AIRCRAFT DESIGN AND SYSTEMS GROUP (AERO)

Conditions for Passenger Aircraft Minimum Fuel Consumption, Direct Operating Costs and Environmental Impact

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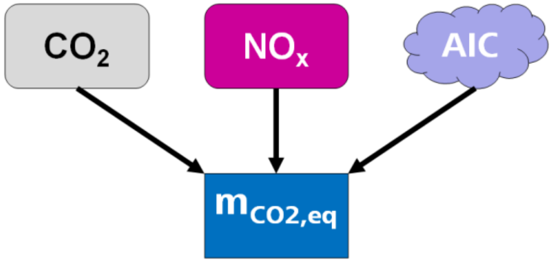
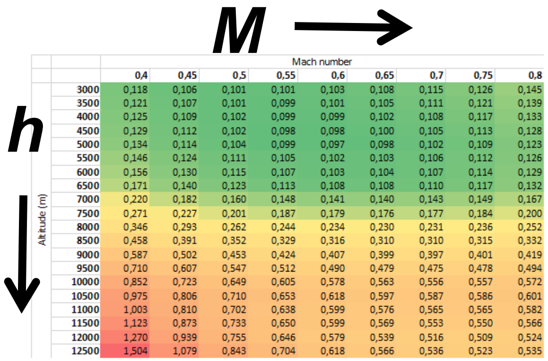


$$m_{CO2,eq} = f\,(M,\,h)$$



Altitude (m)	Mach number								
	0,4	0,45	0,5	0,55	0,6	0,65	0,7	0,75	0,8
3000	0,118	0,106	0,101	0,101	0,103	0,108	0,115	0,126	0,145
3500	0,121	0,107	0,101	0,099	0,101	0,105	0,111	0,121	0,139
4000	0,125	0,109	0,102	0,099	0,099	0,102	0,108	0,117	0,133
4500	0,129	0,112	0,102	0,098	0,098	0,100	0,105	0,113	0,128
5000	0,134	0,114	0,104	0,099	0,097	0,098	0,102	0,109	0,123
5500	0,146	0,124	0,111	0,105	0,102	0,103	0,106	0,112	0,126
6000	0,156	0,130	0,115	0,107	0,103	0,104	0,107	0,114	0,129
6500	0,171	0,140	0,123	0,113	0,108	0,108	0,110	0,117	0,132
7000	0,220	0,182	0,160	0,148	0,141	0,140	0,143	0,149	0,167
7500	0,271	0,227	0,201	0,187	0,179	0,176	0,177	0,184	0,200
8000	0,346	0,293	0,262	0,244	0,234	0,230	0,231	0,236	0,252
8500	0,458	0,391	0,352	0,329	0,316	0,310	0,310	0,315	0,332
9000	0,587	0,502	0,453	0,424	0,407	0,399	0,397	0,401	0,419
9500	0,710	0,607	0,547	0,512	0,490	0,479	0,475	0,478	0,494
10000	0,852	0,723	0,649	0,605	0,578	0,563	0,556	0,557	0,572
10500	0,975	0,806	0,710	0,653	0,618	0,597	0,587	0,586	0,601
11000	1,003	0,810	0,702	0,638	0,599	0,576	0,565	0,565	0,582
11500	1,123	0,873	0,733	0,650	0,599	0,569	0,553	0,550	0,566
12000	1,270	0,939	0,755	0,646	0,579	0,539	0,516	0,509	0,524
12500	1,504	1,079	0,843	0,704	0,618	0,566	0,536	0,523	0,535

Abstract

Purpose – Find optimal flight and design parameters for three objectives: minimum fuel consumption, Direct Operating Costs (DOC), and environmental impact of a passenger jet air-craft.

Approach – Combining multiple models (this includes aerodynamics, specific fuel consumption, DOC, and equivalent CO2 mass) into one generic model. In this combined model, each objective's importance is determined by a weighting factor. Additionally, the possibility of further optimizing this model by altering an aircraft's wing loading is analyzed.

Findings – When optimizing for a compromise between economic and ecologic benefits, the general outcome is a reduction in cruise altitude and an unaltered cruise Mach number com-pared to common practice. Decreasing cruise speed would benefit the environmental impact but has a negative effect on seat-mile cost. An increase in wing loading could further optimize the general outcome. Albeit at the cost of a greater required landing distance, therefore limiting the operational opportunities of this aircraft.

Research limitations – Most models use estimating equations based on first principles and statistical data.

Practical implications – The optimal cruise altitude and speed for a specific objective can be approximated for any passenger jet aircraft.

Social implications – By using a simple approach, the discussion of optimizing aircraft opens up to a level where everyone can participate.

Value – To find a general answer on how to optimize aviation, operational and design-wise, by using a simple approach.

Contents

- Introduction
- Fundamental Models
- Fuel Consumption
- Direct Operating Costs
- Environmental Impact
- Combined Model
- Influence of Wing Loading
- Summary

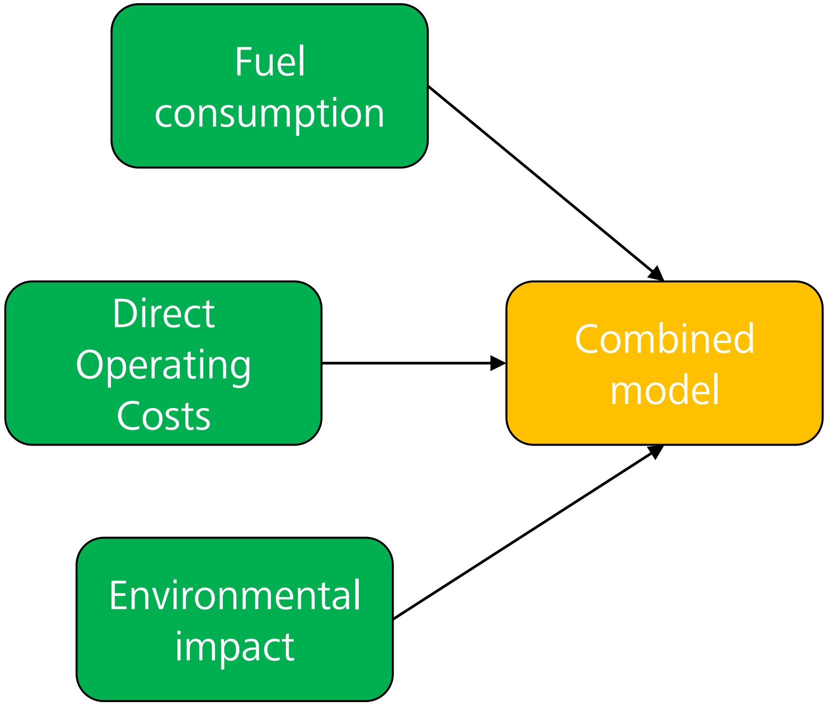
Introduction

Objective

Influence of:

- Mach
- Altitude
- Wing loading

On:



Fuel consumption

Direct Operating Costs

Environmental impact

Combined model

Fundamental Models

Aerodynamics

$$\boxed{C_D = C_{D0} + \Delta C_{Dw} + K \cdot C_L^2}$$

$$K = \frac{1}{\pi \cdot A \cdot e}$$

$$C_{D0} = \frac{\pi \cdot A \cdot e}{4 \cdot E_{max}} \longleftarrow A = b^2 / S$$

$$\Delta C_{Dw} = A \cdot \tan\left(B \cdot \left(\frac{M}{M_{crit}}\right) - B\right) \cdot cos^3(\varphi_{25,w}) \longleftarrow$$

	Result
A	0.001272
B	3.477

$$e = e_{theo} \cdot k_{e,F} \cdot k_{e,D0} \cdot k_{e,M}$$

Scholz 2015

Thrust Specific Fuel Consumption (TSFC)

Input variables:

- **Cruise Mach number**
- **Cruise altitude**
- Bypass ratio
- Take-off thrust (one engine)
- Overall pressure ratio (if known)
- Turbine entry temperature

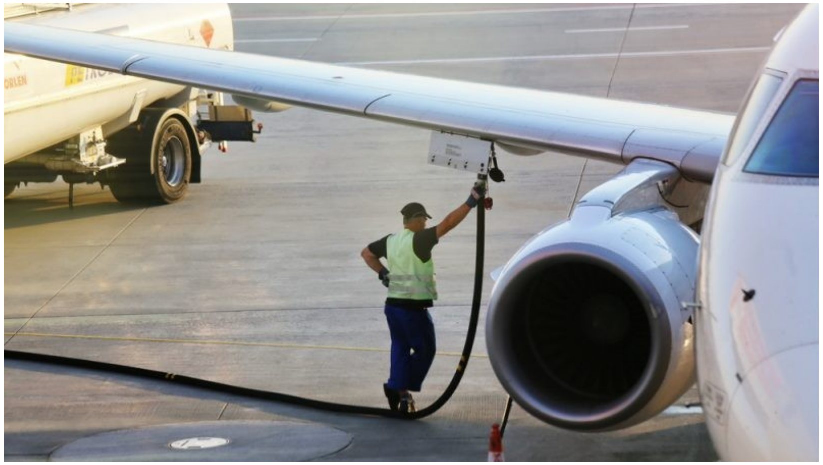


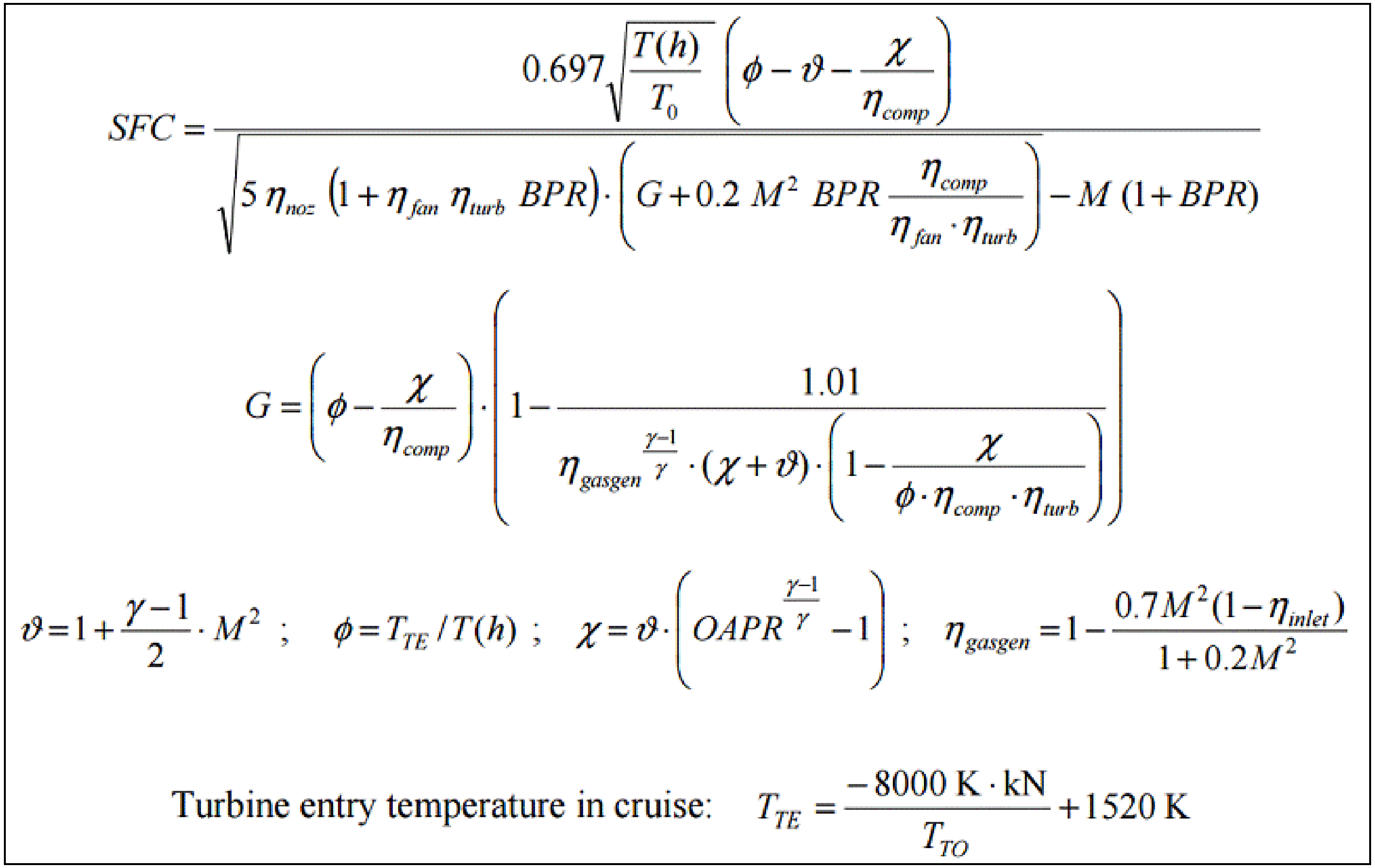
Photo: MikeDotta / Shutterstock

Result: TSFC in kg/Ns

$$\boxed{\frac{kg\ fuel}{NM\ flown\ .\ kg\ of\ aircraft}} \qquad \boxed{\frac{kg\ fuel}{km\ flown}} \qquad \boxed{\frac{l\ fuel}{100\ km\ flown\ .\ seat}}$$

Herrmann 2010

Thrust Specific Fuel Consumption (TSFC)



$$SFC = \frac{0.697\sqrt{\frac{T(h)}{T_0}}\left(\phi - \vartheta - \frac{\chi}{\eta_{comp}}\right)}{\sqrt{5\,\eta_{noz}\left(1+\eta_{fan}\,\eta_{turb}\;BPR\right)\cdot\left(G+0.2\;M^2\;BPR\,\frac{\eta_{comp}}{\eta_{fan}\cdot\eta_{turb}}\right)}-M\,(1+BPR)}$$

$$G = \left(\phi - \frac{\chi}{\eta_{comp}}\right)\cdot\left(1-\frac{1.01}{\eta_{gasgen}^{\frac{\gamma-1}{\gamma}}\cdot(\chi+\vartheta)\cdot\left(1-\frac{\chi}{\phi\cdot\eta_{comp}\cdot\eta_{turb}}\right)}\right)$$

$$\vartheta = 1+\frac{\gamma-1}{2}\cdot M^2\;;\quad \phi = T_{TE}/T(h)\;;\quad \chi = \vartheta\cdot\left(OAPR^{\frac{\gamma-1}{\gamma}}-1\right)\;;\quad \eta_{gasgen} = 1-\frac{0.7M^2(1-\eta_{inlet})}{1+0.2M^2}$$

Turbine entry temperature in cruise: $T_{TE} = \frac{-8000\ \mathrm{K}\cdot\mathrm{kN}}{T_{TO}}+1520\ \mathrm{K}$

Herrmann 2010

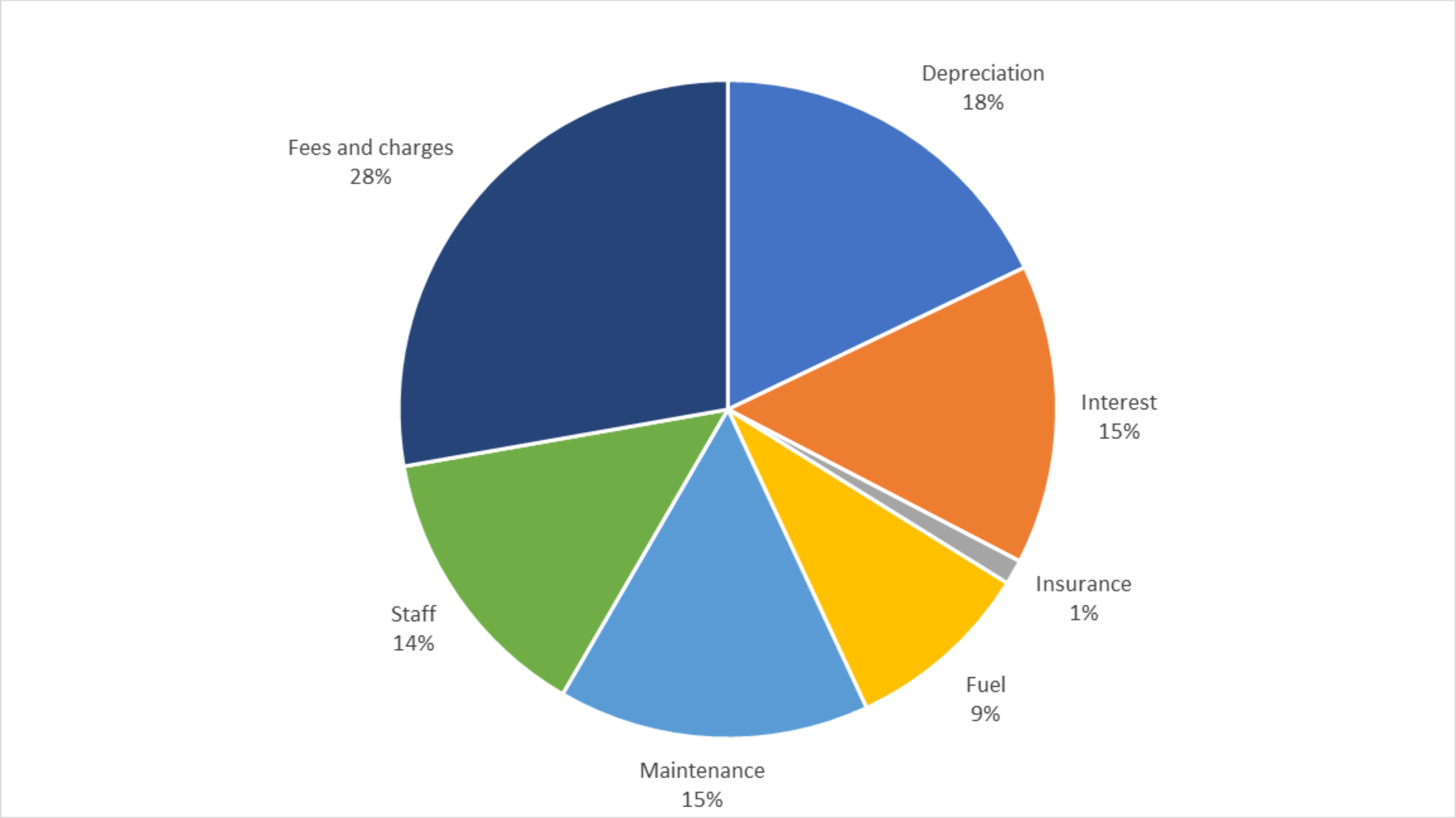
Direct Operating Costs (DOC)

DOC model by Association of European Airlines (AEA 1989)
presented by Scholz in his Lecture Notes (online).

$$C_{s,m} = \frac{\boxed{C_{a/c,a}}}{n_{seat} \cdot n_{t,a} \cdot R_{DOC}}$$

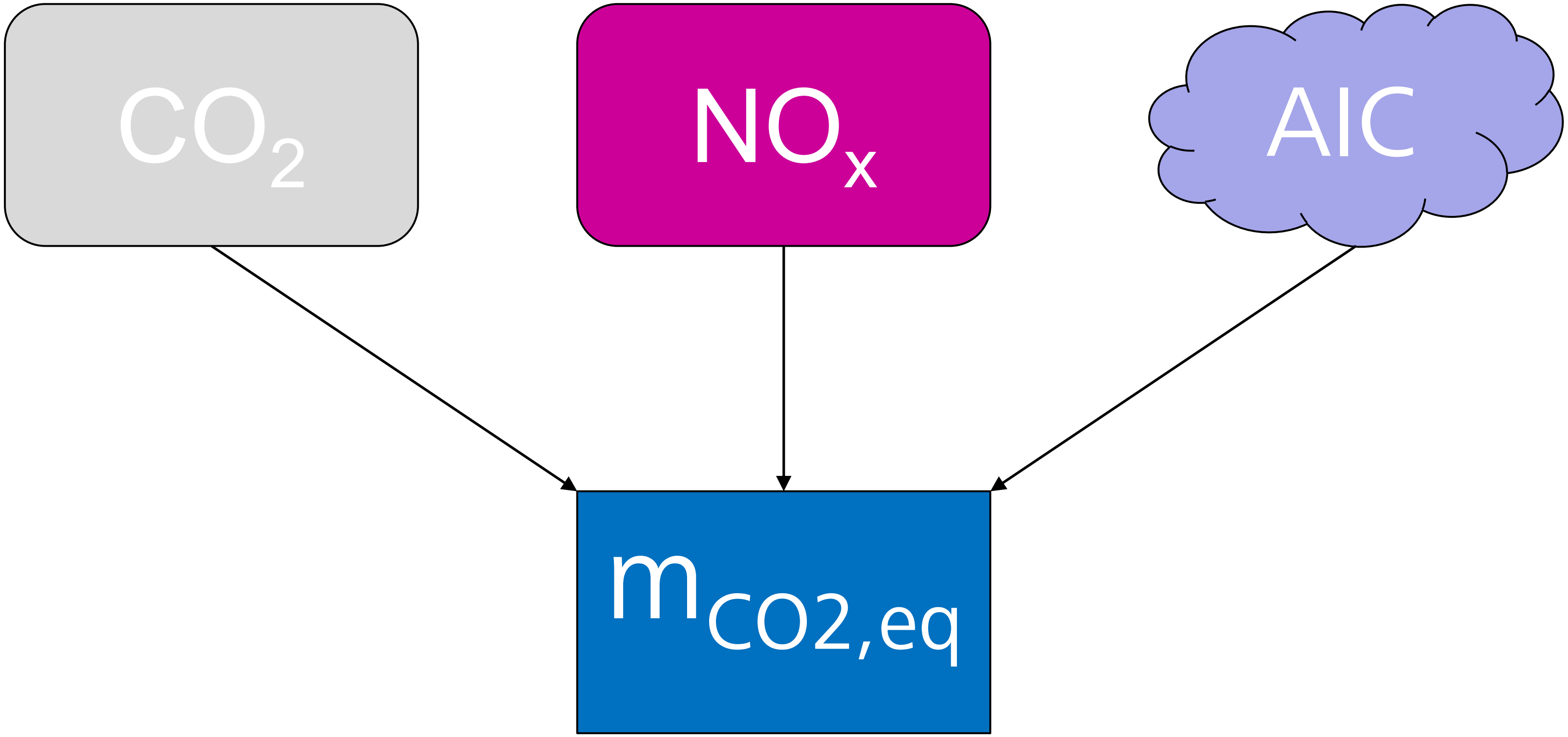
Scholz 2015

Direct Operating Costs (DOC)



Calculation of DOC distribution for an Airbus A320-200 at Mach 0.78 and 11 500 m

Equivalent CO_2 Mass



CO_2

NO_x

AIC

$m_{CO2,eq}$

Equivalent CO$_2$ Mass

$$m_{CO2,eq} = \frac{EI_{CO2} \cdot f_{NM}}{n_{seat}} \cdot 1 + \frac{EI_{NOx} \cdot f_{NM}}{n_{seat}} \cdot CF_{midpoint,NOx} + \frac{R_{NM}}{R_{NM} \cdot n_{seat}} \cdot CF_{midpoint,AIC}$$

$$\Big\downarrow$$

units only

$$\frac{kg\ CO2}{NM \cdot n_{seat}} =$$

$$\frac{kg\ CO2/kg\ fuel \cdot kg\ fuel/NM}{n_{seat}} \cdot 1 + \frac{kg\ NOx/kg\ fuel \cdot kg\ fuel/NM}{n_{seat}} \cdot \frac{kg\ CO2}{kg\ NOx} + \frac{NM}{NM \cdot n_{seat}} \cdot \frac{kg\ CO2}{NM}$$

Schwarz 2011

Equivalent CO_2 Mass

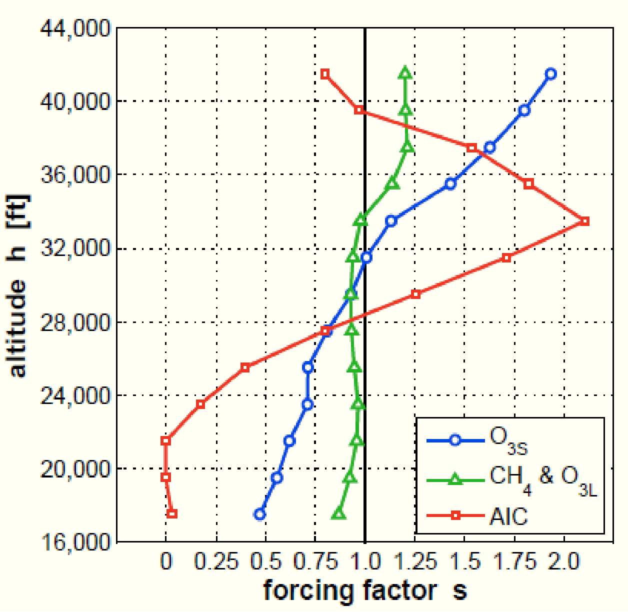
$$CF_{midpoint,AIC} = \frac{SGTP_{contrails,100}}{SGTP_{CO2,100}} \cdot s_{contrails}(H) + \frac{SGTP_{cirrus,100}}{SGTP_{CO2,100}} \cdot s_{cirrus}(H)$$

SGTP Values*

Species	$SGTP_{i,100}$
CO_2 (K/kg CO_2)	$3{,}58 \cdot 10^{-14}$
Short O_3 (K/kg NO_x)	$7{,}79 \cdot 10^{-12}$
Long O_3 (K/NO_x)	$-9{,}14 \cdot 10^{-13}$
CH_4 (K/kg NO_x)	$-3{,}90 \cdot 10^{-12}$
Contrails (K/NM)	$2{,}54 \cdot 10^{-13}$
Contrails (K/km)	$1{,}37 \cdot 10^{-13}$
Cirrus (K/NM)	$7{,}63 \cdot 10^{-13}$
Cirrus (K/km)	$4{,}12 \cdot 10^{-13}$

* **Sustained Global Temperature** change **Potential**

Forcing Factor *s* = f(*h*)



Schwarz 2009, Schwarz 2011

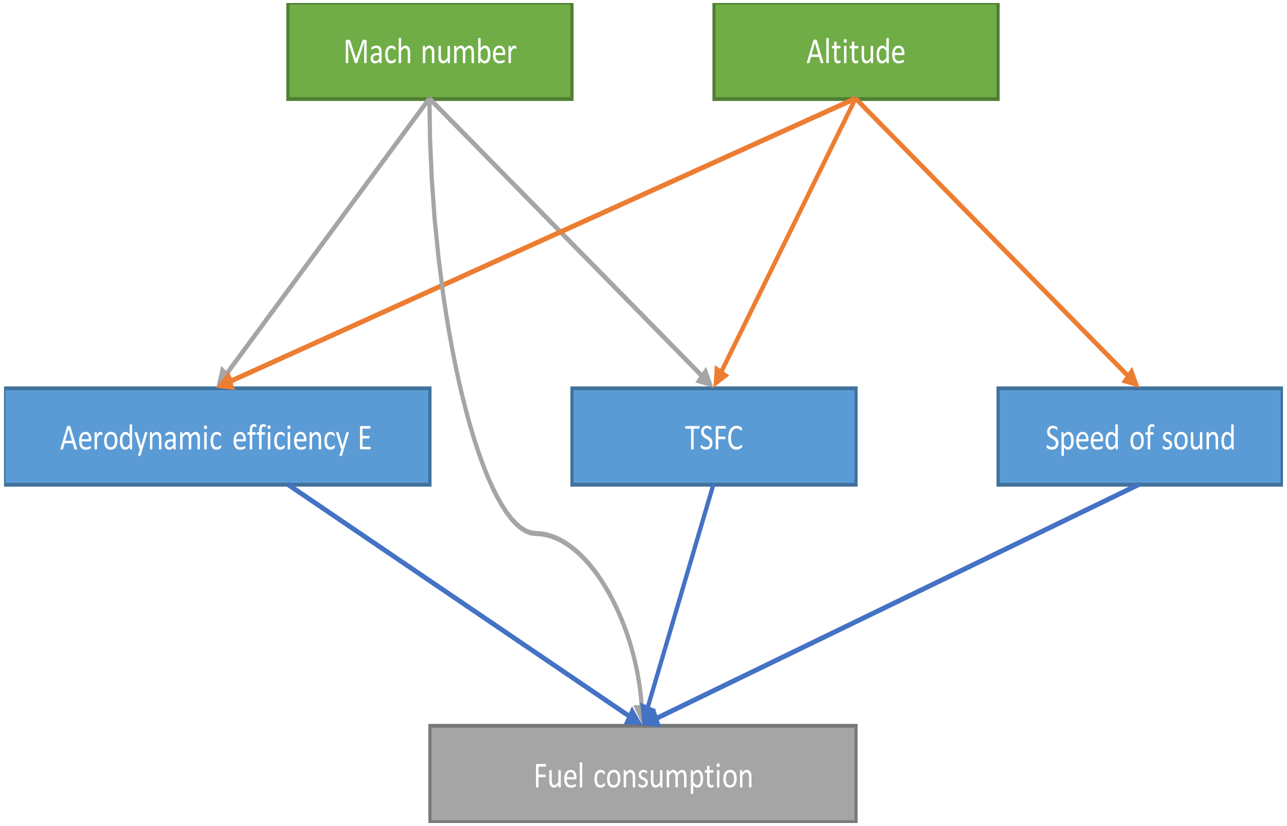
Equivalent CO_2 Mass – Remarks About Results

- All results are for an Airbus A320-200
    - Note: Single-aisle aircraft make up 69% of all passenger aircraft
- All calculations have one or more factors based on statistical data
    - This means: Accurate when comparing different aircraft
- Results withing expected order of magnitude

➔ Goal is to visualize general trends (independent of specific aircraft)

Fuel Consumption

Fuel Consumption



Specific Air Range, SAR

$$SAR = -\frac{dR}{dm} = \frac{V}{Q}$$

Jet: $$SAR = -\frac{dR}{dm} = \frac{V\,E}{c\,g} \cdot \frac{1}{m}$$

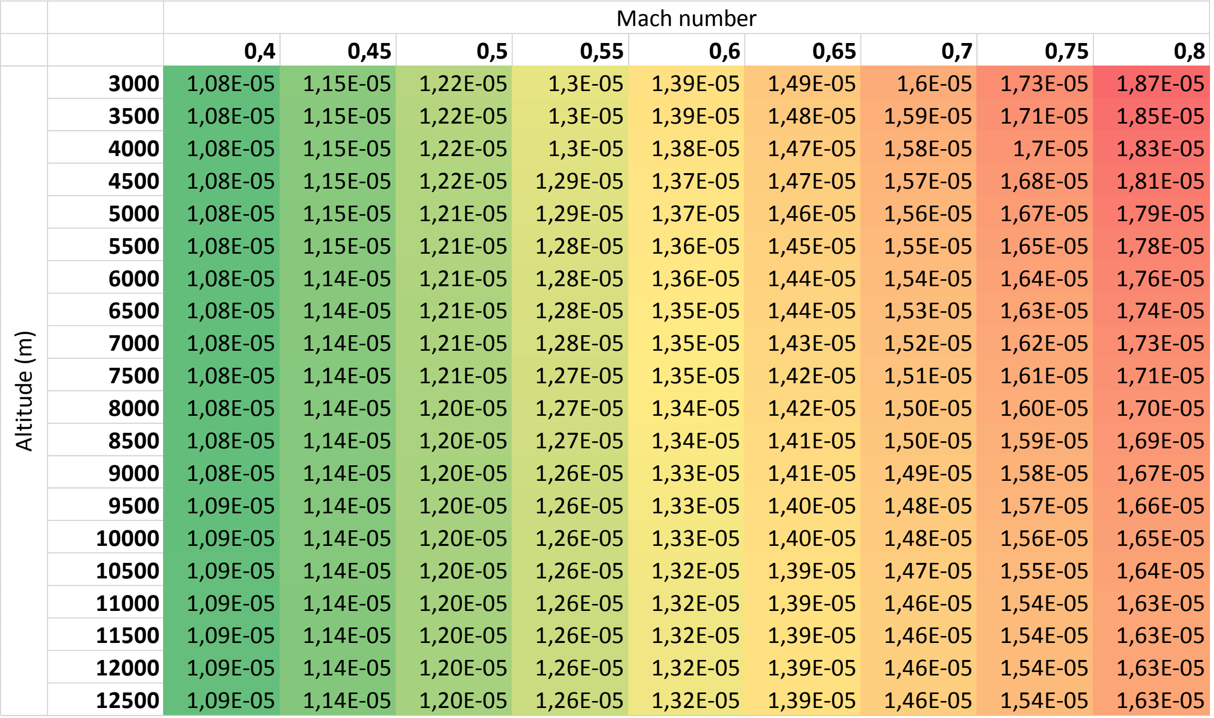
Generic Fuel Consumption:

$1/SAR/m_{MTO}$

$$f_{MTOW} = \frac{c \cdot g}{M \cdot a \cdot E}$$

$c = TSFC$

Fuel Consumption – TSFC



		Mach number								
		0,4	0,45	0,5	0,55	0,6	0,65	0,7	0,75	0,8
Altitude (m)	**3000**	1,08E-05	1,15E-05	1,22E-05	1,3E-05	1,39E-05	1,49E-05	1,6E-05	1,73E-05	1,87E-05
	3500	1,08E-05	1,15E-05	1,22E-05	1,3E-05	1,39E-05	1,48E-05	1,59E-05	1,71E-05	1,85E-05
	4000	1,08E-05	1,15E-05	1,22E-05	1,3E-05	1,38E-05	1,47E-05	1,58E-05	1,7E-05	1,83E-05
	4500	1,08E-05	1,15E-05	1,22E-05	1,29E-05	1,37E-05	1,47E-05	1,57E-05	1,68E-05	1,81E-05
	5000	1,08E-05	1,15E-05	1,21E-05	1,29E-05	1,37E-05	1,46E-05	1,56E-05	1,67E-05	1,79E-05
	5500	1,08E-05	1,15E-05	1,21E-05	1,28E-05	1,36E-05	1,45E-05	1,55E-05	1,65E-05	1,78E-05
	6000	1,08E-05	1,14E-05	1,21E-05	1,28E-05	1,36E-05	1,44E-05	1,54E-05	1,64E-05	1,76E-05
	6500	1,08E-05	1,14E-05	1,21E-05	1,28E-05	1,35E-05	1,44E-05	1,53E-05	1,63E-05	1,74E-05
	7000	1,08E-05	1,14E-05	1,21E-05	1,28E-05	1,35E-05	1,43E-05	1,52E-05	1,62E-05	1,73E-05
	7500	1,08E-05	1,14E-05	1,21E-05	1,27E-05	1,35E-05	1,42E-05	1,51E-05	1,61E-05	1,71E-05
	8000	1,08E-05	1,14E-05	1,20E-05	1,27E-05	1,34E-05	1,42E-05	1,50E-05	1,60E-05	1,70E-05
	8500	1,08E-05	1,14E-05	1,20E-05	1,27E-05	1,34E-05	1,41E-05	1,50E-05	1,59E-05	1,69E-05
	9000	1,08E-05	1,14E-05	1,20E-05	1,26E-05	1,33E-05	1,41E-05	1,49E-05	1,58E-05	1,67E-05
	9500	1,09E-05	1,14E-05	1,20E-05	1,26E-05	1,33E-05	1,40E-05	1,48E-05	1,57E-05	1,66E-05
	10000	1,09E-05	1,14E-05	1,20E-05	1,26E-05	1,33E-05	1,40E-05	1,48E-05	1,56E-05	1,65E-05
	10500	1,09E-05	1,14E-05	1,20E-05	1,26E-05	1,32E-05	1,39E-05	1,47E-05	1,55E-05	1,64E-05
	11000	1,09E-05	1,14E-05	1,20E-05	1,26E-05	1,32E-05	1,39E-05	1,46E-05	1,54E-05	1,63E-05
	11500	1,09E-05	1,14E-05	1,20E-05	1,26E-05	1,32E-05	1,39E-05	1,46E-05	1,54E-05	1,63E-05
	12000	1,09E-05	1,14E-05	1,20E-05	1,26E-05	1,32E-05	1,39E-05	1,46E-05	1,54E-05	1,63E-05
	12500	1,09E-05	1,14E-05	1,20E-05	1,26E-05	1,32E-05	1,39E-05	1,46E-05	1,54E-05	1,63E-05

Units: kg of fuel per N of thrust per second

Higher TAS
=> higher TSFC

Higher altitude
=> lower TAS
for equal Mach number:
$a = f(h)$

Fuel Consumption – TSFC

Accuracy check of the TSFC model

Engine: CFM56-5B4

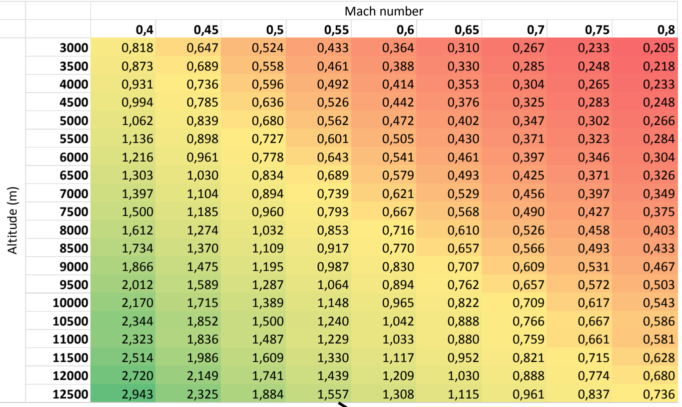
Result **model** (at M = 0.78 and h = 11 500 m): TSFC = $1.59 * 10^{-5}$ kg/Ns

Result **literature** for CFM56 family: TSFC range = $1.54 - 1.89 * 10^{-5}$ kg/Ns

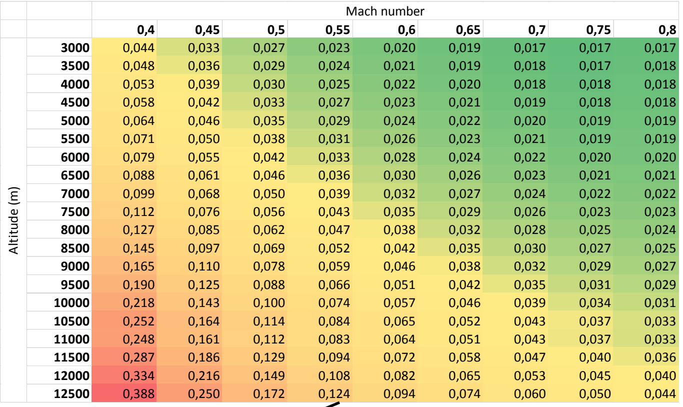
Jenkinson 1999

Fuel Consumption – E

C_L



Altitude (m)	Mach number								
	0,4	**0,45**	**0,5**	**0,55**	**0,6**	**0,65**	**0,7**	**0,75**	**0,8**
3000	0,818	0,647	0,524	0,433	0,364	0,310	0,267	0,233	0,205
3500	0,873	0,689	0,558	0,461	0,388	0,330	0,285	0,248	0,218
4000	0,931	0,736	0,596	0,492	0,414	0,353	0,304	0,265	0,233
4500	0,994	0,785	0,636	0,526	0,442	0,376	0,325	0,283	0,248
5000	1,062	0,839	0,680	0,562	0,472	0,402	0,347	0,302	0,266
5500	1,136	0,898	0,727	0,601	0,505	0,430	0,371	0,323	0,284
6000	1,216	0,961	0,778	0,643	0,541	0,461	0,397	0,346	0,304
6500	1,303	1,030	0,834	0,689	0,579	0,493	0,425	0,371	0,326
7000	1,397	1,104	0,894	0,739	0,621	0,529	0,456	0,397	0,349
7500	1,500	1,185	0,960	0,793	0,667	0,568	0,490	0,427	0,375
8000	1,612	1,274	1,032	0,853	0,716	0,610	0,526	0,458	0,403
8500	1,734	1,370	1,109	0,917	0,770	0,657	0,566	0,493	0,433
9000	1,866	1,475	1,195	0,987	0,830	0,707	0,609	0,531	0,467
9500	2,012	1,589	1,287	1,064	0,894	0,762	0,657	0,572	0,503
10000	2,170	1,715	1,389	1,148	0,965	0,822	0,709	0,617	0,543
10500	2,344	1,852	1,500	1,240	1,042	0,888	0,766	0,667	0,586
11000	2,323	1,836	1,487	1,229	1,033	0,880	0,759	0,661	0,581
11500	2,514	1,986	1,609	1,330	1,117	0,952	0,821	0,715	0,628
12000	2,720	2,149	1,741	1,439	1,209	1,030	0,888	0,774	0,680
12500	2,943	2,325	1,884	1,557	1,308	1,115	0,961	0,837	0,736



Altitude (m)	Mach number								
	0,4	**0,45**	**0,5**	**0,55**	**0,6**	**0,65**	**0,7**	**0,75**	**0,8**
3000	0,044	0,033	0,027	0,023	0,020	0,019	0,017	0,017	0,017
3500	0,048	0,036	0,029	0,024	0,021	0,019	0,018	0,017	0,018
4000	0,053	0,039	0,030	0,025	0,022	0,020	0,018	0,018	0,018
4500	0,058	0,042	0,033	0,027	0,023	0,021	0,019	0,018	0,018
5000	0,064	0,046	0,035	0,029	0,024	0,022	0,020	0,019	0,019
5500	0,071	0,050	0,038	0,031	0,026	0,023	0,021	0,019	0,019
6000	0,079	0,055	0,042	0,033	0,028	0,024	0,022	0,020	0,020
6500	0,088	0,061	0,046	0,036	0,030	0,026	0,023	0,021	0,021
7000	0,099	0,068	0,050	0,039	0,032	0,027	0,024	0,022	0,022
7500	0,112	0,076	0,056	0,043	0,035	0,029	0,026	0,023	0,023
8000	0,127	0,085	0,062	0,047	0,038	0,032	0,028	0,025	0,024
8500	0,145	0,097	0,069	0,052	0,042	0,035	0,030	0,027	0,025
9000	0,165	0,110	0,078	0,059	0,046	0,038	0,032	0,029	0,027
9500	0,190	0,125	0,088	0,066	0,051	0,042	0,035	0,031	0,029
10000	0,218	0,143	0,100	0,074	0,057	0,046	0,039	0,034	0,031
10500	0,252	0,164	0,114	0,084	0,065	0,052	0,043	0,037	0,033
11000	0,248	0,161	0,112	0,083	0,064	0,051	0,043	0,037	0,033
11500	0,287	0,186	0,129	0,094	0,072	0,058	0,047	0,040	0,036
12000	0,334	0,216	0,149	0,108	0,082	0,065	0,053	0,045	0,040
12500	0,388	0,250	0,172	0,124	0,094	0,074	0,060	0,050	0,044

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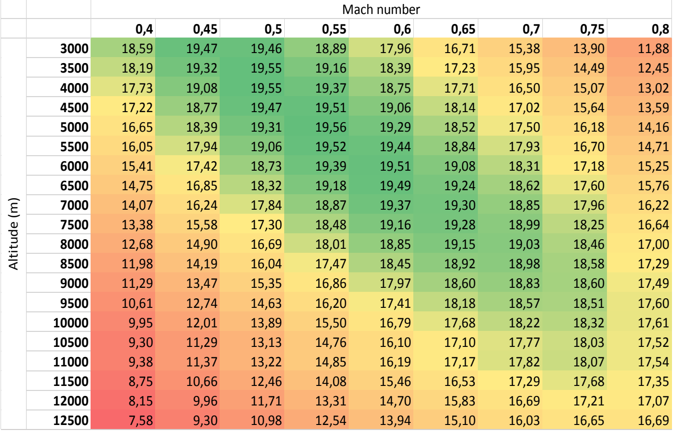
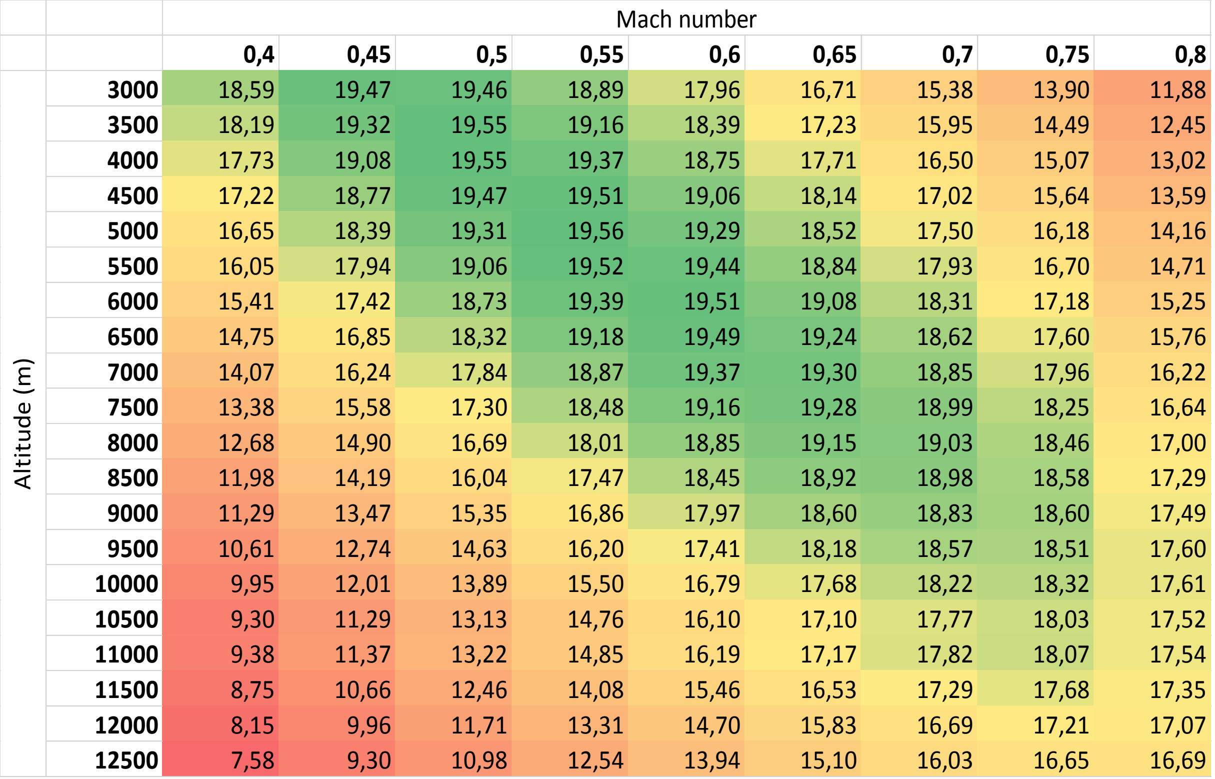


Altitude (m)	Mach number								
	0,4	**0,45**	**0,5**	**0,55**	**0,6**	**0,65**	**0,7**	**0,75**	**0,8**
3000	18,59	19,47	19,46	18,89	17,96	16,71	15,38	13,90	11,88
3500	18,19	19,32	19,55	19,16	18,39	17,23	15,95	14,49	12,45
4000	17,73	19,08	19,55	19,37	18,75	17,71	16,50	15,07	13,02
4500	17,22	18,77	19,47	19,51	19,06	18,14	17,02	15,64	13,59
5000	16,65	18,39	19,31	19,56	19,29	18,52	17,50	16,18	14,16
5500	16,05	17,94	19,06	19,52	19,44	18,84	17,93	16,70	14,71
6000	15,41	17,42	18,73	19,39	19,51	19,08	18,31	17,18	15,25
6500	14,75	16,85	18,32	19,18	19,49	19,24	18,62	17,60	15,76
7000	14,07	16,24	17,84	18,87	19,37	19,30	18,85	17,96	16,22
7500	13,38	15,58	17,30	18,48	19,16	19,28	18,99	18,25	16,64
8000	12,68	14,90	16,69	18,01	18,85	19,15	19,03	18,46	17,00
8500	11,98	14,19	16,04	17,47	18,45	18,92	18,98	18,58	17,29
9000	11,29	13,47	15,35	16,86	17,97	18,60	18,83	18,60	17,49
9500	10,61	12,74	14,63	16,20	17,41	18,18	18,57	18,51	17,60
10000	9,95	12,01	13,89	15,50	16,79	17,68	18,22	18,32	17,61
10500	9,30	11,29	13,13	14,76	16,10	17,10	17,77	18,03	17,52
11000	9,38	11,37	13,22	14,85	16,19	17,17	17,82	18,07	17,54
11500	8,75	10,66	12,46	14,08	15,46	16,53	17,29	17,68	17,35
12000	8,15	9,96	11,71	13,31	14,70	15,83	16,69	17,21	17,07
12500	7,58	9,30	10,98	12,54	13,94	15,10	16,03	16,65	16,69

E

Fuel Consumption – E

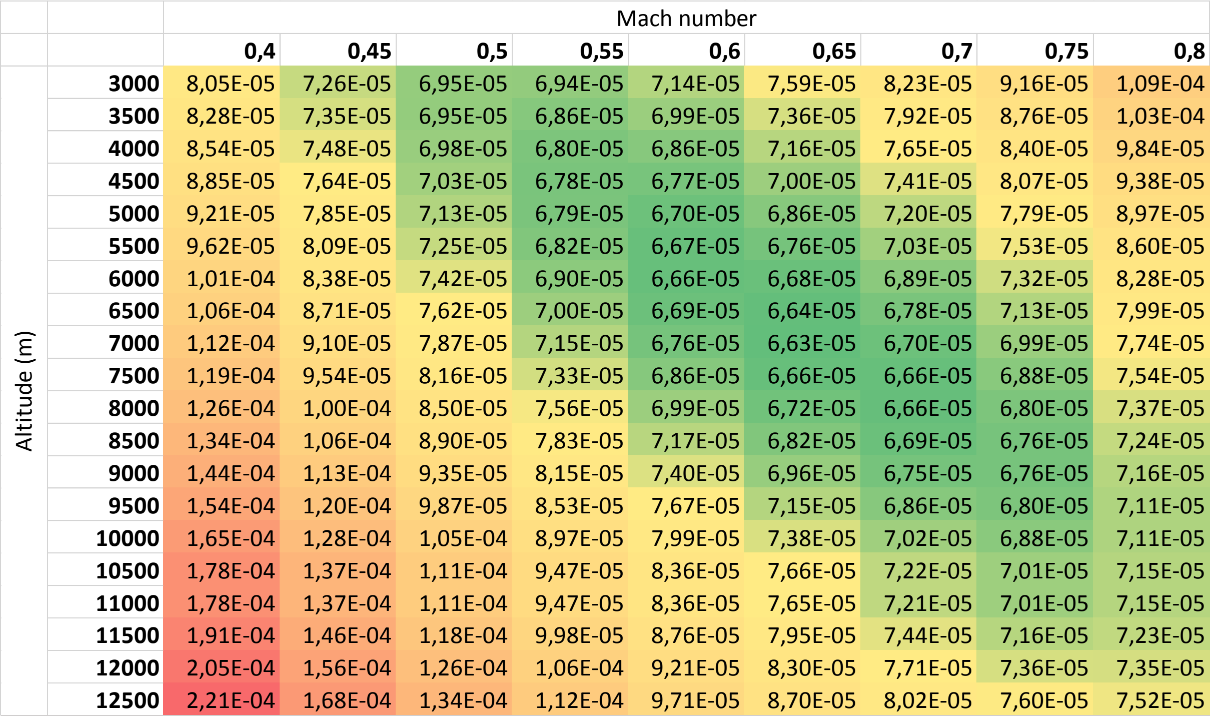


Altitude (m)	Mach number 0,4	0,45	0,5	0,55	0,6	0,65	0,7	0,75	0,8
3000	18,59	19,47	19,46	18,89	17,96	16,71	15,38	13,90	11,88
3500	18,19	19,32	19,55	19,16	18,39	17,23	15,95	14,49	12,45
4000	17,73	19,08	19,55	19,37	18,75	17,71	16,50	15,07	13,02
4500	17,22	18,77	19,47	19,51	19,06	18,14	17,02	15,64	13,59
5000	16,65	18,39	19,31	19,56	19,29	18,52	17,50	16,18	14,16
5500	16,05	17,94	19,06	19,52	19,44	18,84	17,93	16,70	14,71
6000	15,41	17,42	18,73	19,39	19,51	19,08	18,31	17,18	15,25
6500	14,75	16,85	18,32	19,18	19,49	19,24	18,62	17,60	15,76
7000	14,07	16,24	17,84	18,87	19,37	19,30	18,85	17,96	16,22
7500	13,38	15,58	17,30	18,48	19,16	19,28	18,99	18,25	16,64
8000	12,68	14,90	16,69	18,01	18,85	19,15	19,03	18,46	17,00
8500	11,98	14,19	16,04	17,47	18,45	18,92	18,98	18,58	17,29
9000	11,29	13,47	15,35	16,86	17,97	18,60	18,83	18,60	17,49
9500	10,61	12,74	14,63	16,20	17,41	18,18	18,57	18,51	17,60
10000	9,95	12,01	13,89	15,50	16,79	17,68	18,22	18,32	17,61
10500	9,30	11,29	13,13	14,76	16,10	17,10	17,77	18,03	17,52
11000	9,38	11,37	13,22	14,85	16,19	17,17	17,82	18,07	17,54
11500	8,75	10,66	12,46	14,08	15,46	16,53	17,29	17,68	17,35
12000	8,15	9,96	11,71	13,31	14,70	15,83	16,69	17,21	17,07
12500	7,58	9,30	10,98	12,54	13,94	15,10	16,03	16,65	16,69

E values follow "diagonal" rising Mach number – rising altitude pattern

Optimum E at low altitude and low Mach number
=> Cruise Speed Reduction (CSR)

Fuel Consumption – Result from E and TSFC



	Mach number								
Altitude (m)	0,4	0,45	0,5	0,55	0,6	0,65	0,7	0,75	0,8
3000	8,05E-05	7,26E-05	6,95E-05	6,94E-05	7,14E-05	7,59E-05	8,23E-05	9,16E-05	1,09E-04
3500	8,28E-05	7,35E-05	6,95E-05	6,86E-05	6,99E-05	7,36E-05	7,92E-05	8,76E-05	1,03E-04
4000	8,54E-05	7,48E-05	6,98E-05	6,80E-05	6,86E-05	7,16E-05	7,65E-05	8,40E-05	9,84E-05
4500	8,85E-05	7,64E-05	7,03E-05	6,78E-05	6,77E-05	7,00E-05	7,41E-05	8,07E-05	9,38E-05
5000	9,21E-05	7,85E-05	7,13E-05	6,79E-05	6,70E-05	6,86E-05	7,20E-05	7,79E-05	8,97E-05
5500	9,62E-05	8,09E-05	7,25E-05	6,82E-05	6,67E-05	6,76E-05	7,03E-05	7,53E-05	8,60E-05
6000	1,01E-04	8,38E-05	7,42E-05	6,90E-05	6,66E-05	6,68E-05	6,89E-05	7,32E-05	8,28E-05
6500	1,06E-04	8,71E-05	7,62E-05	7,00E-05	6,69E-05	6,64E-05	6,78E-05	7,13E-05	7,99E-05
7000	1,12E-04	9,10E-05	7,87E-05	7,15E-05	6,76E-05	6,63E-05	6,70E-05	6,99E-05	7,74E-05
7500	1,19E-04	9,54E-05	8,16E-05	7,33E-05	6,86E-05	6,66E-05	6,66E-05	6,88E-05	7,54E-05
8000	1,26E-04	1,00E-04	8,50E-05	7,56E-05	6,99E-05	6,72E-05	6,66E-05	6,80E-05	7,37E-05
8500	1,34E-04	1,06E-04	8,90E-05	7,83E-05	7,17E-05	6,82E-05	6,69E-05	6,76E-05	7,24E-05
9000	1,44E-04	1,13E-04	9,35E-05	8,15E-05	7,40E-05	6,96E-05	6,75E-05	6,76E-05	7,16E-05
9500	1,54E-04	1,20E-04	9,87E-05	8,53E-05	7,67E-05	7,15E-05	6,86E-05	6,80E-05	7,11E-05
10000	1,65E-04	1,28E-04	1,05E-04	8,97E-05	7,99E-05	7,38E-05	7,02E-05	6,88E-05	7,11E-05
10500	1,78E-04	1,37E-04	1,11E-04	9,47E-05	8,36E-05	7,66E-05	7,22E-05	7,01E-05	7,15E-05
11000	1,78E-04	1,37E-04	1,11E-04	9,47E-05	8,36E-05	7,65E-05	7,21E-05	7,01E-05	7,15E-05
11500	1,91E-04	1,46E-04	1,18E-04	9,98E-05	8,76E-05	7,95E-05	7,44E-05	7,16E-05	7,23E-05
12000	2,05E-04	1,56E-04	1,26E-04	1,06E-04	9,21E-05	8,30E-05	7,71E-05	7,36E-05	7,35E-05
12500	2,21E-04	1,68E-04	1,34E-04	1,12E-04	9,71E-05	8,70E-05	8,02E-05	7,60E-05	7,52E-05

Big influence of E "diagonal" pattern

Pattern shifted higher due to TSFC

Pattern shifted faster due to Mach number in denominator

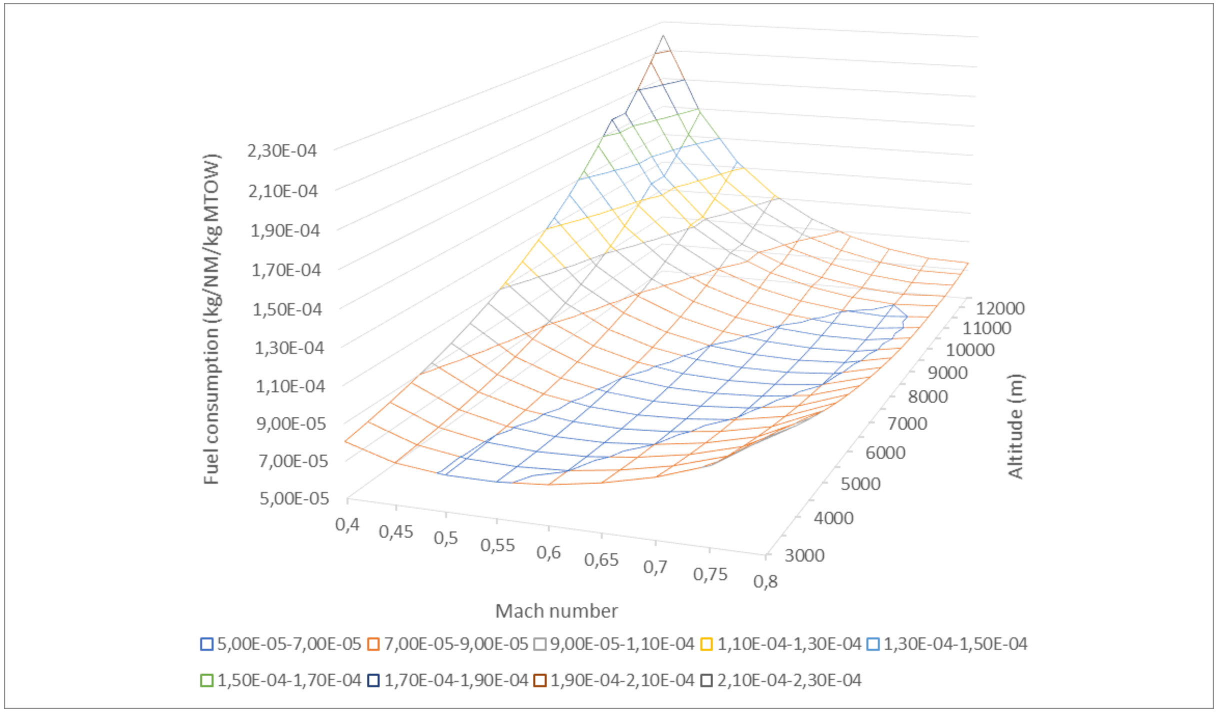
Units: kg of fuel per NM flown, per kg of aircraft MTOW

Generic Fuel Consumption:

1/SAR/m$_{MTO}$

$$f_{MTOW} = \frac{c \cdot g}{M \cdot a \cdot E}$$

Fuel consumption - Result



Units: kg of fuel per NM flown, per kg of aircraft MTOW

Optimum:

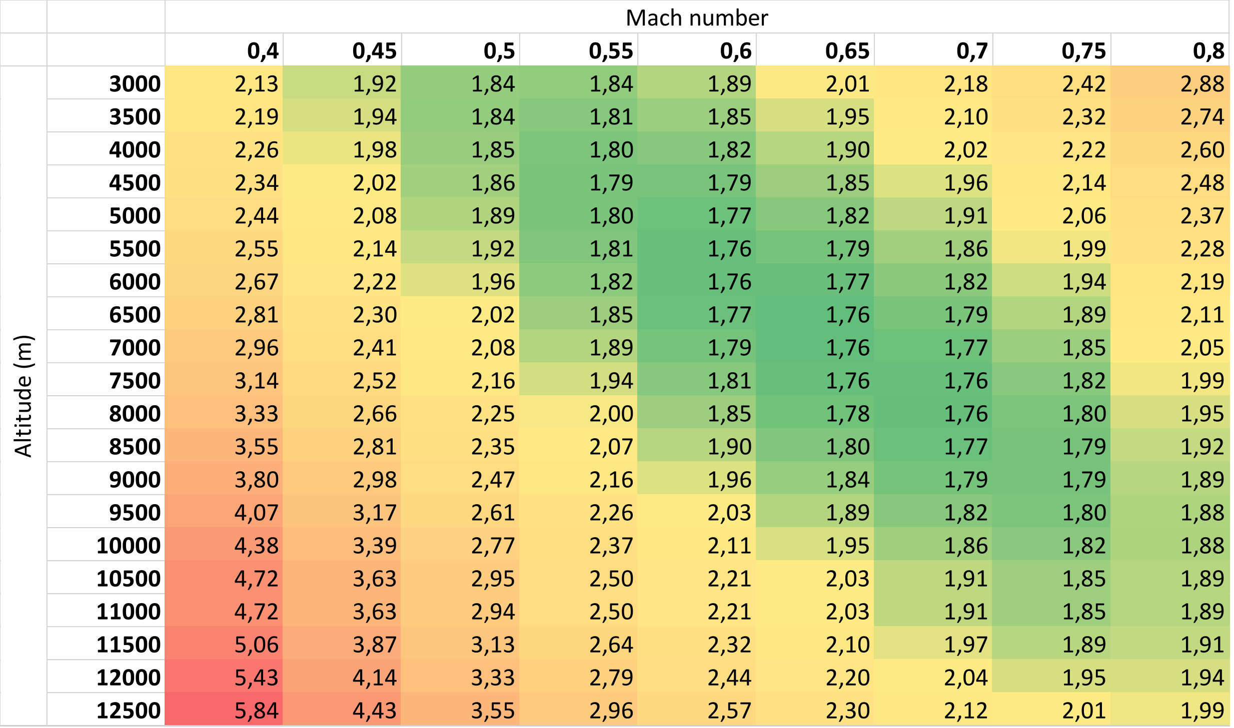
0.76 Mach
7000 m

7 % less fuel consumed compared to

0.78 Mach
11 500 m
Cruise Speed Reduction, CSR

Dark blue zone: max 2.5 % from optimum

Fuel Consumption – Result Compared to a Car



		Mach number								
		0,4	0,45	0,5	0,55	0,6	0,65	0,7	0,75	0,8
Altitude (m)	3000	2,13	1,92	1,84	1,84	1,89	2,01	2,18	2,42	2,88
	3500	2,19	1,94	1,84	1,81	1,85	1,95	2,10	2,32	2,74
	4000	2,26	1,98	1,85	1,80	1,82	1,90	2,02	2,22	2,60
	4500	2,34	2,02	1,86	1,79	1,79	1,85	1,96	2,14	2,48
	5000	2,44	2,08	1,89	1,80	1,77	1,82	1,91	2,06	2,37
	5500	2,55	2,14	1,92	1,81	1,76	1,79	1,86	1,99	2,28
	6000	2,67	2,22	1,96	1,82	1,76	1,77	1,82	1,94	2,19
	6500	2,81	2,30	2,02	1,85	1,77	1,76	1,79	1,89	2,11
	7000	2,96	2,41	2,08	1,89	1,79	1,76	1,77	1,85	2,05
	7500	3,14	2,52	2,16	1,94	1,81	1,76	1,76	1,82	1,99
	8000	3,33	2,66	2,25	2,00	1,85	1,78	1,76	1,80	1,95
	8500	3,55	2,81	2,35	2,07	1,90	1,80	1,77	1,79	1,92
	9000	3,80	2,98	2,47	2,16	1,96	1,84	1,79	1,79	1,89
	9500	4,07	3,17	2,61	2,26	2,03	1,89	1,82	1,80	1,88
	10000	4,38	3,39	2,77	2,37	2,11	1,95	1,86	1,82	1,88
	10500	4,72	3,63	2,95	2,50	2,21	2,03	1,91	1,85	1,89
	11000	4,72	3,63	2,94	2,50	2,21	2,03	1,91	1,85	1,89
	11500	5,06	3,87	3,13	2,64	2,32	2,10	1,97	1,89	1,91
	12000	5,43	4,14	3,33	2,79	2,44	2,20	2,04	1,95	1,94
	12500	5,84	4,43	3,55	2,96	2,57	2,30	2,12	2,01	1,99

Units: kg of fuel per 100 km flown, per seat

Minimum: 1.76 kg / 100 km / seat
(only cruise flight, without Take-Off , Landing, ...)

Average car: 6 l / 100 km
= 4.53 kg /100 km
= 0.90 kg /100 km / seat

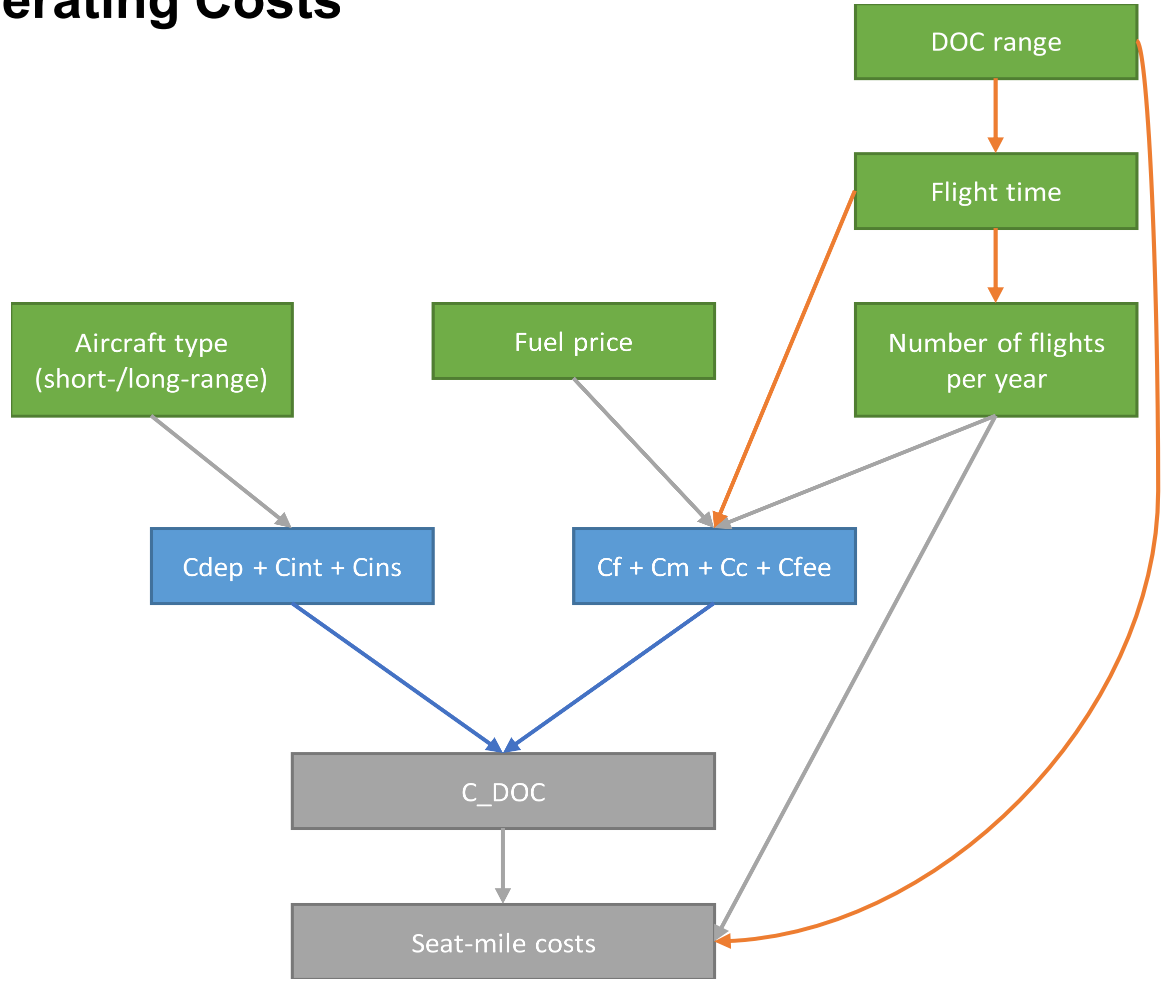
But:
Car can carry 5 people, but only 1 ... 2 on average in the car. Load factor ≈ 30%

Aircraft has a load factor of 70% ... 80%

Fuel consumption per person (load factor!):
Car:
3.0 kg / 100 km/ pax
Aircraft:
2.3 kg /100km/ pax
comparable, but aircraft flies much longer distance

Direct Operating Costs

Direct Operating Costs



DOC range

Flight time

Aircraft type (short-/long-range)

Fuel price

Number of flights per year

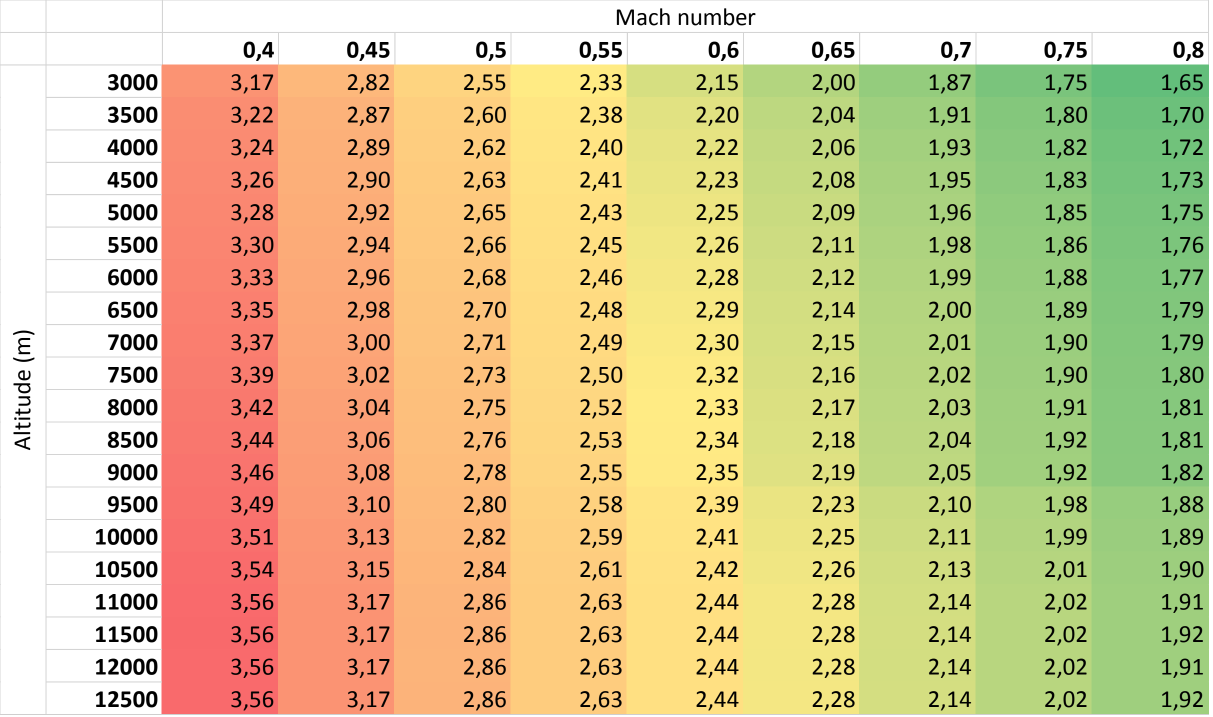
Cdep + Cint + Cins

Cf + Cm + Cc + Cfee

C_DOC

Seat-mile costs

Direct Operating Costs – Flight Time



		Mach number								
		0,4	0,45	0,5	0,55	0,6	0,65	0,7	0,75	0,8
Altitude (m)	3000	3,17	2,82	2,55	2,33	2,15	2,00	1,87	1,75	1,65
	3500	3,22	2,87	2,60	2,38	2,20	2,04	1,91	1,80	1,70
	4000	3,24	2,89	2,62	2,40	2,22	2,06	1,93	1,82	1,72
	4500	3,26	2,90	2,63	2,41	2,23	2,08	1,95	1,83	1,73
	5000	3,28	2,92	2,65	2,43	2,25	2,09	1,96	1,85	1,75
	5500	3,30	2,94	2,66	2,45	2,26	2,11	1,98	1,86	1,76
	6000	3,33	2,96	2,68	2,46	2,28	2,12	1,99	1,88	1,77
	6500	3,35	2,98	2,70	2,48	2,29	2,14	2,00	1,89	1,79
	7000	3,37	3,00	2,71	2,49	2,30	2,15	2,01	1,90	1,79
	7500	3,39	3,02	2,73	2,50	2,32	2,16	2,02	1,90	1,80
	8000	3,42	3,04	2,75	2,52	2,33	2,17	2,03	1,91	1,81
	8500	3,44	3,06	2,76	2,53	2,34	2,18	2,04	1,92	1,81
	9000	3,46	3,08	2,78	2,55	2,35	2,19	2,05	1,92	1,82
	9500	3,49	3,10	2,80	2,58	2,39	2,23	2,10	1,98	1,88
	10000	3,51	3,13	2,82	2,59	2,41	2,25	2,11	1,99	1,89
	10500	3,54	3,15	2,84	2,61	2,42	2,26	2,13	2,01	1,90
	11000	3,56	3,17	2,86	2,63	2,44	2,28	2,14	2,02	1,91
	11500	3,56	3,17	2,86	2,63	2,44	2,28	2,14	2,02	1,92
	12000	3,56	3,17	2,86	2,63	2,44	2,28	2,14	2,02	1,91
	12500	3,56	3,17	2,86	2,63	2,44	2,28	2,14	2,02	1,92

Units: hours

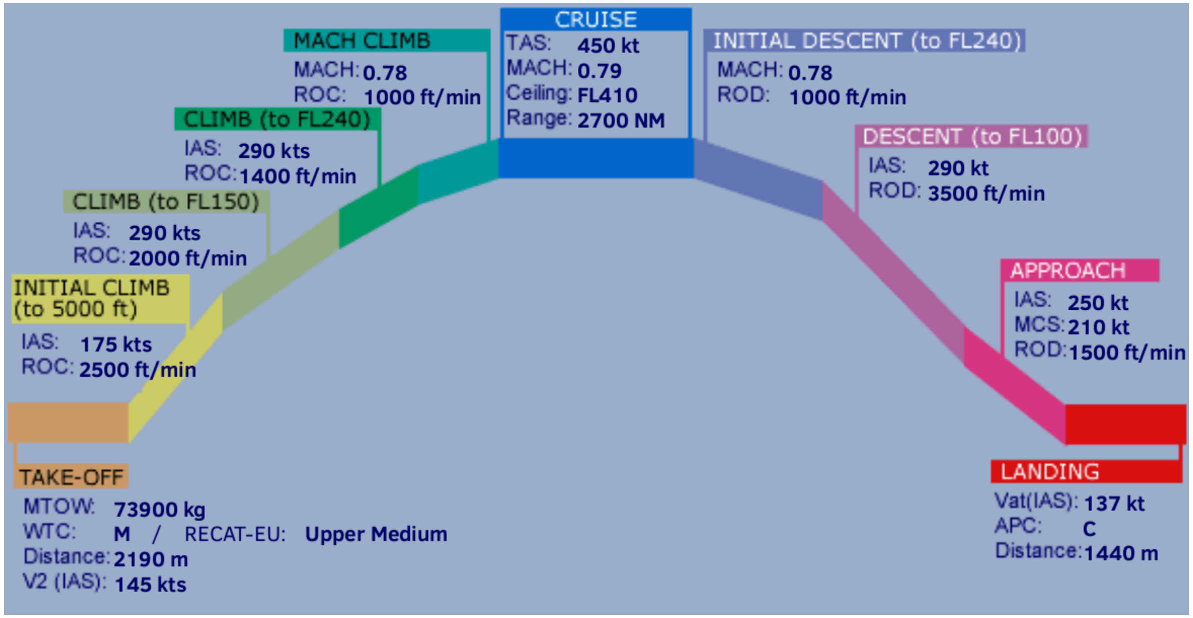
Higher TAS
=> lower flight time
=> lower costs per distance

TAS = $M * a$

a = f(H)

Not considered here:
TAS is limited below
≈ 7000 m

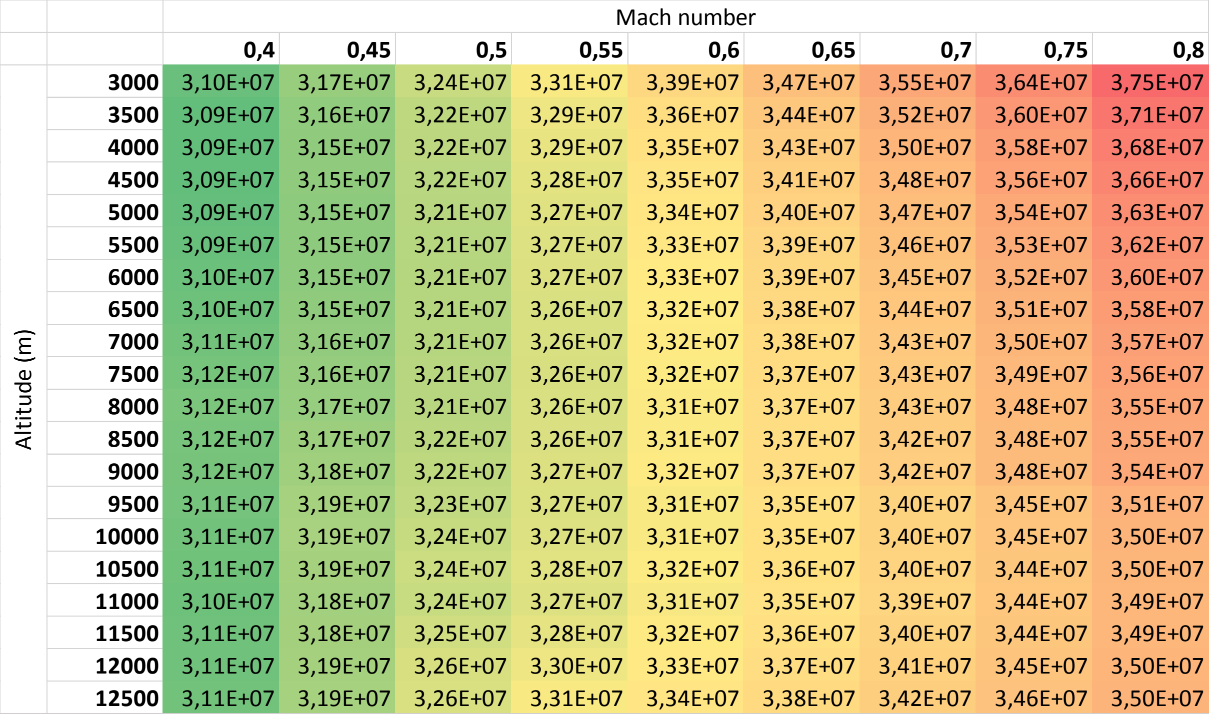
Direct Operating Costs – Flight Time



$$\boxed{t_f = \frac{R_{DOC}}{V}}$$

Eurocontrol 2019

Direct Operating Costs – Annual DOC



		Mach number								
		0,4	0,45	0,5	0,55	0,6	0,65	0,7	0,75	0,8
Altitude (m)	3000	3,10E+07	3,17E+07	3,24E+07	3,31E+07	3,39E+07	3,47E+07	3,55E+07	3,64E+07	3,75E+07
	3500	3,09E+07	3,16E+07	3,22E+07	3,29E+07	3,36E+07	3,44E+07	3,52E+07	3,60E+07	3,71E+07
	4000	3,09E+07	3,15E+07	3,22E+07	3,29E+07	3,35E+07	3,43E+07	3,50E+07	3,58E+07	3,68E+07
	4500	3,09E+07	3,15E+07	3,22E+07	3,28E+07	3,35E+07	3,41E+07	3,48E+07	3,56E+07	3,66E+07
	5000	3,09E+07	3,15E+07	3,21E+07	3,27E+07	3,34E+07	3,40E+07	3,47E+07	3,54E+07	3,63E+07
	5500	3,09E+07	3,15E+07	3,21E+07	3,27E+07	3,33E+07	3,39E+07	3,46E+07	3,53E+07	3,62E+07
	6000	3,10E+07	3,15E+07	3,21E+07	3,27E+07	3,33E+07	3,39E+07	3,45E+07	3,52E+07	3,60E+07
	6500	3,10E+07	3,15E+07	3,21E+07	3,26E+07	3,32E+07	3,38E+07	3,44E+07	3,51E+07	3,58E+07
	7000	3,11E+07	3,16E+07	3,21E+07	3,26E+07	3,32E+07	3,38E+07	3,43E+07	3,50E+07	3,57E+07
	7500	3,12E+07	3,16E+07	3,21E+07	3,26E+07	3,32E+07	3,37E+07	3,43E+07	3,49E+07	3,56E+07
	8000	3,12E+07	3,17E+07	3,21E+07	3,26E+07	3,31E+07	3,37E+07	3,43E+07	3,48E+07	3,55E+07
	8500	3,12E+07	3,17E+07	3,22E+07	3,26E+07	3,31E+07	3,37E+07	3,42E+07	3,48E+07	3,55E+07
	9000	3,12E+07	3,18E+07	3,22E+07	3,27E+07	3,32E+07	3,37E+07	3,42E+07	3,48E+07	3,54E+07
	9500	3,11E+07	3,19E+07	3,23E+07	3,27E+07	3,31E+07	3,35E+07	3,40E+07	3,45E+07	3,51E+07
	10000	3,11E+07	3,19E+07	3,24E+07	3,27E+07	3,31E+07	3,35E+07	3,40E+07	3,45E+07	3,50E+07
	10500	3,11E+07	3,19E+07	3,24E+07	3,28E+07	3,32E+07	3,36E+07	3,40E+07	3,44E+07	3,50E+07
	11000	3,10E+07	3,18E+07	3,24E+07	3,27E+07	3,31E+07	3,35E+07	3,39E+07	3,44E+07	3,49E+07
	11500	3,11E+07	3,18E+07	3,25E+07	3,28E+07	3,32E+07	3,36E+07	3,40E+07	3,44E+07	3,49E+07
	12000	3,11E+07	3,19E+07	3,26E+07	3,30E+07	3,33E+07	3,37E+07	3,41E+07	3,45E+07	3,50E+07
	12500	3,11E+07	3,19E+07	3,26E+07	3,31E+07	3,34E+07	3,38E+07	3,42E+07	3,46E+07	3,50E+07

Units: USD

Higher flight time
=> less flights per year
=> lower time-dependent costs:

- Fuel
- Maintenance
- Crew costs
- Fees and charges

Min. value per Mach number
=> at min. fuel consumption

Direct Operating Costs – Seat-Mile Cost

		Mach number								
		0,4	**0,45**	**0,5**	**0,55**	**0,6**	**0,65**	**0,7**	**0,75**	**0,8**
Altitude (m)	**3000**	0,266	0,248	0,235	0,224	0,216	0,209	0,204	0,200	0,198
	3500	0,269	0,251	0,237	0,226	0,218	0,211	0,205	0,201	0,199
	4000	0,271	0,252	0,238	0,227	0,218	0,211	0,206	0,202	0,199
	4500	0,272	0,253	0,239	0,228	0,219	0,212	0,206	0,202	0,199
	5000	0,274	0,254	0,240	0,229	0,220	0,213	0,207	0,202	0,199
	5500	0,276	0,256	0,241	0,229	0,220	0,213	0,207	0,203	0,199
	6000	0,277	0,257	0,242	0,230	0,221	0,214	0,208	0,203	0,199
	6500	0,279	0,258	0,243	0,231	0,222	0,214	0,208	0,203	0,200
	7000	0,281	0,260	0,244	0,232	0,222	0,215	0,208	0,203	0,199
	7500	0,283	0,262	0,245	0,233	0,223	0,215	0,209	0,203	0,200
	8000	0,286	0,264	0,247	0,234	0,224	0,216	0,209	0,204	0,200
	8500	0,287	0,265	0,248	0,235	0,225	0,216	0,209	0,204	0,200
	9000	0,288	0,268	0,250	0,237	0,226	0,217	0,210	0,204	0,200
	9500	0,290	0,270	0,252	0,239	0,228	0,220	0,213	0,207	0,203
	10000	0,291	0,272	0,253	0,240	0,229	0,221	0,214	0,208	0,203
	10500	0,293	0,273	0,255	0,242	0,231	0,222	0,215	0,209	0,204
	11000	0,294	0,274	0,256	0,243	0,232	0,223	0,215	0,209	0,204
	11500	0,294	0,274	0,258	0,243	0,232	0,223	0,216	0,209	0,205
	12000	0,294	0,274	0,258	0,244	0,233	0,224	0,216	0,210	0,205
	12500	0,295	0,274	0,259	0,245	0,234	0,224	0,217	0,210	0,205

Follows pattern of flight time:

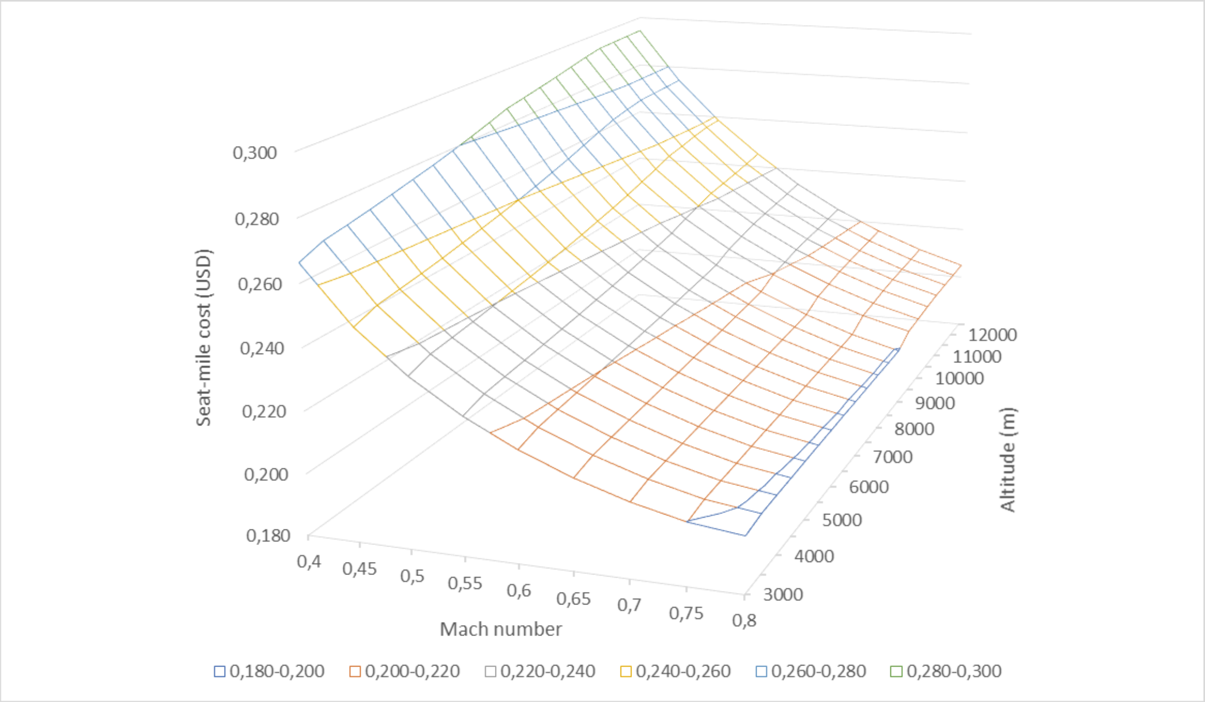
Not considered here: TAS is limited below ≈7000 m

Influence:
Flights per year
and
annual DOC

Altitude has little influence

Units: USD per seat, per NM

Direct Operating Costs – Seat-Mile Cost



Optimum:

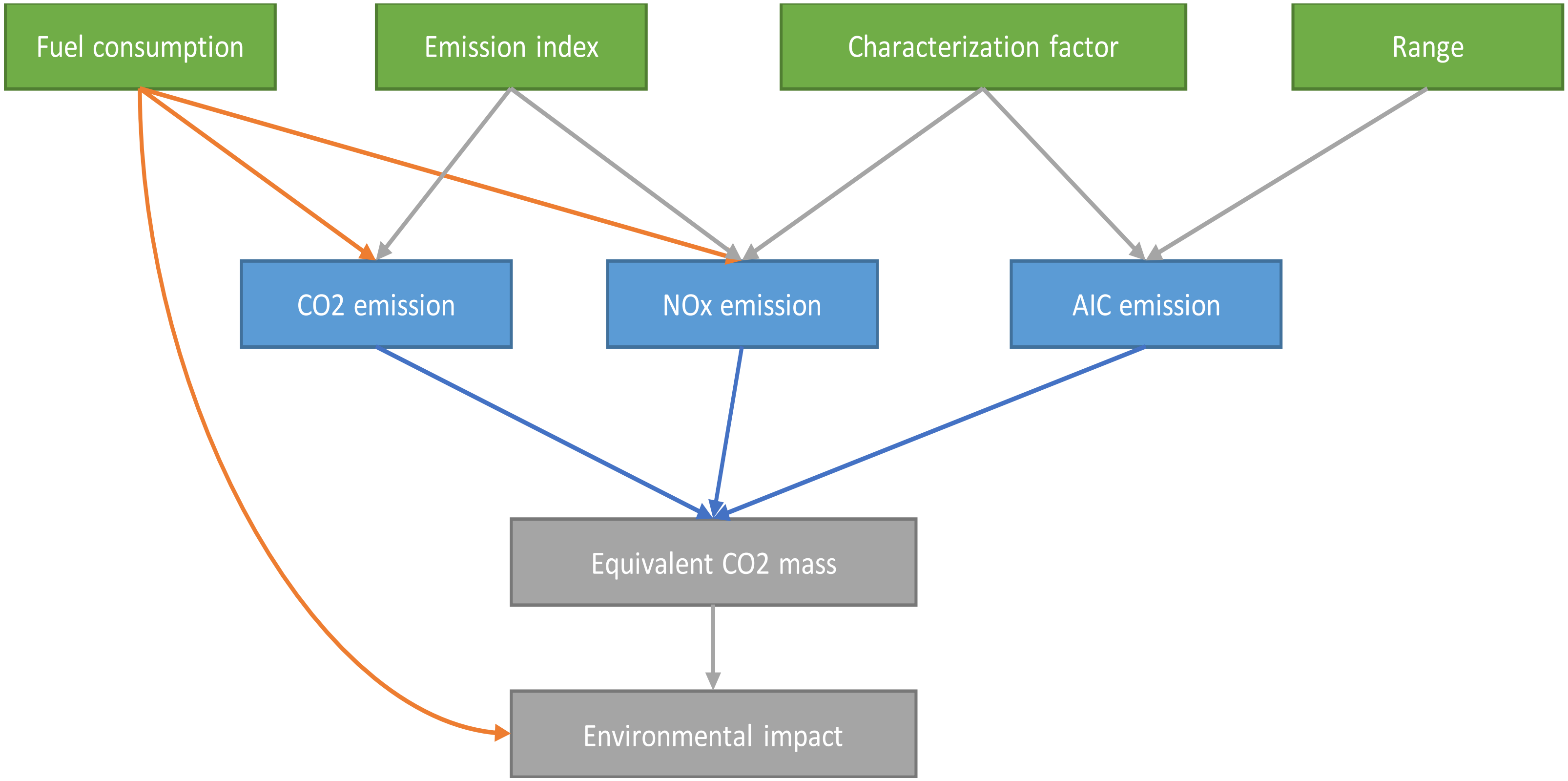
0.8 Mach
3000 m

Not considered here:
TAS is limited below
≈ 7000 m

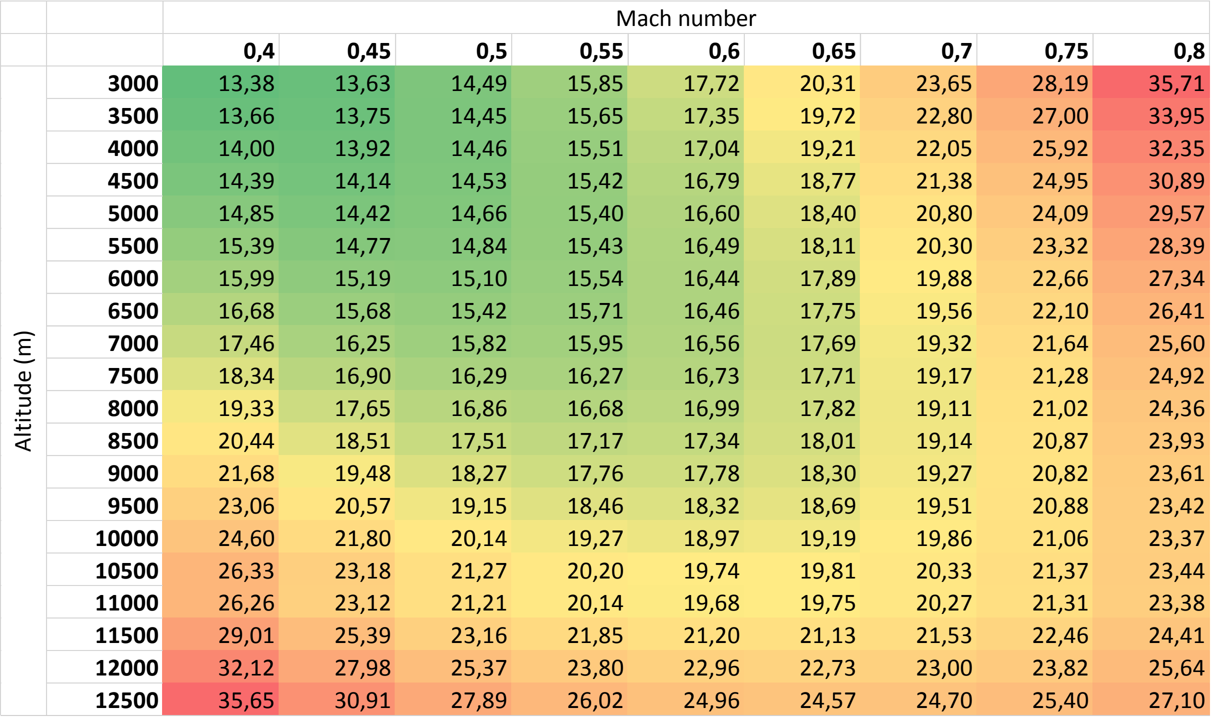
Units: USD per seat, per NM

Environmental Impact

Environmental Impact



Environmental Impact – Emission Index NO_x



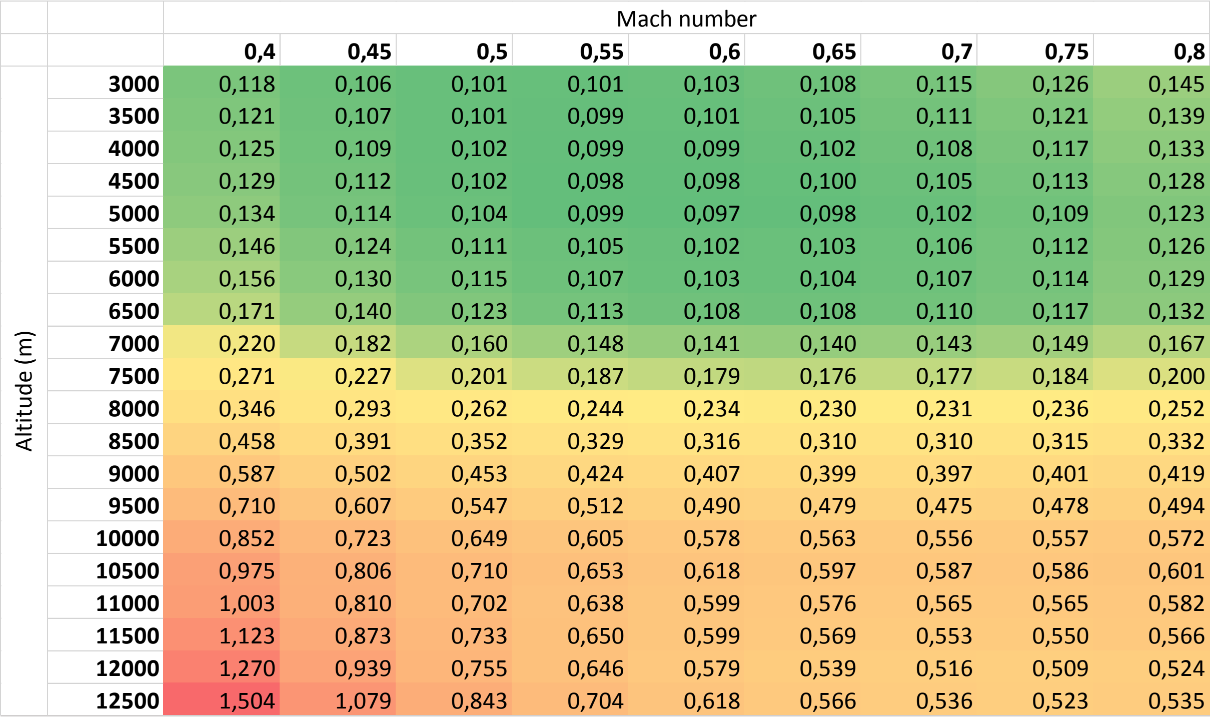
	Mach number								
Altitude (m)	0,4	0,45	0,5	0,55	0,6	0,65	0,7	0,75	0,8
3000	13,38	13,63	14,49	15,85	17,72	20,31	23,65	28,19	35,71
3500	13,66	13,75	14,45	15,65	17,35	19,72	22,80	27,00	33,95
4000	14,00	13,92	14,46	15,51	17,04	19,21	22,05	25,92	32,35
4500	14,39	14,14	14,53	15,42	16,79	18,77	21,38	24,95	30,89
5000	14,85	14,42	14,66	15,40	16,60	18,40	20,80	24,09	29,57
5500	15,39	14,77	14,84	15,43	16,49	18,11	20,30	23,32	28,39
6000	15,99	15,19	15,10	15,54	16,44	17,89	19,88	22,66	27,34
6500	16,68	15,68	15,42	15,71	16,46	17,75	19,56	22,10	26,41
7000	17,46	16,25	15,82	15,95	16,56	17,69	19,32	21,64	25,60
7500	18,34	16,90	16,29	16,27	16,73	17,71	19,17	21,28	24,92
8000	19,33	17,65	16,86	16,68	16,99	17,82	19,11	21,02	24,36
8500	20,44	18,51	17,51	17,17	17,34	18,01	19,14	20,87	23,93
9000	21,68	19,48	18,27	17,76	17,78	18,30	19,27	20,82	23,61
9500	23,06	20,57	19,15	18,46	18,32	18,69	19,51	20,88	23,42
10000	24,60	21,80	20,14	19,27	18,97	19,19	19,86	21,06	23,37
10500	26,33	23,18	21,27	20,20	19,74	19,81	20,33	21,37	23,44
11000	26,26	23,12	21,21	20,14	19,68	19,75	20,27	21,31	23,38
11500	29,01	25,39	23,16	21,85	21,20	21,13	21,53	22,46	24,41
12000	32,12	27,98	25,37	23,80	22,96	22,73	23,00	23,82	25,64
12500	35,65	30,91	27,89	26,02	24,96	24,57	24,70	25,40	27,10

Calculated using Boeing Fuel Flow Method 2, BFFM2

Pattern of fuel consumption visible (corrected fuel flow)

Units: g of NO_x emitted per kg of fuel burned

Environmental Impact – Equivalent CO_2 Mass



		Mach number								
		0,4	0,45	0,5	0,55	0,6	0,65	0,7	0,75	0,8
Altitude (m)	3000	0,118	0,106	0,101	0,101	0,103	0,108	0,115	0,126	0,145
	3500	0,121	0,107	0,101	0,099	0,101	0,105	0,111	0,121	0,139
	4000	0,125	0,109	0,102	0,099	0,099	0,102	0,108	0,117	0,133
	4500	0,129	0,112	0,102	0,098	0,098	0,100	0,105	0,113	0,128
	5000	0,134	0,114	0,104	0,099	0,097	0,098	0,102	0,109	0,123
	5500	0,146	0,124	0,111	0,105	0,102	0,103	0,106	0,112	0,126
	6000	0,156	0,130	0,115	0,107	0,103	0,104	0,107	0,114	0,129
	6500	0,171	0,140	0,123	0,113	0,108	0,108	0,110	0,117	0,132
	7000	0,220	0,182	0,160	0,148	0,141	0,140	0,143	0,149	0,167
	7500	0,271	0,227	0,201	0,187	0,179	0,176	0,177	0,184	0,200
	8000	0,346	0,293	0,262	0,244	0,234	0,230	0,231	0,236	0,252
	8500	0,458	0,391	0,352	0,329	0,316	0,310	0,310	0,315	0,332
	9000	0,587	0,502	0,453	0,424	0,407	0,399	0,397	0,401	0,419
	9500	0,710	0,607	0,547	0,512	0,490	0,479	0,475	0,478	0,494
	10000	0,852	0,723	0,649	0,605	0,578	0,563	0,556	0,557	0,572
	10500	0,975	0,806	0,710	0,653	0,618	0,597	0,587	0,586	0,601
	11000	1,003	0,810	0,702	0,638	0,599	0,576	0,565	0,565	0,582
	11500	1,123	0,873	0,733	0,650	0,599	0,569	0,553	0,550	0,566
	12000	1,270	0,939	0,755	0,646	0,579	0,539	0,516	0,509	0,524
	12500	1,504	1,079	0,843	0,704	0,618	0,566	0,536	0,523	0,535

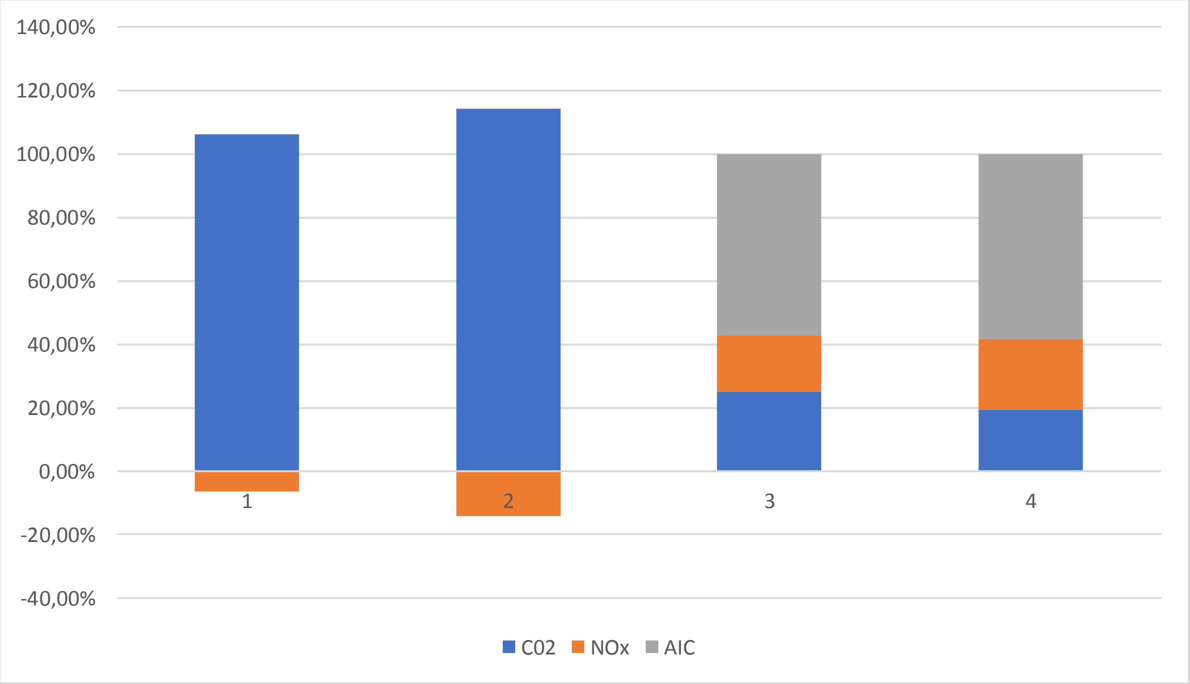
Noticeable altitude-dependency above 7000 m:
AIC effect kicks in

Orange band around 10000 m ... 11 500 m
=> AIC maximum

Units: kg of CO_2 emitted per seat, per NM

Environmental Impact – Equivalent CO_2 Mass

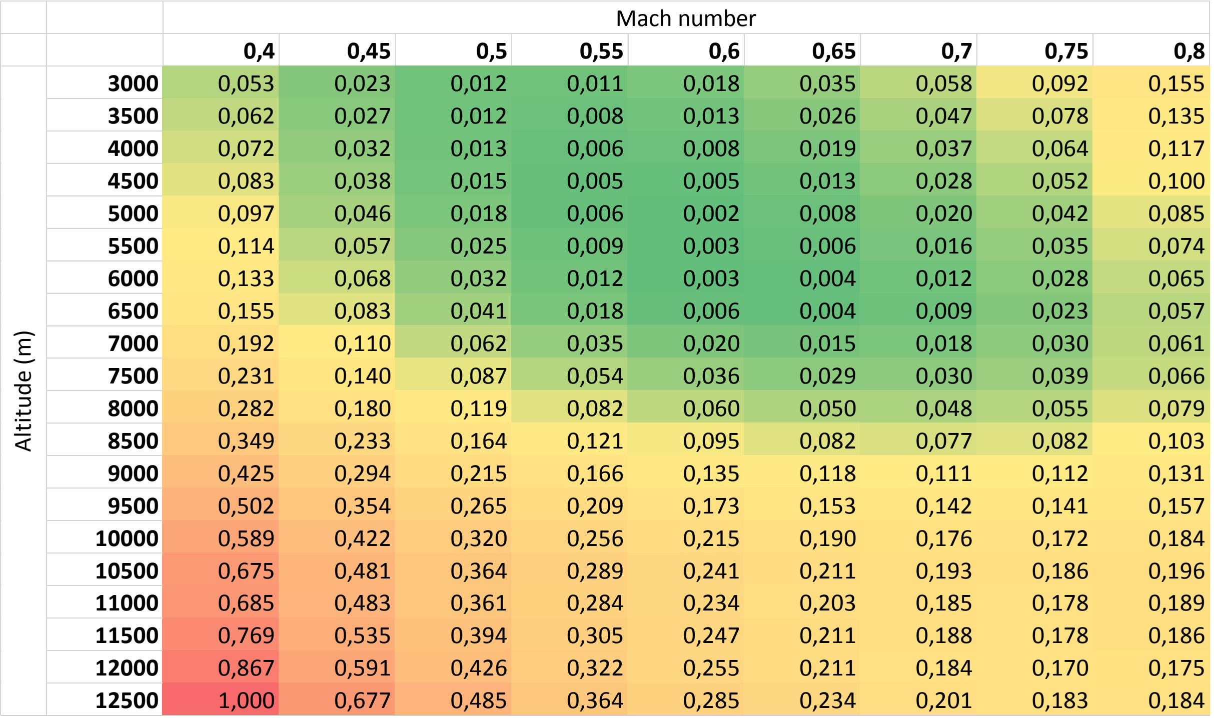
	Case 1	Case 2	Case 3	Case 4
M	0,55	0,8	0,5	0,75
H (m)	5000	4000	10000	11000
C02	106,33%	114,29%	24,90%	19,15%
NOx	-6,33%	-14,29%	18,02%	22,46%
AIC	0,00%	0,00%	57,08%	58,39%



AIC: No influence at low altitude. No cirrus below 5000 m

NO_x can have warming and cooling effect

Environmental Impact – Result



		Mach number								
		0,4	**0,45**	**0,5**	**0,55**	**0,6**	**0,65**	**0,7**	**0,75**	**0,8**
Altitude (m)	**3000**	0,053	0,023	0,012	0,011	0,018	0,035	0,058	0,092	0,155
	3500	0,062	0,027	0,012	0,008	0,013	0,026	0,047	0,078	0,135
	4000	0,072	0,032	0,013	0,006	0,008	0,019	0,037	0,064	0,117
	4500	0,083	0,038	0,015	0,005	0,005	0,013	0,028	0,052	0,100
	5000	0,097	0,046	0,018	0,006	0,002	0,008	0,020	0,042	0,085
	5500	0,114	0,057	0,025	0,009	0,003	0,006	0,016	0,035	0,074
	6000	0,133	0,068	0,032	0,012	0,003	0,004	0,012	0,028	0,065
	6500	0,155	0,083	0,041	0,018	0,006	0,004	0,009	0,023	0,057
	7000	0,192	0,110	0,062	0,035	0,020	0,015	0,018	0,030	0,061
	7500	0,231	0,140	0,087	0,054	0,036	0,029	0,030	0,039	0,066
	8000	0,282	0,180	0,119	0,082	0,060	0,050	0,048	0,055	0,079
	8500	0,349	0,233	0,164	0,121	0,095	0,082	0,077	0,082	0,103
	9000	0,425	0,294	0,215	0,166	0,135	0,118	0,111	0,112	0,131
	9500	0,502	0,354	0,265	0,209	0,173	0,153	0,142	0,141	0,157
	10000	0,589	0,422	0,320	0,256	0,215	0,190	0,176	0,172	0,184
	10500	0,675	0,481	0,364	0,289	0,241	0,211	0,193	0,186	0,196
	11000	0,685	0,483	0,361	0,284	0,234	0,203	0,185	0,178	0,189
	11500	0,769	0,535	0,394	0,305	0,247	0,211	0,188	0,178	0,186
	12000	0,867	0,591	0,426	0,322	0,255	0,211	0,184	0,170	0,175
	12500	1,000	0,677	0,485	0,364	0,285	0,234	0,201	0,183	0,184

“Neutral” mix of 50 – 50 resource depletion and engine emissions

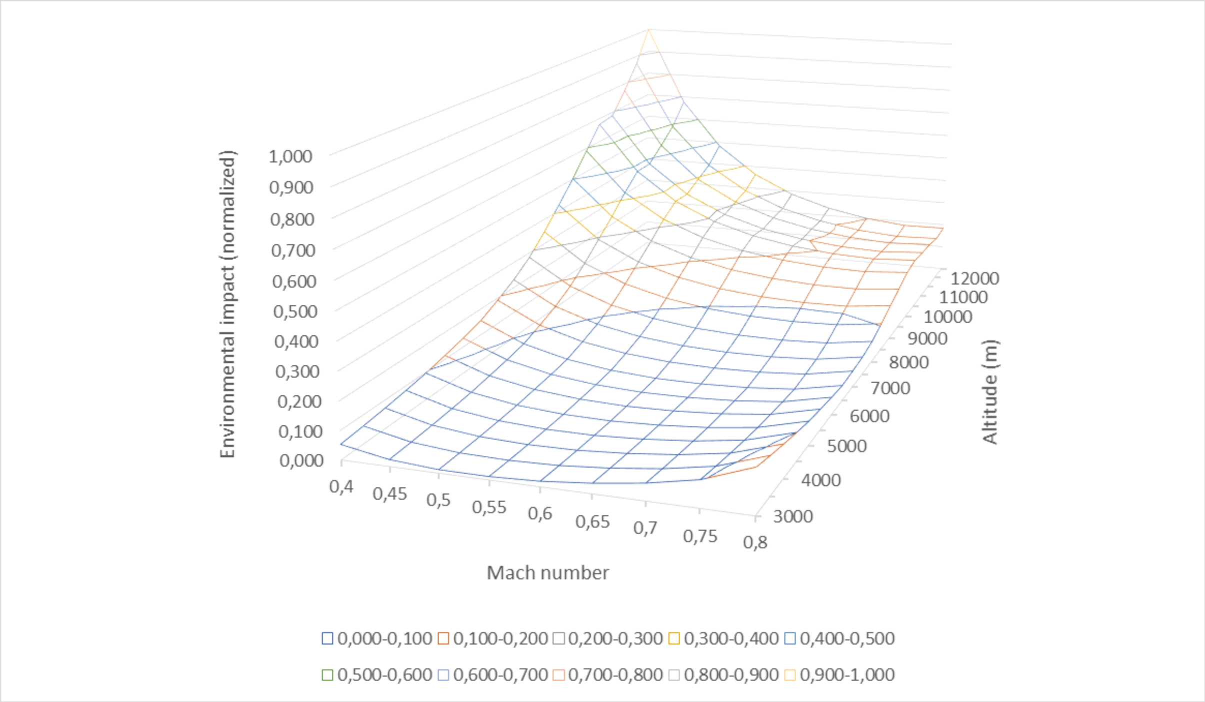
Clear altitude boundary from $m_{CO2,eq}$ visible

Fuel consumption shape visible

Fly low and slow

Units: normalized value between 0 and 1

Environmental Impact – Result



Optimum:

0.6 Mach
5000 m

"Better" option:

0.78 Mach
6500 m

77.7 % less $m_{CO2,eq}$
5.6 % more fuel cons.

Units: normalized value between 0 and 1

Environmental Impact – Result

Changing the regular cruise altitude of an Airbus A320-200 of about 11500 m to an altitude of 6500 m at a constant Mach 0.78 would result in:

- a decrease of equivalent CO2 mass of 78 % and
- an increase of fuel consumption of 5.6 %.

  The increase of fuel consumption is mostly influenced by

  - an increase of TSFC of 6.0 % and
  - a decrease of the aerodynamic efficiency of 5.4 %.

Combining equivalent CO2 mass and resource depletion (fuel consumption) into the environmental impact would result in a decrease of 70 % in environmental impact.

As the Mach number is kept constant, DOC are only effected by fuel consumption and increase by only 0.6%.

Environmental Impact – Result

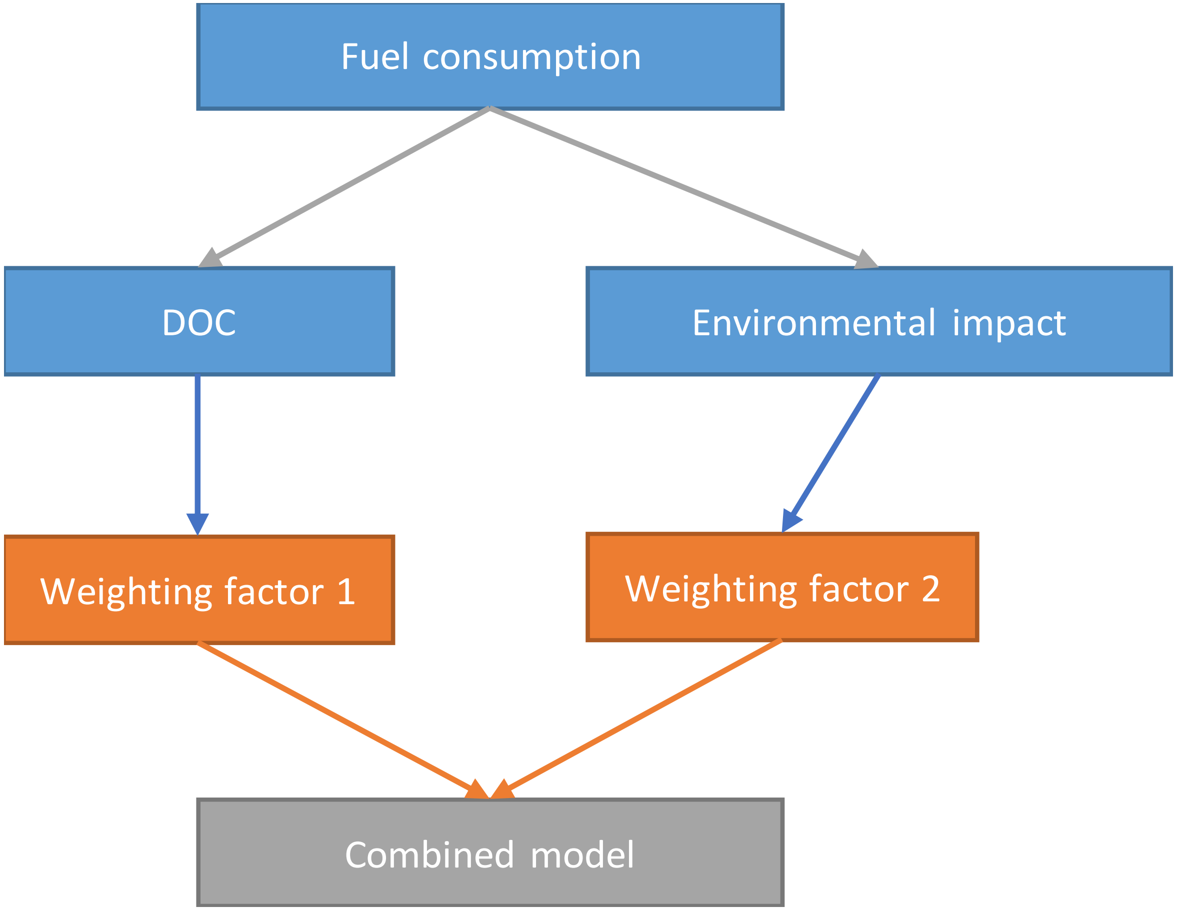
Changing the regular cruise altitude of an Airbus A320-200 of about 11500 m to and Mach 0.78 to an altitude of 6500 m and cruise speed reduction to Mach 0.65 would result in:

- resulting in a reduction of 83 % in environmental impact,
- this can be explained by the fuel consumption pattern: Mach 0.65 at 6500 m is right in the optimal dark green zone.
- DOC would be increased due to lower speed.

- The flight parameters for a minimal environmental impact are Mach 0.6 at an altitude of 5000 m.

Combined Model

Combined Model



Fuel consumption

DOC

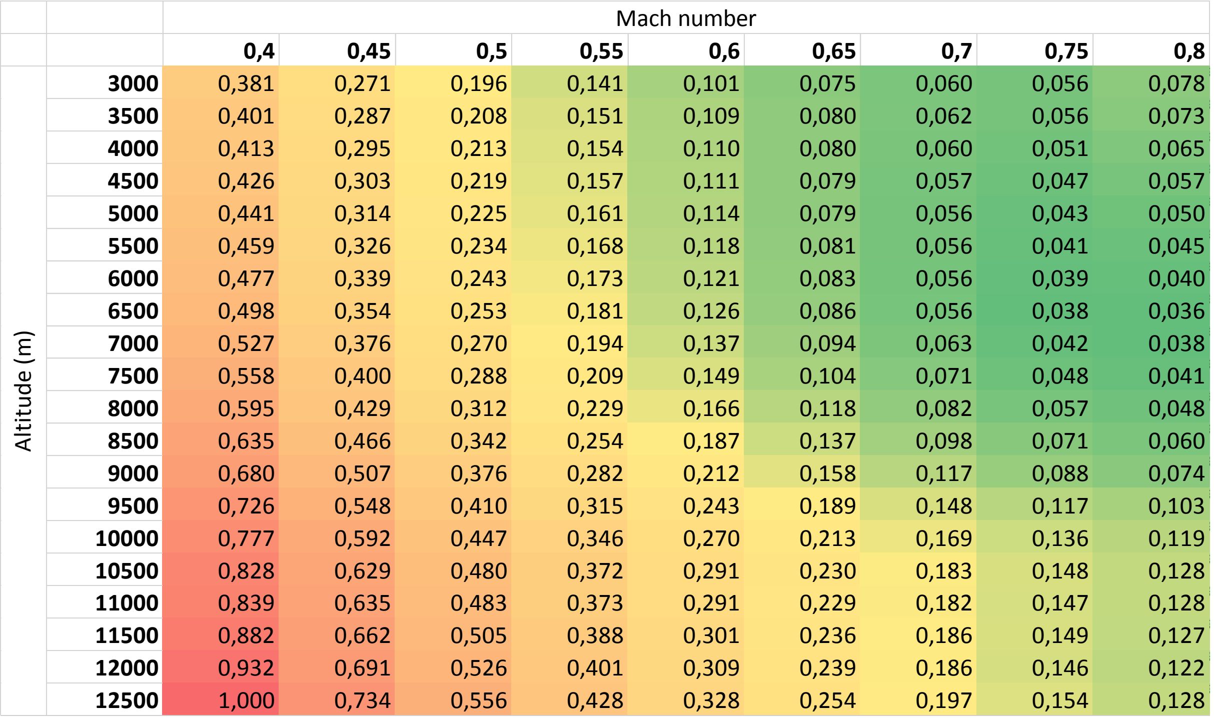
Environmental impact

Weighting factor 1

Weighting factor 2

Combined model

Combined Model – Equal DOC and Environmental Impact



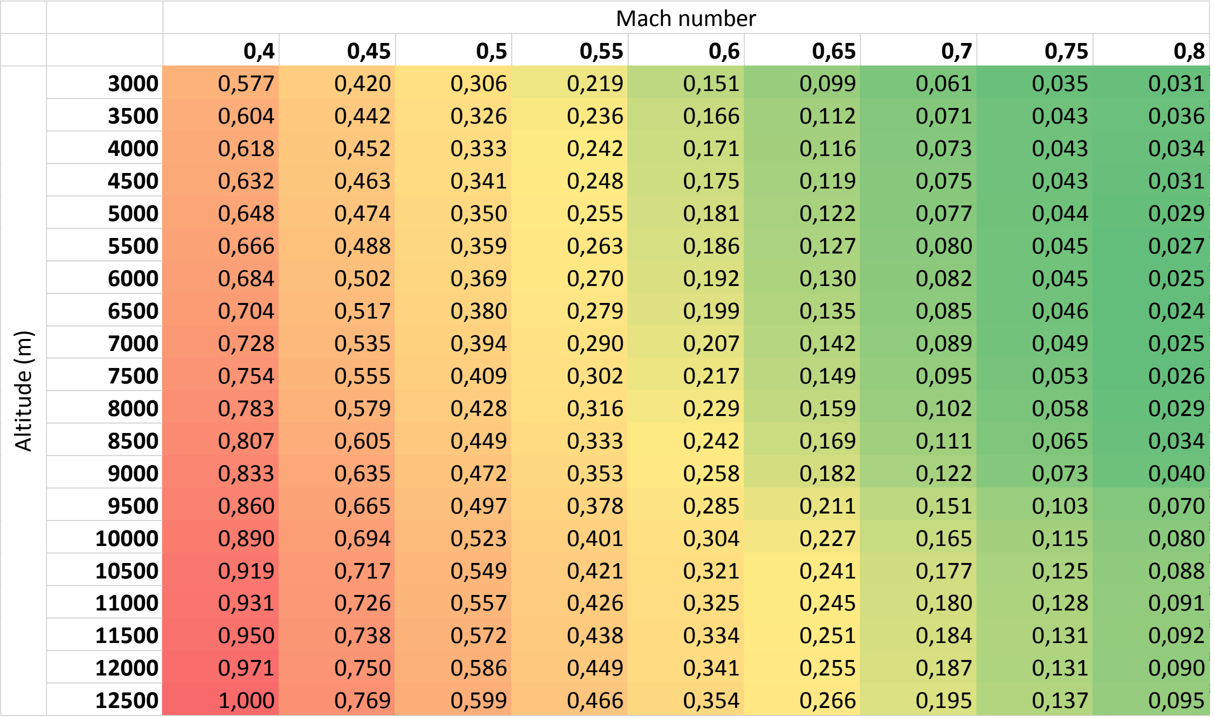
		Mach number								
		0,4	**0,45**	**0,5**	**0,55**	**0,6**	**0,65**	**0,7**	**0,75**	**0,8**
Altitude (m)	**3000**	0,381	0,271	0,196	0,141	0,101	0,075	0,060	0,056	0,078
	3500	0,401	0,287	0,208	0,151	0,109	0,080	0,062	0,056	0,073
	4000	0,413	0,295	0,213	0,154	0,110	0,080	0,060	0,051	0,065
	4500	0,426	0,303	0,219	0,157	0,111	0,079	0,057	0,047	0,057
	5000	0,441	0,314	0,225	0,161	0,114	0,079	0,056	0,043	0,050
	5500	0,459	0,326	0,234	0,168	0,118	0,081	0,056	0,041	0,045
	6000	0,477	0,339	0,243	0,173	0,121	0,083	0,056	0,039	0,040
	6500	0,498	0,354	0,253	0,181	0,126	0,086	0,056	0,038	0,036
	7000	0,527	0,376	0,270	0,194	0,137	0,094	0,063	0,042	0,038
	7500	0,558	0,400	0,288	0,209	0,149	0,104	0,071	0,048	0,041
	8000	0,595	0,429	0,312	0,229	0,166	0,118	0,082	0,057	0,048
	8500	0,635	0,466	0,342	0,254	0,187	0,137	0,098	0,071	0,060
	9000	0,680	0,507	0,376	0,282	0,212	0,158	0,117	0,088	0,074
	9500	0,726	0,548	0,410	0,315	0,243	0,189	0,148	0,117	0,103
	10000	0,777	0,592	0,447	0,346	0,270	0,213	0,169	0,136	0,119
	10500	0,828	0,629	0,480	0,372	0,291	0,230	0,183	0,148	0,128
	11000	0,839	0,635	0,483	0,373	0,291	0,229	0,182	0,147	0,128
	11500	0,882	0,662	0,505	0,388	0,301	0,236	0,186	0,149	0,127
	12000	0,932	0,691	0,526	0,401	0,309	0,239	0,186	0,146	0,122
	12500	1,000	0,734	0,556	0,428	0,328	0,254	0,197	0,154	0,128

DOC shifts environmental impact optimum to a higher Mach number

Not considered here: TAS is limited below ≈ 7000 m

Units: normalized value between 0 and 1

Combined Model – Emphasis on DOC



	Mach number								
Altitude (m)	0,4	0,45	0,5	0,55	0,6	0,65	0,7	0,75	0,8
3000	0,577	0,420	0,306	0,219	0,151	0,099	0,061	0,035	0,031
3500	0,604	0,442	0,326	0,236	0,166	0,112	0,071	0,043	0,036
4000	0,618	0,452	0,333	0,242	0,171	0,116	0,073	0,043	0,034
4500	0,632	0,463	0,341	0,248	0,175	0,119	0,075	0,043	0,031
5000	0,648	0,474	0,350	0,255	0,181	0,122	0,077	0,044	0,029
5500	0,666	0,488	0,359	0,263	0,186	0,127	0,080	0,045	0,027
6000	0,684	0,502	0,369	0,270	0,192	0,130	0,082	0,045	0,025
6500	0,704	0,517	0,380	0,279	0,199	0,135	0,085	0,046	0,024
7000	0,728	0,535	0,394	0,290	0,207	0,142	0,089	0,049	0,025
7500	0,754	0,555	0,409	0,302	0,217	0,149	0,095	0,053	0,026
8000	0,783	0,579	0,428	0,316	0,229	0,159	0,102	0,058	0,029
8500	0,807	0,605	0,449	0,333	0,242	0,169	0,111	0,065	0,034
9000	0,833	0,635	0,472	0,353	0,258	0,182	0,122	0,073	0,040
9500	0,860	0,665	0,497	0,378	0,285	0,211	0,151	0,103	0,070
10000	0,890	0,694	0,523	0,401	0,304	0,227	0,165	0,115	0,080
10500	0,919	0,717	0,549	0,421	0,321	0,241	0,177	0,125	0,088
11000	0,931	0,726	0,557	0,426	0,325	0,245	0,180	0,128	0,091
11500	0,950	0,738	0,572	0,438	0,334	0,251	0,184	0,131	0,092
12000	0,971	0,750	0,586	0,449	0,341	0,255	0,187	0,131	0,090
12500	1,000	0,769	0,599	0,466	0,354	0,266	0,195	0,137	0,095

Environmental impact almost indiscernible

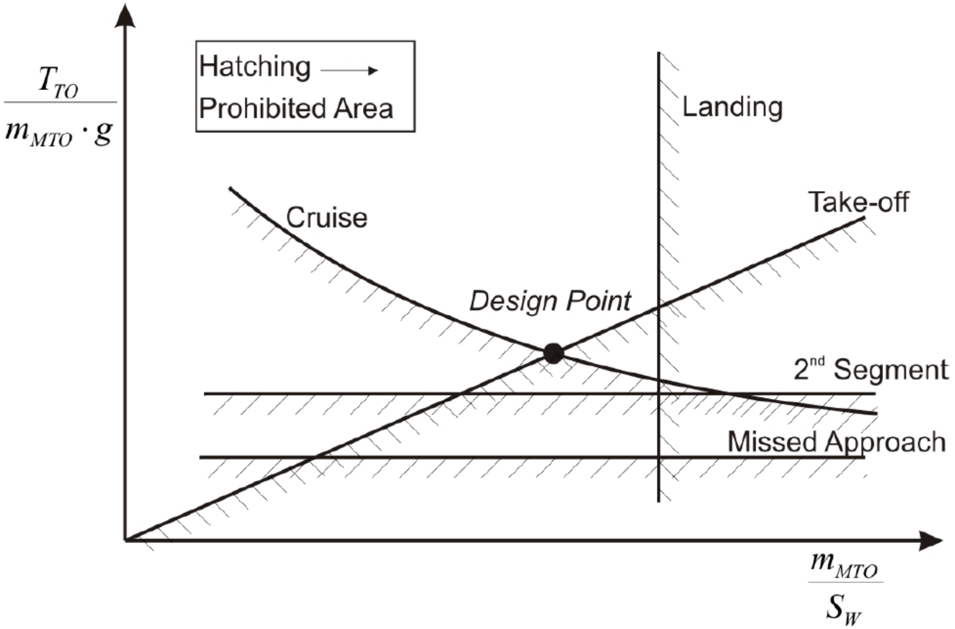
Optimum is better: impact DOC

Not considered here: TAS is limited below ≈ 7000 m

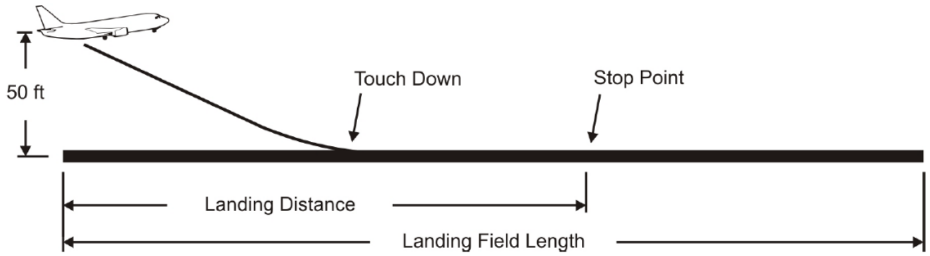
Units: normalized value between 0 and 1

Influence of Wing Loading

Influence of Wing Loading



Higher wing loading is limited by requirement for Landing Field Length, LFL



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Influence of Wing Loading

$$C_L(m/S) = \frac{2 \cdot g \cdot (m/S)}{\rho \cdot M^2 \cdot a^2}$$

Higher wing loading (due to smaller wing area)

=> higher lift coefficient for the same TAS = *M* * *a* and altitude or:

  => the same lift coefficient at lower flight altitude possible for the same TAS, but at lower Mach number

    => higher glide ratio E due to lower Mach number

    => lower fuel consumption,

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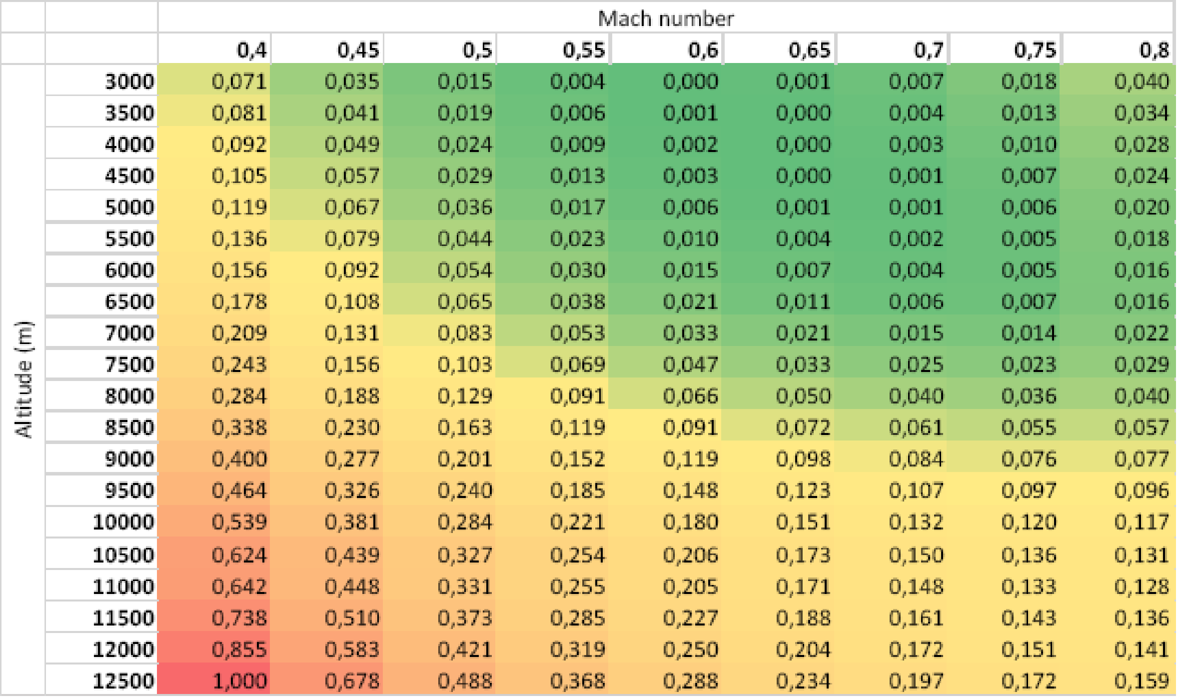
Influence of Wing Loading – 50% Higher Wing Loading



		Mach number								
		0,4	0,45	0,5	0,55	0,6	0,65	0,7	0,75	0,8
Altitude (m)	3000	0,071	0,035	0,015	0,004	0,000	0,001	0,007	0,018	0,040
	3500	0,081	0,041	0,019	0,006	0,001	0,000	0,004	0,013	0,034
	4000	0,092	0,049	0,024	0,009	0,002	0,000	0,003	0,010	0,028
	4500	0,105	0,057	0,029	0,013	0,003	0,000	0,001	0,007	0,024
	5000	0,119	0,067	0,036	0,017	0,006	0,001	0,001	0,006	0,020
	5500	0,136	0,079	0,044	0,023	0,010	0,004	0,002	0,005	0,018
	6000	0,156	0,092	0,054	0,030	0,015	0,007	0,004	0,005	0,016
	6500	0,178	0,108	0,065	0,038	0,021	0,011	0,006	0,007	0,016
	7000	0,209	0,131	0,083	0,053	0,033	0,021	0,015	0,014	0,022
	7500	0,243	0,156	0,103	0,069	0,047	0,033	0,025	0,023	0,029
	8000	0,284	0,188	0,129	0,091	0,066	0,050	0,040	0,036	0,040
	8500	0,338	0,230	0,163	0,119	0,091	0,072	0,061	0,055	0,057
	9000	0,400	0,277	0,201	0,152	0,119	0,098	0,084	0,076	0,077
	9500	0,464	0,326	0,240	0,185	0,148	0,123	0,107	0,097	0,096
	10000	0,539	0,381	0,284	0,221	0,180	0,151	0,132	0,120	0,117
	10500	0,624	0,439	0,327	0,254	0,206	0,173	0,150	0,136	0,131
	11000	0,642	0,448	0,331	0,255	0,205	0,171	0,148	0,133	0,128
	11500	0,738	0,510	0,373	0,285	0,227	0,188	0,161	0,143	0,136
	12000	0,855	0,583	0,421	0,319	0,250	0,204	0,172	0,151	0,141
	12500	1,000	0,678	0,488	0,368	0,288	0,234	0,197	0,172	0,159

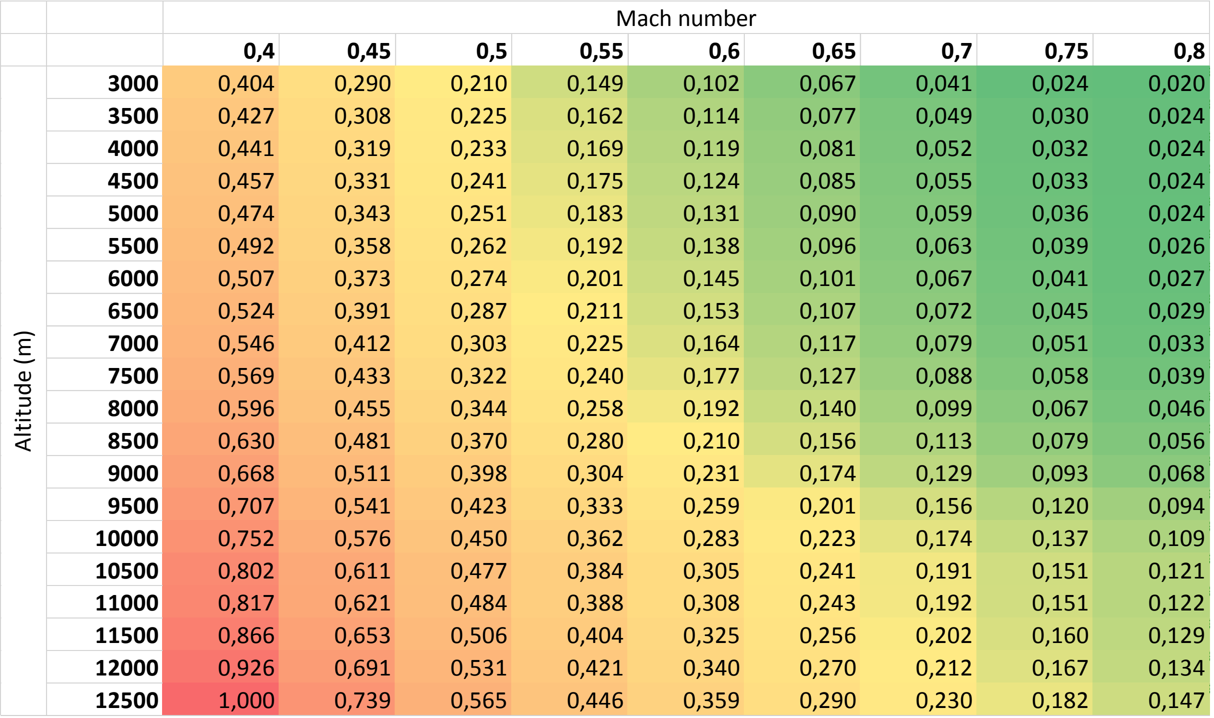
Units: normalized value between 0 and 1

Environmental Impact

Optima of fuel consumption and equivalent CO2 mass are closer to each other, because of lower altitude possible.

Note, with higher wing loading:
=> Longer Landing Field Length, LFL needs to be accepted
=> Not all airports can be served

Influence of Wing Loading – 50% Higher Wing Loading



		Mach number								
		0,4	**0,45**	**0,5**	**0,55**	**0,6**	**0,65**	**0,7**	**0,75**	**0,8**
Altitude (m)	**3000**	0,404	0,290	0,210	0,149	0,102	0,067	0,041	0,024	0,020
	3500	0,427	0,308	0,225	0,162	0,114	0,077	0,049	0,030	0,024
	4000	0,441	0,319	0,233	0,169	0,119	0,081	0,052	0,032	0,024
	4500	0,457	0,331	0,241	0,175	0,124	0,085	0,055	0,033	0,024
	5000	0,474	0,343	0,251	0,183	0,131	0,090	0,059	0,036	0,024
	5500	0,492	0,358	0,262	0,192	0,138	0,096	0,063	0,039	0,026
	6000	0,507	0,373	0,274	0,201	0,145	0,101	0,067	0,041	0,027
	6500	0,524	0,391	0,287	0,211	0,153	0,107	0,072	0,045	0,029
	7000	0,546	0,412	0,303	0,225	0,164	0,117	0,079	0,051	0,033
	7500	0,569	0,433	0,322	0,240	0,177	0,127	0,088	0,058	0,039
	8000	0,596	0,455	0,344	0,258	0,192	0,140	0,099	0,067	0,046
	8500	0,630	0,481	0,370	0,280	0,210	0,156	0,113	0,079	0,056
	9000	0,668	0,511	0,398	0,304	0,231	0,174	0,129	0,093	0,068
	9500	0,707	0,541	0,423	0,333	0,259	0,201	0,156	0,120	0,094
	10000	0,752	0,576	0,450	0,362	0,283	0,223	0,174	0,137	0,109
	10500	0,802	0,611	0,477	0,384	0,305	0,241	0,191	0,151	0,121
	11000	0,817	0,621	0,484	0,388	0,308	0,243	0,192	0,151	0,122
	11500	0,866	0,653	0,506	0,404	0,325	0,256	0,202	0,160	0,129
	12000	0,926	0,691	0,531	0,421	0,340	0,270	0,212	0,167	0,134
	12500	1,000	0,739	0,565	0,446	0,359	0,290	0,230	0,182	0,147

Optima of DOC and environmental impact are closer to each other, because of higher speed possible.

Note:
=> Longer Landing Field Length, LFL needs to be accepted
=> Not all airports can be served

Units: normalized value between 0 and 1

Combined Model – Equal DOC and Environmental Impact

Summary

Summary

- Decisions in the aviation industry are made around economic considerations. For the short/medium range fuel consumption accounts only for about 9 %. This means an improvement in environmental impact is unlikely to be driven by market forces for these type of aircraft (rather by maintenance costs and labor costs). *See page 11.*

- In cruise flight CO_2 emissions account for less than 20 %, while AIC accounts for almost 60 % of the equivalent CO_2 mass. This implies an “H_2O problem” rather than a CO_2 problem. Many activities in the industry to lower CO_2 emissions lose their justification in this context. However: The precise impact of AIC is still shrouded in uncertainties. *See page 36.*

- Savings can also be made in the design stage of an aircraft if we are willing to sacrifice some present-day operational capalities or adapt future airports to the longer required landing field length. *See page 49.*

- **Finally: There is no need to wait for newer, more efficient aircraft. Today, flying at an altitude of 6500 m would reduce the environmental impact by 70 % combined with an increase of 6 % in fuel consumption and only about 0.6 % increase in DOC for short / medium range aircraft.** *See page 39.*

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Based on my Master Thesis

Download:

https://nbn-resolving.org/urn:nbn:de:gbv:18302-aero2019-07-28.013

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