

Conditional Variational Autoencoders

for aircraft type-specific trajectory generation

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Trajectory generation is essential for:

- Capacity prediction
- Airspace and procedure design
- **Collision risk modelling and safety assessment**

Traditional approaches:

- Physics-based models (BADA, OpenAP): physically realistic but miss statistical variability
- Pure data-driven models: capture variability but may generate unflyable trajectories

Challenge: Improve both statistical realism and physical plausibility

Our earlier work used Variational Autoencoders (VAE) for trajectory generation:

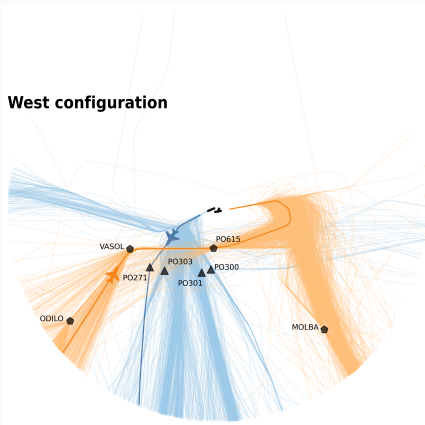
- Temporal Convolutional Networks (TCN) for sequential data
- VampPrior for improved latent space structure
- Good statistical properties for collision risk estimation

Limitation: No explicit aircraft type modeling

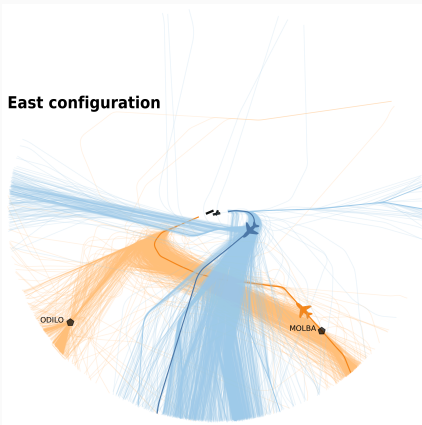
- Mixed aircraft characteristics in generated trajectories
- Cannot generate type-specific performance profiles
- Problematic for under-represented aircraft types

The data imbalance problem – a case study at Paris–Orly airport

West configuration



East configuration



The data imbalance problem

Aircraft Type	Count	Aircraft Type	Count
B738	31,358	A333	1,186
A320	21,732	A332	1,113
A321	9,573	B77W	649
A319	5,538	A339	493
A20N	3,690	A35K	484

- Domestic/short-haul: well-represented (A320, B737 families)
- Long-haul wide-bodies: sparse but **critical for safety** (different climb profiles)

Training separate models per aircraft type is not feasible for rare types

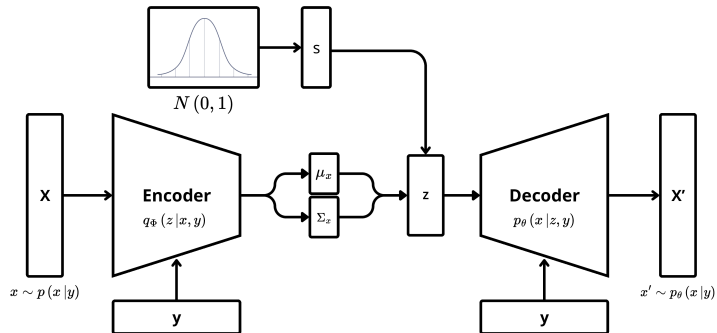
Conditional Variational Autoencoder (CVAE):

- Model the conditional distribution $p(x|y)$ where y is the aircraft type
- Single model handles multiple aircraft types
- Benefits from shared learning across all categories

Key advantages:

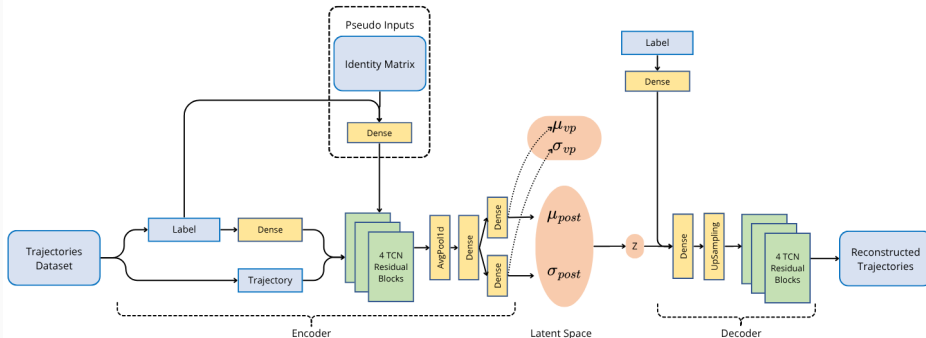
1. Comparable performance to dedicated VAE models for well-represented types
2. Enables generation for sparsely represented aircraft types
3. Improved regularization of generated trajectories

CVAE Architecture



Conditioning variable y (aircraft type) influences both encoder and decoder

CVAE with TCN and VampPrior



- One-hot encoded aircraft type concatenated with trajectory features
- Conditional VampPrior:

$$p(z|y) = \frac{1}{N} \sum_{i=1}^N \omega_i(y) q_{\varphi}(z|\chi_i(y), y)$$

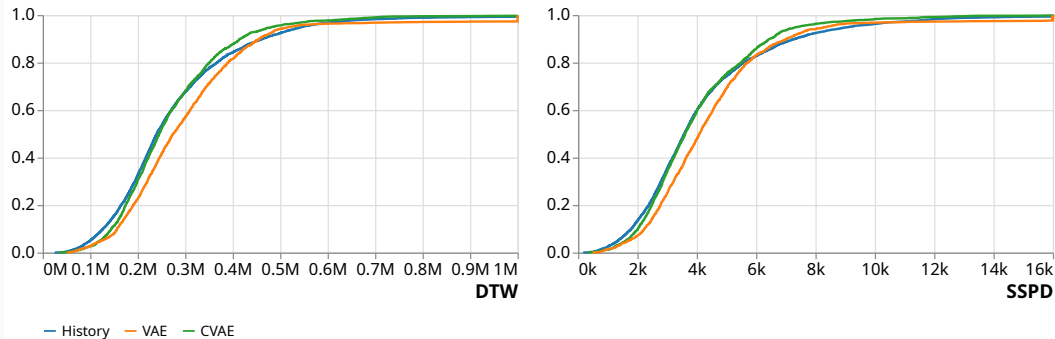
Dataset: 4 years of ADS-B data (2021-2024), Paris–Orly runway 07 departures

- 110,000+ trajectories after filtering
- Resampled to 200 points within 50 NM
- Features: track angle, ground speed, altitude, δ_t

Training configuration:

- 5 aircraft types: B738, A321, A320, A318, A21N
- **Deliberately limited A320 to 108 samples** to test performance on sparse data
- Compare CVAE vs. dedicated VAE models per type

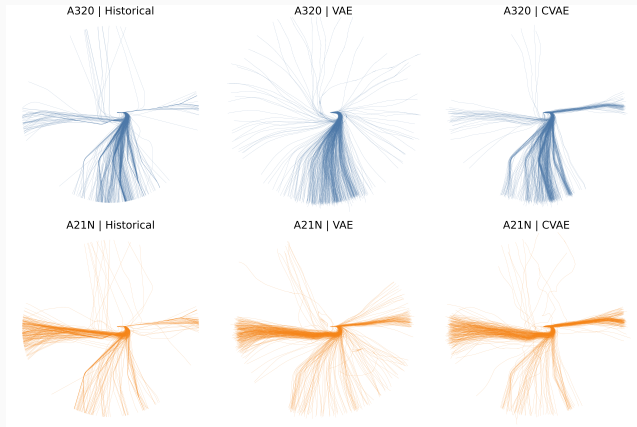
Physical realism: simulator replay



Trajectories replayed in BlueSky simulator.

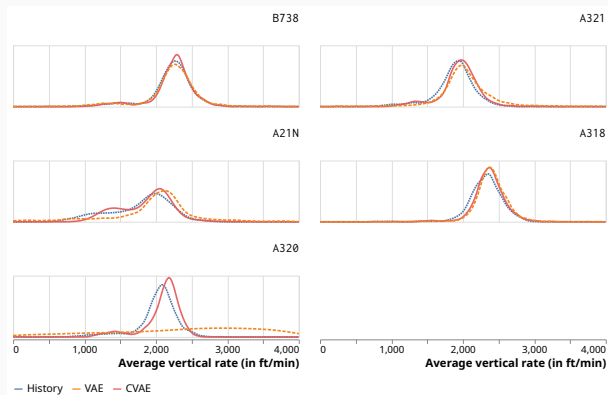
CVAE outperforms VAE on distance metrics (DTW, SSPD)

Lateral distribution quality



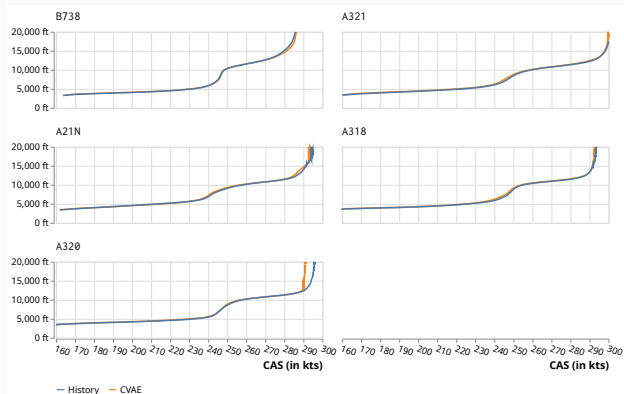
CVAE produces better-separated routes, fewer off-route samples, acts as regularizer

Vertical rate distributions



For sparse A320 data (108 samples): CVAE matches historical distribution better than VAE

Climb profile consistency



CVAE correctly reproduces 250 kts limit below 10,000 ft across all aircraft types

Key contributions

- **Single model for multiple aircraft types** with type-specific generation
- **Handles data imbalance:** good performance even with 108 training samples
- **Improved physical realism:**
 - Better simulator replay accuracy
 - Correct vertical rate distributions
 - Compliance with operational constraints
- **Enhanced regularization:** trajectories concentrate around realistic patterns

Current limitations:

- Memory constraints limit number of aircraft types and pseudo-inputs
- Wind effects not modelled (approximation: ground speed $\approx$ true airspeed)

Future directions:

- Additional contextual information (weather, airline, route)
- Transfer learning: leverage well-represented types from other airports
- Extend to arrival trajectories and other airport configurations

CVAE framework successfully addresses aircraft type-specific trajectory generation

- Simple yet effective extension of VAE-VampPrior
- Balances statistical realism and physical plausibility
- Practical solution for collision risk modeling with mixed fleets

Another nice related talk:

- *A Neural ODE Approach for Aircraft Flight Dynamics Modelling*
Gabriel Jarry (speaker), Wednesday 2:15pm