How to Achieve CDOs for All Aircraft: Automated Separation in TMAs

Enabling Flexible Entry Times and Accounting for Wake Turbulence Categories

Tatiana Polishchuk
Valentin Polishchuk
Christiane Schmidt

Raúl Sáez
Xavier Prats

Henrik Hardell

Lucie Smetanová

LINKÖPING UNIVERSITY

UNIVERSITAT POLITÈCNICA DE CATALUNYA BARCELONATECH

LFV

LINKÖPING UNIVERSITY

CTU CZECH TECHNICAL UNIVERSITY IN PRAGUE

High air-traffic volumes projected for future—despite Covid19

→ High environmental impact

→ Dramatically increased complexity for ATCOs

Particularly in TMAs

Goal: Optimize arrival and departure procedures to alleviate environmental impact and ATCO workload

Continuous descent operations (CDOs)

Promising solution according to Eurocontrol:

CDOs "allow aircraft to follow a flexible, optimum flight path that delivers major environmental and economic benefits—reduced fuel burn, gaseous emissions, noise and fuel costs—without any adverse effect on safety".

- TOD : top of descent
- FAP : final approach point

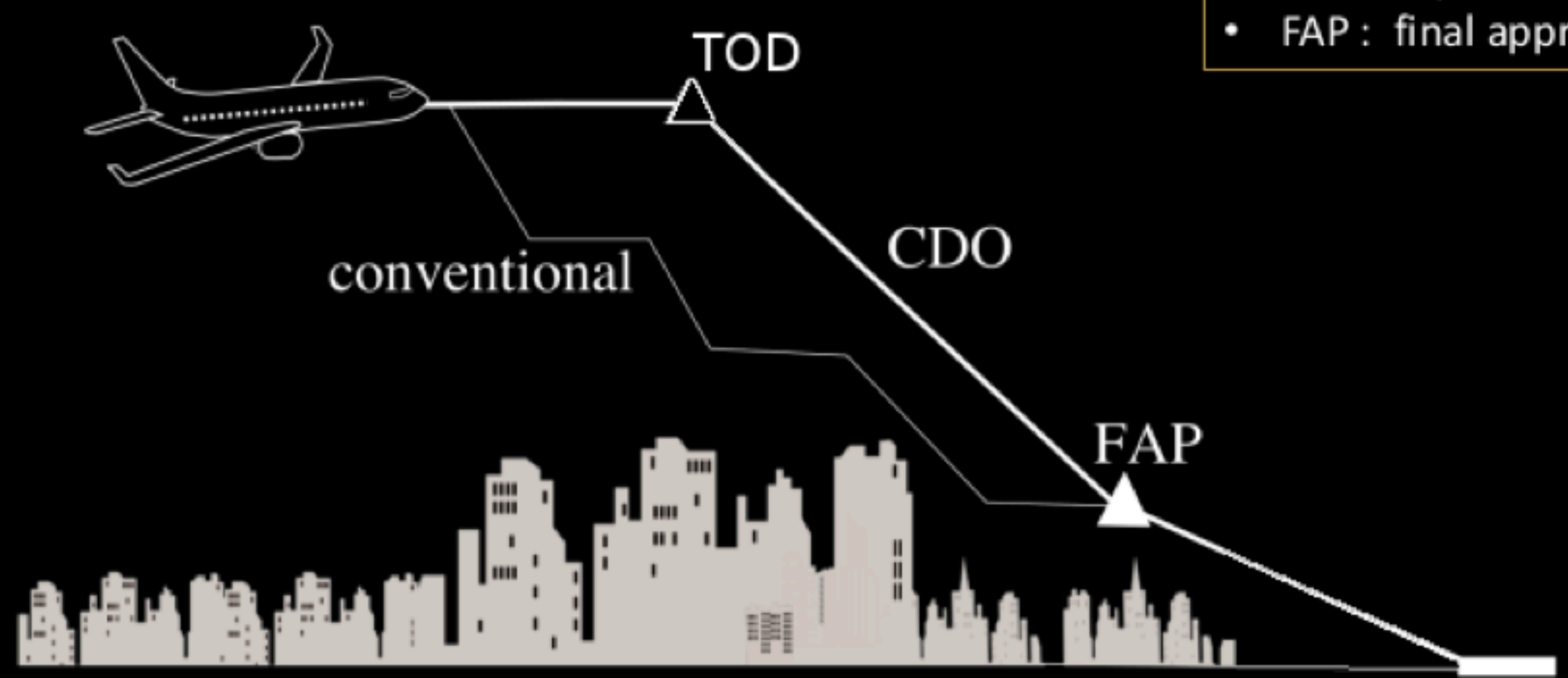


Figure source: Performance comparison between TEMO and a typical FMS in presence of CTA and wind uncertainties, by Ramon Dalmau, Xavier Prats, Ronald Verhoeven and Nico de Gelder, DASC 2016

CDOs:

- Optimized to aircraft's operating capability
- ➡ Aircraft with different characteristics have different opt. trajectories
- But: STARs (strategic) w/o operating capability of each aircraft
- ➡ Limit option of performing optimum descent trajectories
- Different optimum trajectories ➡ reduced vertical and temporal predictability of incoming traffic
- ➡ Increased ATCO workload
- ➡ ATCOs increase separation buffers (use altitude assignments, speed adjustments and path stretching)
- ➡ Losses in airspace and runway capacity
- ➡ ATCO techniques degrade performance of descent operations
- ➡ Higher environmental impact
- Duration of open-loop vector instructions and when a/c will rejoin the initial route unknown to crew
- ➡ Impossible for flight management system (FMS) to predict the remaining distance-to-go
- ➡ Impossible to optimize trajectory: most environmentally-friendly descent profile
- ➡ Busy TMAs: hardly CDOs
- ➡ Important: support ATCOs in separation task using automation tools!

What we had done so far:

- Optimization framework for a/c arrival routes
- Guaranteeing temporal separation of all a/c arriving to a TMA within a given time period (used 2 mins in experiments)
- Using realistic CDO speed profiles (all a/c flying descents with idle thrust and no speed brakes)
- Arrival time to TMA entry points fixed

In experiments for Stockholm TMA we could accommodate only ca. 78% of flights performing energy-efficient CDO profiles (average traffic intensity, 1h)

Why?

- Not computational limit of optimization framework or solvers used
- Input: if aircraft arrive at TMA entry points with distance <2 mins (required uniform temporal separation)
    - ➡ Infeasible problem
    - ➡ We filter out these aircraft
- Possible solution: non-optimal speed profiles, but then no CDO benefits

Today:

- We assume speed profiles along en-route segments can be adapted (e.g., using linear holding)

➡ Aircraft's possible arrival time is given as a time window

➡ We can pick the actual arrival time in that time window

➡ Profile: RTA at TMA entry point + route length in the TMA

➡ We obtain a high runway throughput: for Stockholm TMA, one of busiest hours of operation 2018, all arriving aircraft fly CDOs

- Another improvement: separation determined by the leading and trailing aircraft types (which may change over time for merging arrival routes!)

Concept of Operations

Concept of Operations

- Aircraft arriving to E-TMA (E_a, E_b, E_c)
- In E-TMA: follow published route to TMA entry points (T_a, T_b, T_c)

▸ For us: a/c still in en-route phase

➡ FMS computes earliest and latest possible time of arrival at TMA entry point (~ a/c performance, weather conditions, etc.)

➡ ATCO requests: 1 profile per route length for discrete sets of RTAs ∈[earliest,latest] (complying with RTA)

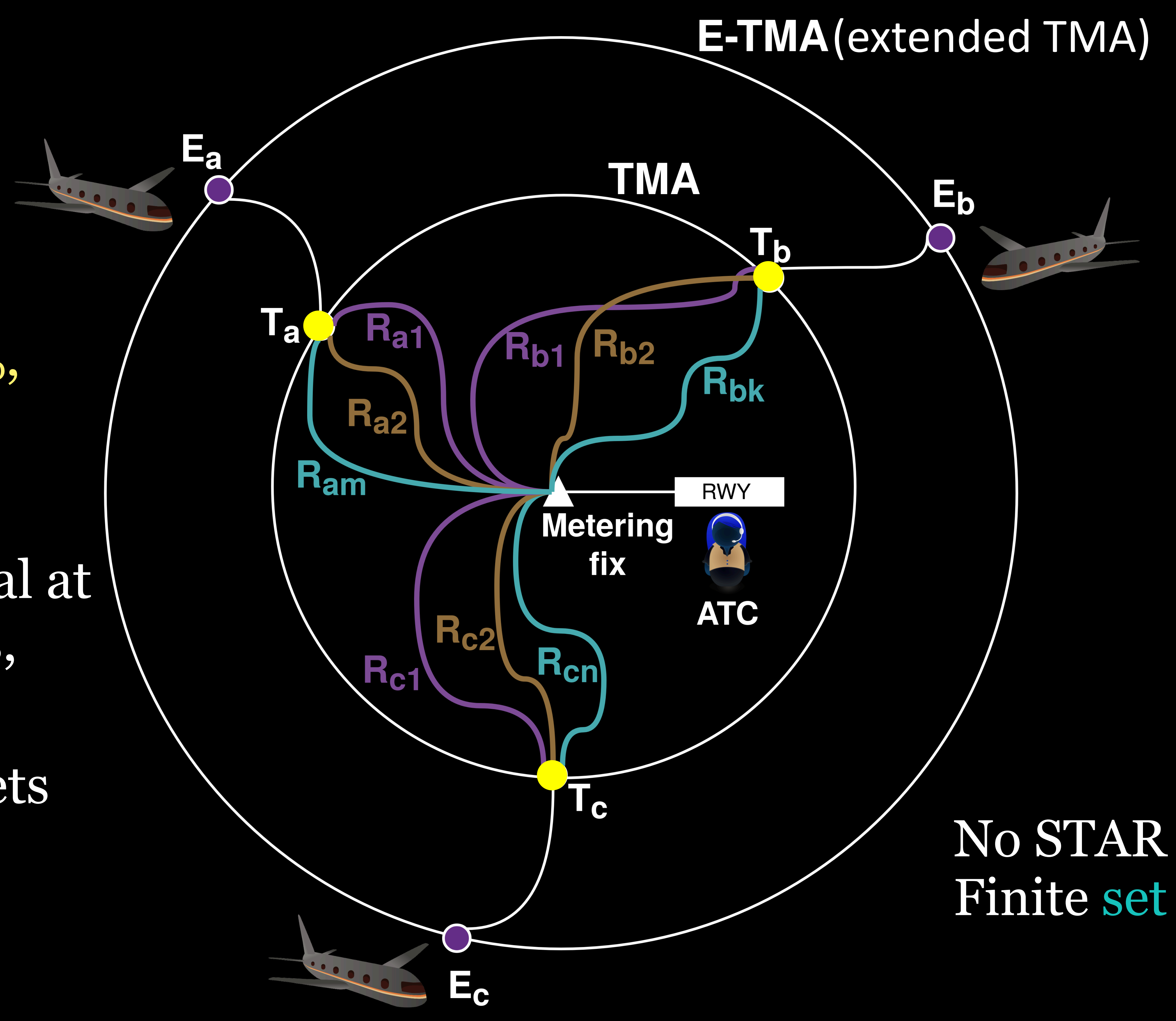
➡ Automated ground system: ATCO generates optimal arrival tree and assigns RTA

- One arrival route per entry point to metering fix
- Optimized for specific time interval → changes during day

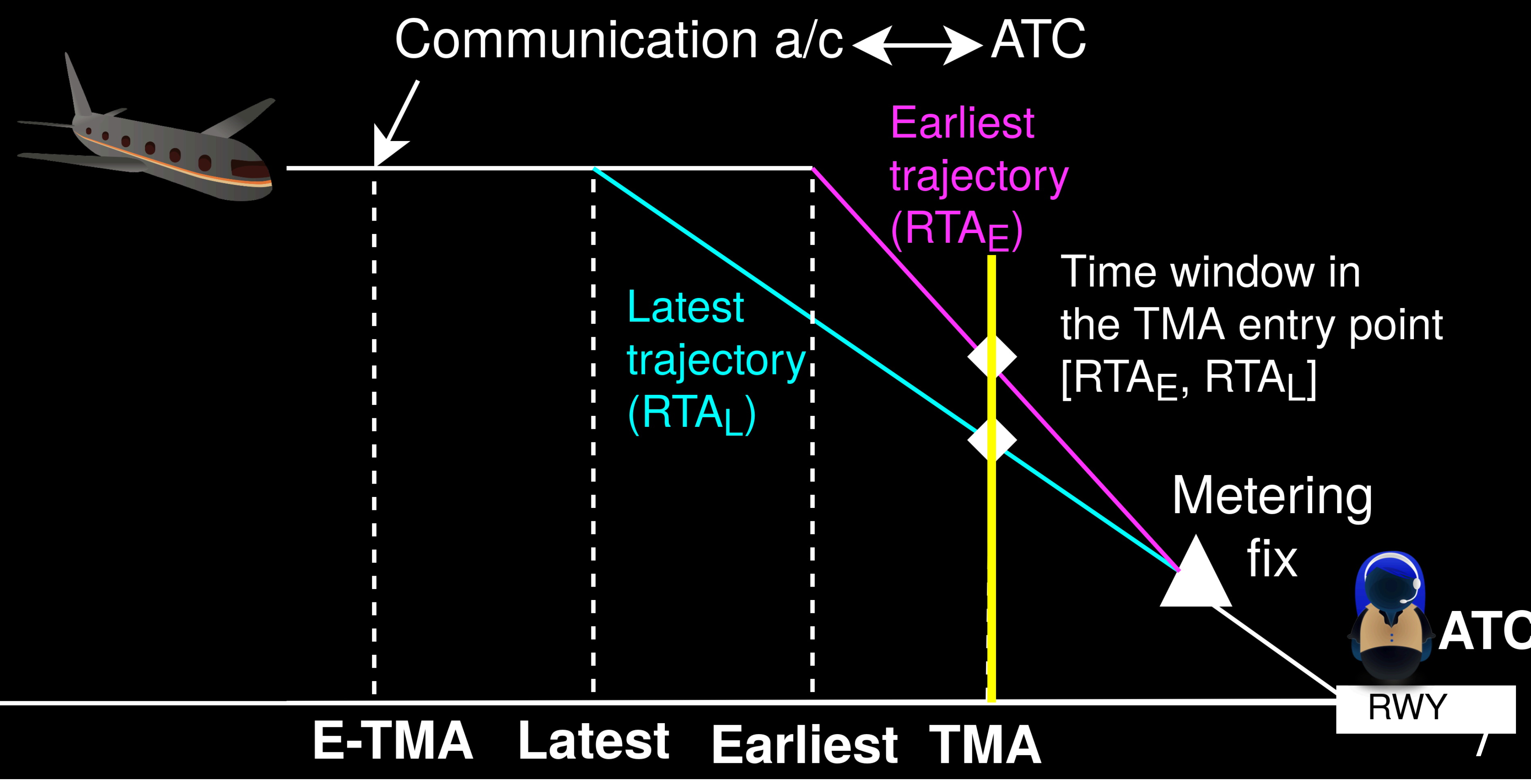
➡ New TOD

- We want: a/c know RTA+arrival tree at TMA entry point
- Or: communication a/c ↔ ATCO established before E-TMA

➡ Enough time for required computations



No STAR published
Finite set of possible routes



Framework Components

Our Framework

1. Computation of CDO speed profiles for different lengths of the entry-point–runway path for all aircraft in the considered time interval.

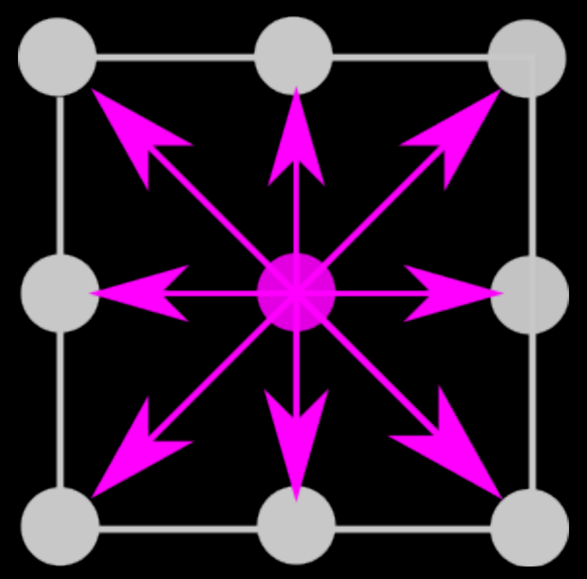
   Optimize vertical profile for given route length (neutral CDOs for all descents)

2. Computation of the arrival trees, that allow for temporal separation of all considered aircraft flying along the computed arrival paths using CDO speed profiles, for the considered time interval, where the required temporal separation depends on the aircraft categories of the leading and trailing aircraft.

   Mixed Integer Programming (MIP) formulation

   Discretization:

   - Overlay TMA with a square grid (snap entry points and runway to grid)
   - Directed edges to 8 grid neighbours
   - ⬆Building blocks for our arrival trees

   ➡Any entry-point—runway path has a length from discrete set

   ➡ For each possible discrete path length + each a/c: compute CDO speed profile

Grid-Based MIP Formulation

Our Previous MIP Model

- Arrival trees
- Aircraft following specific speed profiles
- Guaranteed temporal separation: σ between each pair of consecutive aircraft (no a/c categories)
- Arrival time of aircraft to entry point fixed
- Operational requirements
  - ❖ **No more than two routes merge at a point:** in-degree ≤ 2
  - ❖ **Merge point separation:** distance threshold L
  - ❖ Aircraft dynamics → **No sharp turns:** angle threshold α, minimum edge length L
  - ❖ **Obstacle avoidance** (e.g., no-fly zones)
  - ❖ **Smooth transition** between consecutive trees when switching

We add:

- Flexible time of arrival at TMA entry points
- Separation with different wake turbulence categories

Our Previous MIP Model

Binary variables $y_{a,\,j,p,n,t}$: indicate whether a/c *a* using speed profile *p* occupies the *n*-th vertex (on the path from its entry point) *j* at time *t*

New Constraints: Flexible Time of Arrival at TMA Entry Points

- Before: aircraft a arrives at entry point $b \in \mathcal{P}$ at given time $t^b{}_a$
- Now: aircraft a arrives at entry point $b \in \mathcal{P}$ within interval $[\, t^{b,1}{}_a \,,\, t^{b,2}{}_a \,]$

$$
\begin{aligned}
\sum_{t=t_a^{b,1}}^{t_a^{b,2}} \sum_{p \in \mathcal{S}(a)} y_{a,b,p,1,t} &= 1 && \forall b \in \mathcal{P}, \forall a \in \mathcal{A}_b \\
y_{a,b,p,k,t} &= 0 && \forall b \in \mathcal{P}, \forall a \in \mathcal{A}_b, \forall p \in \mathcal{S}(a), \forall t \leq t_a^{b,1}, \forall k \neq 1 \in \mathcal{L} \\
y_{a,b,p,1,t_a^b} &= 0 && \forall b \in \mathcal{P}, \forall a \in \mathcal{A}_b, \forall p \in \mathcal{S}(a), \forall t \in T : t_a^{b,1} < t < t_a^{b,2} \\
\sum_{t=t_a^{b,1}}^{t_a^{b,2}} y_{a,b,p,1,t} &= 1 - \psi_{b,a,p} && \forall b \in \mathcal{P}, \forall a \in \mathcal{A}_b, \forall p \in \mathcal{S}(a) \\
y_{a,j,p,k,t} &= 0 && \forall b \in \mathcal{P}, \forall a \in \mathcal{A}_b, \forall p \in \mathcal{S}(a), \forall t < t_a^{b,1}, \forall k \in \mathcal{L}
\end{aligned}
$$

New Constraints: Separation with Different Wake Turbulence Categories

- Before: Uniform temporal separation of σ for any pair of consecutive aircraft
- Now: We use ICAO's aircraft categories LIGHT (L), MEDIUM (M), HEAVY (H) (+SUPER)
  - $\sigma_{A,B}$: temporal separation if leading a/c category A, trailing aircraft category B
  - We use categories C1={H,M}, C2={L}

If leading and trailing aircraft are of two different (A≠B) categories, we enforce a temporal separation of $\sigma_{A,B}$

$$\sum_{a\in B}\sum_{p\in\mathcal{S}(a)}\sum_{k\in\mathcal{L}}\sum_{\tau=t}^{t+\sigma_{AB}-1} y_{a,j,p,k,\tau} \leq \Omega - \Omega\cdot\sum_{a'\in A}\sum_{\substack{p'\in\\ \mathcal{S}(a')}}\sum_{k'\in\mathcal{L}} y_{a',j,p',k',t} \quad \forall j\in V, \forall t\in\{0,\dots,\overline{T}-\sigma_{A,B}\}$$

$$\sum_{a\neq a'\in A}\sum_{p\in\mathcal{S}(a)}\sum_{k\in\mathcal{L}}\sum_{\tau=t}^{t+\sigma_{AA}-1} y_{a,j,p,k,\tau} \leq \Omega - \Omega\cdot y_{a',j,p',k',t} \quad \forall a'\in A, \forall p\in\mathcal{S}(a')\forall j\in V, \forall t\in\{0,\dots,\overline{T}-\sigma_{A,A}\}$$

If leading and trailing aircraft are of the same category A, we enforce a temporal separation of $\sigma_{A,A}$

Generation of CDO Profiles

Generation of CDO Profiles

Compute descent trajectories for:
- Each arriving aircraft
- Each possible route length within TMA
- Neutral CDOs for all descents: idle thrust, no speed brakes

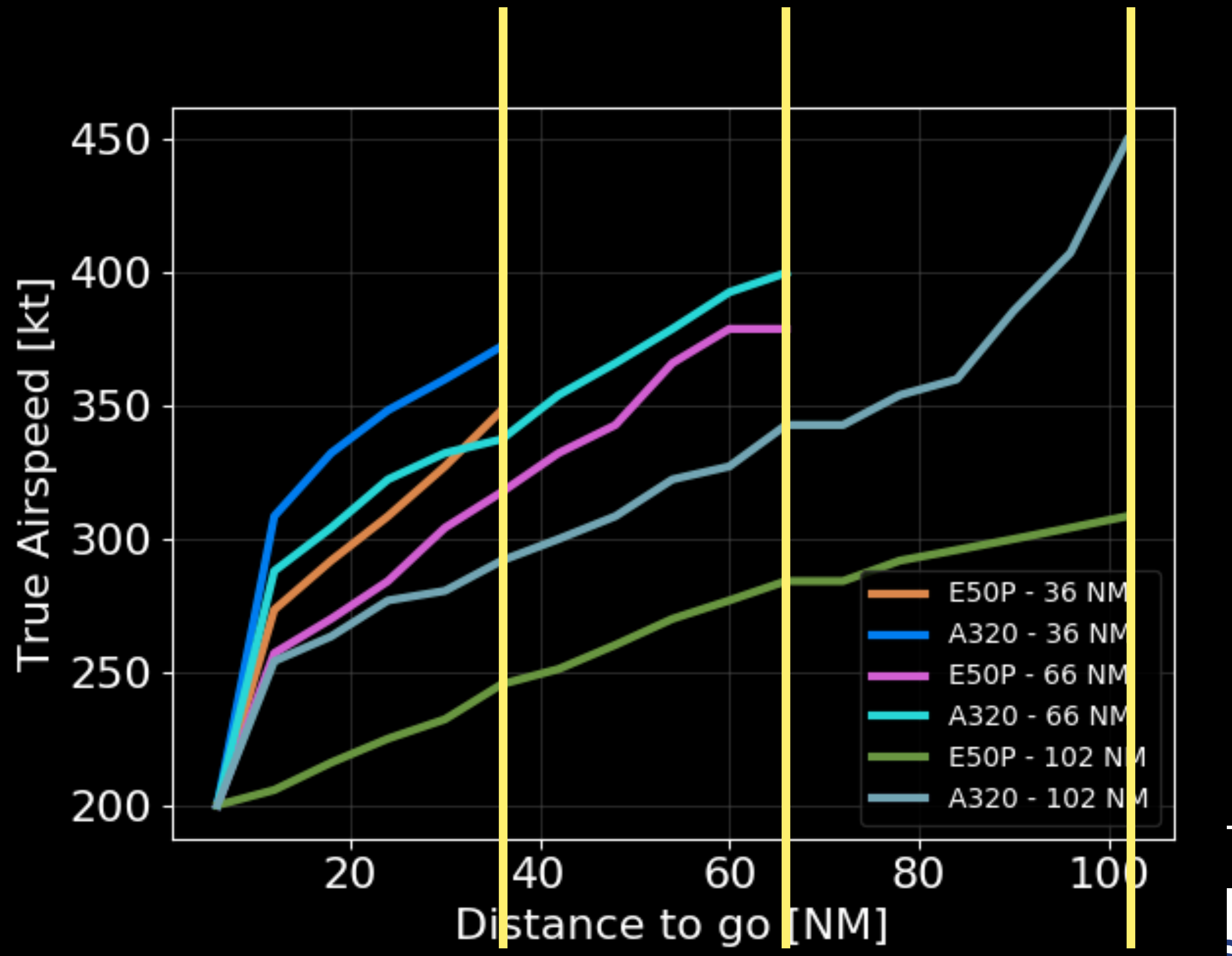
Route length → Fixed distance-to-go
➡ Optimization of the vertical profile (altitude+speed) stated as an optimal control problem

Realistic neutral CDO speed profiles, assumptions:
- No wind
- International standard atmospheric conditions

Plus:
- Aircraft model
- Current altitude
- True airspeed at TOD
- Distance to go

Examples: Airbus A320 (medium)
+ Embraer EMB Phenom 100 (light)

Same distance to go: airspeed of light a/c lower than of medium a/c
➜ Takes longer to fly each segment in TMA



Experimental Study: Stockholm TMA

Experiments

- Data:
  - One of the busiest hours of operation 2018: May 16, 2018, 5:00AM-6:00AM
  - Historical flight trajectories from Opensky
  - Aircraft performance parameters (CDO generation): BADA 4.1
  - Aircraft model not in BADA: we use comparable aircraft (performance+dimensions)
- MIP solver Gurobi (on Tetralith server, utilizing Intel HNS2600BPB computer nodes with 32 CPU cores, 384 GB)
- Split hour in 2x30 minutes

➡ Constraints for consistency between trees of consecutive time periods

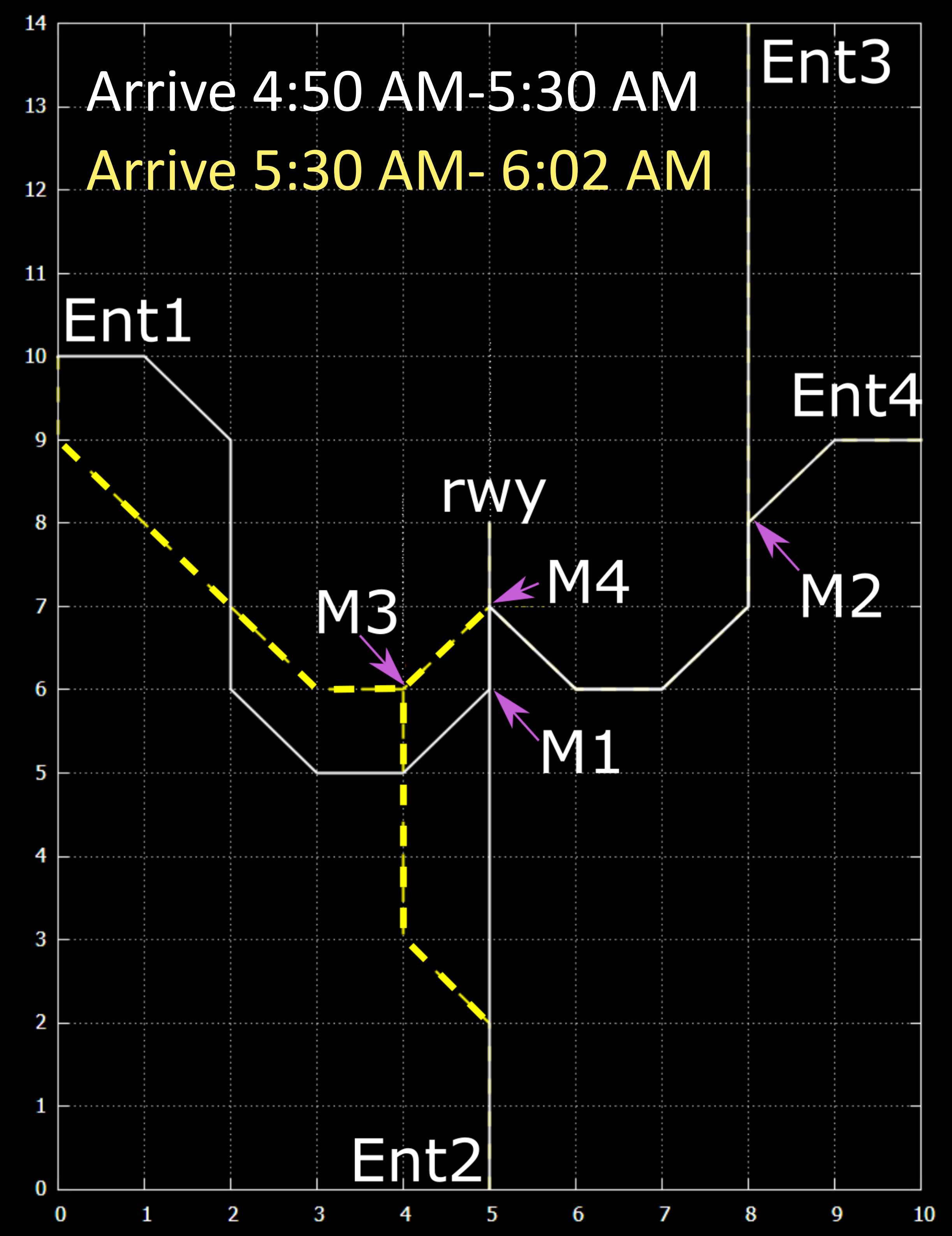
- 11x15 grid (➜ merge point separation of ~6NM, current op 5NM ➜ in operational range)
- ICAO's separation minima: $\sigma_{C1,C2}$= 3 mins, $\sigma_{C1,C1}=\sigma_{C2,C2}=\sigma_{C2,C1}$=2 mins (C1={H,M}, C2={L})
- All a/c scheduled to arrive within +/- 5 min of original arrival time ($[\, t^{b,1}_a , t^{b,2}_a \,] = [t^b_a$ - 5mins, t^b_a + 5 mins])
- Given flight: paths lengths 30 NM - 108 NM

➡ 14 possible path lengths

➡ 14 trajectories, all with same time at TMA entry point (different cost index values for each trajectory)

Experiment 1: Original Traffic, May 16, 2018, 5:00AM-6:00AM

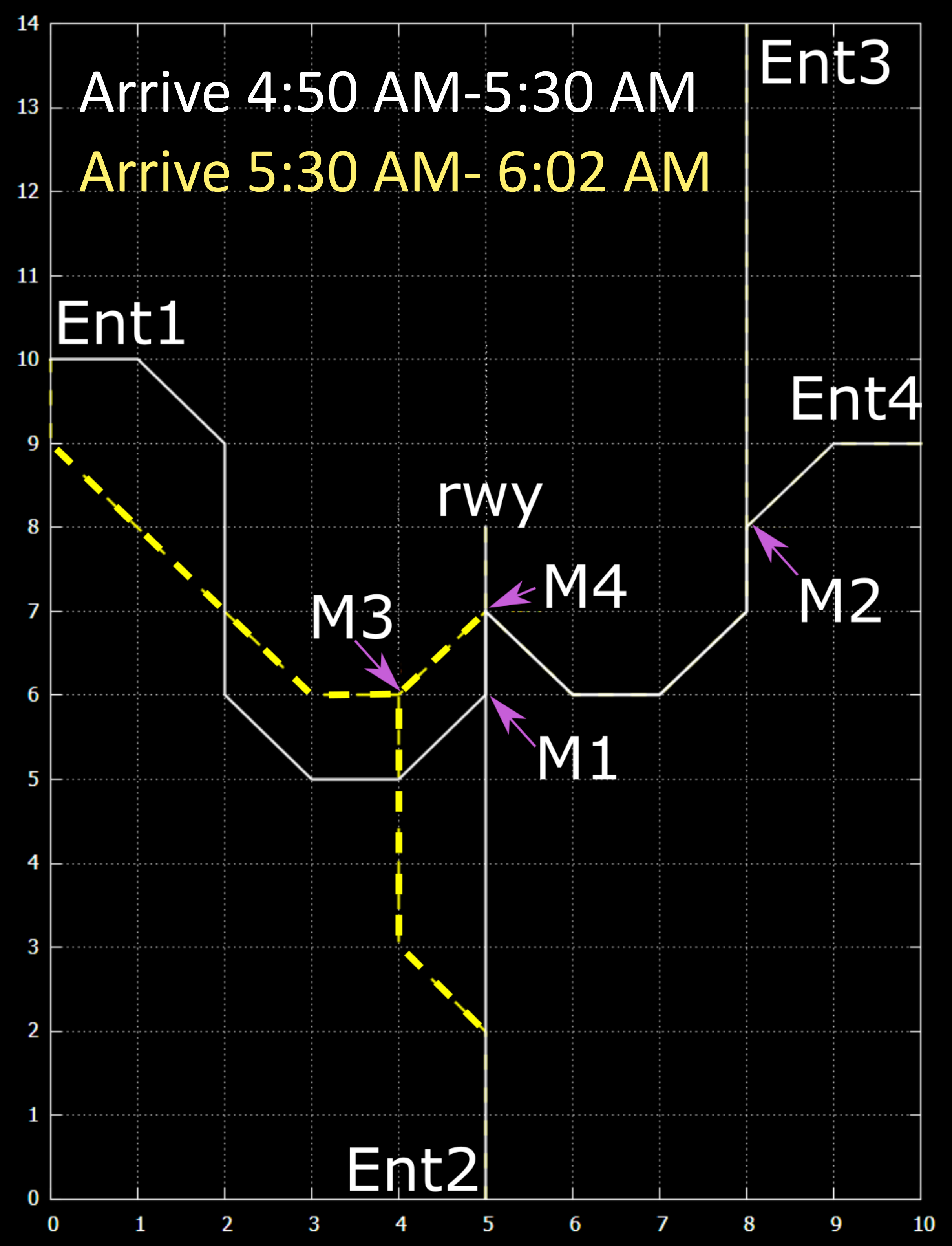
Experiment 1: Original Traffic, May 16, 2018, 5:00AM-6:00AM

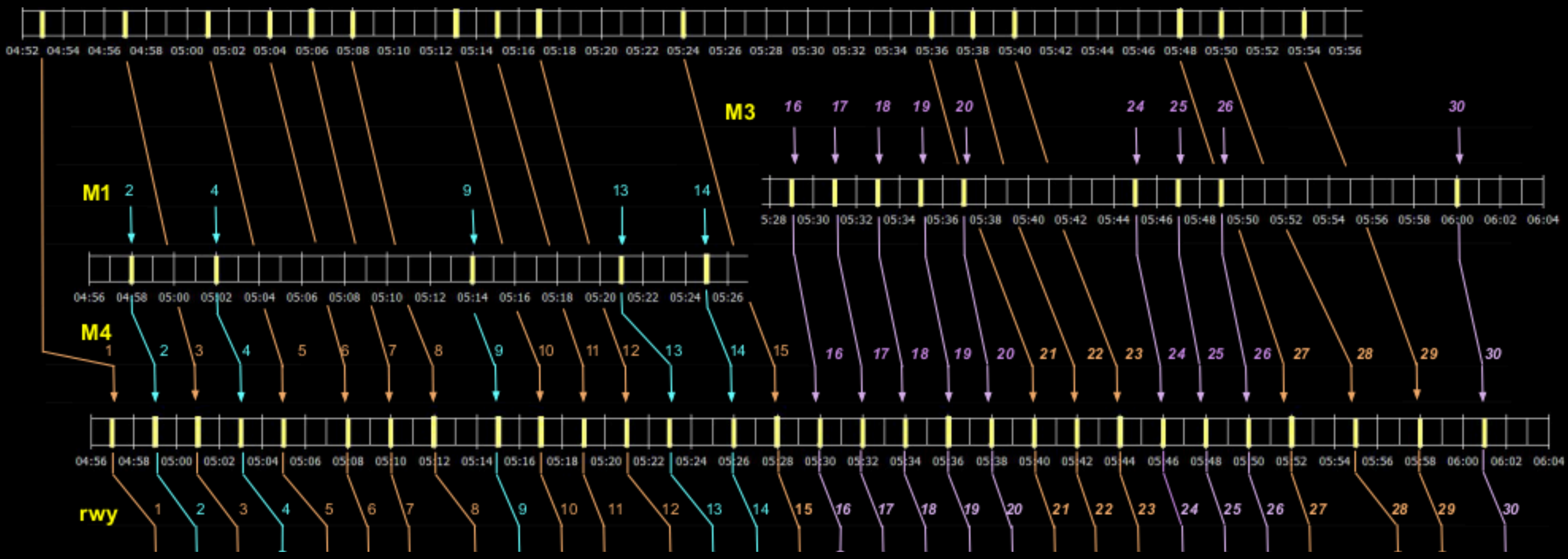


Average entry time deviation: 2.27 minutes

Aircraft	Entry point	Entry	M1	M2	M3	M4	rwy
a1	Ent1 (West)	4:51	-	4:53	-	4:57	4:59
a2	Ent2 (South)	4:52	4:58	-	-	4:59	5:01
a3	Ent3 (North)	4:51	-	4:57	-	5:01	5:03
a4	Ent2	4:56	5:02	-	-	5:03	5:05
a5	Ent3	4:55	-	5:01	-	5:05	5:07
a6	Ent3	4:58	-	5:04	-	5:08	5:09
a7	Ent1	5:04	-	5:06	-	5:10	5:11
a8	Ent1	5:06	-	5:08	-	5:12	5:14
a9	Ent4 (East)	5:06	5:14	-	-	5:15	5:16
a10	Ent3	5:07	-	5:13	-	5:17	5:18
a11	Ent3	5:09	-	5:15	-	5:19	5:20
a12	Ent3	5:11	-	5:17	-	5:21	5:23
a13	Ent2	5:09	5:21	-	-	5:23	5:25
a14	Ent4	5:17	5:25	-	-	5:26	5:27
a15	Ent3	5:18	-	5:24	-	5:28	5:29
a16	Ent4	5:24	-	-	5:29	5:30	5:31
a17	Ent2	5:25	-	-	5:31	5:32	5:33
a18	Ent2	5:27	-	-	5:33	5:34	5:35
a19	Ent2	5:29	-	-	5:35	5:36	5:37
a20	Ent4	5:32	-	-	5:37	5:38	5:39
a21	Ent3	5:30	-	5:36	-	5:40	5:41
a22	Ent1	5:36	-	5:38	-	5:42	5:43
a23	Ent1	5:38	-	5:40	-	5:44	5:45
a24	Ent4	5:40	-	-	5:45	5:46	5:47
a25	Ent4	5:42	-	-	5:47	5:48	5:49
a26	Ent4	5:44	-	-	5:49	5:50	5:51
a27	Ent1	5:46	-	5:48	-	5:52	5:53
a28	Ent3	5:44	-	5:50	-	5:55	5:57
a29	Ent3	5:48	-	5:54	-	5:58	5:59
a30	Ent2	5:54	-	-	6:00	6:01	6:02

Experiment 1: Original Traffic, May 16, 2018, 5:00AM-6:00AM





Average time separation at runway: 2.14 mins

Experiment 2: Changed Fleet Mix–More Light Aircraft

Experiment 2: Changed Fleet Mix–More Light Aircraft

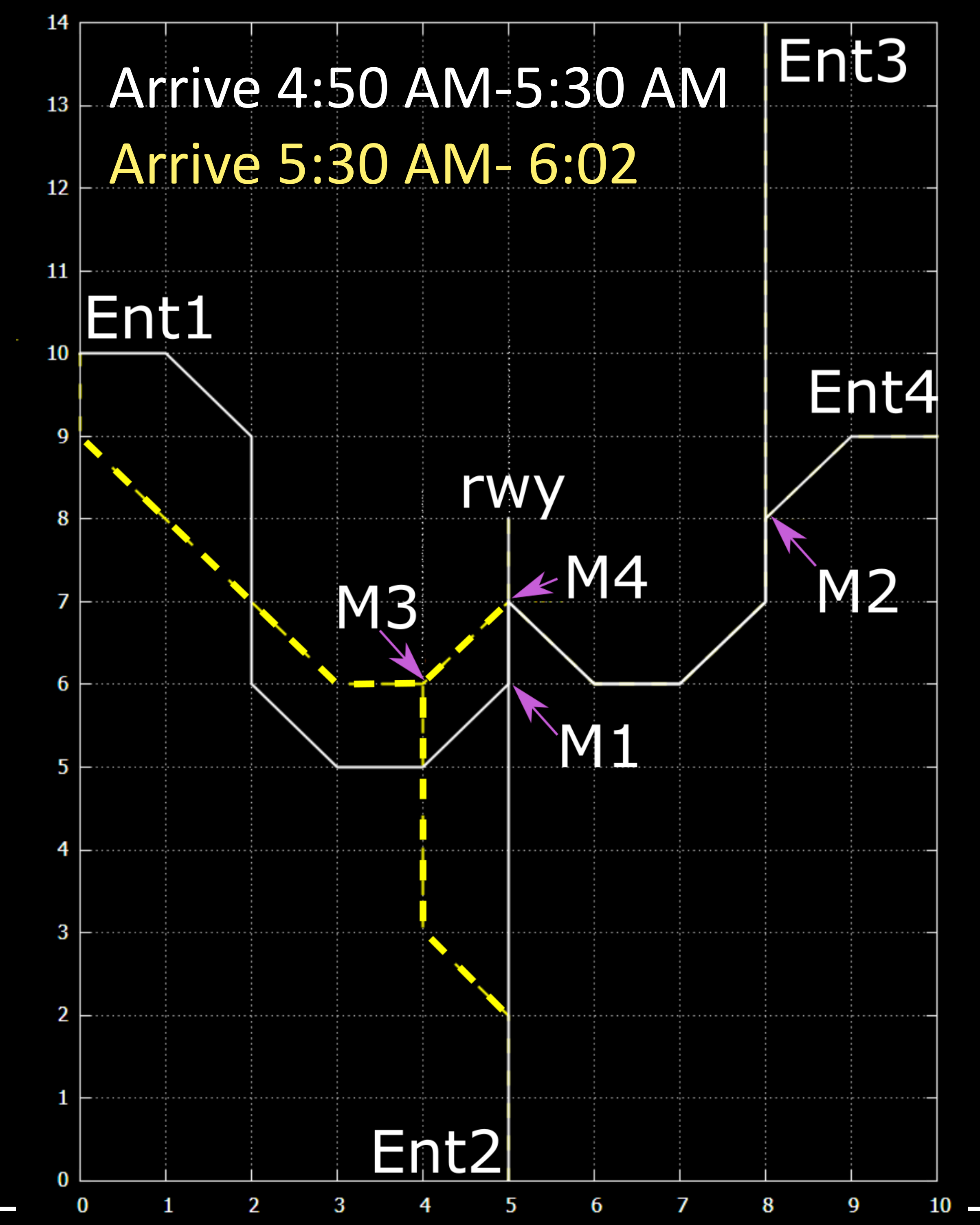
Goal: highlight influence of different a/c categories in the mix

➡ Increase share of light a/c to 20% (↔ in 2018 not more than 1% of the total traffic!)

➡ 6 randomly chosen a/c substituted by Embraer EMB-500 Phenom 100

- Lighter aircraft usually slower speed profiles for arrivals

➡ We could only schedule 25 of 30 aircraft



Average entry time deviation: 2.03 minutes

randomly added light aircraft

Aircraft	Entry point	Entry	M1	M2	M3	M4	rwy
a1	Ent1 (West)	4:51	-	4:53	-	4:57	4:59
a2	Ent2 (South)	4:52	4:58	-	-	4:59	5:01
a3	Ent3 (North)	4:51	-	4:57	-	5:01	5:03
a4	Ent3	4:54	-	5:00	-	5:04	5:06
a5	Ent3	4:57	-	5:03	-	5:07	5:09
a6	Ent1	5:04	-	5:06	-	5:10	5:11
a7	Ent1	5:06	-	5:08	-	5:12	5:14
a8	Ent4 (East)	5:06	5:14	-	-	5:15	5:16
a9	Ent3	5:07	-	5:13	-	5:17	5:18
a10	Ent3	5:09	-	5:15	-	5:19	5:20
a11	Ent3	5:11	-	5:17	-	5:21	5:23
a12	Ent2	5:09	5:21	-	-	5:23	5:25
a13	Ent4	5:17	5:25	-	-	5:26	5:27
a14	Ent4	5:23	-	-	5:28	5:29	5:30
a15	Ent2	5:24	-	-	5:30	5:31	5:32
a16	Ent2	5:26	-	-	5:32	5:33	5:34
a17	Ent4	5:29	-	-	5:34	5:35	5:36
a18	Ent4	5:32	-	-	5:37	5:38	5:39
a19	Ent2	5:34	-	-	5:40	5:41	5:42
a20	Ent1	5:37	-	5:39	-	5:43	5:44
a21	Ent3	5:37	-	5:43	-	5:48	5:50
a22	Ent2	5:44	-	-	5:50	5:51	5:53
a23	Ent1	5:48	-	5:50	-	5:54	5:56
a24	Ent3	5:47	-	5:53	-	5:57	5:58
a25	Ent4	5:53	-	-	5:58	5:59	6:00

Experiment 2: Changed Fleet Mix–More Light Aircraft

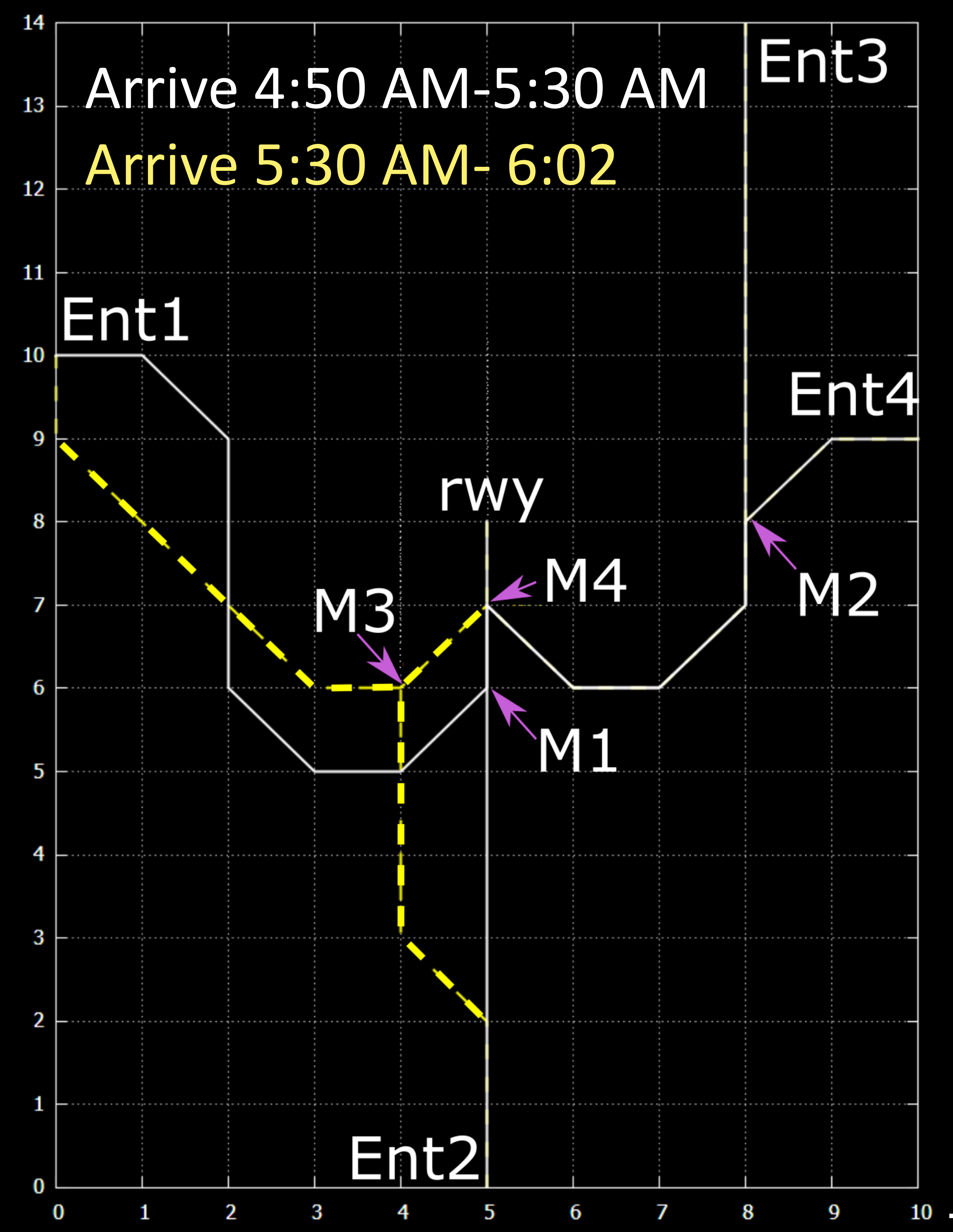
Goal: highlight influence of different a/c categories in the mix

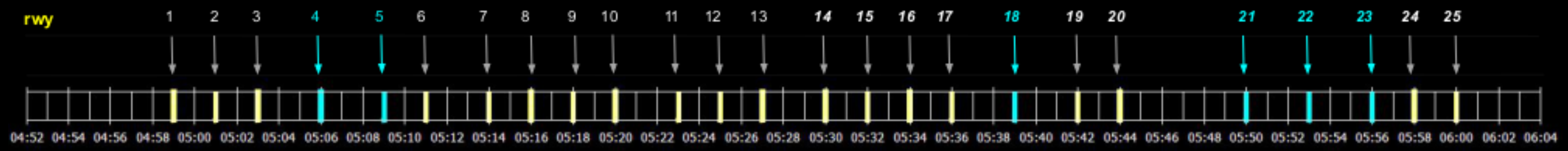
➡ Increase share of light a/c to 20% (↔ in 2018 not more than 1% of the total traffic!)

➡ 6 randomly chosen a/c substituted by Embraer EMB-500 Phenom 100

• Lighter aircraft usually slower speed profiles for arrivals

➡ We could only schedule 25 of 30 aircraft





Evaluation of Arrival Sequencing

Evaluation of Arrival Sequencing

Evaluation using set of KPIs proposed by Eurocontrol EEC

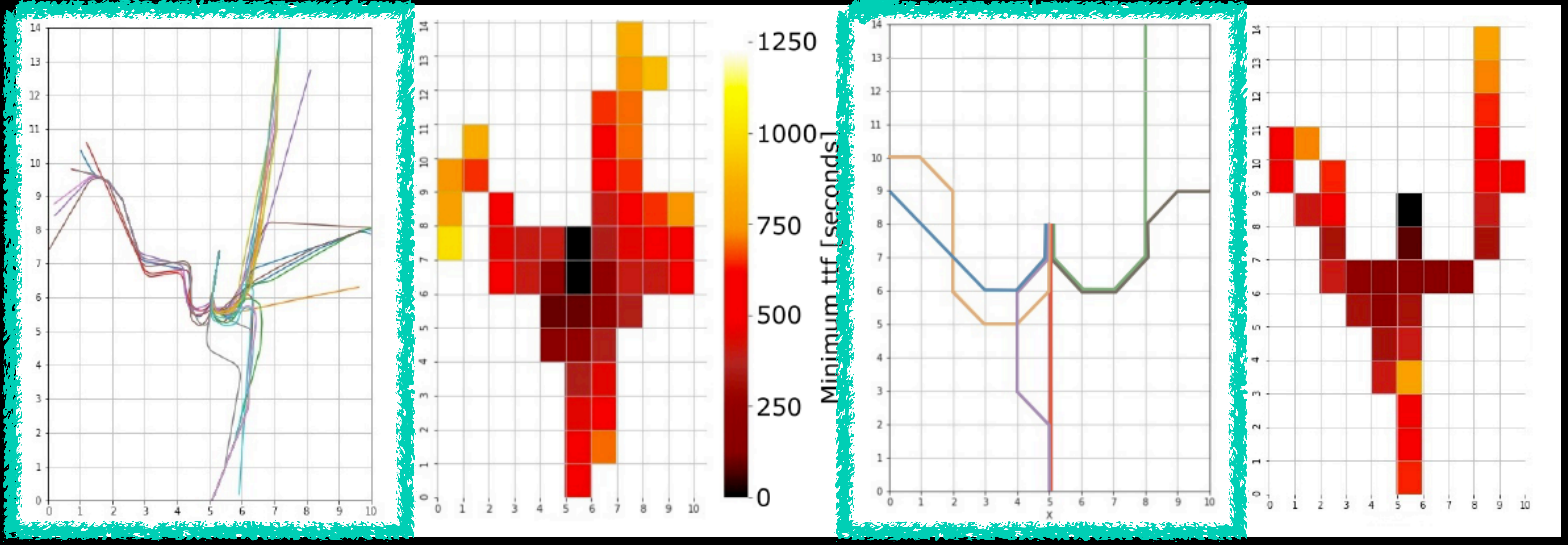
Minimum Time to Final:

- Time to final (ttf): time from a/c's current position to final approach point
- Minimum ttf: Min time needed from any point within a grid cell to the final approach along the aircraft trajectories passing the cell

Reduction lateral dispersion (all a/c follow predefined routes)

Significant reduction in average time in TMA (9.5 mins vs. 15.1 mins)

minimum ttf lies between 0 and 986, with an average of 494 seconds (SD=228)



minimum ttf lies between 0 and 660, with an average of 331 seconds (SD=161)

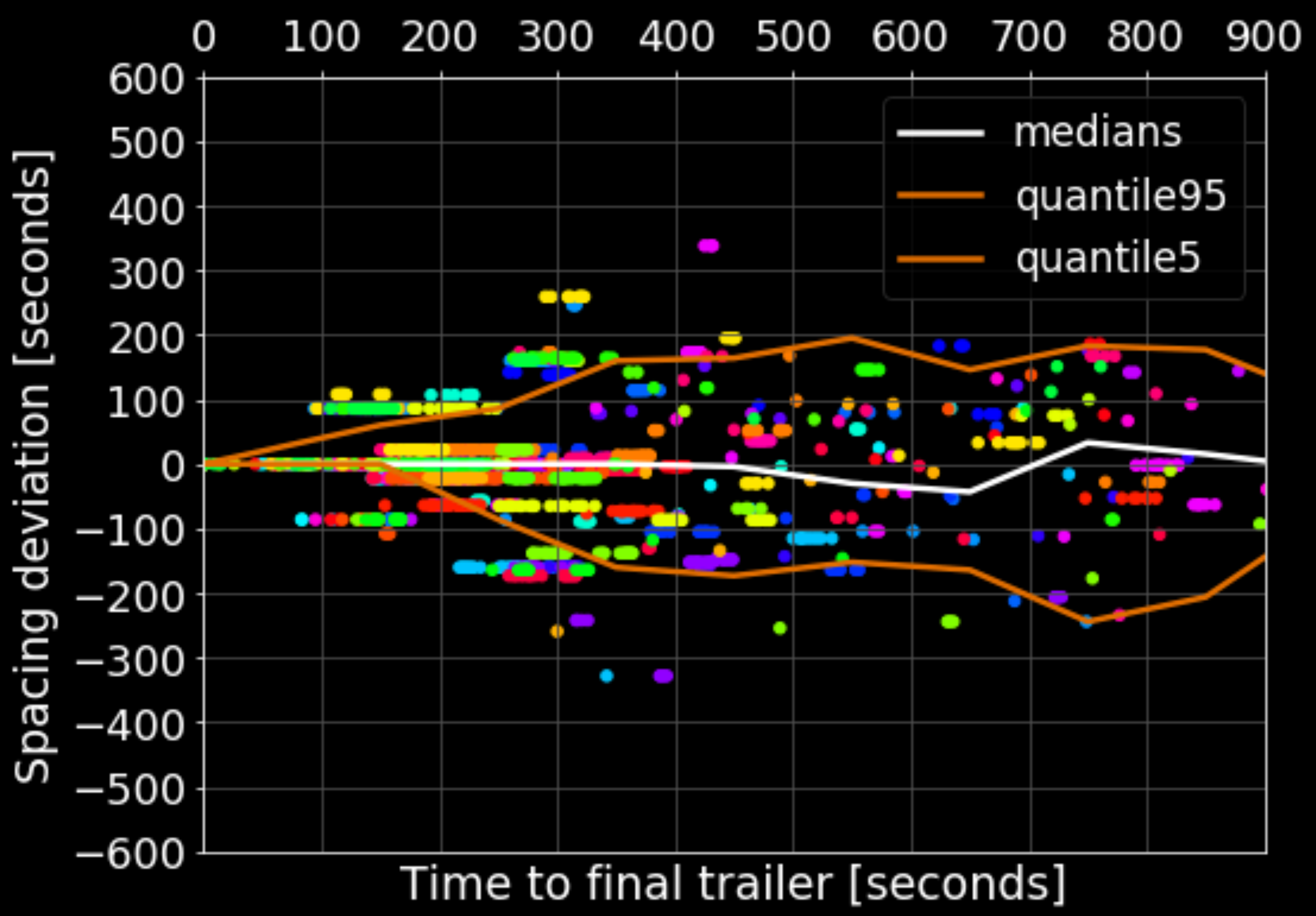
Evaluation of Arrival Sequencing

Spacing Deviation:

- Spacing for pair of arriving a/c: difference in ttf
- Spacing deviation (sd) for pair of leading and trailing a/c at time *t*:
  $sd(t) = \min ttf(trailer\ (t)) - \min ttf(leader(t - s_{rwy}))$ (s_{rwy} temporal separation at runway)
- Info on control error (accuracy of spacing around airport)

sd lies between -328 and 338, with an average of -2.86 seconds (SD=86.25)

Max width of 90th quantile: 427



sd lies between -300 and 300, with an average of 16.42 seconds (SD=69.46)

Max width of 90th quantile: 537

Not significantly reduced.

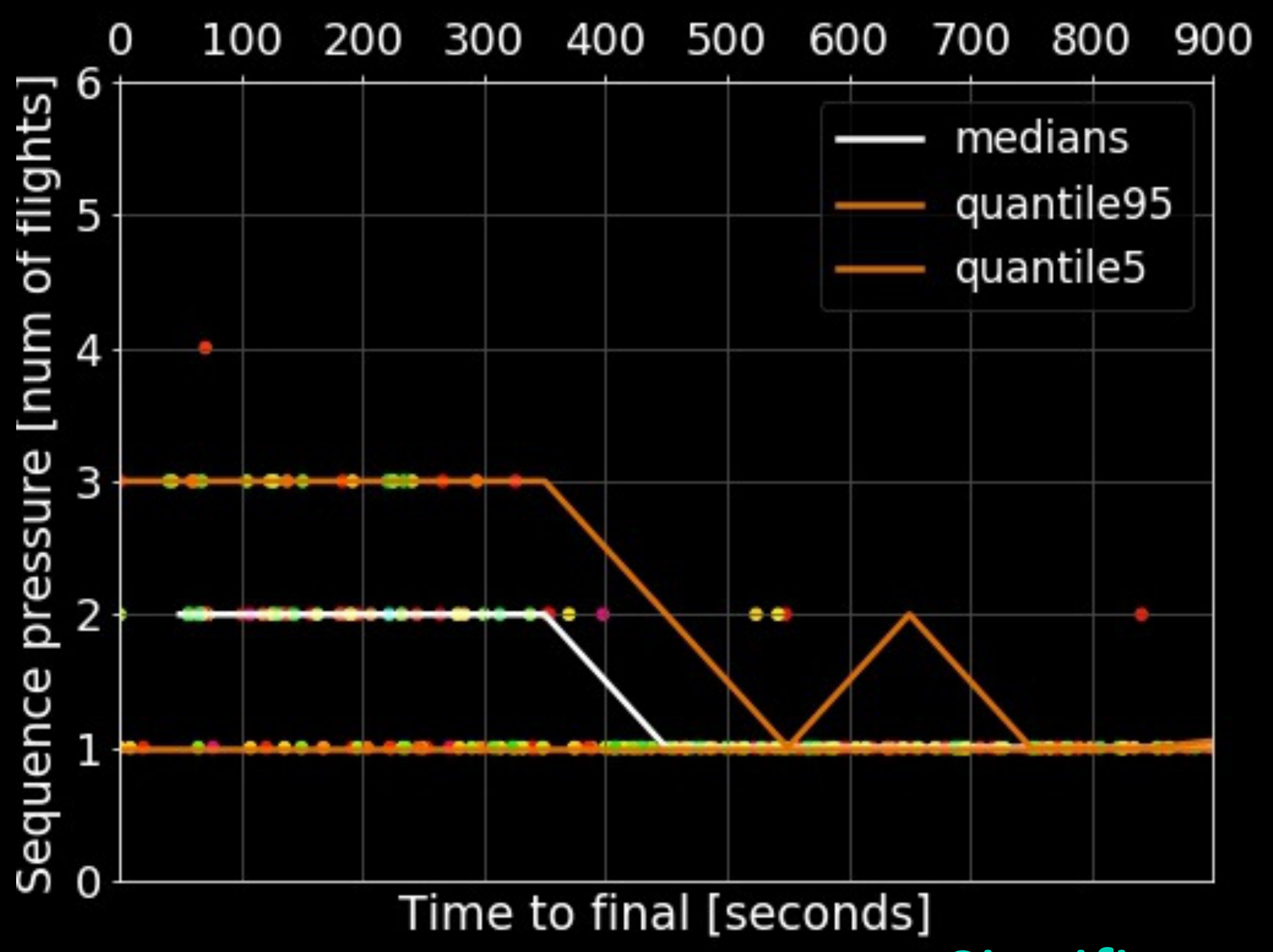
But: implementation is expected to reduce ATCO workload (not responsible for vectoring, but monitoring progress and minor corrections)

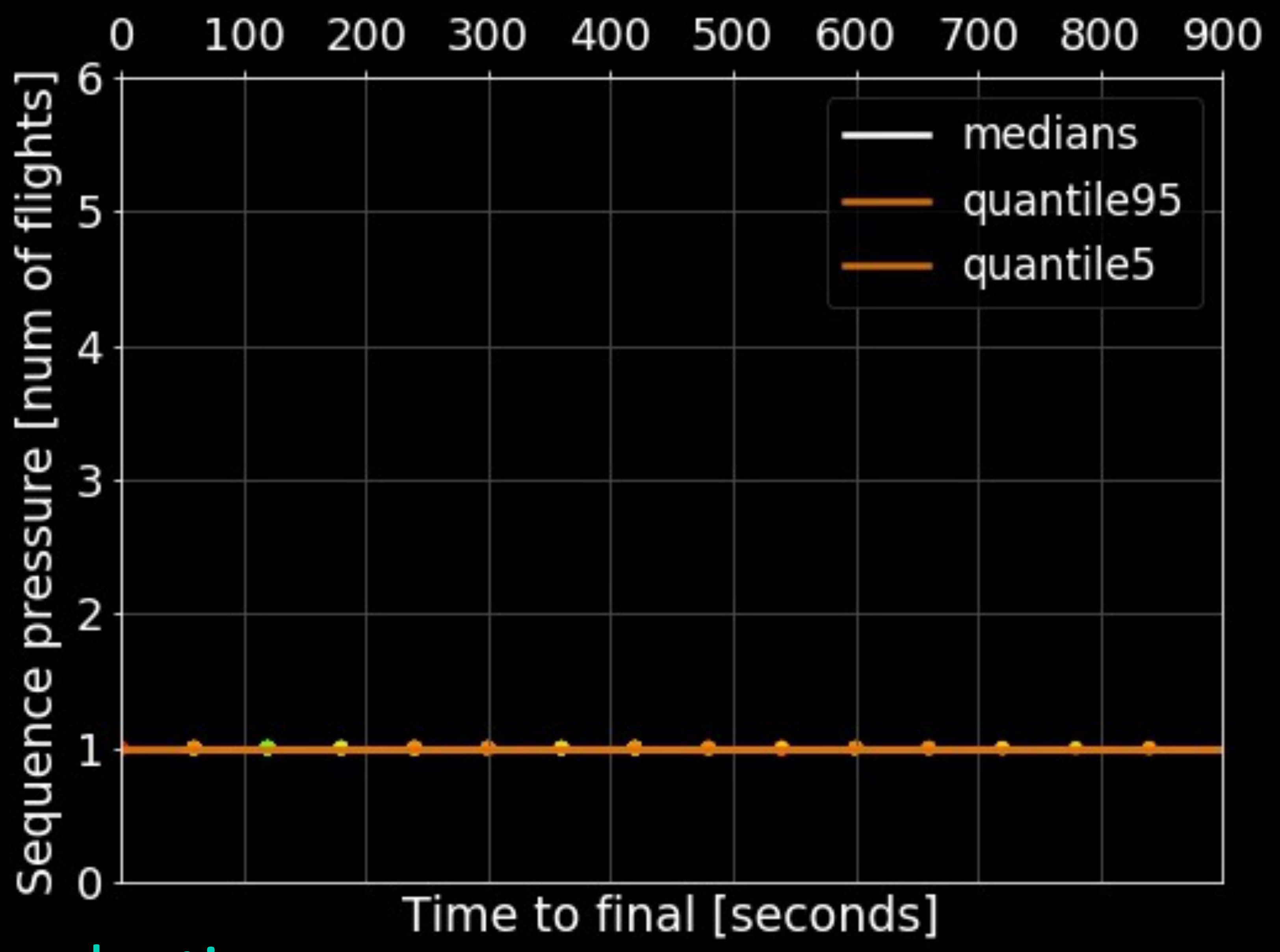
Evaluation of Arrival Sequencing

Sequence Pressure:

- Sequence Pressure for a/c at *t*: #aircraft with same ttf in given time window (here: 2mins)
- Reflects aircraft density
- We calculate it for each a/c when present in TMA, in discrete time steps

Sequence pressure at 120 seconds lies between 4 and 1 with an average of 1.38 (SD=0.65)





Sequence pressure at 120 seconds is 1 (average 1, SD=0)

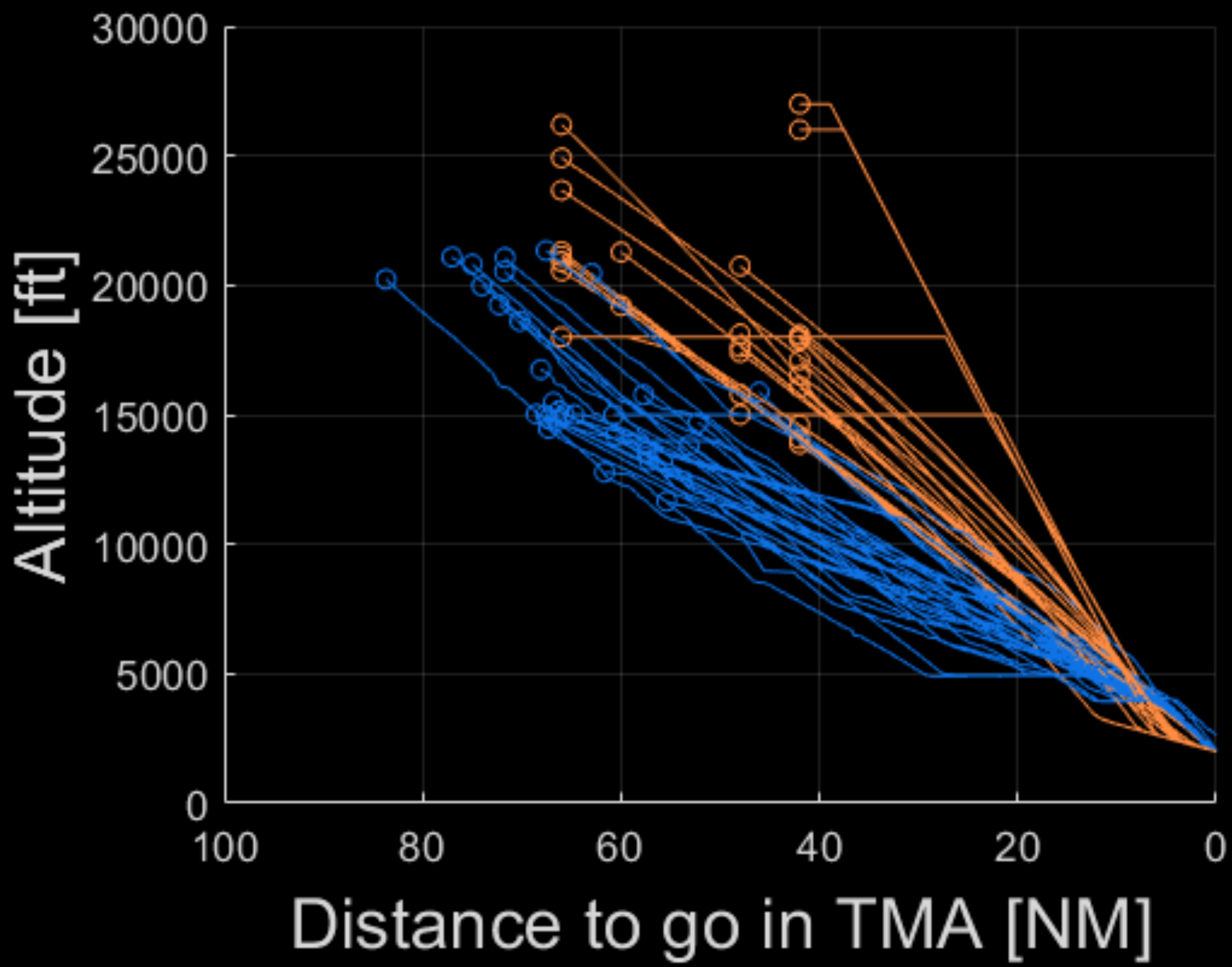
Significant reduction

Vertical Efficiency + Distance Flown in TMA

Vertical Efficiency

Actual routes

Optimised CDO-enabled routes



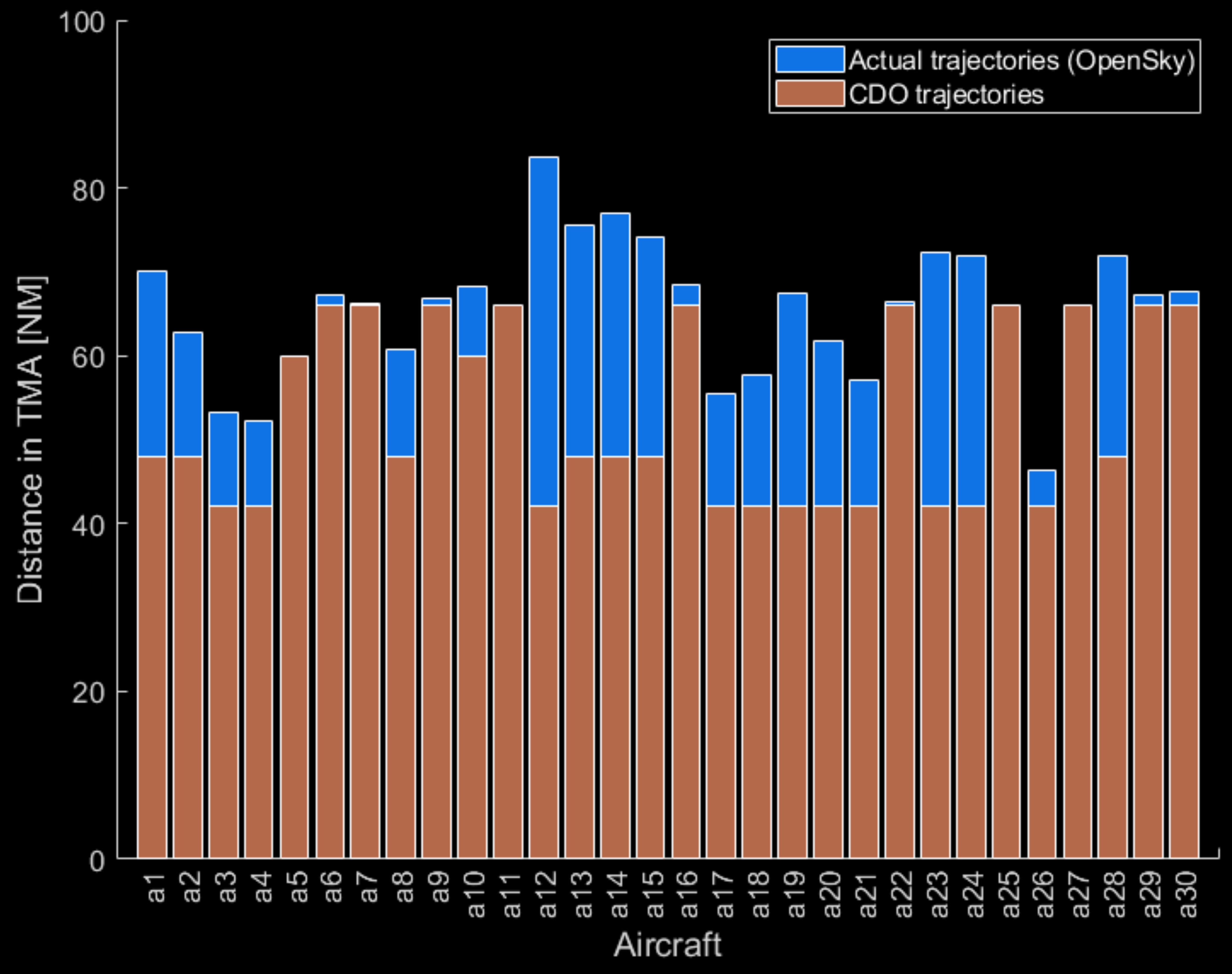
Reach lower altitude earlier

Long periods of level flight (some at very low altitudes)

➡ Results in extra fuel burn and high levels of noise

Distance in TMA

Actual routes
Optimised CDO-enabled routes



Approximation!

Total distance covered in TMA: 1958NM vs. 1578 NM

Conclusion and Outlook

Conclusion and Outlook

We show:

- Enabling flexible entry times ➜ all a/c arriving to Stockholm Arland during one of the busiest hours of operation can fly CDOs on arrival routes
- The arrival routes guarantee temporal separation
- Separation requirements based on a/c categories taken into account

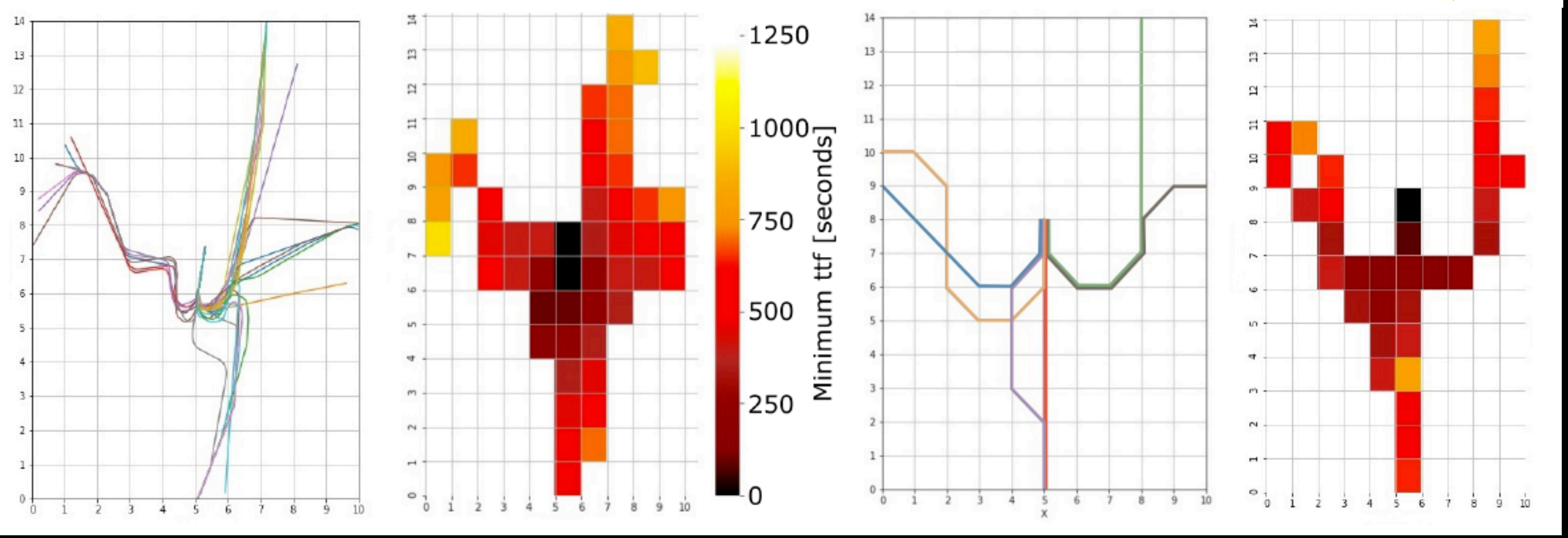
➡ Contributes to:

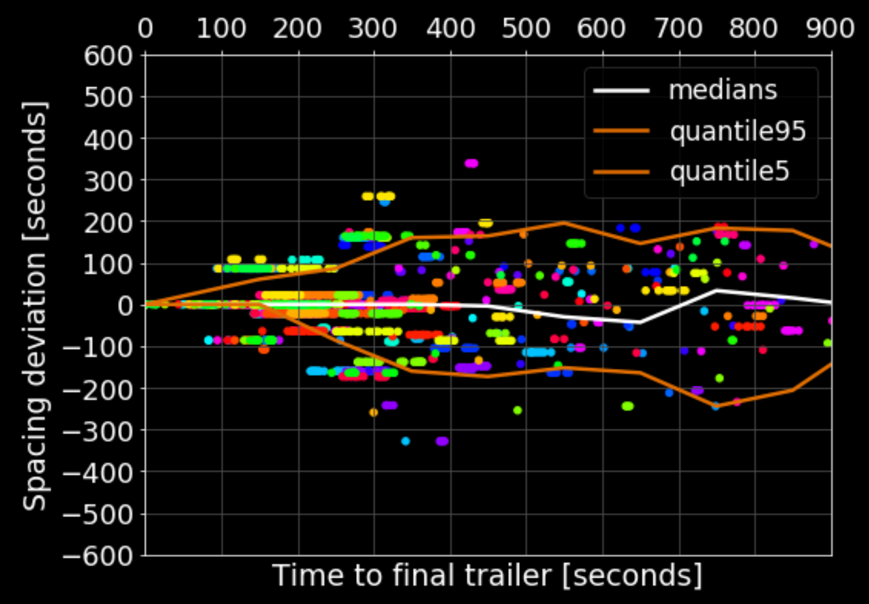
  - Reduced environmental impact
  - Automated ground support for ATCOs

- Our routes improve:
  - Vertical efficiency
  - Distance + average time in TMA
- Propose concept of operations where ATCOs contact a/c in a hypothetical E-TMA entry point or in the en-route phase

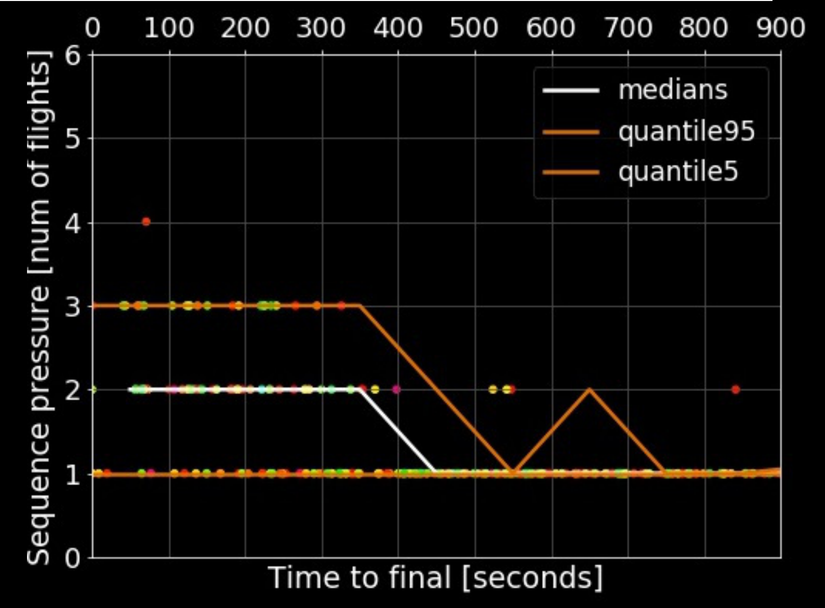
Future work:

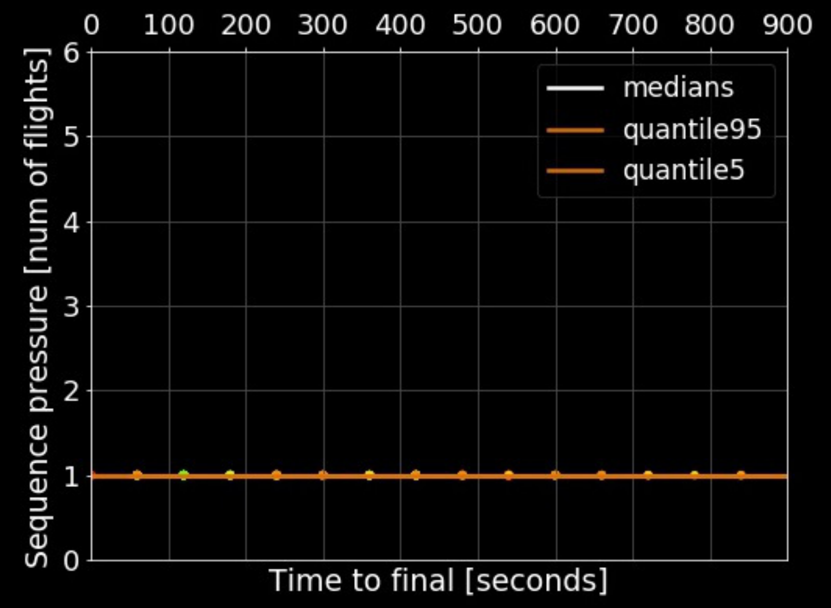
- Evaluate
  - Noise impact
  - Lateral efficiency
- Trade-off robustness/uncertainty?
- Influence of time window

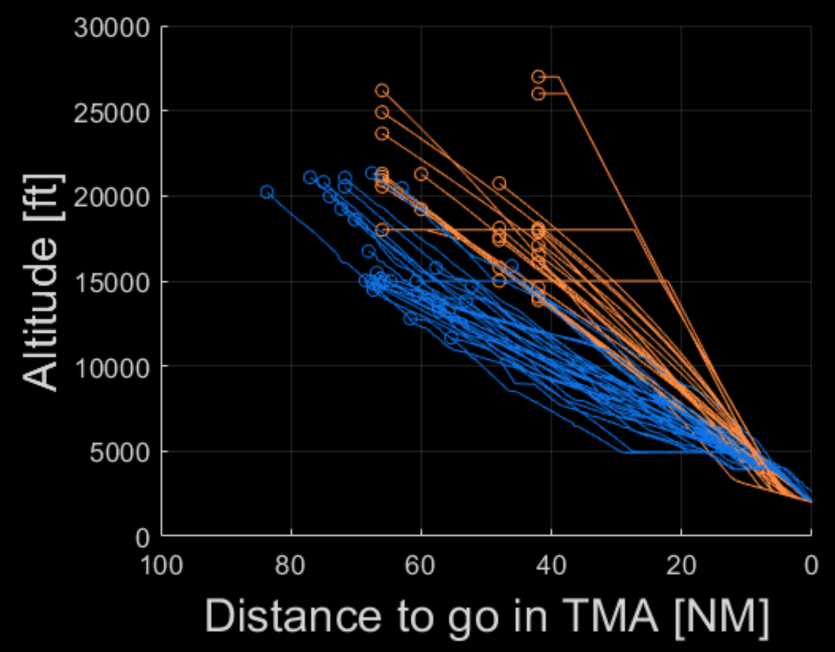


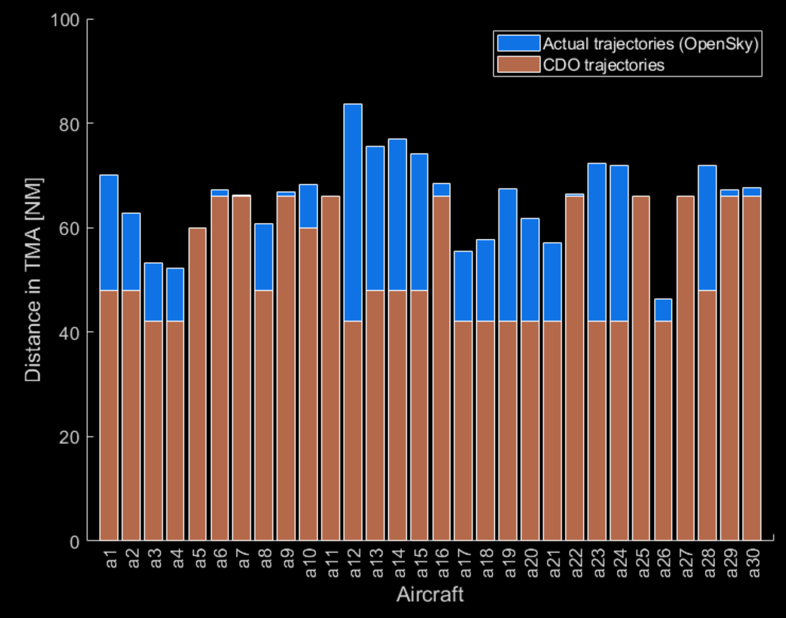


Thank you.









LINKÖPING UNIVERSITY

christiane.schmidt@liu.se
itn.liu.se/~chrsc91/