Hochschule für Angewandte Wissenschaften Hamburg

Hamburg University of Applied Sciences

AIRCRAFT DESIGN AND SYSTEMS GROUP (AERO)

Direct Operating Costs, Fuel Consumption, and Cabin Layout of the Airbus A321LR

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Abstract

Purpose – Assessment of the Direct Operating Costs (DOC) and fuel consumption of the Airbus A321LR using typical use-cases and comparison with those from similar aircraft. Investigation of the flexibility of the cabin layout using examples from different airlines. Calculation of Ecolabels based on different cabin configurations.

Methodology – All aircraft-related data is retrieved from the Original Equipment Manufacturers' (OEM) manuals. The DOC assessment uses the Association of European Airlines (AEA) and the TU Berlin method. The fuel consumption is assessed with a tool based on the Breguet Range equation, using successive iterations. The Ecolabel considers resource depletion, global warming, local air quality, and noise pollution, weighted and combined into one overall rating. A cabin study contrast layouts from Airbus with those from operators and also considering ergonomics.

Findings – The A321LR offers improvements in flight range compared to A321CEO and A321NEO. It can operate medium range very efficiently with only minor payload reduction. Very low-density layouts of a few airlines are purely their marketing preferences. Costs per seat and Ecolabel rating vary significantly between low-density and high-density cabin configurations. Predictions for the A321XLR are also very favorable.

Research Limitations – DOC results are not unique numbers but depend on the DOC method applied. Some of the characteristics for the XLR can so far only be estimated, since its entry into service is scheduled for 2023 and, as such, after the submission of this thesis.

Practical Implications – Good reasons for operating the A321LR are elaborated. The Ecolabel allows passengers and operators to openly discuss the ecological implications of different cabin layouts.

Originality – This seems to be the first scientific report that extensively investigates economic and ecologic aspects when operating the A321LR with different cabin layouts.

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Introduction

General Considerations

Facts

- The A321LR was launched in 2018, as an extended-range variant of A321neo and it offers two engine variants: CFM LEAP-1A or PW-1100G
- Actual operators : TAP Air Portugal, JetBlue, Air Astana, Air Transat, Aer Lingus, ...
- Technology: up to 3 Additional Center Tanks (ACTs) → more fuel → fly longer. An extra-long range (XLR) variant is scheduled for 2023

Questions/Presumptions

- Structural weight limits with ACTs installation → reduced maximum payload→fewer passengers:
  - e.g., JetBlue's A321LR cabin fits 138 seats while most A321neo fit 180-220 passengers! → reflects in the cost per seating passenger → much higher ticket prices

What does Airbus/ airlines say?

"… with a range of up to 4,000 NM (7,400 km), the A321LR is the unrivalled long-range route opener, featuring true transatlantic capability and premium wide-body comfort in a single-aisle aircraft cabin." (Airbus 2019a)

"It [A321LR] delivers 30% fuel savings and nearly 50% reduction in noise footprint compared to previous-generation competitor aircraft." (Airbus 2019a)

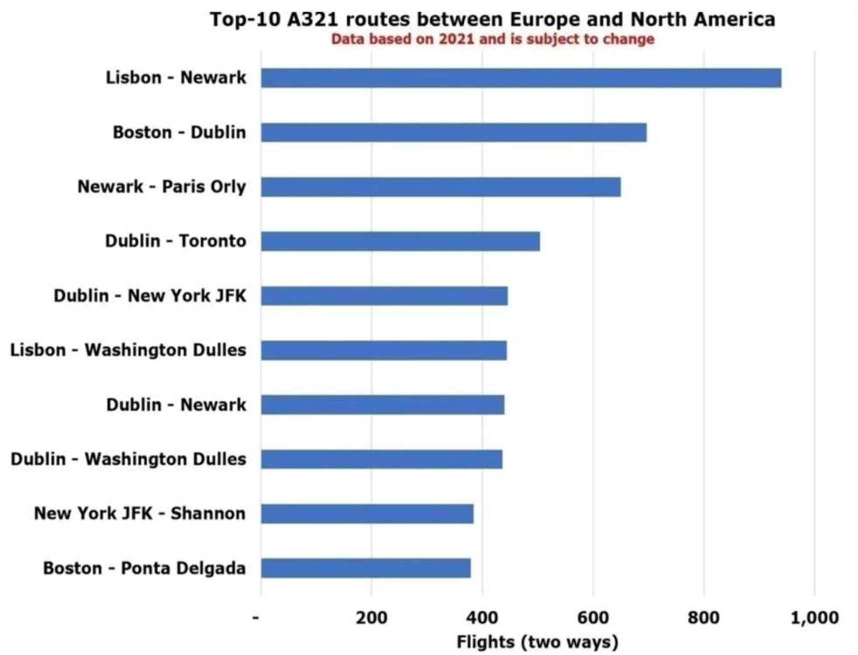
What speaks for the LR?

- Crescent popularity of long-range missions operated with single-aisle aircraft: lower financial risk, strategical decison – e.g., COVID-19 (less demand) and Airbus A380 (expensive, more seats)
- Pilots and cabin crew do not need additional training due to commonality along the A320 family (world's best selling single-aisle aircraft family)

Which Missions are Being Flown?

Scheduled long-haul flights operated by A321LR aircraft – winter season 2021/22 (edited from Pearson 2021a)

Airline	From	To	Distance (miles)	Distance (km)
TAP	Belém	Lisbon	3,726	6,000
Air Transat	Faro	Toronto	3,693	5,940
SAS	Boston	Copenhagen	3,671	5,910
TAP	Lisbon	Recife	3,628	5,840
TAP	Lisbon	Washington Dulles	3,592	5,780
Air Transat	London Gatwick	Toronto	3,576	5,750
Air Transat/ TAP	Lisbon	Toronto	3,576	5,750
Air Transat	Malaga	Montreal	3,554	5,720
Air Transat	Porto	Toronto	3,515	5,660
TAP	Lisbon	Natal	3,496	5,630
TAP	Fortaleza	Lisbon	3,478	5,600
JetBlue	London Gatwick	New York JFK	3,47	5,580
JetBlue	London Heathrow	New York JFK	3,451	5,550
Air Transat	Montreal	Paris CDG	3,442	5,540
Air Transat	Manchester	Toronto	3,434	5,530
Aer Lingus	Dublin	Washington Dulles	3,404	5,480
TAP	Lisbon	Newark	3,384	5,450
TAP	Lisbon	New York JFK	3,366	5,420
Aer Lingus	Manchester	New York JFK	3,341	5,380
Air Transat	Glasgow	Toronto	3,293	5,300



Top ten A321 routes between Europe and North America in 2021, according to number of flights (Pearson 2021b)

Aircraft and Missions Considered

- Mission 1 (M1) coincides with the range at maximum payload of the A321LR – 5.600 km
- Mission 2 (M2) is equidistant to the ranges of M1 and M2 – 6.500km
- Mission 3 (M3) coincides with the range at maximum fuel weight of the A321LR – 7.400 km

(Airbus 2020 and 2021c)

AIRCRAFT	MTOW [kg]	MZFW [kg]	OEW [kg]	MFW [kg]	Max. Payload [kg]	Range(B) [km]	Range(C) [km]	Range(D) [km]
A321ceo	89.000	71.500	48.436	18.600	23.571	3.704	4.198	5.865
A321neo	93.500	75.600	50.774	18.440	25.000	4.630	4.990	6.960
A321LR	97.000	75.600	52.060	25.790	23.540	5.600	7.400	9.400
A321XLR	101.000	74.374*	52.660*	31.016	22.314*	6.750*	8.700	11.800*
A330-900 neo	242.000	181.000	135.640	109.186	45.360	7.700	8.900	17.287

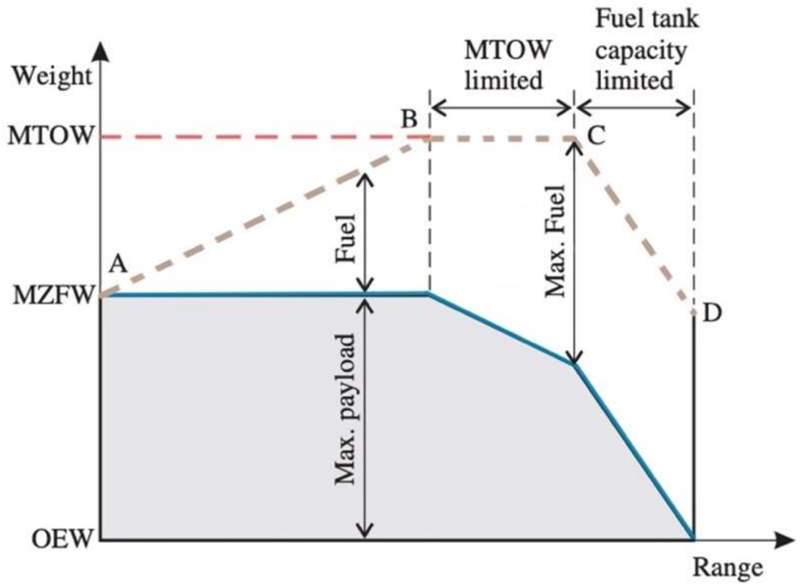
MTOW: Maximum Take-Off Weight
MZFW: Maximum Zero Fuel Weight
OEW: Operating Empty Weight
MFW: Maximum Fuel Weight

The passenger mass considered = 97,0 kg (pax + luggage)

Fuel Consumption

of the Airbus A321LR

The Breguet Range and Aircraft Weight



Extended Payload-Range diagram; based on Young (2017)

Breguet Factor:

$$B = \frac{R}{ln\left(\frac{m_1}{m_2}\right)}$$

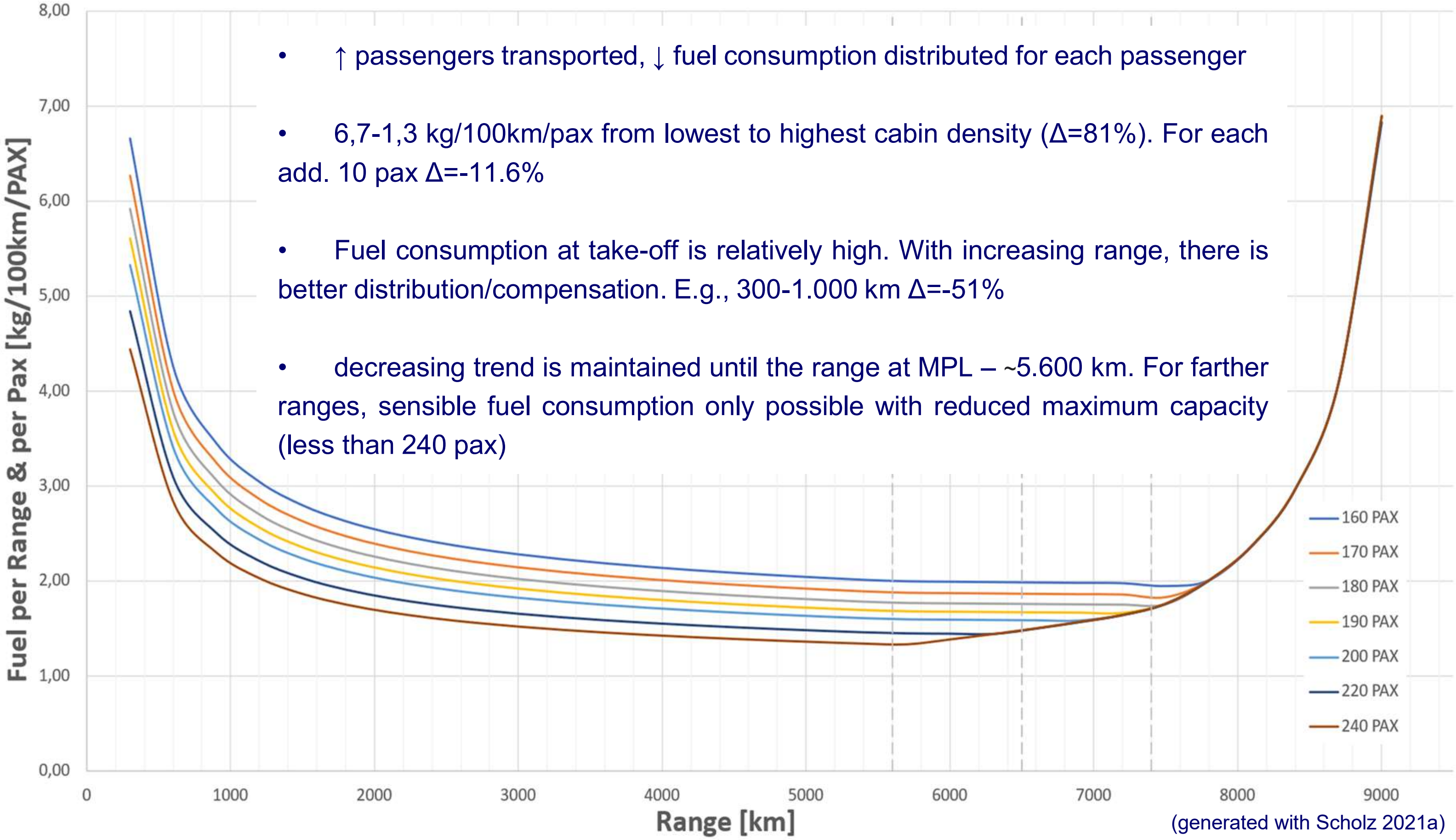
Mission Fuel Mass:

$$m_{fuel} = m_2\left(e^{\frac{R}{B}} - 1\right)$$

Range (at Point)	Take-off weight (**m_1**)	Landing weight (**m_2**)
B (range max. payload)	MTOW	MZFW
C (design range)	MTOW	MTOW-MFW
D (ferry range)	OEW+MFW	OEW

MTOW: Maximum Take-Off Weight
MZFW: Maximum Zero Fuel Weight
OEW: Operating Empty Weight
MFW: Maximum Fuel Weight

Fuel Consumption – kg/100km/PAX



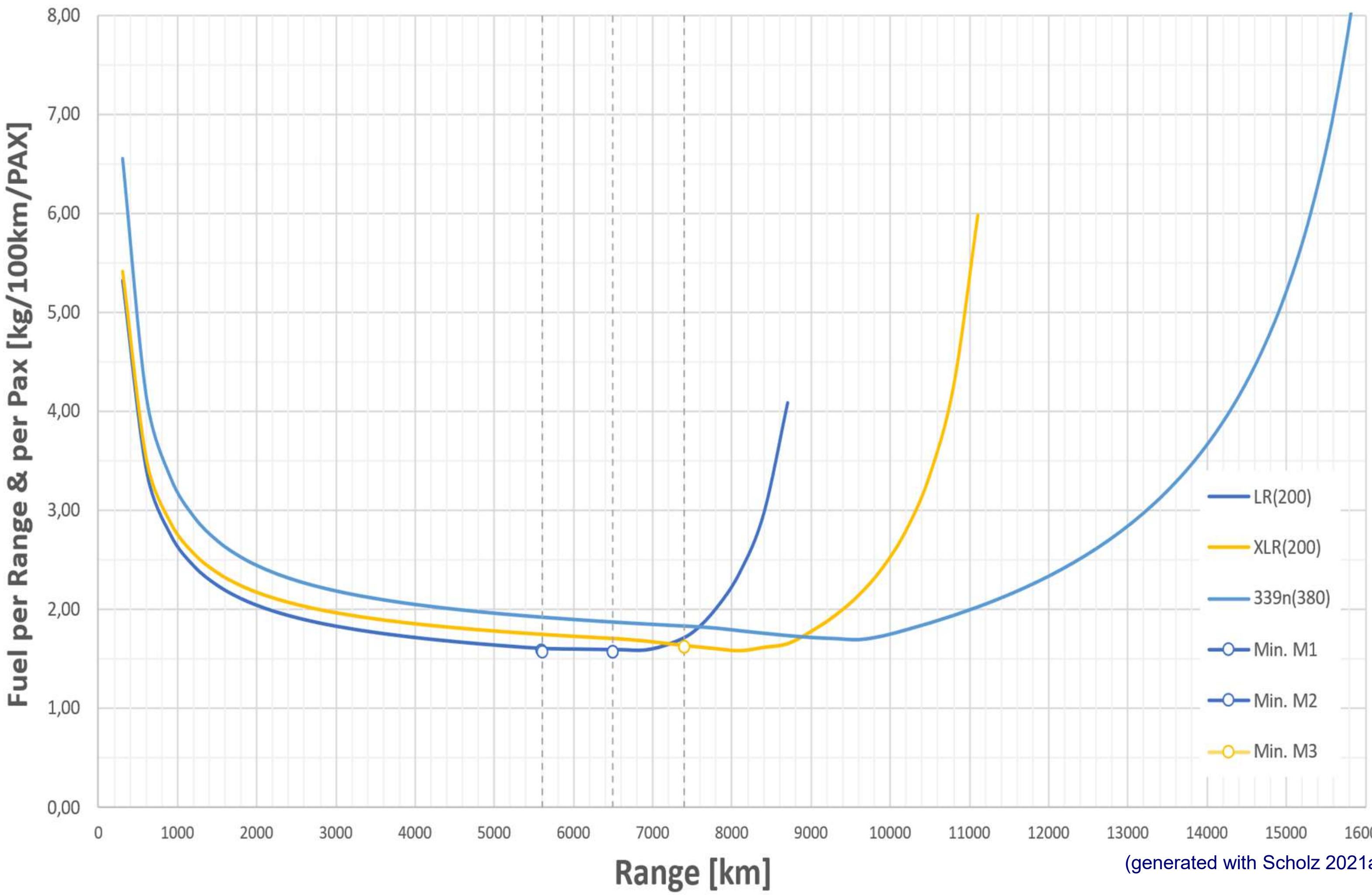
(generated with Scholz 2021a)

- ↑ passengers transported, ↓ fuel consumption distributed for each passenger
- 6,7-1,3 kg/100km/pax from lowest to highest cabin density (Δ=81%). For each add. 10 pax Δ=-11.6%
- Fuel consumption at take-off is relatively high. With increasing range, there is better distribution/compensation. E.g., 300-1.000 km Δ=-51%
- decreasing trend is maintained until the range at MPL – ~5.600 km. For farther ranges, sensible fuel consumption only possible with reduced maximum capacity (less than 240 pax)

Fuel consumption per range and passenger over flown distance for the **A321LR**

Note: *from the moment the slope of the curve is inverted, the range is not supported anymore with the corresponding number of pax →* ***passenger reduction must take place –*** the fuel is distributed to an (ever) decreasing number of passengers

Fuel Consumption – kg/100km/PAX



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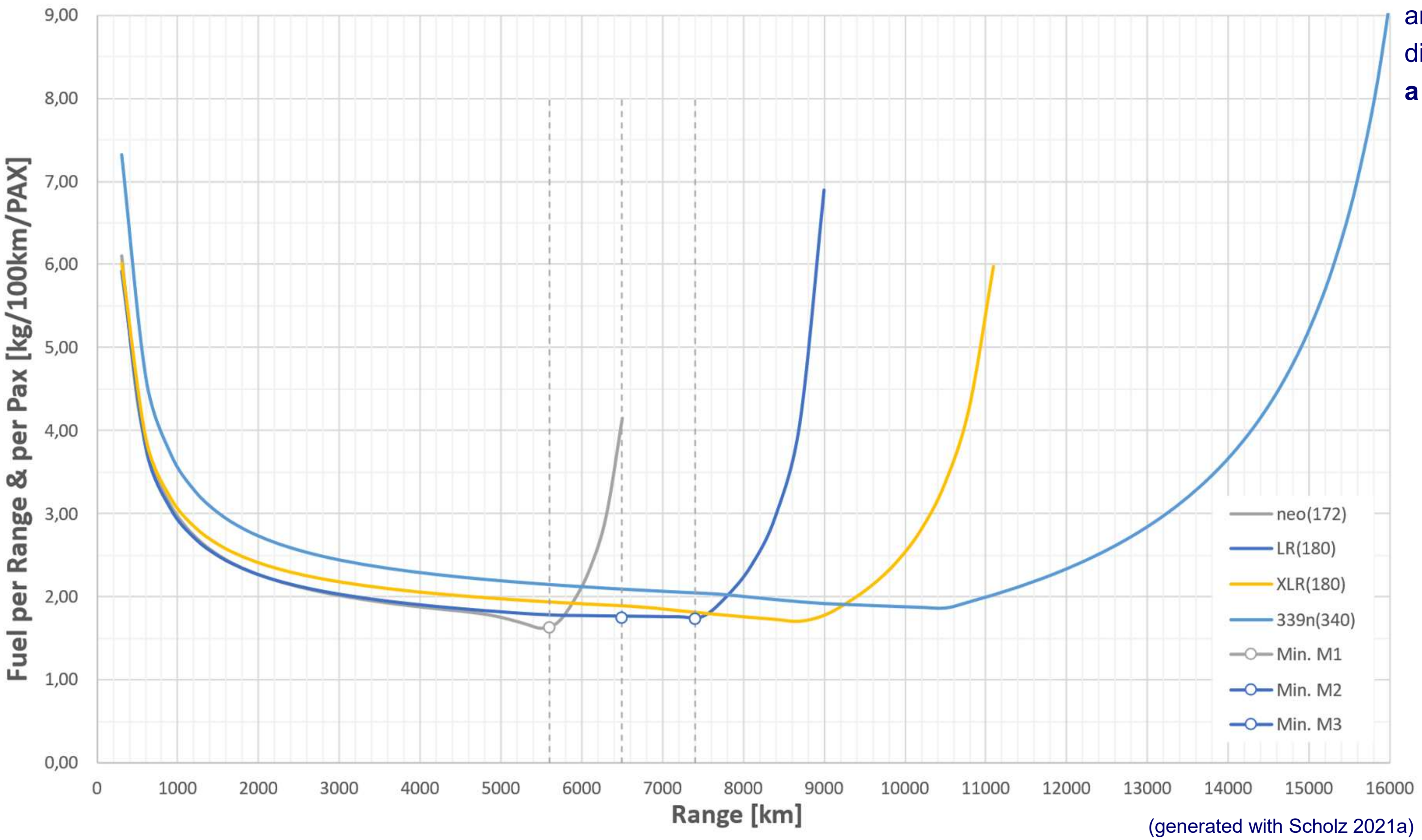
Fuel consumption per range and passenger over flown distance: **Comparison for a standard cabin density**

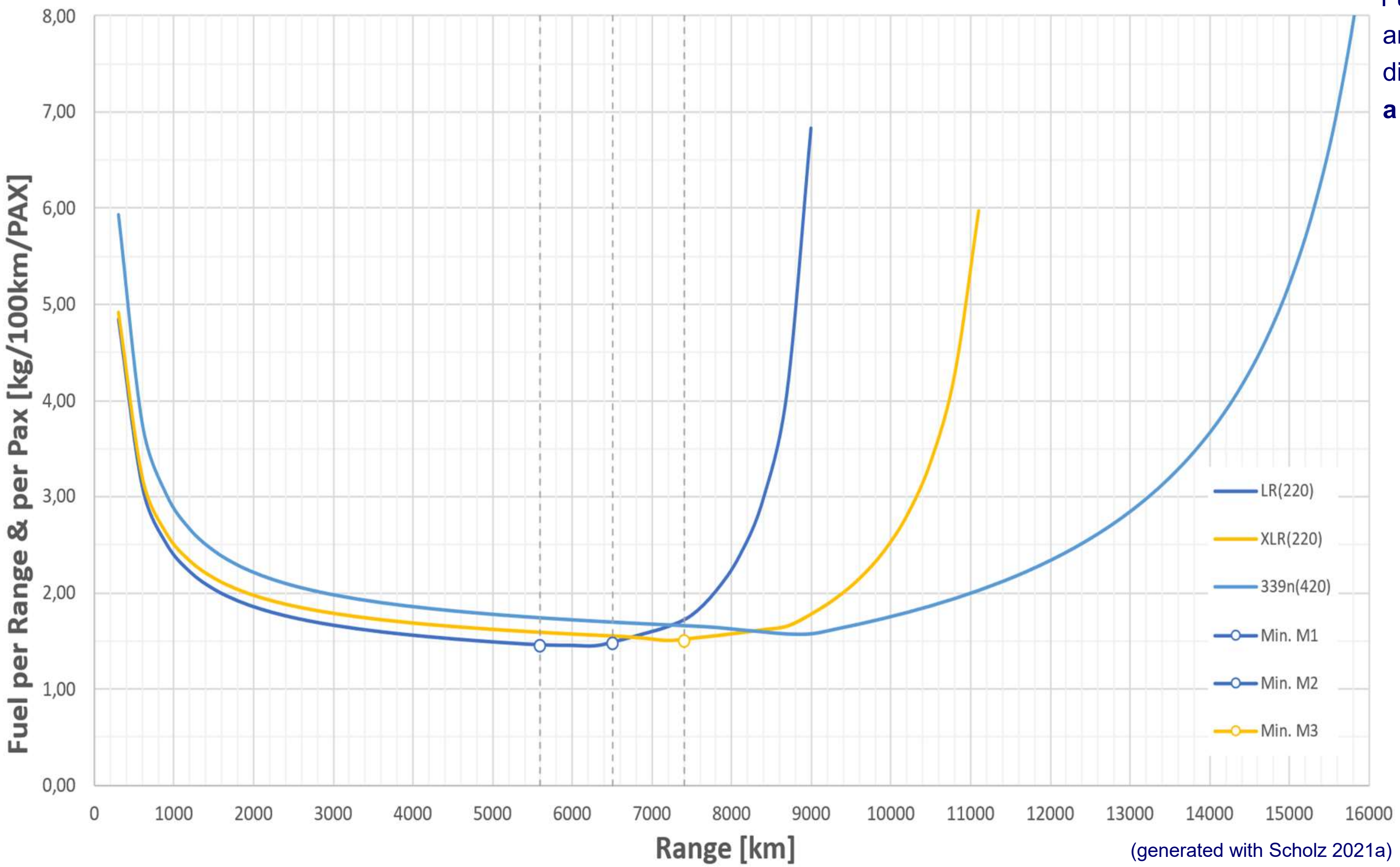
Fuel Consumption – kg/100km/PAX



Fuel consumption per range and passenger over flown distance: **Comparison for a low-density cabin**

(generated with Scholz 2021a)

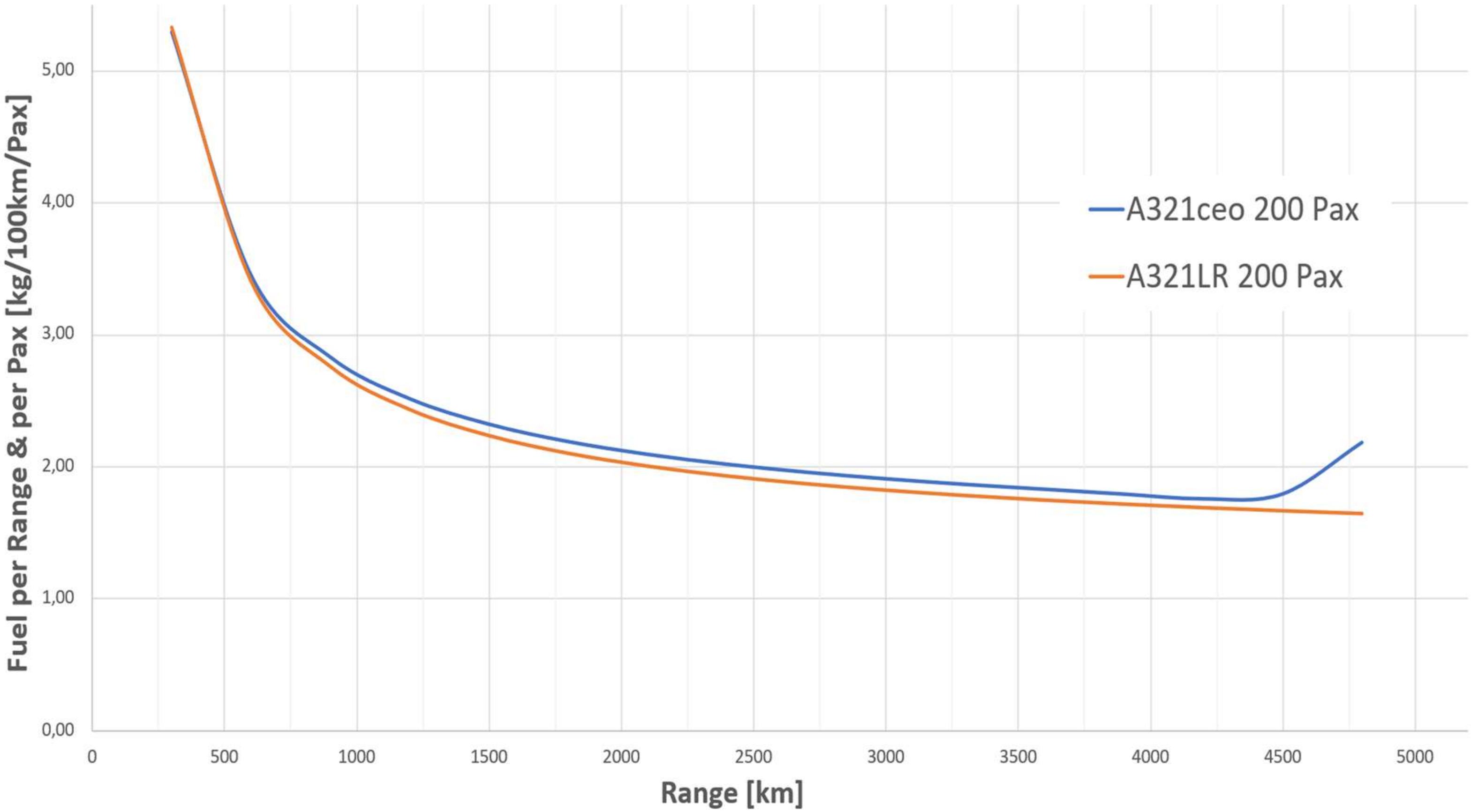
Fuel Consumption – kg/100km/PAX



(generated with Scholz 2021a)

Fuel consumption per range and passenger over flown distance: **Comparison for a high-density density**

Fuel Consumption – kg/100km/PAX



Comparison of the fuel consumption A321ceo and the A321LR – 200 pax

Fuel consumption per range and passenger over flown distance: **Engine comparison, standard density cabin**

(generated with Scholz 2021a)

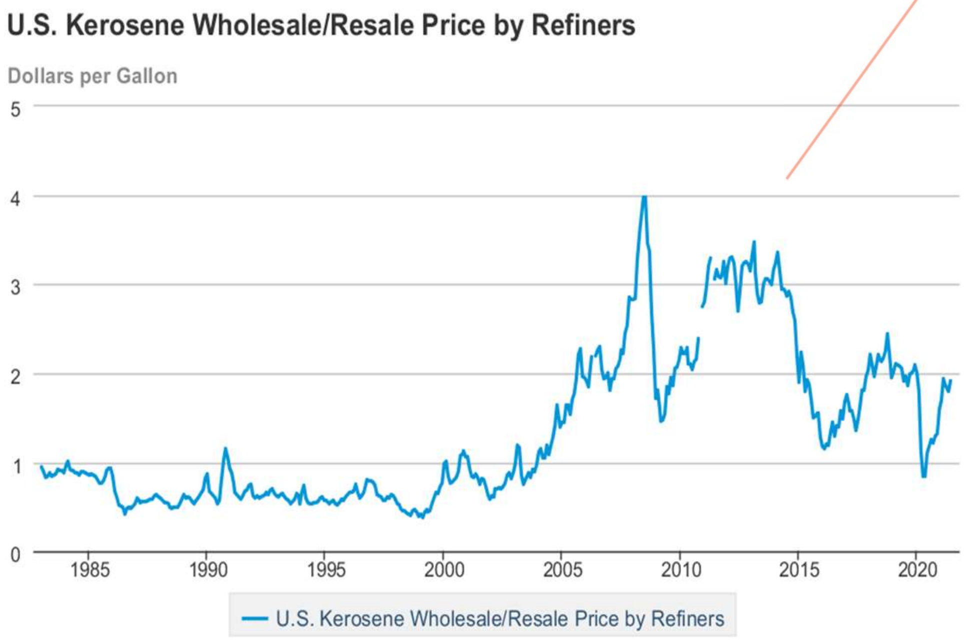
Direct Operating Costs

of the Airbus A321LR

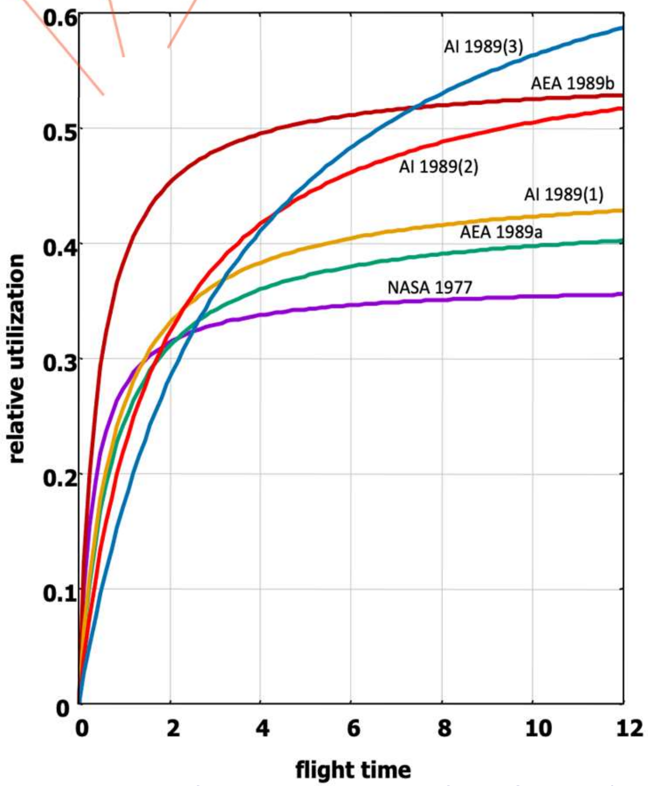
General Composition of the DOC

$$C_{DOC} = C_{DEP} + C_{INT} + C_{INS} + C_F + C_M + C_C + C_{FEE}$$

C_{DEP}: Depreciation costs
C_{INT}: Interest costs
C_{INS}: Insurance costs
C_F: Fuel costs
C_M: Maintenance costs
C_C: Crew costs
C_C: Fees and charges



Development of the kerosene price from 1980 to 2021 (EIA 2021)



Relative aircraft utilization; edited from Scholz (2015)

→ The longer the flight time the fewer the maximum allowed flight-trips (per day, month or year)

Calculation of the DOCs: Two Methods – AEA and TU Berlin

Aircraft	A321LR - M1		
	w/cargo	no cargo	Unit
Number of PAX	160		-
Range (Mission)	5.600		km
MTOW	97.000		kg
MZFW	75.600		kg
OEW	52.060		kg
Max Payload (Point B)	23.540		kg
Breguet Factor B(B)	-	22.467	km
Landing Weight (B)	-	67.580	kg
Mass Payload (Mission)	23.540	15.520	kg
Mass Pax (Mission)	15.520		kg
Mass Cargo (Mission)	8.020	0	kg
Mass Fuel (Mission)	21.400	19.130	kg
Flight Speed	850		km/h
Flight Time	6,6		h
SLST	145		kN
Engine Weight	3.000		kg
Nr. cabin crew	4		-
Cockpit crew hourly rate	246,5		US$/h
Cabin crew hourly rate	81		US$/h
Block Time	1,83		h
CC	5		-

General values for DOC computation of the A321LR with/without cargo – TUB method, M1: 160 pax

Direct Operating Costs

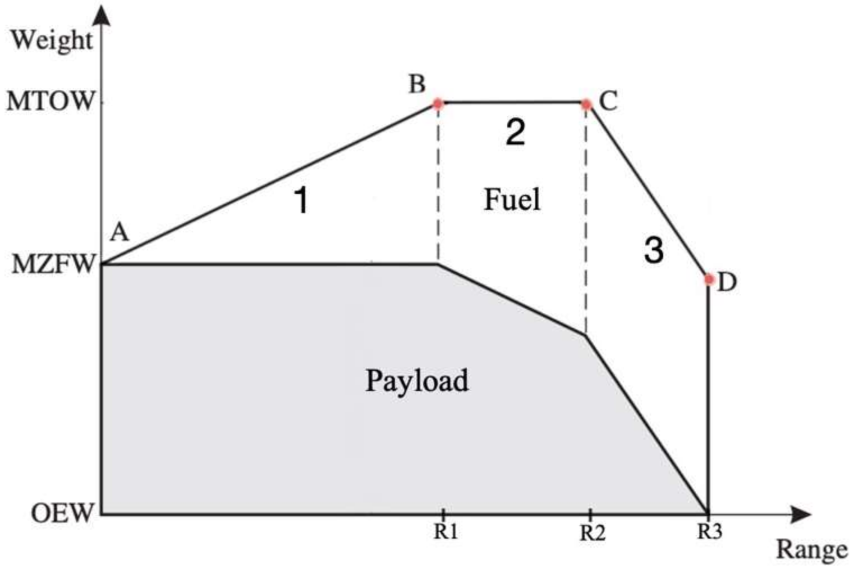
1. Input data from previous design phases

Number of engines	n_E	2	[-]	Airframe mass	m_{AF}	46060	[kg]
Take-off thrust of ONE engine	$T_{T/O,E}$	145,16	[KN]	Payload mass	m_{PL}	23540	[kg]
Max. Take-off mass	m_{MTO}	97000	[kg]	Baggage mass	$m_{Baggage}$	3520	[kg]
Operating empty mass	m_{OE}	52060	[kg]	Cargo mass	m_{Cargo}	8020	[kg]
Number of passengers	n_{PAX}	160	[-]	Passenger mass	m_{PAX}	12000	[kg]
Design range	R	5600	[km]	Fuel mass	m_F	21400	[kg]
Engines mass	$m_{E,inst}$	6000	[kg]				

General values for DOC computation of the A321LR with/without cargo – AEA method, M1: 160 pax; **Scholz 2021b**)

AEA Association of European Airlines
TUB Technical University of Berlin

Breguet Factor Calculated from the Payload-Range Diagram?



Extended Payload-Range diagram; based on Young (2017)

1

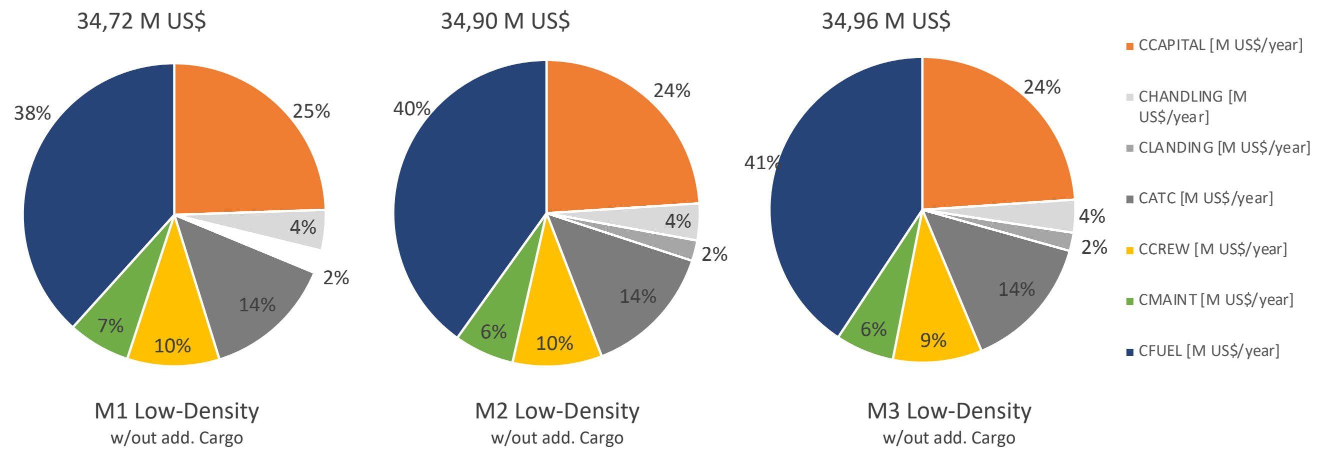
$$B = \frac{R}{ln\left(\frac{m_1}{m_2}\right)} = \frac{R}{ln\left(\frac{OEW + PL + MFW}{LW}\right)} = \frac{6500\ km}{ln\left(\frac{52060 + 20795 + 23595}{52060 + 20795}\right)\frac{kg}{kg}} = 23.168\ km$$

or

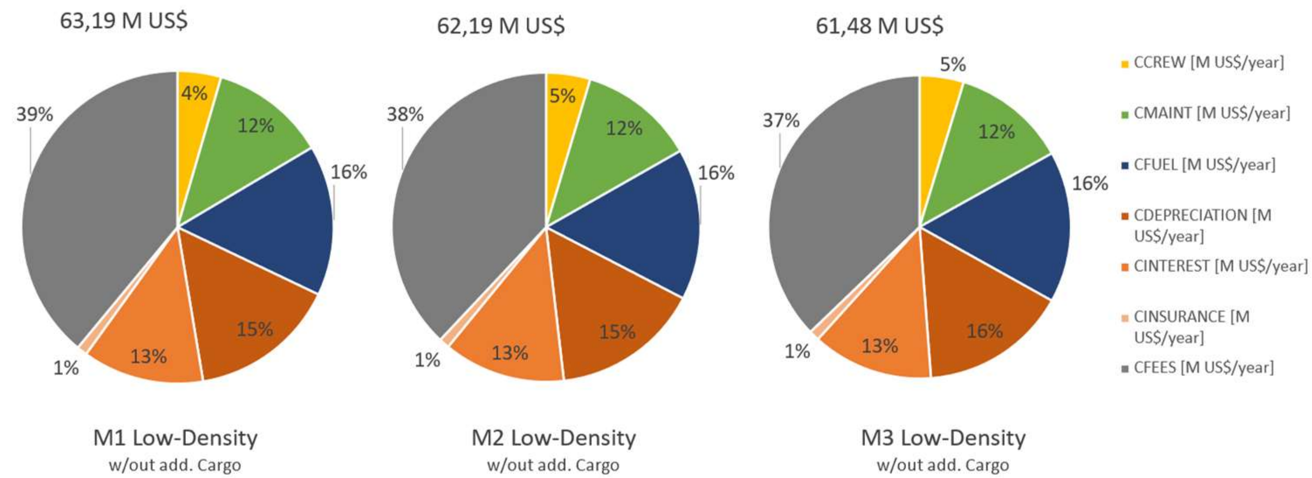
2

$$m_{fuel} = m_2\left(e^{\frac{R}{B}} - 1\right) \Leftrightarrow \frac{R}{B} = \ln\left(\frac{m_{fuel}}{m_2} + 1\right) \Leftrightarrow B = \frac{R}{\ln\left(\frac{m_{fuel}}{m_2} + 1\right)} = \frac{6500\ km}{\ln\left(\frac{23595}{72855} + 1\right)\frac{kg}{kg}} = 23.168\ km$$

Yearly DOCs with Both Methods

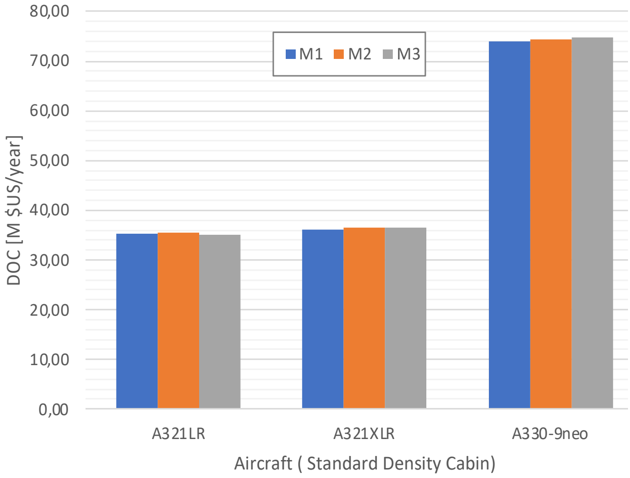


DOC distribution for the A321LR in M1, M2, and M3: low-density cabin configuration, without additional cargo – TUB Method

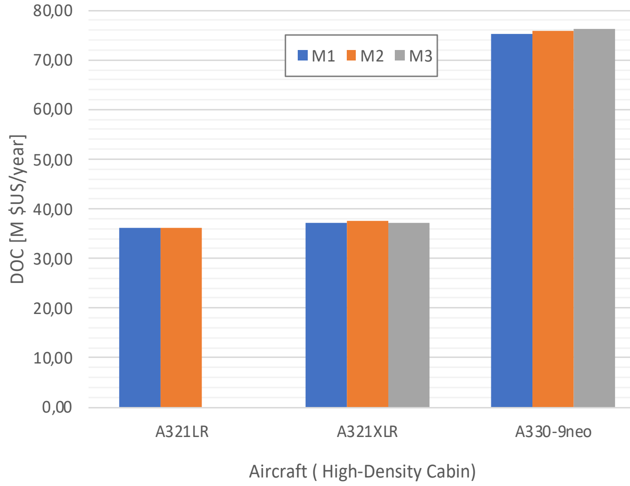


DOC distribution for the A321LR in M1, M2, and M3: low-density cabin configuration, without additional cargo – AEA Method

DOC Comparison between Aircraft

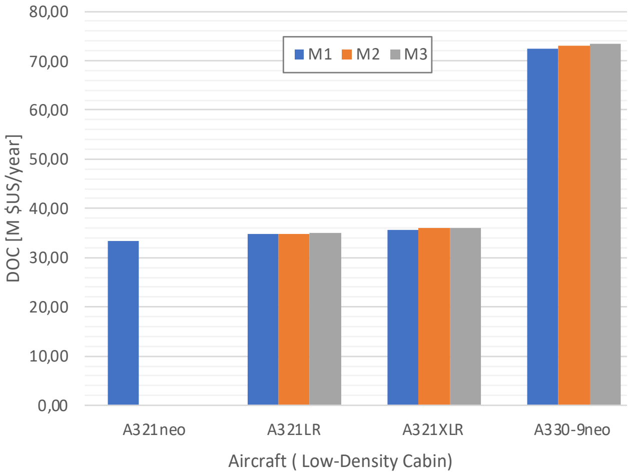


DOC comparison: standard density cabin: TUB Method

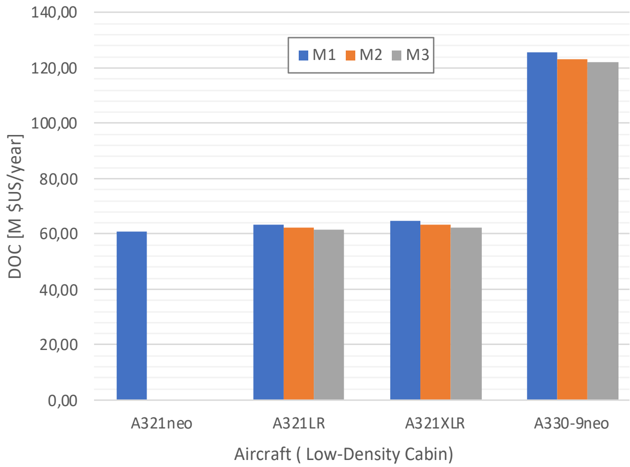


DOC comparison: high-density cabin: TUB Method

- different accounting for the nr. of flight trip contributes to distinguished variations along the missions and methods

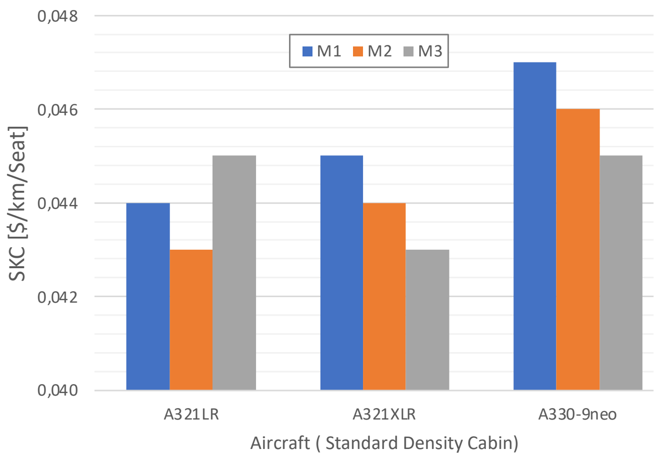


DOC comparison: low-density cabin: TUB Method

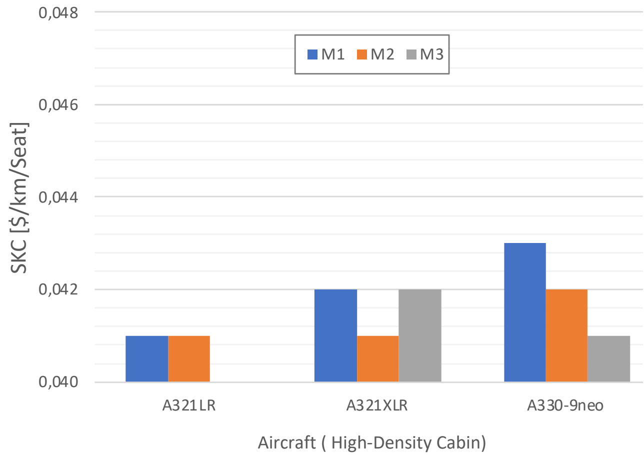


DOC comparison: low-density cabin: AEA Method

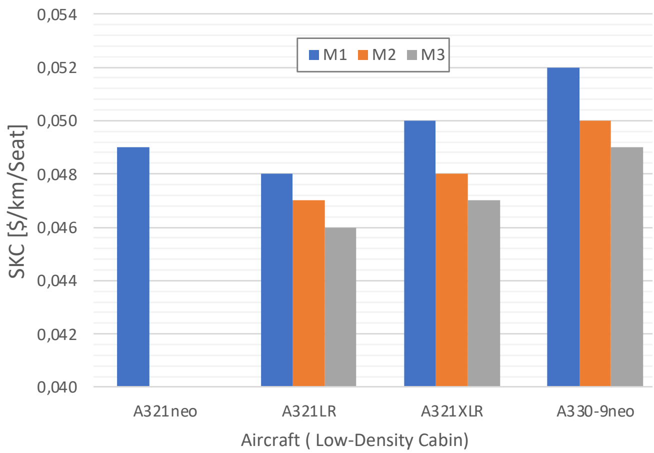
Seat-Kilometer Cost Comparison between Aircraft



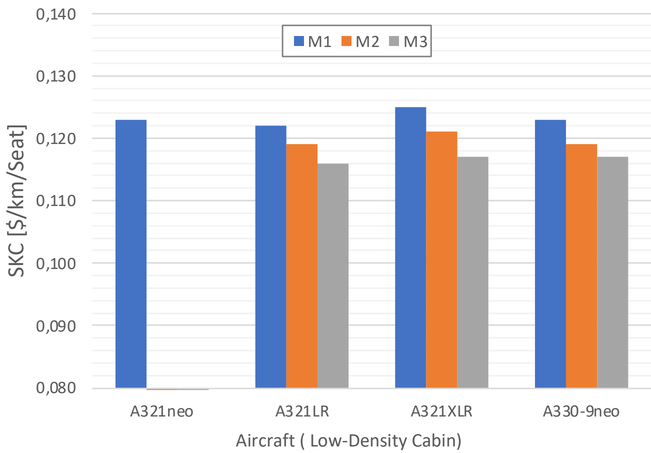
SKC comparison: standard density cabin: TUB Method



SKC comparison: high-density cabin: TUB Method



SKC comparison: low-density cabin: TUB Method



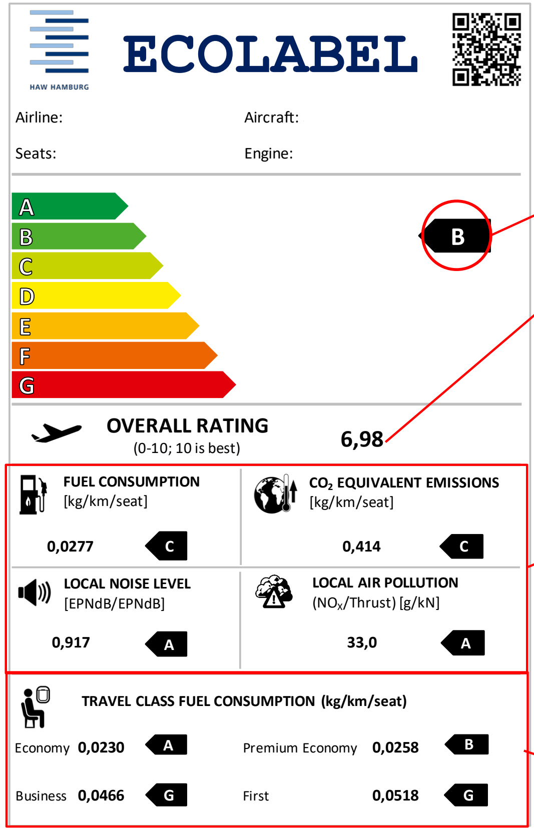
SKC comparison: low-density cabin: AEA Method

Ecolabel

Applied to the Airbus A321LR

Ecolabel Applied to the Airbus A321LR

General Considerations and Limitations



Exemplary layout of the Ecolabel (Hurtecant 2021)

Flyer explaining the Ecolabel to the general public or passengers (Hurtecant 2021)

RATING METHOD

Each score in the ecolabel is valid for a specific type of aircraft with a particular type of engine operated by a given airline. All these variables are defined at the top of the label.

The ecolabel consists of several environmental impact indicators, each with its score. The lower this score is, the better. This is also represented by a scale from A to G. An A score is very good, while a G score is relatively weak.

OVERALL RATING

The overall rating summarises the four impact indicators in one single rating: fuel performance, CO_2 equivalent emissions, local noise level and local air pollution. This results in a score out of 10, which can be translated into an A to G rating. A higher score means a better overall rating and, therefore, a more environmentally friendly aircraft.

FUEL PERFORMANCE

The fuel performance rating expresses the amount of fuel (in kilograms) an aircraft burns per travelled kilometre and per available seat. The fuel performance can also be expressed as an A to G rating.

CO_2 EQUIVALENT EMISSIONS

The carbon dioxide (CO_2) equivalent is used to compare the emissions from various greenhouse gases based on their global warming potential (GWP). This global warming potential is the amount of heat absorbed by any greenhouse gas in the atmosphere, as a multiple of the heat that the same mass of CO_2 would absorb.

In short, the CO_2 equivalent emission is the amount of emitted CO_2 plus the amount of other emitted gases like nitrogen oxides (NO_x) and water vapour converted to the equivalent amount of carbon dioxide with the same global warming potential.

LOCAL NOISE LEVEL

The local noise level is a metric that describes the average noise level produced by a specific aircraft during 3 phases of a flight in the vicinity of airports.

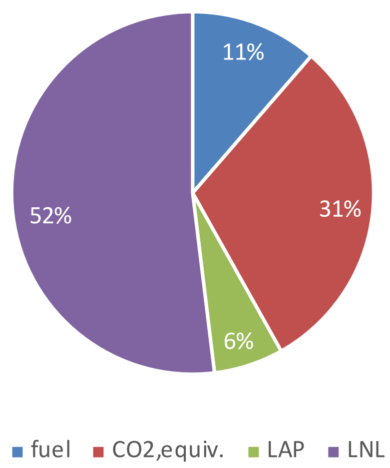
LOCAL AIR POLLUTION

Aircraft engines form pollutants in the air. Besides CO_2, H_2O and SO_x, nitrogen oxides (NO_x), carbon monoxide (CO), unburned hydrocarbons (HC) and soot are generated. The amount of emitted nitrogen oxides is defined as the key indicator to rate the local air quality. Therefore, the local air pollution is a measure of the amount of emitted NO_x.

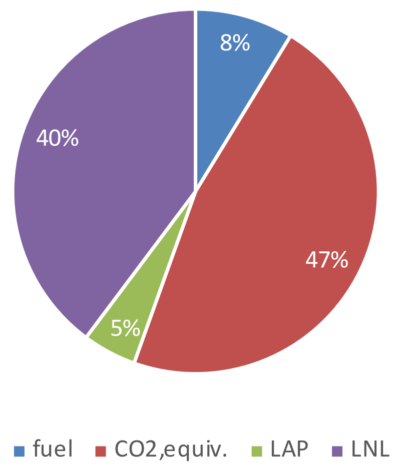
TRAVEL CLASS FUEL PERFORMANCE

The travel class fuel performance is the same as the standard fuel performance. However, it does consider the travel classes that are available on the specific aircraft. The more comfort and, therefore, the more space per seat is desired, the larger the fuel consumption per seat will be. This is reflected in a rating per travel class.

General Considerations and Limitations



Ecolabel: exemplary distribution of the impact categories – weighted (Hurtecant 2021)



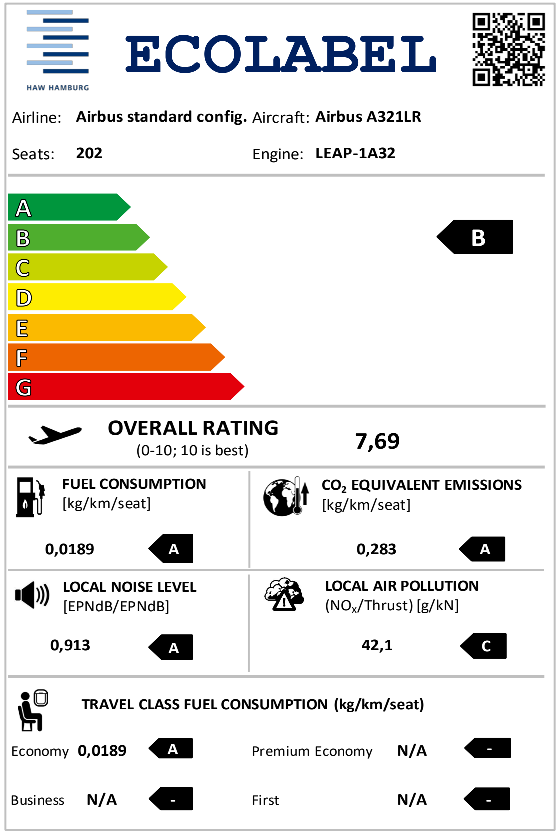
Ecolabel: exemplary distribution of the impact categories – unweighted (Hurtecant 2021)

Comparison of EI_{NOx} between the EEA emission calculator and the Ecolabel

Aircraft	EEA Emission Calculator		Ecolabel		Variation
	Engine	EI_NOx [kg/kg]	Engine	EI_NOx (eng) [kg/kg]	%
A321	Not specified	0,0171	CFM56-5B1/2P	0,0205	+20%

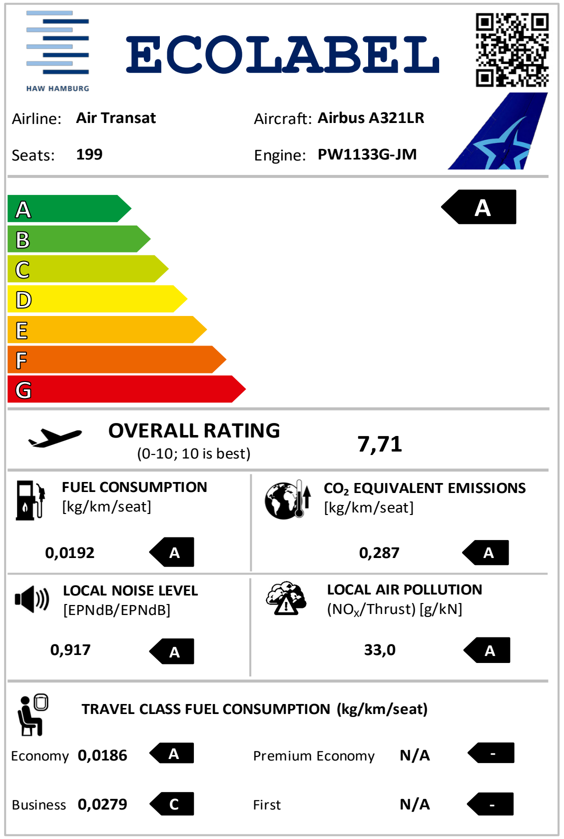
Ecolabels: A321LR

generated with Hurtecant (2021)



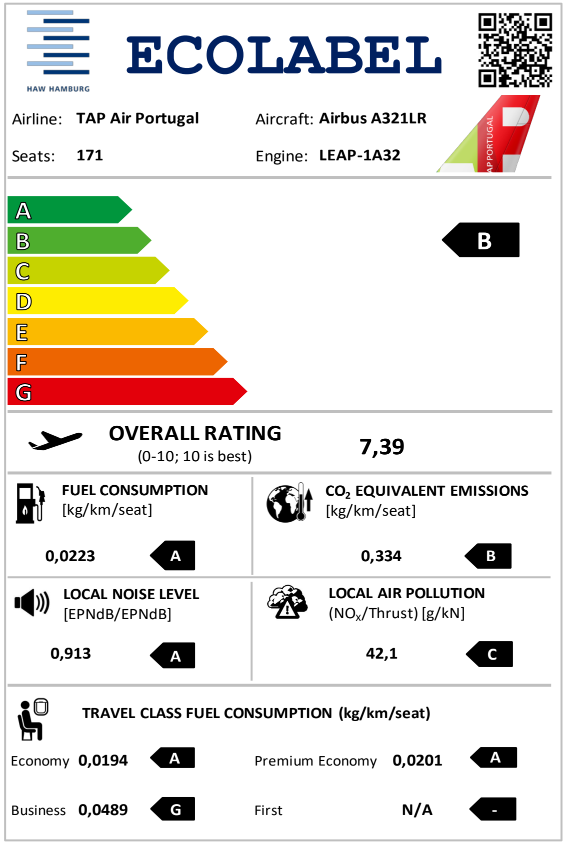
Ecolabel for the Airbus A321LR: Airbus standard configuration

- 202 passengers in Y/C



Ecolabel for the Airbus A321LR: Air Transat

- 187 passengers in Y/C
- 12 passengers in B/C



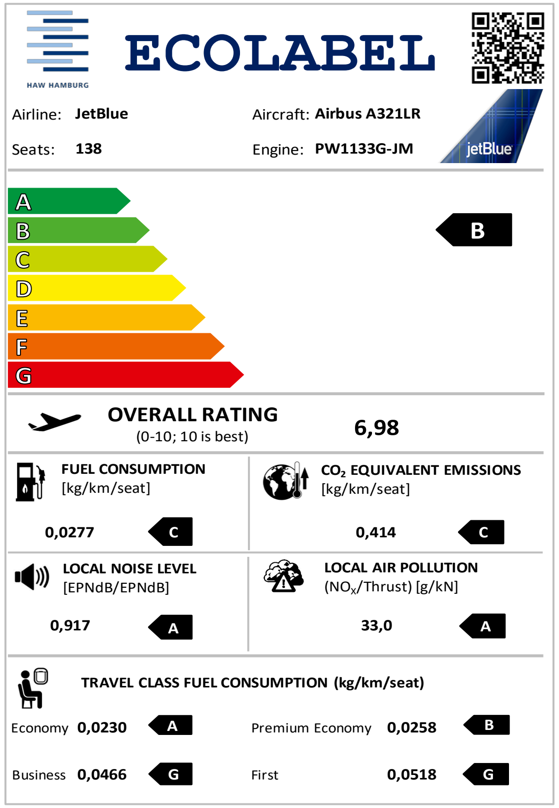
Ecolabel for the Airbus A321LR: TAP Air Portugal

- 113 passengers in Y/C
- 42 passengers in premium Y/C
- 16 passengers in B/C

*** Y/C: Economy Class; B/C: Business Class; F/C: First Class**

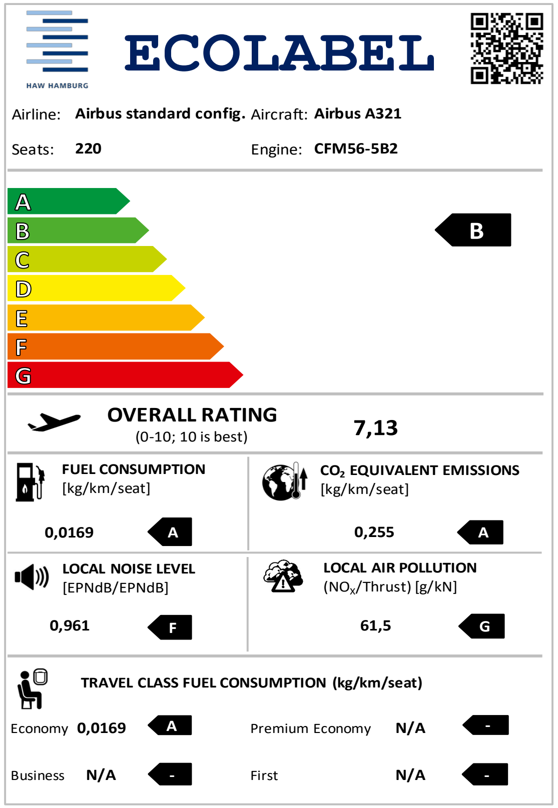
Ecolabels: A321LR, A321ceo, and A321neo

generated with Hurtecant (2021)



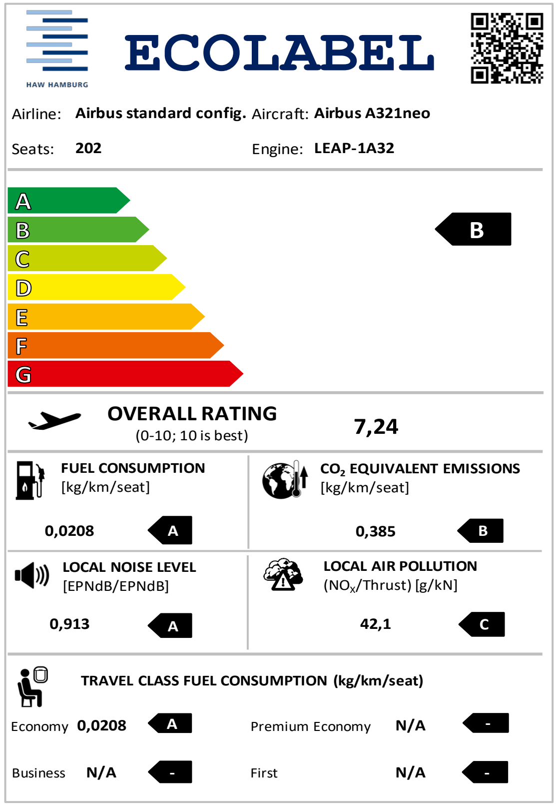
Ecolabel for the Airbus A321LR:
JetBlue

- 90 passengers in Y/C
- 24 passengers in premium Y/C
- 22 passengers in B/C
- 2 passengers in F/C



Ecolabel for the A321ceo:
Airbus std. configuration

- 220 passengers in Y/C



Ecolabel for the A321neo:
Airbus std. configuration

- 202 passengers in Y/C

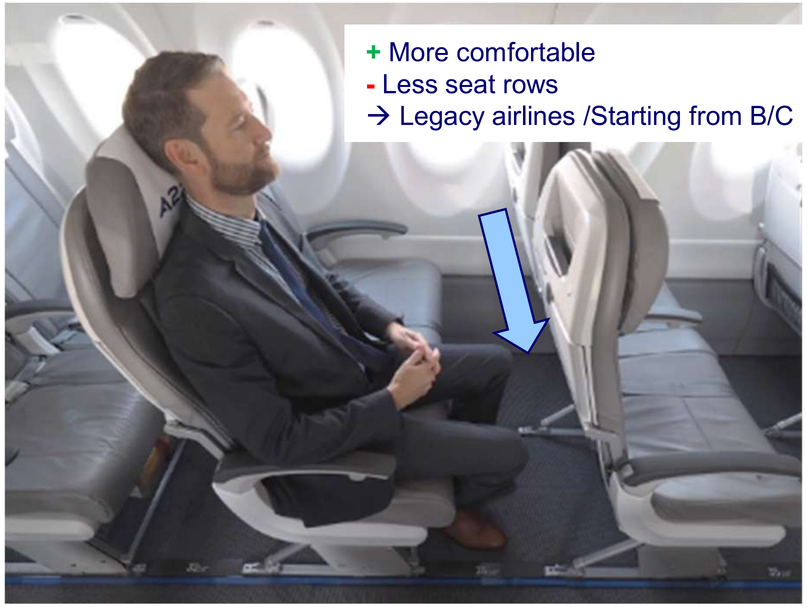
*** Y/C: Economy Class; B/C: Business Class; F/C: First Class**

Cabin Layout

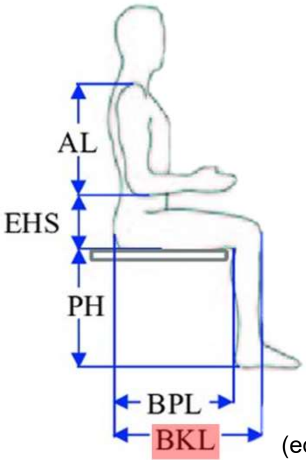
of the Airbus A321LR

Cabin Layout of the A321LR: The Role of the Seat Pitch

Seat pitch 31" (Honig 2018)



Seat pitch 34" (Honig 2018)



Percentile	5% american female		95% american male	
Backrest	estimated at 3,14" (80 mm)			
BKL	21,3" (542,1 mm)		26,3" (667,4 mm)	
Seat pitch	29" 737 mm	34" 864 mm	29" 737 mm	34" 864 mm
Legroom	25,9" 657 mm	30,9" 784 mm	25,9" 657 mm	30,9" 784 mm
Clearance (at knee height)	4,51" 114,5 mm	9,51" 241,5 mm	-	4,57" 116,2 mm

Clearance (at knee height) **= Legroom - BKL**

(edited from Gosende 2017)

Conditioned by:

- **Demography (body height, weight) –** e.g., population of the USA vs. Japan
- **Gender**
- **Market strategy –** low-cost vs. legacy airlines

Table 6.1 Legroom for considered percentiles at a 29" and 34" seat pitch (SeatMaestro 2021a and Ergocenter NCSU 2006)

Exemplary Seats (Classes)

JetBlue Mint Studio – business class (JetBlue 2021b)

JetBlue coach seats – economy class (JetBlue 2021b)

Assessment of A321LR Operators – Seat Pitch / Width

Table 6.2 Cabin configurations for different airlines (measurements in inch)

Airline	Total PAX	Economy Class			Premium Economy Class			Business Class			First Class		
		Seat Pitch	Seat Width	PAX	Seat Pitch	Seat Width	PAX	Seat Pitch	Seat Width	PAX	Seat Pitch	Seat Width	PAX
Airbus std.	202	32	18	202	0	0	0	0	0	0	0	0	0
Air Transat	199	31	18	187	0	0	0	38	22	12	0	0	0
Aer Lingus	184	31	18	168	0	0	0	61,5	20	16	0	0	0
TAP Portugal	171	31	17,7	113	32	17,7	42	62	22,3	16	0	0	0
Air Astana	166	30	20,5	150	0	0	0	45	28,5	16	0	0	0
JetBlue	138	33	17,8	90	37	17,8	24	58	20,5	22	60	22	2

(Airbus 2020; SeatGuru 2021a, 2021d, 2021b; Air Astana 2021 and JetBlue 2021b)

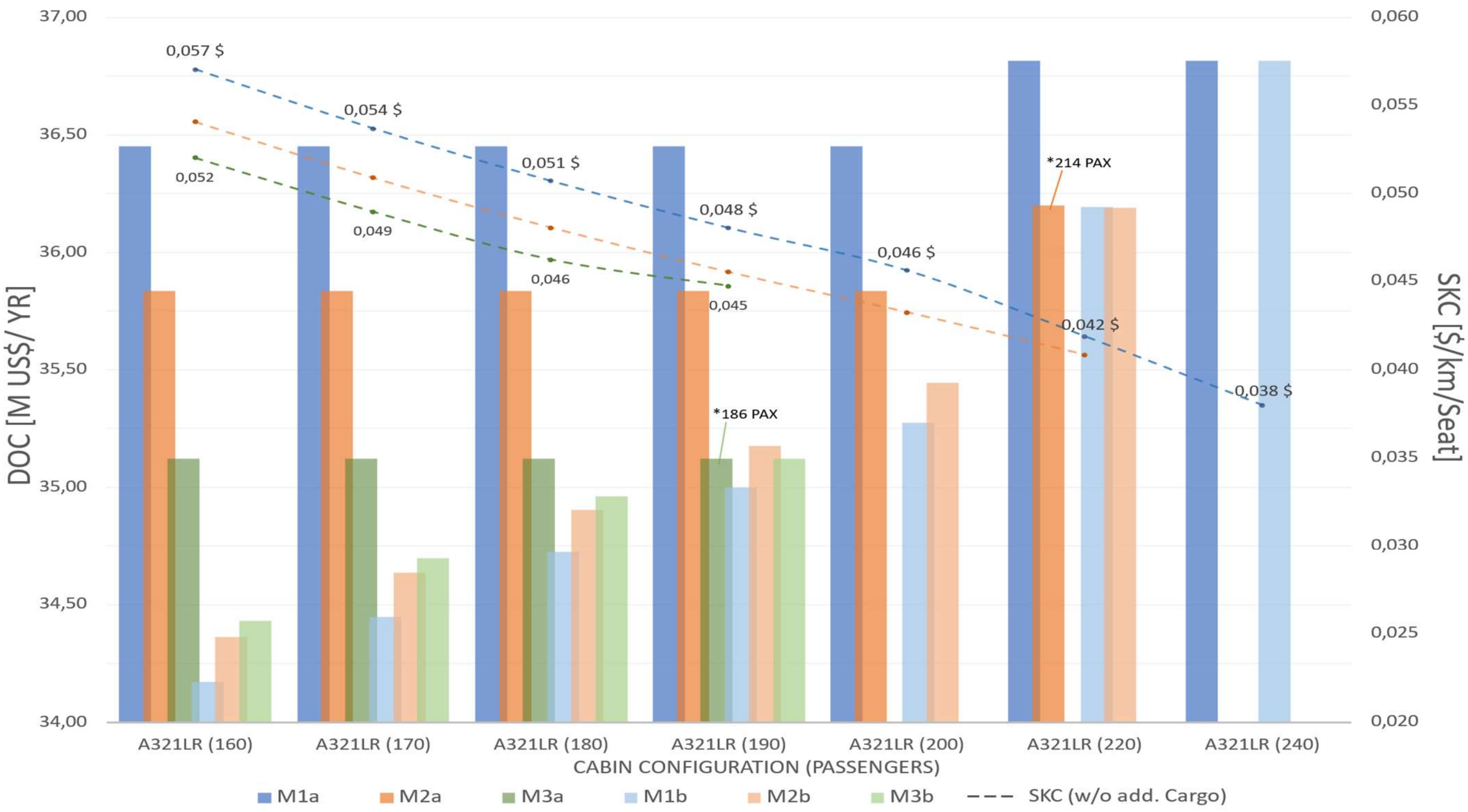
Summary and Conclusions

„Ideal“ Fuel Consumption for Specific Airlines

Overall fuel consumption evaluation regarding the cabin configurations of the A321LR by different airlines

Airline	Cabin Config. (PAX)	Recommended Max. Range (RMR)	Fuel Consumption at RMR (kg/100km/Pax)
Airbus Std.*	202	6800 km	1,57
Air Transat	199	6800 km	1,60
Aer Lingus	184	7400 km	1,76
TAP Air Portugal	171	7450 km	1,83
Air Astana	166	7550 km	1,90
JetBlue	138	7600 km	2,01

Overview of the DOCs and SKC for the A321LR – Chart, TUB Method



Yearly DOCs and SKCs of the A321LR with the **TUB Method**: all missions and cabin configurations; a: with cargo; b: without cargo

DOC Observations

In terms of the ratio DOC/flexibility (without cargo), it seems reasonable to operate the LR with a cabin configuration of around 190 pax since there is only an insignificant difference between the DOCs (and SKCs) of the contemplated missions → **airlines have the most flexibility while choosing routes and with minimal DOC difference :**

- 35,00 M US$/yr with 713 flight cycles à 5.600 km;
- 35,17 M US$/yr with 673 flight cycles à 6.500 km;
- 35,12 M US$/yr with 570 flight cycles à 7.400 km.

Reason: effects of flight cycles and flight distance (inversely proportional) neutralize each other in this particular case: C_{FEES} vs. C_{FUEL}, respectively

→ Most profitable option depends on ticket prices, i.e., medium-haul versus long-haul, and multiply it by the number of flight cycles.

Final Conclusions

1. Deeper insight into the Airbus A321LR: better understanding of operational aspects
2. Theoretical DOC methods will deliver different costs than those from airlines. The assessment allowed to rank operating costs and clarify the relationship between flight cycles, flight time, and total costs.
3. Better understanding the implementation of the ACTs (to the A321neo) in order to fly larger ranges → The accommodation of ACTs **does not have significant impact** on the maximum possible payload in the LR for the given missions. Geometrical/cabin limitations already limit the number of seating passengers in the neo(despite higher MPL)
4. The neo engines (A321neo, LR, XLR) have showed clear advantage towards the ceo (emissions and fuel consumption) – 20 years gap between both engines
5. An update from the neo to the LR is not justifiable if only (very) low-density cabin configurations are employed. In all other cases the LR is the best choice.
6. The XLR can accommodate 20,3% more fuel, due to a +4,3% MTOW and -5,2% MPL but is only sensible after a range of 7.400 km compared to the LR
7. A higher density cabin is ecologically always the best choice. Advantage for low-cost carriers!
8. The seat pitch and market strategy dictate the cabin layout and influence the passenger comfort. This happens in contradiction to the ecological best choice

Infographic and possible routes for the Airbus A321LR (Lothar 2021)

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