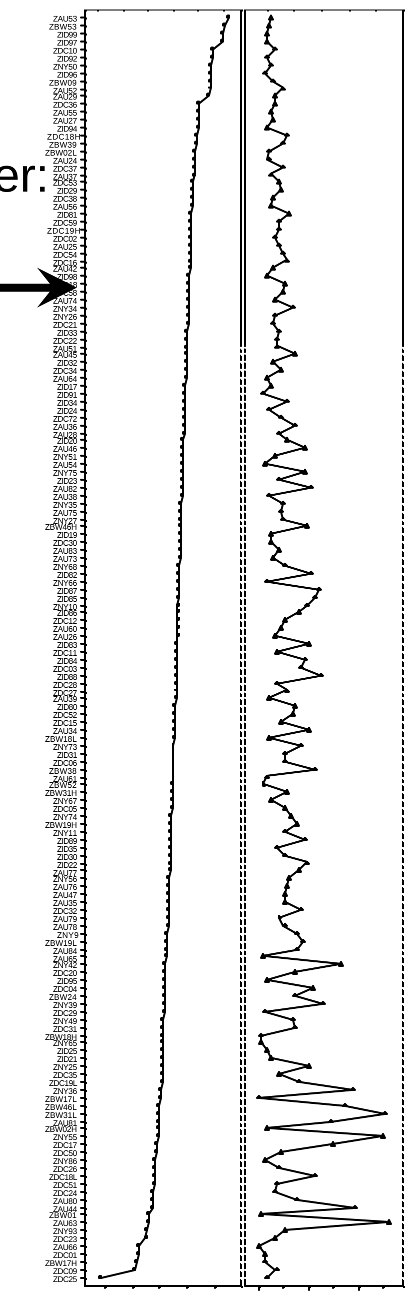
- High altitude
- Small volume
- Structured but also many crossing traffic
- Proximity of two large airports (BWI and PHL)
- Proximity of SUA

Daily movement

CI: mean=1.86, max=2.61, min=0.7

Complexity order: 36/162





Notes and Summary

- Complexity Index as a airspace complexity metric is described.
  - CI appears to capture critical complexity factors.
  - Results of CI computation supports the recent studies in structured airspace.
  - Minimizing CI could be an objective in future airspace design.
  - Designing sectors with more uniform complexities might enhance the airspace safety and efficiency.
- Computation of CI requires a highly detailed airspace model:
  - TAAM *(detailed but slow)*, RAMS *(detailed but no access)*, FACET *(detailed?, faster).*
- Future work:
  - Conduct evaluation by comparing CI to qualitative ATC assessments.
  - Research on a new airspace design using CI as one of the objective parameters.