Development and Validation of an Automated Simulation Capability in Support of Integrated Demand Management

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Human-in-the-loop (HITL) simulations

• Study integration of strategic and tactical planning tools
  – Strategic:
    • Pre-departure ground delay
      ⇔ Adjusts demand to roughly meet airport arrival constraint
  – Tactical:
    • Airborne delay near arrival airport
    • Pre-departure ground delay for short-haul flights
      ⇔ Delivers demand to actual arrival rate constraint

• Subject matter expert participants:
  – Air traffic controllers
  – Traffic flow managers
Challenges of HITL simulations

• Expensive
  – Subject matter expert participants
  – Simulation support staff

• Time consuming
  Minimum of 5 hours to capture long-haul flights pre-departure

• Limitations
  – Number of simulations executed
  – Number of airspace sectors that can be populated with traffic
  – Traffic volume
Motivation

- Evaluate over larger variation in parameters
- Simulate larger, more realistic traffic scenarios
- Augment HITL with automated background traffic
Objectives

• Automate HITL simulation
• Emulate HITL simulation results
• Maintain high fidelity trajectory simulation
• Incorporate updates to strategic planning tool
Outline

• Simulation structure
  – HITL simulation
  – HITL participant actions
  – Automated simulation capability

• Initial validation

• Conclusions and future work
Simulation structure
Simulation structure

Strategic Planner

Trajectory Simulator
Simulation structure

Strategic Planner

Trajectory Simulator

Tactical Planner
Simulation structure

- Departure schedule
- Estimated flight times
Simulation structure

Strategic Planner → Trajectory Simulator → Tactical Planner

Departure delay
Simulation structure

- Strategic Planner
- Trajectory Simulator
- Tactical Planner

Airborne flight timeline
Simulation structure

- Strategic Planner
- Tactical Planner
- Trajectory Simulator

- Departure delay
- Airborne delay
Simulation structure

- Trajectory Simulator
- Strategic Planner
- Tactical Planner
Simulation structure

Start communication server

- Trajectory Simulator
  - Strategic Planner
  - Tactical Planner
Simulation structure

Start communication server
Set simulation parameters

Trajectory Simulator

Strategic Planner

Tactical Planner
Simulation structure

- Start communication server
- Set simulation parameters
- Trajectory Simulator
- Strategic Planner
- Tactical Planner
- Set program parameters
Simulation structure

- Start communication server
- Set simulation parameters

Simulation structure:

- Trajectory Simulator
  - Strategic Planner
  - Tactical Planner

- Set program parameters
- Run algorithm
Simulation structure

- Start communication server
- Set simulation parameters

Trajectory Simulator

- Strategic Planner
- Tactical Planner

- Set program parameters
- Run algorithm
- Send new departure times
Start communication server
Set simulation parameters

Trajectory Simulator

Strategic Planner
Set program parameters
Run algorithm
Send new departure times

Tactical Planner
Schedule departures
Simulation structure

- Start communication server
- Set simulation parameters

Strategic Planner
- Set program parameters
- Run algorithm
- Send new departure times

Trajectory Simulator

Tactical Planner
- Schedule departures
- Control aircraft to meet arrival time
• Schedule departures
• Control aircraft to meet arrival time

• Start communication server
• Set simulation parameters

Simulation structure

Start communication server
Set simulation parameters

Trajectory Simulator

Strategic Planner
- Set program parameters
- Run algorithm
- Send new departure times

Tactical Planner
- Schedule departures
- Control aircraft to meet arrival time
Simulation structure

- Start communication server
- Set simulation parameters

Strategic Planner
- Set program parameters
- Run algorithm
- Send new departure times

Trajectory Simulator

Tactical Planner
- Schedule departures
- Control aircraft to meet arrival time
Simulation structure

- Start communication server
- Set simulation parameters

Trajectory Simulator

- Strategic Planner
  - Set program parameters
  - Run algorithm
  - Send new departure times

- Tactical Planner
  - Schedule departures
  - Control aircraft to meet arrival time
Simulation structure

- Start communication server
- Set simulation parameters

Trajectory Simulator

- Set program parameters
- Run algorithm
- Send new departure times

Strategic Planner

- Schedule departures

Tactical Planner

- Control aircraft to meet arrival time
Simulation structure

Start communication server
Set simulation parameters

Trajectory Simulator

Strategic Planner
- Set program parameters
- Run algorithm
- Send new departure times

Tactical Planner
- Schedule departures
- Control aircraft to meet arrival time
Simulation structure

- Start communication server
- Set simulation parameters

- Strategic Planner
  - Set program parameters
  - Run algorithm
  - Send new departure times

- Tactical Planner
  - Schedule departures
  - Control aircraft to meet arrival time

- Trajectory Simulator
  - Set simulation parameters
Tactical planner emulator

- Scheduler developed in house at NASA
  - Can run in fast-time
  - Code easily accessible for modification
- Adapted for Newark Liberty International Airport
- Modified to schedule internal departures automatically
Tactical planning

Freeze Horizon

400 nmi

Runway Threshold
Tactical planning

 Freeze Horizon

 Runway Threshold

 400 nmi
Tactical planning

Runway Threshold

Freeze Horizon

400 nmi

Expected Time

Scheduled Time
Tactical planning

Expected Time

Scheduled Time

Freeze Horizon

Runway Threshold

400 nmi

Runway Threshold
Tactical planning

- Freeze Horizon
- Runway Threshold

400 nmi

Expected Time
Scheduled Time

+3 min

Runway Threshold
Tactical planning

Freeze Horizon

400 nmi

Runway Threshold

Expected Time

Scheduled Time

+3 min

Runway Threshold
Freeze Horizon

Tactical planning

400 nmi

Expected Time

Scheduled Time

Runway Threshold

+3 min
Tactical planning

Freeze Horizon

Expected Time

Scheduled Time

400 nmi

Runway Threshold

+3 min

Runway Threshold
Tactical planning

Freeze Horizon

400 nmi

Runway Threshold

Expected Time

Scheduled Time

+3 min

Runway Threshold
Tactical planning

- Freeze Horizon
- Runway Threshold
- Expected Time
  - Priority to airborne flights
  - 400 nmi
- Scheduled Time
  - +3 min
Tactical planning

Runway Threshold

Priority to airborne flights

Expected Time
+15 min

Scheduled Time

Runway Threshold

Freeze Horizon

400 nmi
Tactical planning

Freeze Horizon

400 nmi

Runway Threshold

Priority to airborne flights

Expected Time

+15 min

Scheduled Time

+0 min

+3 min

Runway Threshold
Tactical planning

- Freeze Horizon
- Runway Threshold

Expected Time vs. Scheduled Time

+3 min
Tactical planning

Priority to internal departures

Expected Time

Scheduled Time

Runway Threshold

Freeze Horizon

400 nmi

Runway Threshold

+3 min
Tactical planning

Priority to internal departures

Expected Time

Scheduled Time

+3 min

Runway Threshold

Freeze Horizon

400 nmi

Runway Threshold
Tactical planning

Runway Threshold

Freeze Horizon

400 nmi

Priority to internal departures

Expected Time

Scheduled Time

+3 min

Runway Threshold
Tactical planning

Runway Threshold

Priority to internal departures

Expected Time

Scheduled Time

+3 min

+0 min

+3 min

Runway Threshold
Experimental setup

• Duration of 5 hours
• 253 flights
  – 98 airborne at simulation start
  – 91 external departures
  – 64 internal departures
• Flights depart with some error
• Tactical scheduling paradigms
  – Priority given to airborne flights
  – Priority given to internal departures
Expected results

• Generate results *qualitatively* similar HITL
• HITL simulations have shown:
  – Priority given to airborne flights
    ➞ Relatively high ground delay for internal departures
  – Priority given to internal departures
    ➞ Significant reduction in ground delay for internal departures
    ➞ Required airborne delay is manageable
Internal departure ground delay

![Histogram of Internal Departure Ground Delay]

- **Ground Delay [min]**: 0, 5, 10, 15, 20
- **Number of Flights**: 0, 10, 20, 30, 40, 50, 60
- **Priority Airborne**

The histogram illustrates the distribution of internal departure ground delay, showing the number of flights affected by delays of different durations.
Internal departure ground delay

![Graph showing internal departure ground delay with bars for Priority Airborne and Priority Internal flights. The x-axis represents Ground Delay [min] ranging from 0 to 60 minutes, and the y-axis represents the Number of Flights. The bars indicate the distribution of flights with delays of varying lengths.]
Airborne delay

![Bar chart showing airborne delay distribution](chart.png)

- **Acceptable**: < 7 min
- **Marginal**: 7 to 14 min
- **Unacceptable**: > 14 min

**Number of Flights**

- **Priority Airborne**

<table>
<thead>
<tr>
<th>Airborne Delay [min]</th>
<th>Number of Flights</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 - 5</td>
<td>30</td>
</tr>
<tr>
<td>5 - 10</td>
<td>20</td>
</tr>
<tr>
<td>10 - 15</td>
<td>10</td>
</tr>
<tr>
<td>15 - 20</td>
<td>0</td>
</tr>
<tr>
<td>20 - 25</td>
<td>0</td>
</tr>
</tbody>
</table>
Airborne delay

- Acceptable: < 7 min
- Marginal: 7 to 14 min
- Unacceptable: > 14 min

Number of Flights

Airborne Delay [min]

- Priority Airborne
- Priority Internal
## Comparison to HITL simulation

<table>
<thead>
<tr>
<th>Tactical Scheduling Paradigm</th>
<th>Simulation</th>
<th>Tactical Airborne Delay</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Acceptable (&lt;7 min)</td>
</tr>
<tr>
<td>Priority Internals</td>
<td>HITL</td>
<td>82 %</td>
</tr>
<tr>
<td></td>
<td>Automated</td>
<td>87 %</td>
</tr>
<tr>
<td>Priority Airborne</td>
<td>HITL</td>
<td>94 %</td>
</tr>
<tr>
<td></td>
<td>Automated</td>
<td></td>
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</tbody>
</table>
Comparison to week-long HITL

<table>
<thead>
<tr>
<th></th>
<th>HITL</th>
<th>Automated</th>
<th>Automated fast-time (5x)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Subject matter experts</td>
<td>320 hours</td>
<td>0 hours</td>
<td>0 hours</td>
</tr>
<tr>
<td>Simulation technician</td>
<td>32 hours</td>
<td>1 hour</td>
<td>1 hour</td>
</tr>
<tr>
<td>Number of simulations</td>
<td>4</td>
<td>20</td>
<td>104</td>
</tr>
<tr>
<td>Active Simulation Time</td>
<td>20 hours</td>
<td>100 hours</td>
<td>104 hours</td>
</tr>
</tbody>
</table>
Conclusions

Automated simulation capability

• Automate HITL simulation
• Emulate HITL simulation results
• Maintain high fidelity trajectory simulation
• Incorporate updates to strategic planning tool
Conclusions

Automated simulation capability

• Automate HITL simulation
• Emulate HITL simulation results
• Maintain high fidelity trajectory simulation
• Incorporate updates to strategic planning tool

Benefits

• Evaluate over larger variation in parameters
• Simulate larger, more realistic traffic scenarios
• Augment HITL by automated background traffic
Future work

**Development**

- Add other New York airports:
  - LaGuardia Airport (LGA)
  - John F. Kennedy International Airport (JFK)
- Augment HITL simulations with more traffic
- Enable fast-time simulation (up to 5x real-time)

**Research**

- Parameter studies
- Uncertainty in departure and flight time
Backup
Fast Time MACS
Fast time MACS

- Flights analyzed: 196
- FlightState data output from MACS
- Trajectory information every 12 seconds
- Resampled in 1 minute intervals
  (for 1x reference sim and 1x, 5x, 10x, 25x sim)
Distance measure

- real-time
- fast-time
- along-track
- cross-track
Along-track distance

No Wind

Along-track Distance from 1x Track [nmi]

Simulation Speed

1x 5x 10x 25x

-1.00 -0.75 -0.50 -0.25 0.00 0.25 0.50 0.75 1.00

90th percentile
75th percentile
median
25th percentile
10th percentile
With wind, 25x: along-track distance
Flight time difference

No Wind

Total Flight Time Difference [sec]

1x 5x 10x 25x

-15 -10 -5 0 5 10 15

25th percentile
75th percentile
90th percentile
median
25th percentile
10th percentile
No Wind

Total Flight Time Difference [sec]

1x 5x 10x

-15 -10 -5 0 5 10 15

RTA sim departure error [Yoo 2016]

Departure Errors (Seconds)

Frequency

-300 -60 0 300

300 200 100 0 -100 -200 -300

No Wind

Flight time difference

RTA sim departure error [Yoo 2016]

Department Errors (Seconds)

Frequency

-300 -60 0 300

300 200 100 0 -100 -200 -300

No Wind

Flight time difference

RTA sim departure error [Yoo 2016]

Department Errors (Seconds)

Frequency

-300 -60 0 300

300 200 100 0 -100 -200 -300

No Wind

Flight time difference

RTA sim departure error [Yoo 2016]

Department Errors (Seconds)

Frequency

-300 -60 0 300

300 200 100 0 -100 -200 -300

No Wind

Flight time difference

RTA sim departure error [Yoo 2016]

Department Errors (Seconds)

Frequency

-300 -60 0 300

300 200 100 0 -100 -200 -300

No Wind

Flight time difference

RTA sim departure error [Yoo 2016]

Department Errors (Seconds)

Frequency

-300 -60 0 300

300 200 100 0 -100 -200 -300

No Wind

Flight time difference

RTA sim departure error [Yoo 2016]

Department Errors (Seconds)

Frequency

-300 -60 0 300

300 200 100 0 -100 -200 -300

No Wind

Flight time difference

RTA sim departure error [Yoo 2016]

Department Errors (Seconds)

Frequency
Total Flight Time Difference [sec]

With Wind

-15
-10
-5
0
5
10
15

1x 5x 10x

RTA sim departure error [Yoo 2016]

Departure Errors (Seconds)

0 360 -360 -60 -300 300

Frequency

0 2 4 6 8 10

TABLE I.

<table>
<thead>
<tr>
<th>Condition</th>
<th>Out of Tolerance</th>
<th>Marginal Tolerance Range</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>-60,60</td>
<td></td>
</tr>
<tr>
<td>Non-RTA</td>
<td>12.0%</td>
<td>23.7%</td>
</tr>
<tr>
<td></td>
<td>[-300,-60)</td>
<td>33.6%</td>
</tr>
<tr>
<td></td>
<td>(60,300]</td>
<td>18.2%</td>
</tr>
<tr>
<td></td>
<td>12.4%</td>
<td></td>
</tr>
<tr>
<td>RTA</td>
<td>2.0%</td>
<td>12.1%</td>
</tr>
<tr>
<td></td>
<td>[-60,60]</td>
<td>66.9%</td>
</tr>
<tr>
<td></td>
<td>[-300,-60)</td>
<td>9.8%</td>
</tr>
<tr>
<td></td>
<td>(60,300]</td>
<td>9.1%</td>
</tr>
</tbody>
</table>

E. Dependent Variable

The dependent variable of this study is the Crossing Time (CT) performance, which is the target CT at the FEA minus the actual CT. Hence, a negative error indicates that the flight was late to its target CT, and a positive error indicates that it arrived early to its target CT. The CT performance was measured for all aircraft, whether or not they were assigned an RTA.

IV. HYPOTHESES

The following hypotheses were examined to explore the use of RTA to improve delivery accuracy at the FEAs to see how performance varies under the influence of identified factors.

A. Hypothesis A: Assigning RTA to aircraft will improve Crossing Time performance.

B. Hypothesis B: Strong winds may degrade Crossing Time performance.

C. Hypothesis C: Flight distance may affect Crossing Time performance.

D. Hypothesis D: Crossing Time performance of RTA assigned aircraft will decrease as wind forecast errors increase.

Hypothesis A compares the CT performance of RTA assigned aircraft to Non-RTA assigned aircraft. Hypothesis B examines how wind severity affects the CT performance of RTA and Non-RTA assigned aircraft. Hypothesis C examines the effect of flight distance (the distance from cruise phase until the aircraft crosses the FEA) on the CT performance of both RTA and Non-RTA aircraft. Hypothesis D provides insight on wind forecast accuracy requirements for achieving good CT performance by identifying the relationship between wind forecast errors and CT performance.

V. RESULTS

A. Results of Hypothesis A: Assigning RTA to aircraft improves Crossing Time performance.

A total of 396 aircraft (both pre-departures and airborne) received RTA across all conditions during the study. Of those, 265 (66.9%) aircraft crossed the FEAs within +/- 60 seconds (i.e. the targeted tolerance range for this study) and 352 (88.9%) aircraft crossed the FEAs within +/-300 seconds, which was identified as a marginal tolerance range. In contrast, only 33.6% (133 out of 396) of the Non-RTA assigned aircraft's CT performance met the targeted tolerance range and 75.5% (299 out of 396) crossed the FEAs within the marginal tolerance range. The marginal range of +/- 5 minutes was established based on subject matter experts saying that 5-minute conformance was "workable/marginal" for the TBFM system to manage the arrival flow into EWR. Figure 8 shows the histogram of the CT performance of RTA and Non-RTA assigned aircraft.
TBFM Emulator
Scheduling internal departures

New timeline, frozen list, ref. time

ID internals with EDCT-20 min <= ref. time
- Store for internal departure scheduling list
- Set event trigger to EDCT-20 min

ID externals with FH CT <= ref. time, not in frozen list
- Store for airborne scheduling list
- Set event trigger to FH CT

ID internals that have taken off but are not in frozen list
- Store for airborne scheduling list
- Set event trigger to take off time

Set idx = 0

Sort all event triggers chronologically

Event trigger(idx) <= ref. time?
- idx += 1

flight(idx) in internal departure scheduling list?
- Y: Extract ETAs for all internals in timeline
- N: Extract ETAs for all externals in timeline

Checkbox ON
- Y: Add internal flight(idx) to external flight list
- N: Sort external flight list by THD ETA

Extract ETA from timeline
- ETA += dep. error

Y: Schedule flight(idx) around frozen flights
- N: Add flight(idx) to frozen list

For flight(idx): Set sched. dep = MF STA-transit time
- Set new ETA = STA
- Set event trigger = new dep. time + dep. error

Sort external flight list by THD ETA
- Schedule external flight list around frozen flights
- Extract ETAs for flight(idx)
- Schedule flight(idx) around scheduled externals

For flight(idx): Set sched. dep = MF STA-transit time
- Set new ETA = STA
- Set event trigger = new dep. time + dep. error

N: Extract ETAs for all externals in timeline
- Sort external flight list by THD ETA
- Schedule external flight list around frozen flights
- Extract ETAs for flight(idx)
- Schedule flight(idx) around scheduled externals

Remove flight(idx) from internal departure scheduling list
• Scheduler from Optimized Route Capability (ORC)
  – Fast-time
  – Code easily accessible for modification
• Adapted for EWR
• Modified to schedule internal departures automatically
  – Check box ON/OFF
• Integrated with Automated Simulation Capability / MACS
## TBFM Emulator Capabilities

<table>
<thead>
<tr>
<th>Capability</th>
<th>rTBFM</th>
<th>eTBFM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fast-time</td>
<td>✔</td>
<td>✔</td>
</tr>
<tr>
<td>EWR adaptation</td>
<td>✔</td>
<td>✔</td>
</tr>
<tr>
<td>Schedule flights at Meter Fix</td>
<td>✔</td>
<td>✔</td>
</tr>
<tr>
<td>Schedule flights at Runway Threshold</td>
<td>✔</td>
<td>✔</td>
</tr>
<tr>
<td>Schedule flights at Final Approach Fix</td>
<td>✔</td>
<td>Planned</td>
</tr>
<tr>
<td>Model wind effects inside TRACON</td>
<td>✔</td>
<td>Planned</td>
</tr>
<tr>
<td>Model wind effects upstream of TRACON</td>
<td>✔</td>
<td>✔</td>
</tr>
<tr>
<td>Automated scheduling of internal departures (Check Box ON/OFF)</td>
<td></td>
<td>✔</td>
</tr>
<tr>
<td>Extended metering</td>
<td>✔</td>
<td>Planned</td>
</tr>
<tr>
<td>Coupled scheduling</td>
<td>✔</td>
<td></td>
</tr>
<tr>
<td>Integrated with Automated Simulation Capability / MACS</td>
<td></td>
<td>✔</td>
</tr>
<tr>
<td>Interface directly with SMART-NAS Testbed</td>
<td></td>
<td>Planned</td>
</tr>
</tbody>
</table>
Initial validation: ORC scheduler

<table>
<thead>
<tr>
<th></th>
<th>Meter Fix</th>
<th>Threshold</th>
</tr>
</thead>
<tbody>
<tr>
<td>Avg. hTBFM metering delay (standard deviation)</td>
<td>80 (104)</td>
<td>136 (106)</td>
</tr>
<tr>
<td>Avg. eTBFM emulator metering delay (standard deviation)</td>
<td>143 (131)</td>
<td>180 (135)</td>
</tr>
<tr>
<td>Avg. ETA Error: hTBFM-eTBFM (standard deviation)</td>
<td>19 (75)</td>
<td>52 (77)</td>
</tr>
<tr>
<td>Avg. STA Error: hTBFM-eTBFM (standard deviation)</td>
<td>-43 (104)</td>
<td>7 (100)</td>
</tr>
</tbody>
</table>
## Initial validation: TBFM emulator

<table>
<thead>
<tr>
<th>Metric</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Avg. rTBFM internal departure scheduling delay</td>
<td>66 (72)</td>
</tr>
<tr>
<td>Avg. eTBFM internal departure scheduling delay</td>
<td>70 (90)</td>
</tr>
<tr>
<td>Avg. scheduled departure time error (rTBFM-eTBFM)</td>
<td>-4 (129)</td>
</tr>
</tbody>
</table>

### TBFM Internal Departure Delay

![Graph showing TBFM Internal Departure Delay](image)
Simulation Manager
Communication GUI

**Fast Time Sim**

15:23:52

**Run Mode**
- Manual Run

**Start Macs**
- Scenario File: C:/FastTimeSim/NYTBO/MacsScenarios/Traffic/GAG_V9.txt
- Stop Macs
- Start nCTOP

**Macs On**

**Time Factor**
- 1x

**nCTOP Off**

**Periodic**
- Start Periodic
- Stopped

**Exit**
Create and run batch process

• Create batch file **FTS_bat.txt**

```plaintext
#RunName   Scenario    TimeFactor   RunMinutes    startnCTOPseconds
proc1 C:/fts-tbfm/input_files/EWR/Scenario/GAG_v9.txt    1x 30 10
proc2 C:/fts-tbfm/input_files/EWR/Scenario/MACS_20170421_1hr_traffic_NOdeperr.txt 1x 30 10
```

• Python command

```python
Python FTS_Macs-batch.py FTS_bat.txt
```
Launch MACS
Enable external communication

Communication window
Server Status: Registered Open
Start simulation

- Scenario file name
- Simulation time
- Simulation time factor (simulation speed)
Launch nCTOP

59

Waiting for MACS traffic to settle...

Click here if you are not redirected...
Calculate new departure times
Run simulation

Traffic display screen

Communication window

Simulation setup window
Monitor simulation status

08-04-2017_11-52-02.17
Received a flight data....
Processing the flight data....

stop
Re-schedule internal departure ASQ4672...
Re-schedule internal departure RPA3142...
The flight data is processed....

Received a flight data....
Received a flight data....
Processing the flight data....

The flight data is processed....
Batch process terminated

Received a flight data.....
Processing the flight data....
The flight data is processed....
Waiting for finishing the last data.2017-08-04 12:05:01.056000
Log data
<table>
<thead>
<tr>
<th>nodeID</th>
<th>nodeType</th>
<th>flightID</th>
<th>STA</th>
<th>ETA</th>
<th>delayPassback</th>
<th>NomSpeed</th>
<th>isInternal</th>
<th>eventTrigger</th>
<th>FH_CT</th>
<th>EDCT</th>
<th>depError</th>
<th>TBFMSchedDep</th>
<th>SchedDelay</th>
<th>reqT1</th>
</tr>
</thead>
<tbody>
<tr>
<td>EWR22L</td>
<td>RWY</td>
<td>UAL1116</td>
<td>1501892541</td>
<td>1501892541</td>
<td>0.009999999</td>
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