Modeling aircraft performance parameters with open ADS-B data

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Modeling Aircraft Performance Parameters with Open ADS-B Data

Junzi Sun, Joost Ellerbroek, Jacco Hoekstra

Delft University of Technology

Content

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Objective

- Open data
- Operational performance in all flight phases
  - takeoff, initial climb, climb, cruise, descent, final approach, landing
- Direct performance parameters
  - Speed, vertical rate, distance, etc
- Hidden Performance Parameters
  - Different speed and vertical rate under constant CAS/Mach profile
- As many aircraft types as possible
- Used for kinematic modeling
- Results are reproducible and open-source

Table 1: Performance model parameters

Flight phase	Performance parameters
Takeoff	V_{lof}, d_{tof}, $\bar{a}_{tof}$
Initial Climb	$V_{cas,ic}$, $V_{h,ic}$
Climb	$R_{top,cl}$, $V_{cas,cl}$, M_{cl}, $H_{cas,cl}$, $H_{mach,cl}$, $V_{h,pre\text{-}cas,cl}$, $V_{h,cas,cl}$, $V_{h,mach,cl}$
Cruise	R_{cr}, $R_{max,cr}$, H_{cr}, $H_{max,cr}$, M_{cr}, $M_{max,cr}$
Descent	$R_{top,de}$, M_{de}, $V_{cas,de}$, $H_{mach,cl}$, $H_{cas,cl}$, $V_{h,mach,de}$, $V_{h,cas,de}$, $V_{h,post\text{-}cas,de}$
Final Approach	$V_{cas,fa}$, $V_{h,fa}$
Landing	V_{app}, d_{brk}, $\bar{a}_{brk}$

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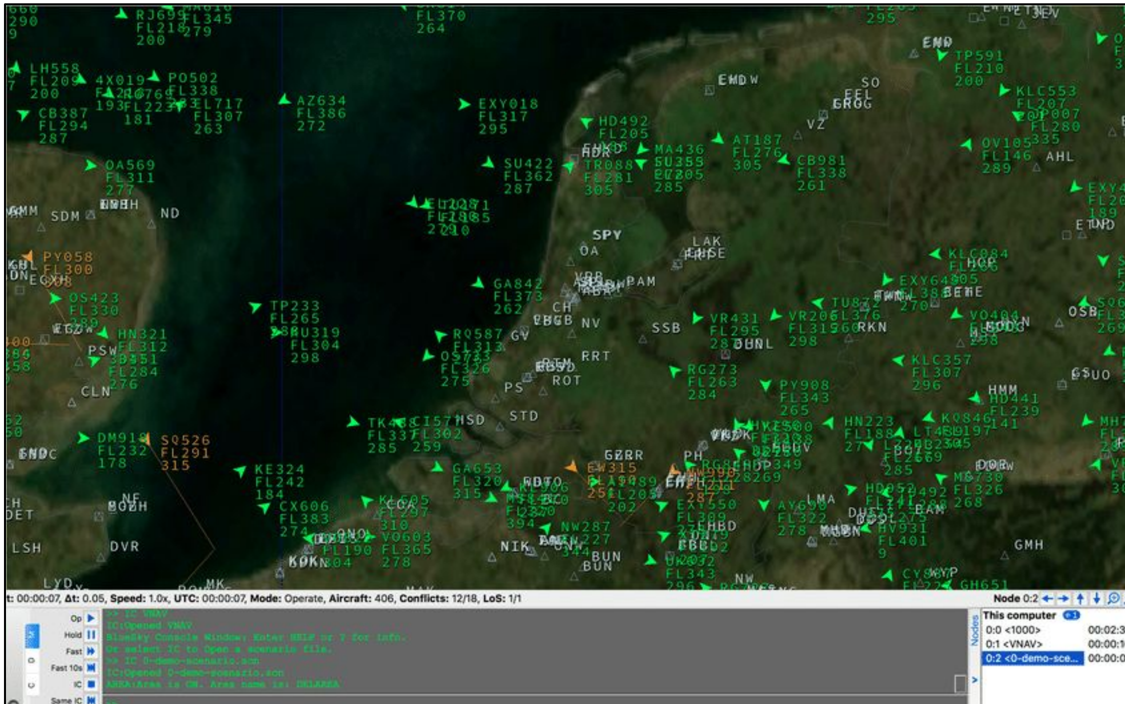
Why another model ?

Open data, open models.

Background (Open-source application)

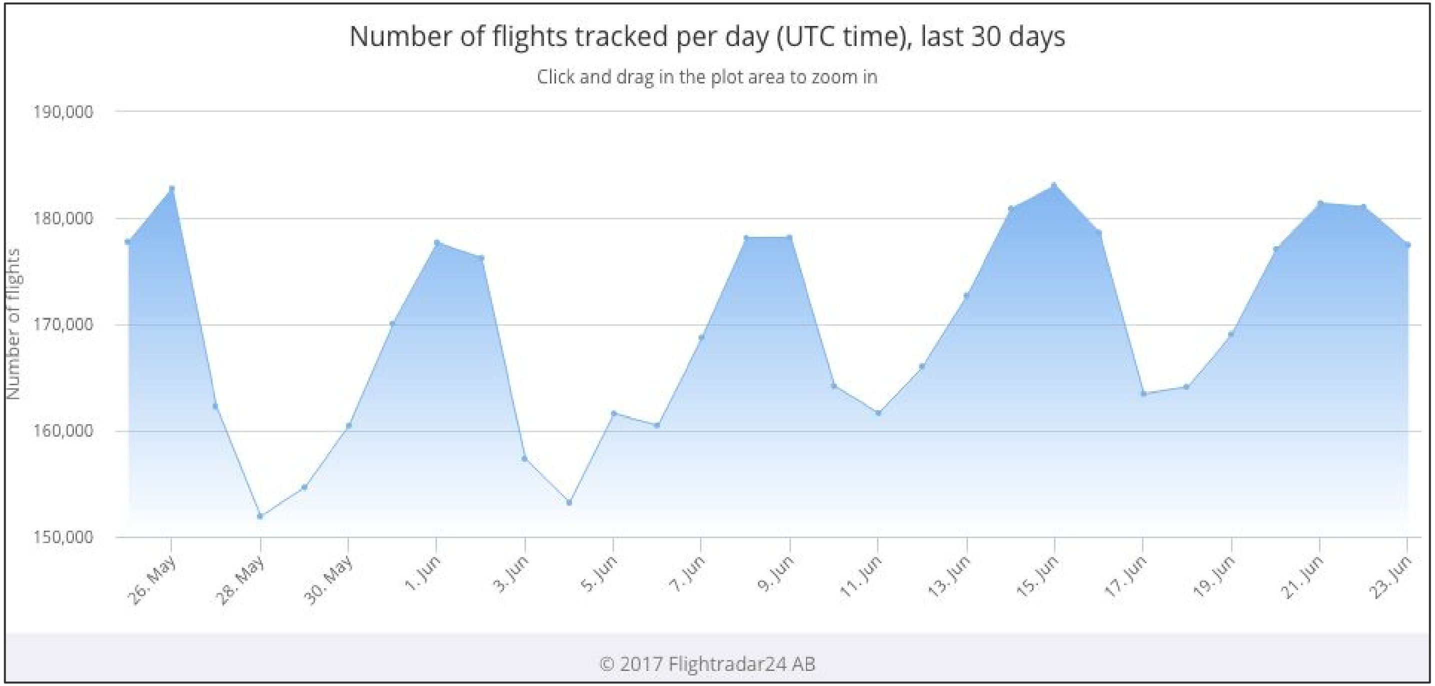
Bluesky - The open-source air traffic simulator



https://github.com/ProfHoekstra/bluesky

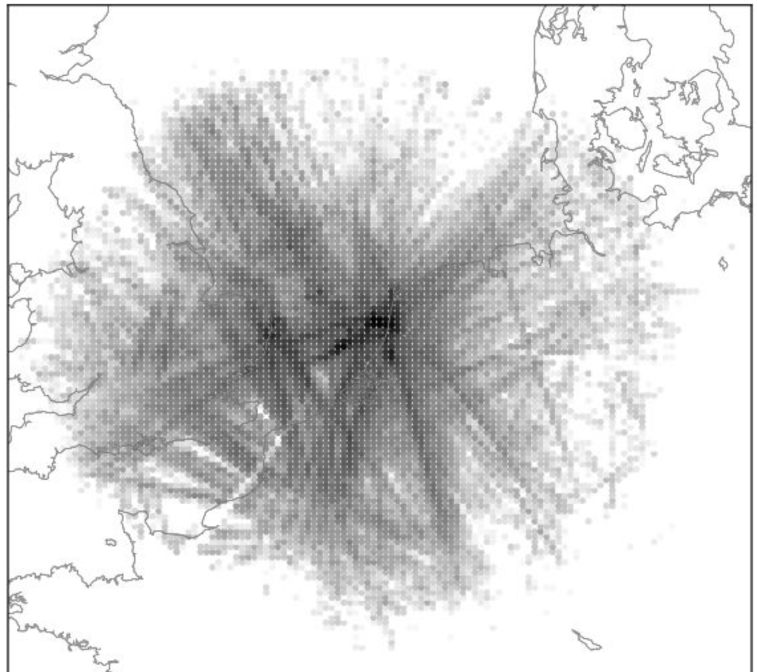
Background (Data)

Large amount of air traffic data from ADS-B



Background (Tool)

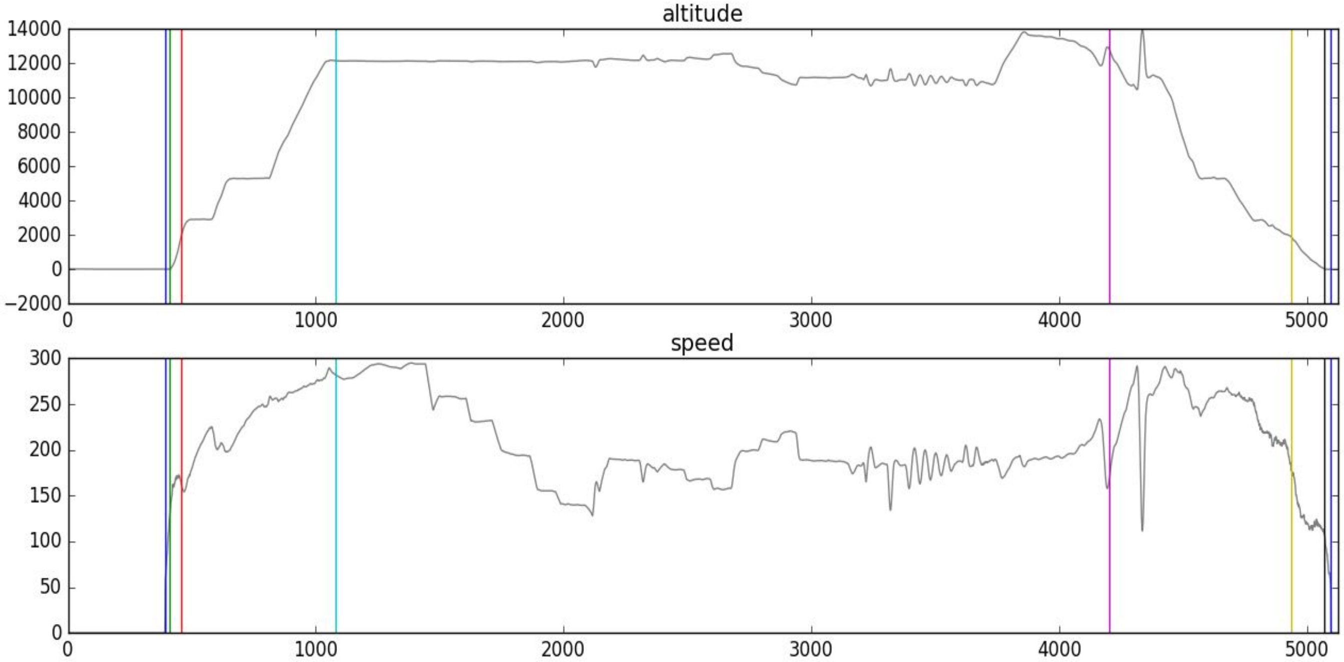
pyModeS - the Python ADS-B and Enhanced Mode-S decoder



https://github.com/junzis/pyModeS

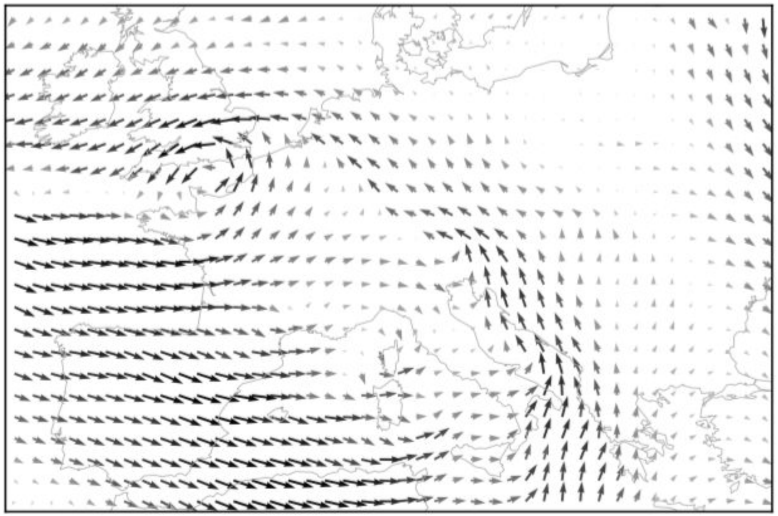
Background (Tool)

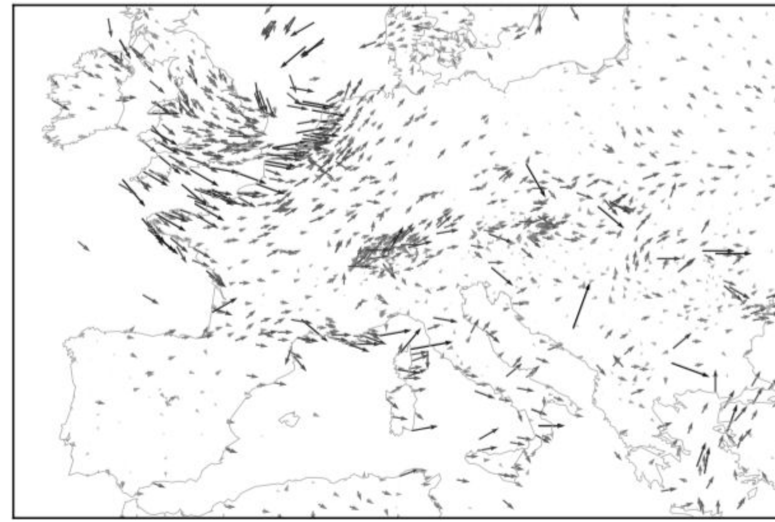
Well designed, automatic, flight phase extraction tools



takeoff > initial climb > climb > cruise > descent > final approach > landing

Background (Open wind data / model)





Global Forecast System

Updated every 6 hours

All vertical levels, except surface

Smooth wind data from GFS model

Integrated Surface Data

Typically updated every hour

Only surface data

Real time wind measurements

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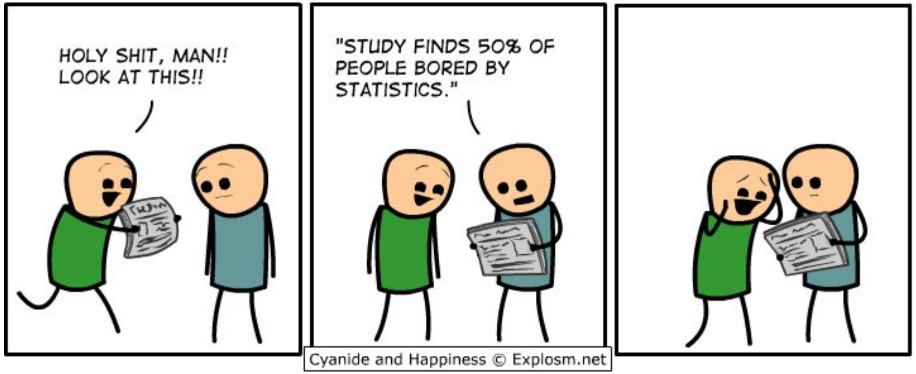
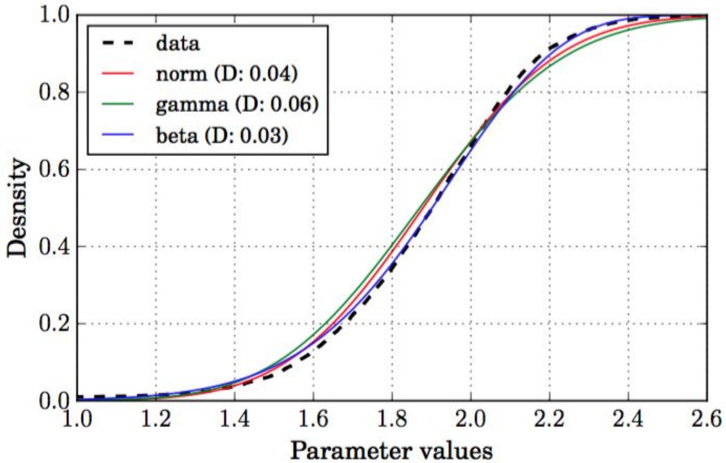
Background (Statistical model)

Parametric / non-parametric analysis

$$\{\hat{\psi}, \psi_{min}, \psi_{max}, *pdf\}$$

$$*pdf = \begin{cases} ['norm', \mu, \sigma] & for\ x \sim \mathcal{N} \\ ['gamma', \alpha, \mu, k] & for\ x \sim \Gamma \\ ['beta', \alpha, \beta, \mu, k] & for\ x \sim B \end{cases}$$





How is it constructed ?

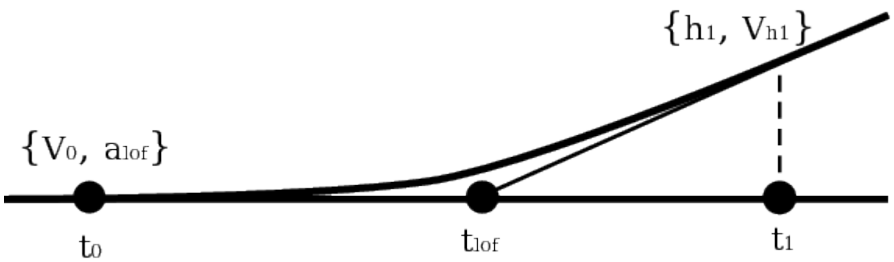
Flight phase and statistics.

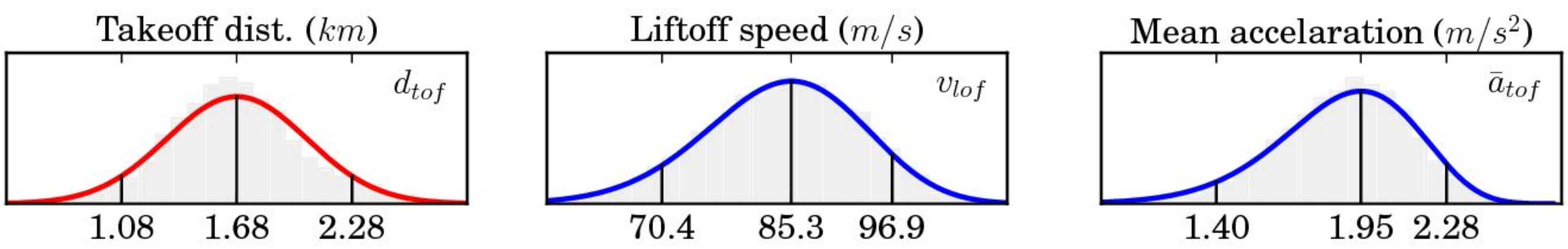
Terms and definitions

- Optimal, minimum, and maximum value
- Confidence intervals
  - 80% for most of the velocity parameters,
  - 98% for range parameters
  - 90% for other parameters.
- Distributions
  - Normal distribution (prefered)
  - Gamma distribution
  - Beta distribution

Takeoff

- Approximate the takeoff moment
- Parameters
  - Takeoff distance
  - Liftoff speed
  - Mean ground acceleration



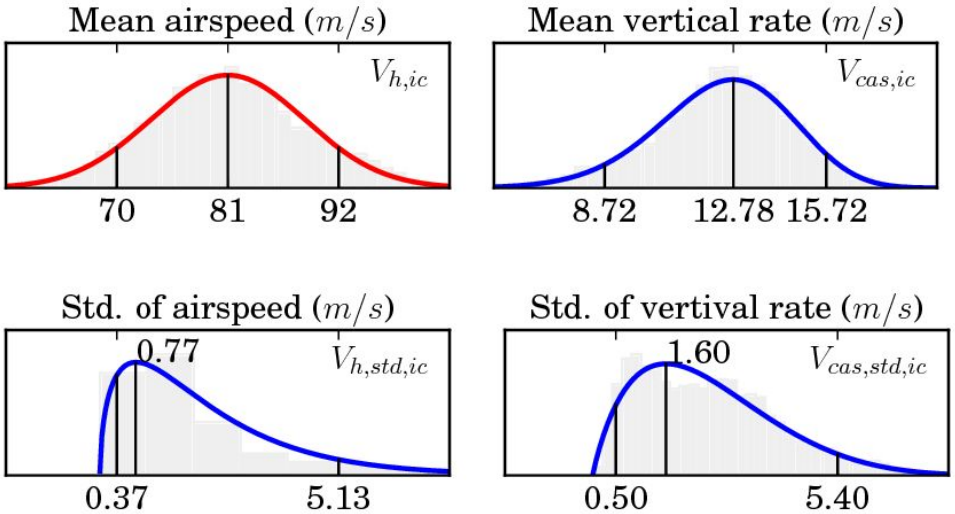


Aircraft: Airbus A320

Initial climb

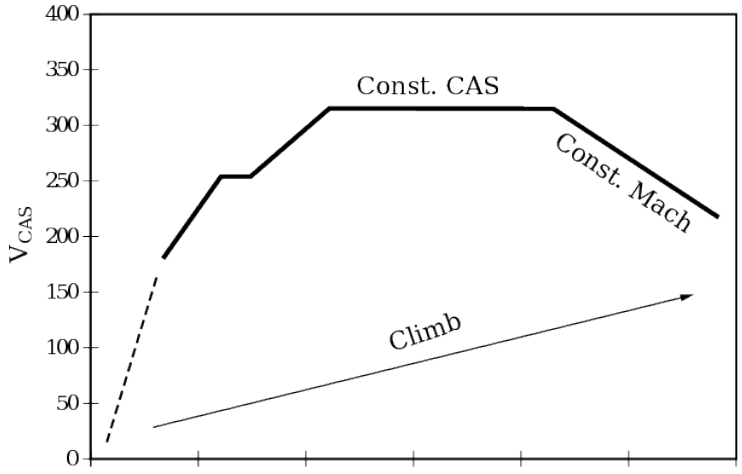
- To altitude 1500 ft
- Parameters
  - Speed
  - Vertical speed

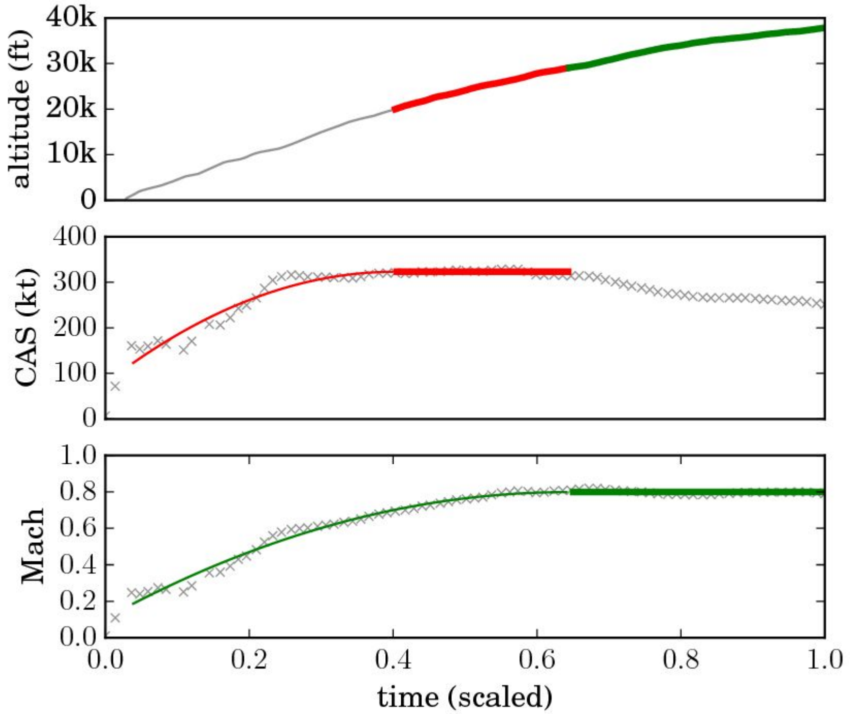
Std. at each flight ->



Climb

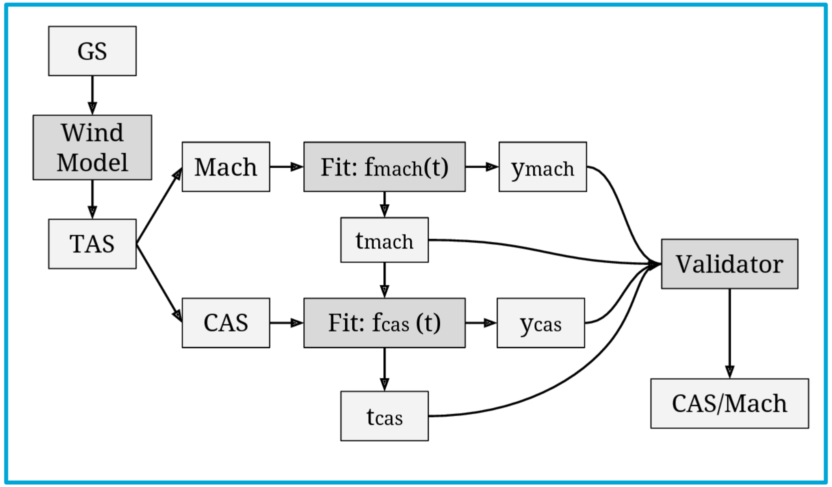
Identification of constant CAS/Mach profiles





Climb

Identification of constant CAS/Mach profiles



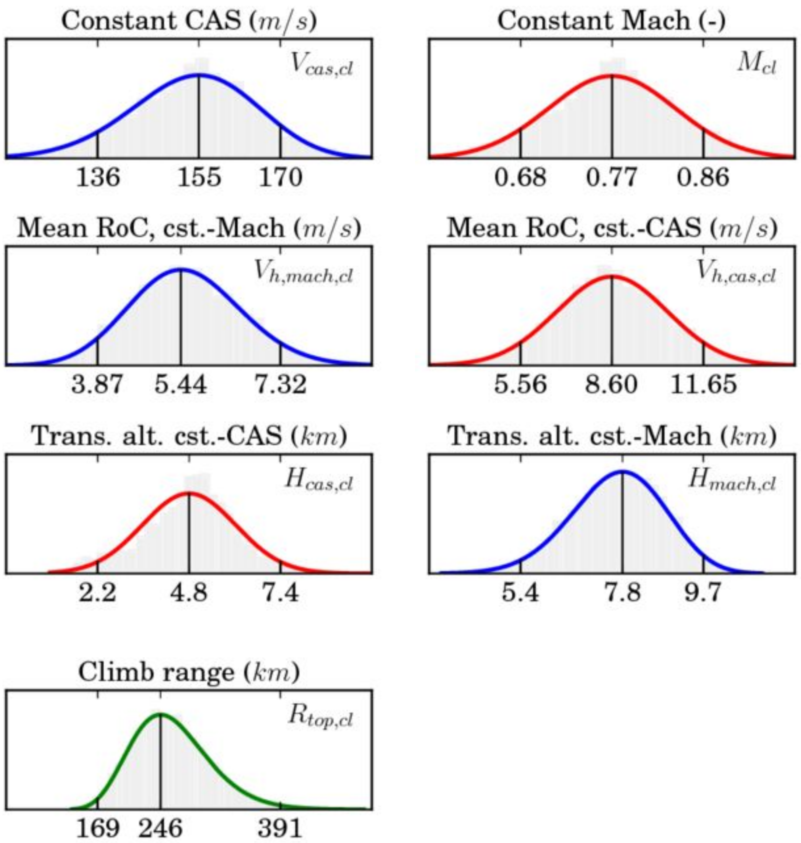
$$f_{mach}(t) = \begin{cases} k_1 \cdot (t - t_{mach})^2 + y_{mach} & t \leq t_{mach} \\ y_{mach} & t \geq t_{mach} \end{cases} \quad (18)$$

$$f_{cas}(t) = \begin{cases} -k_2 \cdot (t - t_{cas})^2 + y_{cas} & t \leq t_{cas} \\ y_{cas} & t_{cas} \leq t \leq t_{mach} \end{cases} \quad (19)$$

Climb

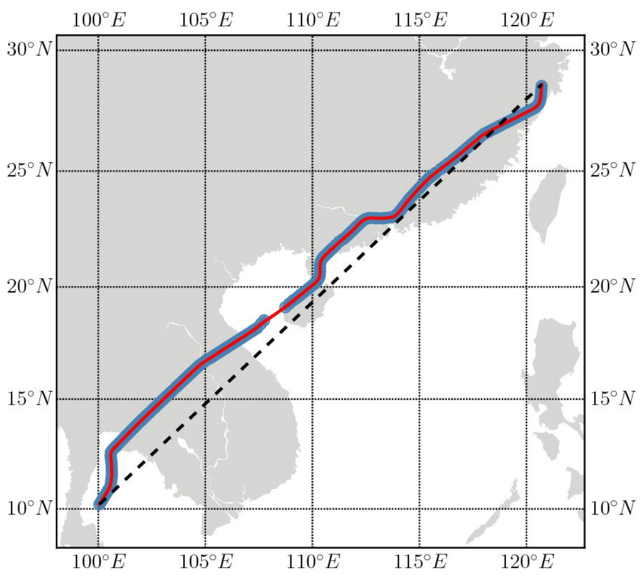
Parameters

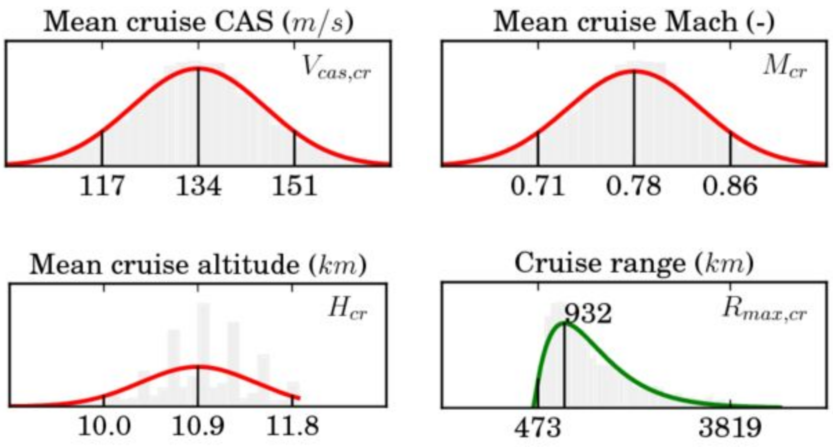
- Speeds
  - CAS
  - Mach
- Vertical rates
  - At different parts
- Transition altitude
- Range of climb



Cruise

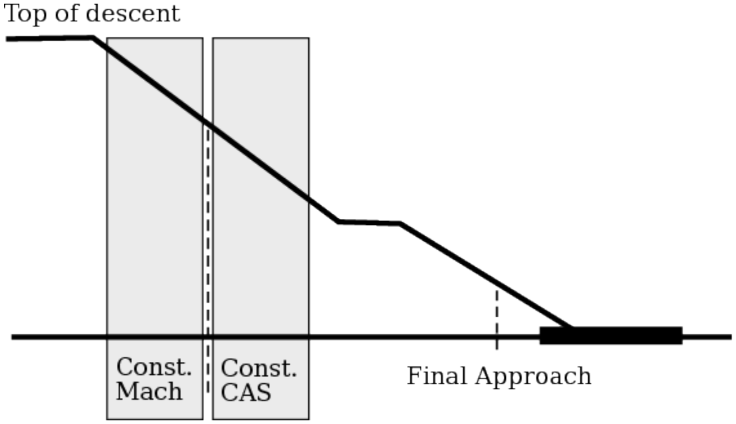
- Parameters
  - Operational and maximum cruise speed
  - Operational and maximum cruise altitude
  - Cruise range

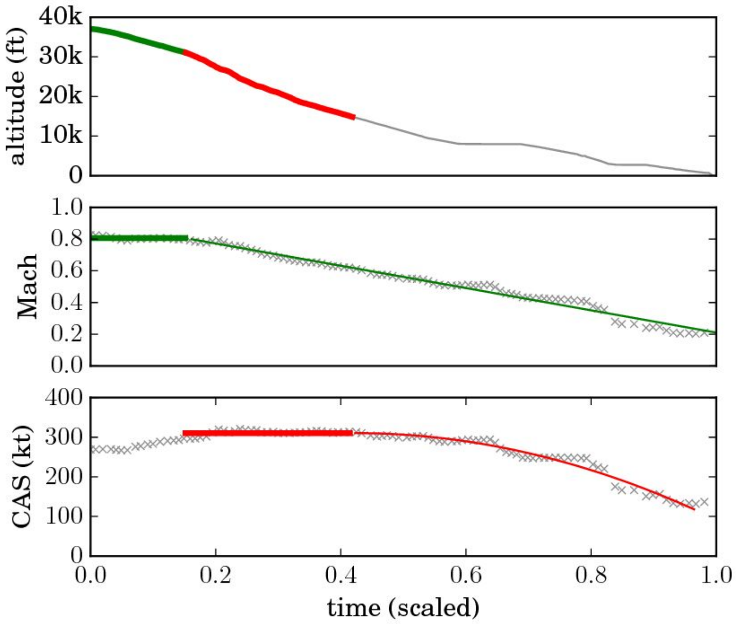




Descent

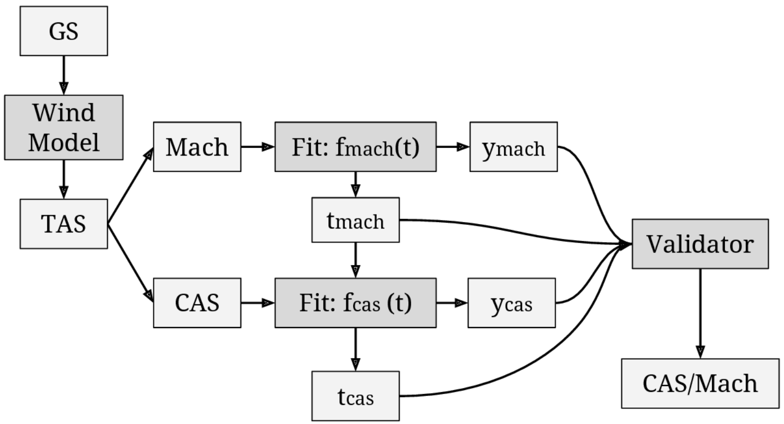
Identification of constant Mach/CAS profiles





Descent

Identification of constant CAS/Mach profiles



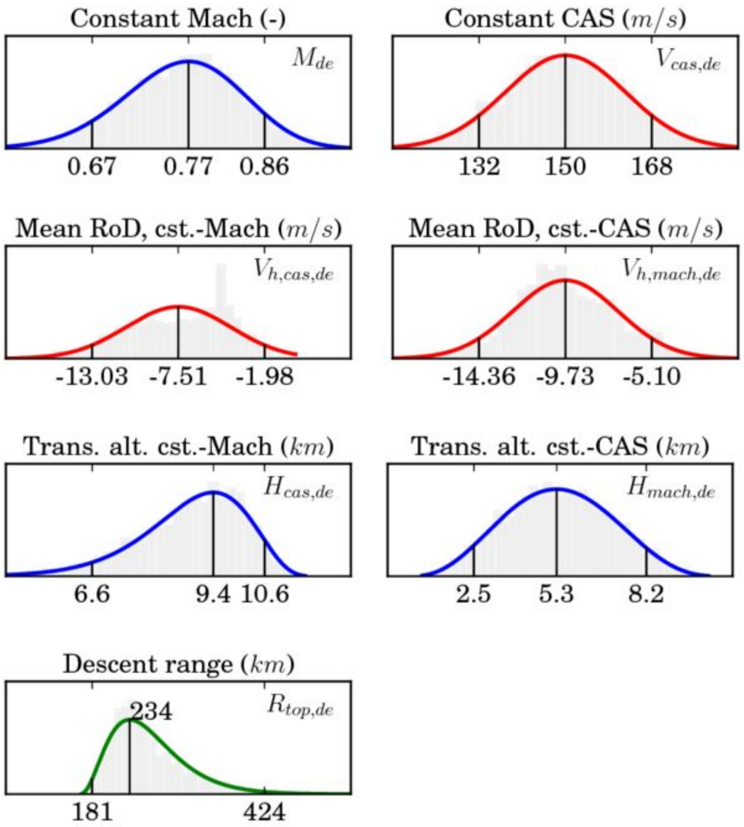
$$f_{mach}(t) = \begin{cases} y_{mach} & t \leq t_{mach} \\ -k_1 \cdot (t - t_{mach}) + y_{mach} & t \geq t_{mach} \end{cases} \quad (21)$$

$$f_{cas}(t) = \begin{cases} -k_2 \cdot (t - t_{cas})^2 + y_{cas} & t \leq t_{cas} \\ y_{cas} & t_{cas} \leq t \leq t_{mach} \end{cases} \quad (22)$$

Descent

Parameters

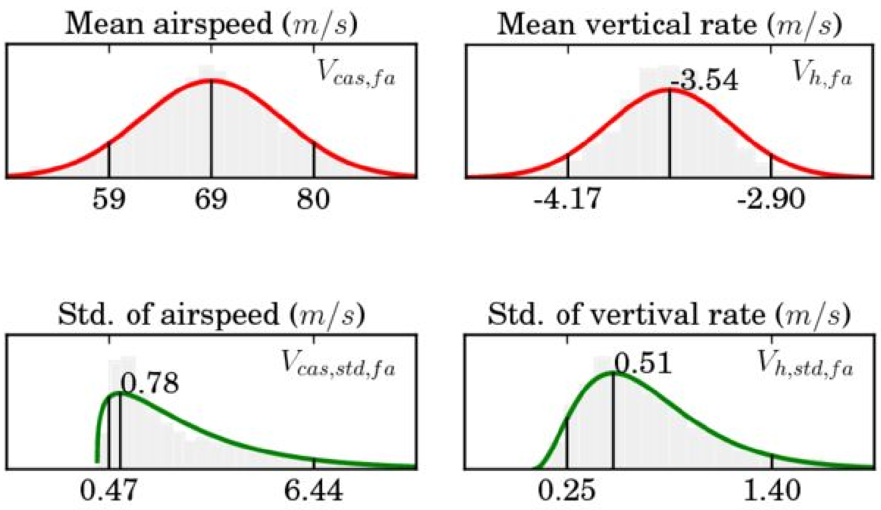
- Speeds
  - CAS
  - Mach
- Vertical rates
- Transition altitude
- Range of descent



Final approach

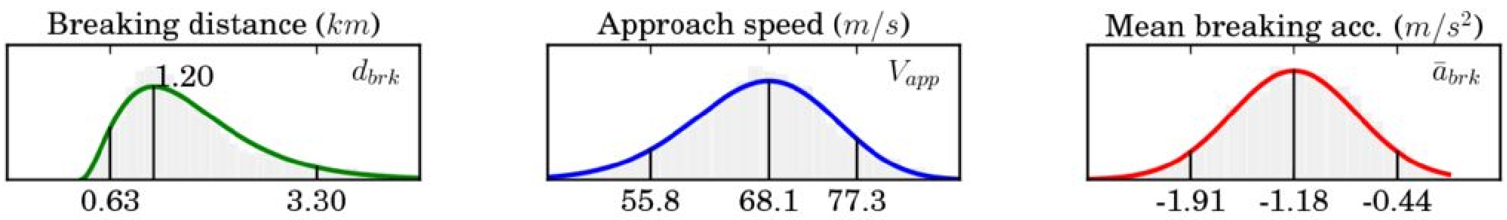
- From altitude 1500 ft
- Parameters
  - Speed
  - Vertical speed

Std. at each flight ->



Landing

- Parameters
  - Landing distance
  - Approach speed
  - Mean ground deceleration



Results

Open sourced

Performance Database

Phase	Param	Unit	A319	A320	A321	A332	A333	A343	A388	B737	B738	B739	B744	B752	B763	B77W	B788	B789	E190
TO	v_{lof}	m/s	80.8	85.3	89.6	91.2	91.5	86.3	88.1	81.3	85.2	90.7	91.9	88.8	92.7	98.2	89.8	95.6	87.0
	d_{tof}	km	1.62	1.68	1.84	2.01	2.05	2.27	2.51	1.59	1.75	2.04	2.31	1.72	1.82	2.24	2.16	2.52	1.81
	$\bar{a}_{tof}$	m/s^2	1.83	1.95	1.95	1.75	1.73	1.37	1.31	1.71	1.77	1.81	1.64	1.85	1.89	1.87	1.56	1.60	1.79
	$V_{h,ic}$	m/s	77	81	85	85	88	82	87	78	85	90	91	86	88	97	87	91	77
	$V_{cas,ic}$	m/s	12.12	12.78	13.20	12.35	12.19	6.74	5.84	11.62	11.90	12.15	9.52	12.93	14.09	12.95	10.40	10.50	11.20
CL	$R_{top,cl}$	km	214	246	244	282	291	290	297	209	222	243	232	227	208	221	278	274	226
	$V_{cas,cl}$	m/s	150	155	156	156	158	158	167	150	153	157	171	160	161	170	162	168	143
	M_{cl}	-	0.77	0.77	0.77	0.80	0.79	0.78	0.83	0.77	0.78	0.78	0.84	0.80	0.80	0.84	0.84	0.84	0.75
	$H_{cas,cl}$	km	4.8	4.8	5.0	5.1	4.9	5.0	5.1	5.0	5.4	5.2	5.8	5.3	5.8	5.8	5.5	5.5	4.4
	$H_{mach,cl}$	km	8.1	7.8	7.4	8.2	7.8	7.4	7.7	8.2	8.3	7.7	7.6	7.8	7.8	7.9	8.5	8.0	8.5
	$V_{h,precas,cl}$	m/s	11.27	10.32	9.50	9.71	8.94	7.15	8.17	11.90	11.06	10.42	8.87	10.44	10.47	9.45	9.69	9.32	10.64
	$V_{h,cas,cl}$	m/s	10.14	8.60	7.89	8.02	7.65	6.93	7.19	11.44	9.96	8.76	8.72	8.91	9.86	8.80	8.49	8.19	9.27
	$V_{h,mach,cl}$	m/s	6.54	5.44	5.35	5.04	4.93	4.40	5.45	7.21	6.44	5.74	6.65	6.38	7.18	6.23	6.10	5.99	5.13
CR	$R_{max,cr}$	km	3613	3819	4065	10622	8773	13263	13928	4485	4417	4404	12083	6528	10531	14839	11338	13685	2380
	$V_{cas,cr}$	m/s	129	134	141	133	135	140	139	122	130	139	149	134	140	152	135	140	131
	$V_{cas,max,cr}$	m/s	135	144	151	148	150	160	160	130	142	150	169	147	158	173	153	159	139
	M_{cr}	-	0.77	0.78	0.78	0.82	0.82	0.82	0.85	0.77	0.78	0.79	0.85	0.80	0.81	0.85	0.85	0.85	0.78
	$M_{max,cr}$	-	0.88	0.86	0.88	0.89	0.88	0.89	0.91	0.87	0.86	0.88	0.92	0.88	0.90	0.91	0.92	0.92	0.88
	H_{cr}	km	11.5	10.9	10.4	12.0	11.5	11.0	11.6	11.7	11.2	10.5	10.8	11.2	10.8	10.5	12.0	11.6	11.0
	$H_{max,cr}$	km	11.4	11.1	10.6	12.0	11.8	11.6	12.1	11.9	11.4	10.7	11.3	11.4	11.2	11.0	12.3	12.0	11.2
DE	$R_{top,de}$	km	239	234	239	285	294	282	321	254	249	247	264	255	245	262	298	304	242
	M_{de}	-	0.76	0.77	0.77	0.80	0.81	0.80	0.82	0.77	0.76	0.76	0.81	0.77	0.79	0.82	0.82	0.83	0.75
	$V_{cas,de}$	m/s	148	150	151	153	152	154	155	147	147	149	152	151	153	157	154	156	147
	$H_{cas,de}$	km	9.5	9.4	8.7	10.1	9.5	9.3	10.1	9.8	9.7	9.4	9.8	9.0	9.1	9.1	10.4	10.3	8.9
	$H_{mach,de}$	km	5.1	5.3	5.9	5.5	5.8	5.5	5.8	5.4	5.5	6.1	6.1	6.0	6.3	6.1	6.5	6.4	5.0
	$V_{h,cas,de}$	m/s	-5.81	-6.30	-5.46	-7.51	-6.00	-6.32	-7.25	-6.96	-7.39	-6.16	-5.89	-6.16	-6.63	-6.57	-8.12	-7.77	-6.90
	$V_{h,mach,de}$	m/s	-9.59	-9.73	-9.14	-9.12	-8.65	-9.17	-8.21	-9.03	-9.71	-8.81	-8.97	-9.31	-9.66	-9.12	-9.34	-8.92	-9.19
	$V_{h,postcas,de}$	m/s	-5.79	-5.88	-5.89	-5.43	-5.53	-5.38	-5.22	-5.71	-6.03	-5.73	-6.07	-5.89	-6.00	-6.04	-5.88	-5.87	-5.77
FA	$V_{cas,fa}$	m/s	64	69	72	70	72	72	71	68	75	76	78	68	75	77	74	76	68
	$V_{h,fa}$	m/s	-3.42	-3.54	-3.68	-3.61	-3.63	-3.64	-3.65	-3.57	-3.82	-3.92	-3.89	-3.42	-3.73	-3.98	-3.89	-4.08	-3.57
LD	V_{app}	m/s	62.2	68.1	69.9	68.9	72.1	70.8	68.1	66.1	73.5	74.7	77.3	65.8	73.0	75.5	70.6	74.4	64.7
	d_{brk}	km	1.66	1.20	1.76	1.66	1.63	1.71	2.25	2.22	1.38	1.64	1.92	1.26	1.60	1.62	2.11	2.51	1.90
	$\bar{a}_{brk}$	m/s^2	-0.77	-1.07	-1.04	-1.08	-1.11	-1.03	-0.94	-0.76	-1.32	-1.23	-1.14	-0.98	-1.05	-1.26	-1.03	-1.02	-0.94

Performance Database

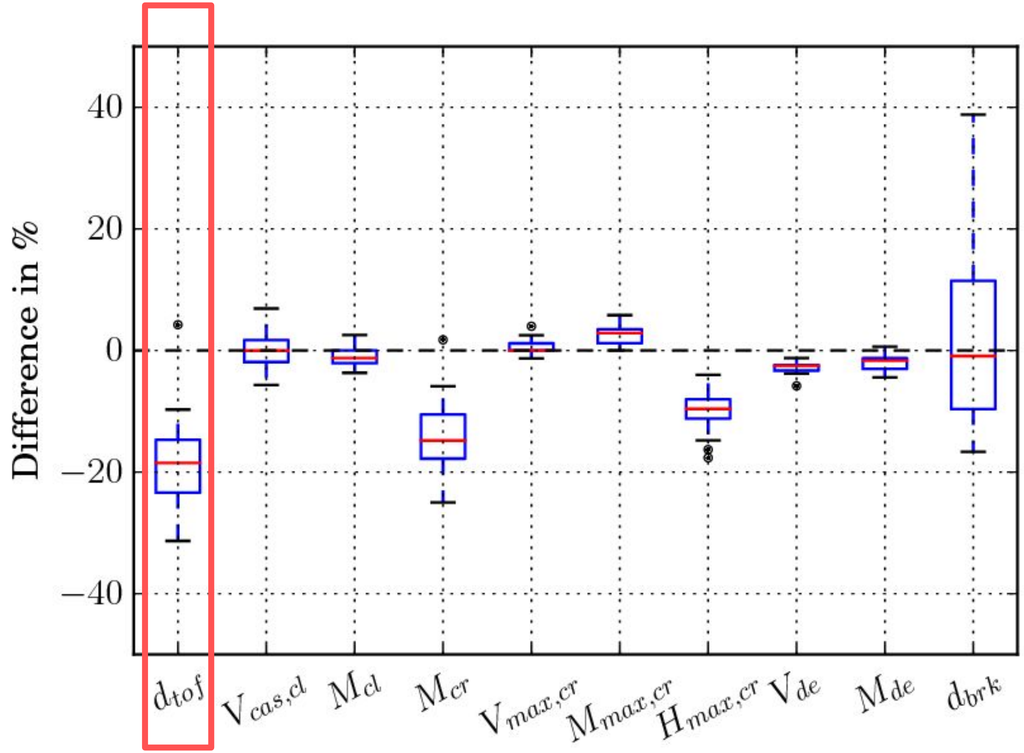
https://github.com/junzis/ofe

phase	param	opt	min	max	model	pm
TO	to_v_lof	85.3	70.4	96.9	beta	155851741.4|56.8|-190963643.3|190963797.1
TO	to_d_tof	1.68	0.83	2.53	norm	1.68|0.36
TO	to_acc_tof	1.95	1.40	2.28	beta	3521203.08|14.02|-252954.22|252957.10
IC	ic_va_avg	81	70	92	norm	81|7
IC	ic_vh_avg	12.78	8.72	15.72	beta	49809564.57|35.98|-17724305.81|17724331.04
CL	cl_d_range	246	169	391	gamma	11|97|13
CL	cl_v_cas_const	155	136	170	beta	87780901|75|-119258618|119258875
CL	cl_v_mach_const	0.77	0.68	0.86	norm	0.77|0.06
CL	cl_h_cas_const	4.8	2.2	7.4	norm	4.8|1.3
CL	cl_h_mach_const	7.8	5.4	9.7	beta	70.4|24.4|-10.5|24.4
CL	cl_vh_avg_pre_cas	10.32	7.71	12.93	norm	10.32|1.58
CL	cl_vh_avg_cas_const	8.60	5.56	11.65	norm	8.60|1.85

Discussions

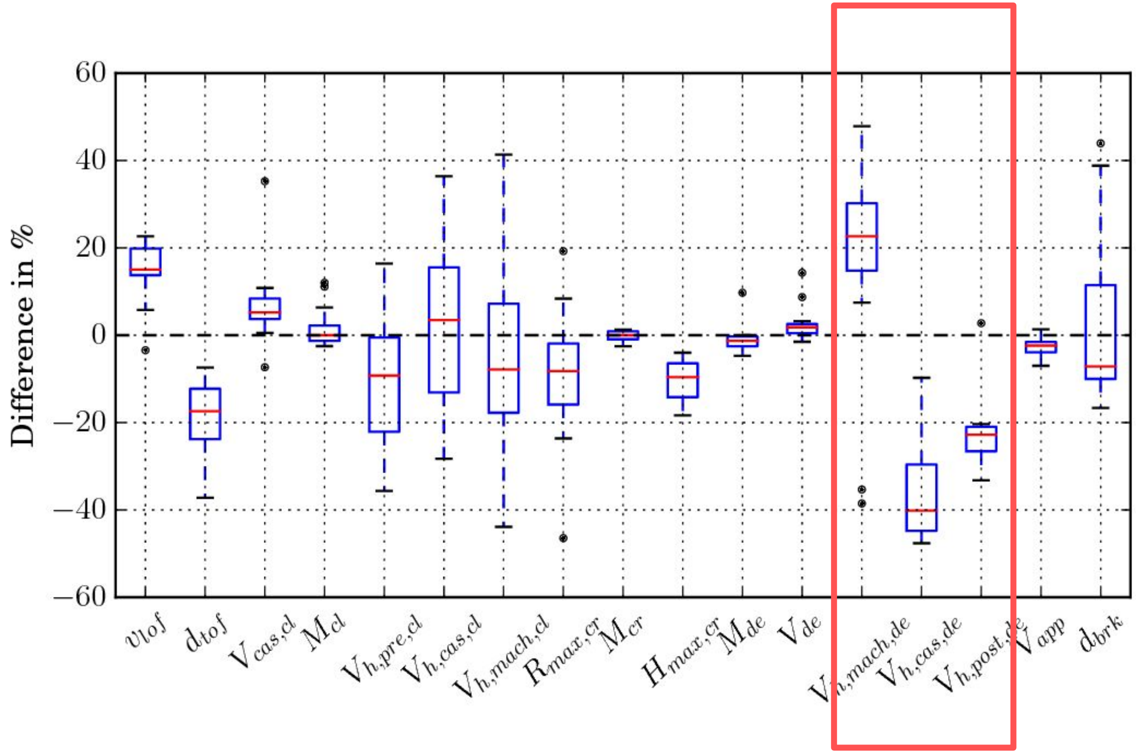
1. Comparison with BADA

10 parameters on 14 different aircraft



2. Comparison with EuroControl aircraft performance database

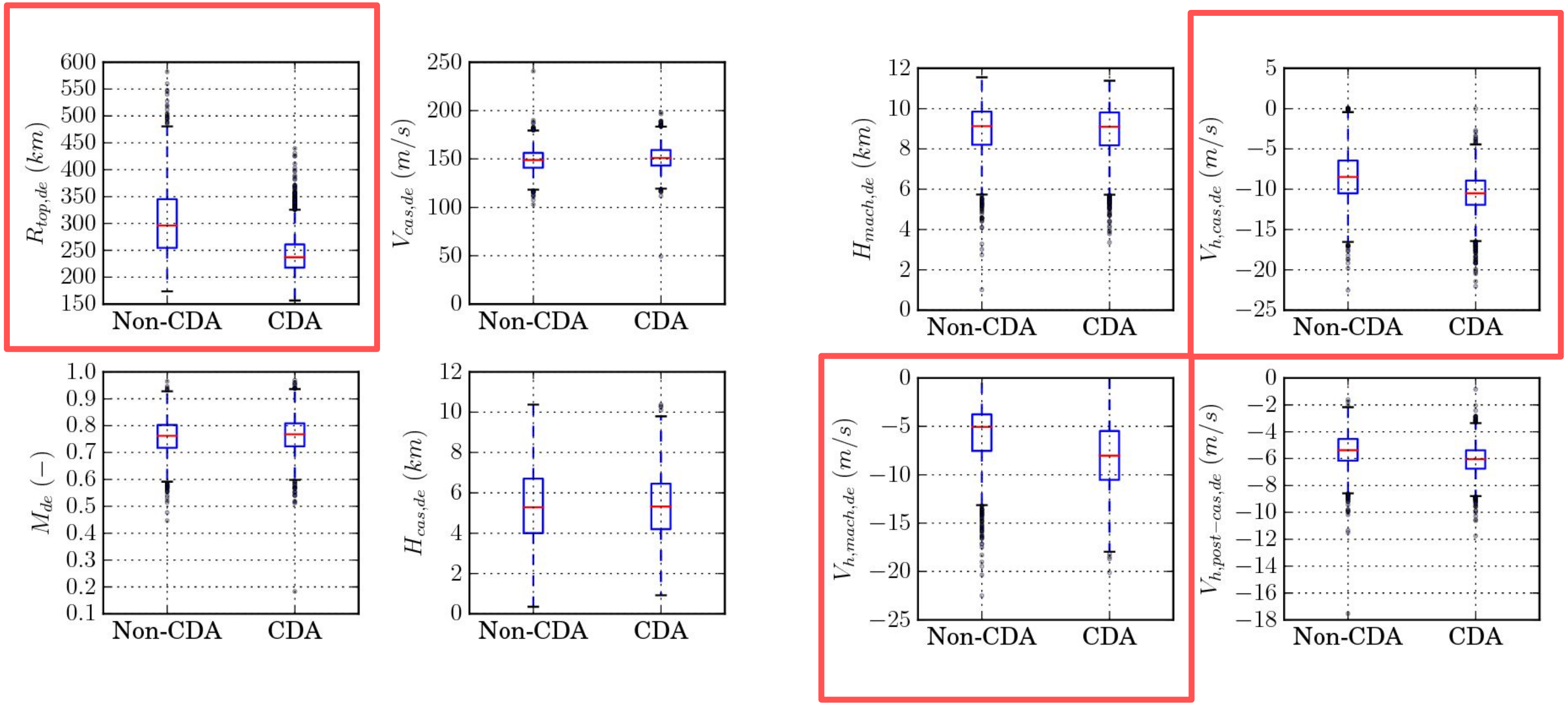
17 parameters on 14 different aircraft



https://contentzone.eurocontrol.int/aircraftperformance/

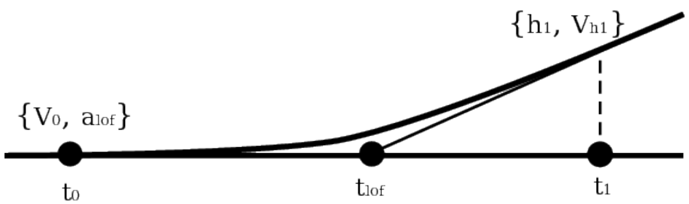
3. CDA vs Non-CDA

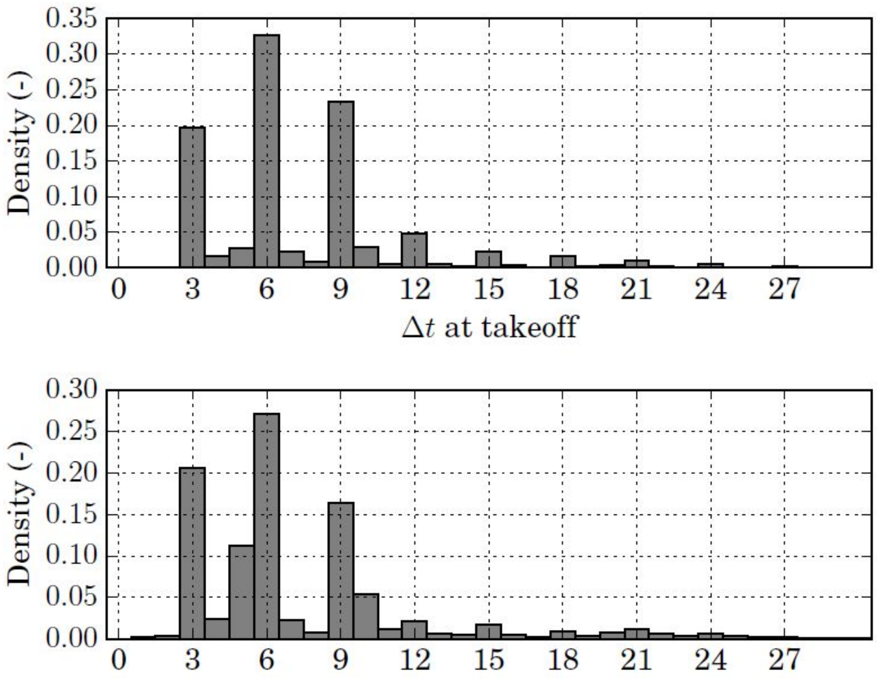
Influence of performance parameter due to continuous descent approach



4. Take-off moment

Locating the take-off moment, limitation in dataset.





Conclusions

- Performance of 31 most common aircraft types
    - 17 included in the paper
- Accurate models based on 1.7 million of flights
- Comparison with BADA and Eurocontrol database
- Open source database
- Future work to improve the number of aircraft types in the database

Take away

- Best suit for kinematic ATM studies
- Flight envelop
    - Optimal, minimum, and maximum value
- Stochastic simulation
    - Parametric probability distribution functions
- [Future] kinetic performance model

Thanks!

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