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Dissemination		
PU	Public	
PP	Restricted to other programme participants (including the Commission Services)	**X**
RE	Restricted to a group specified by the consortium (including the Commission Services)	
CO	Confidential, only for members of the consortium (including the Commission Services)	

CONTENTS

NOTATION

The notation is presented in alphabetical order.

τ	wing taper ratio,
Λ	wing aspect ratio,
$_{25}$	quarter-chord sweep angle of the wing, [rad]
χ_{25H}	quarter-chord sweep angle of the horizontal tail, [rad]
χ_{25V}	quarter-chord sweep angle of the vertical tail, [rad]
$_{FN}$	fuselage nose aspect ratio,
Λ_{FT}	fuselage tip aspect ratio,
τ_H	horizontal tail taper ratio,
Λ_H	horizontal tail aspect ratio,
τ_V	vertical tail taper ratio,
$_V$	vertical tail aspect ratio,
B	wing span, [m]
B_H	horizontal tail span, [m]
D_F	fuselage diameter, [m]
D_{prop}	propeller diameter, [m]
h_{UC}	undercarriage height, [m]
h_V	vertical tail height, [m]
L_F	fuselage length, [m]
M_{FUEL}	fuel mass, [kg]
M_H	payload mass, [kg]
N_{max}	one engine takeoff power, [kW]
n_{pax}	number of passengers,
P_{s0}	one engine takeoff trust, [kN]
S	wing area, [m^2]
$S_{H\_} = S_H/S$	relative horizontal tail area,
$S_{V\_} = S_V/S$	relative vertical tail area,
$x_{w\_} = x_W/L_F$	relative centre of gravity position.

1. INTRODUCTION

This report is a part of program no. ASA6-CT-2006-044549 SSA “EPATS Study” as a T4.3. (Fuel consumption and transportation energy effectiveness analysis) of WP4 (Missions Requirements for EPATS Aircraft).

For the needs of WP2 and WP4 (Specific fuel consumption requirement) a comparison analysis of mission fuel consumption and transportation energy effectiveness for various aircraft categories and size were made.

Objectives:

1. Work out a methodology of SFC (specific fuel consumption) valuation
2. Work out a mathematical model of aircraft fuel consumption
3. Carry out comparative analysis of SFC for various types of airplanes operating in real conditions
4. Determine SFC dependence of seating capacity (payload), cruising speed, range, flight profile etc. taking into consideration real flight conditions
5. Results analysis and generalization of conclusions
6. Determine courses of action for increasing energetic effectiveness at air transport

2. FUEL CONSUMPTION AND TRANSPORTATION ENERGY

A need for increased speed, range, and payload are everpresent. In conjunction with these factors is fuel efficiency. Identifying the amount of fuel consumed by a given aircraft while moving in both airspace and ground networks is critical to air transport economics. Reducing the amount of fuel consumed involves knowing the effect of alternate profiles and procedures on fuel consumption or fuel flow for the various aircraft types operating in the system. Within the system a penalty in one area may be offset by benefits in other areas, hence, a net benefit in the system. The aviation community is striving to provide more fuel efficient operations in the system. Critical to many of the efforts is the ability to estimate fuel consumption. A methodology of SFC (specific fuel consumption) valuation relating to aircraft performance and actual flight profile is the main of goal of Task 4.3.

At one time extraction costs and availability of aviation fuel had little impact on the evolution of the air transportation industry. Today, fuel conservation in aviation is one of the most critical concerns to air transportation companies. By the early 1970s it had become increasingly evident that the era of plentiful, inexpensive petroleum-based fuel was ending. The fuel cost was becoming more significant in air transport economies.

The commercial air transportation industry is faced with the challenge of maintaining a viable economic position in the face of aviation fuel costs in combination with increasing fuel consumption. In order to achieve improved system efficiency a key requirement is an improved capability to accommodate fuel efficient aircraft operations. The close linkage between fuel usage and operator profitability necessitates the development and application of models that deliver energy performance of aircraft.

3. MODEL DESCRIPTION

The model description is intended to present a descriptive presentation of the aircraft fuel consumption model.

Aircraft fuel consumption model consist of two main models (fig. 3.1). The first is the aircraft computational model, with sub-models: geometrical, aerodynamic, mass, power unit. Using this models we can find static performances of the aircraft. The second is utilization model, namely transport operation model. The flight profile (fig. 3.2) consists of five stages: take off, climb, cruise, descent, and landing (transitions states were disregarded).

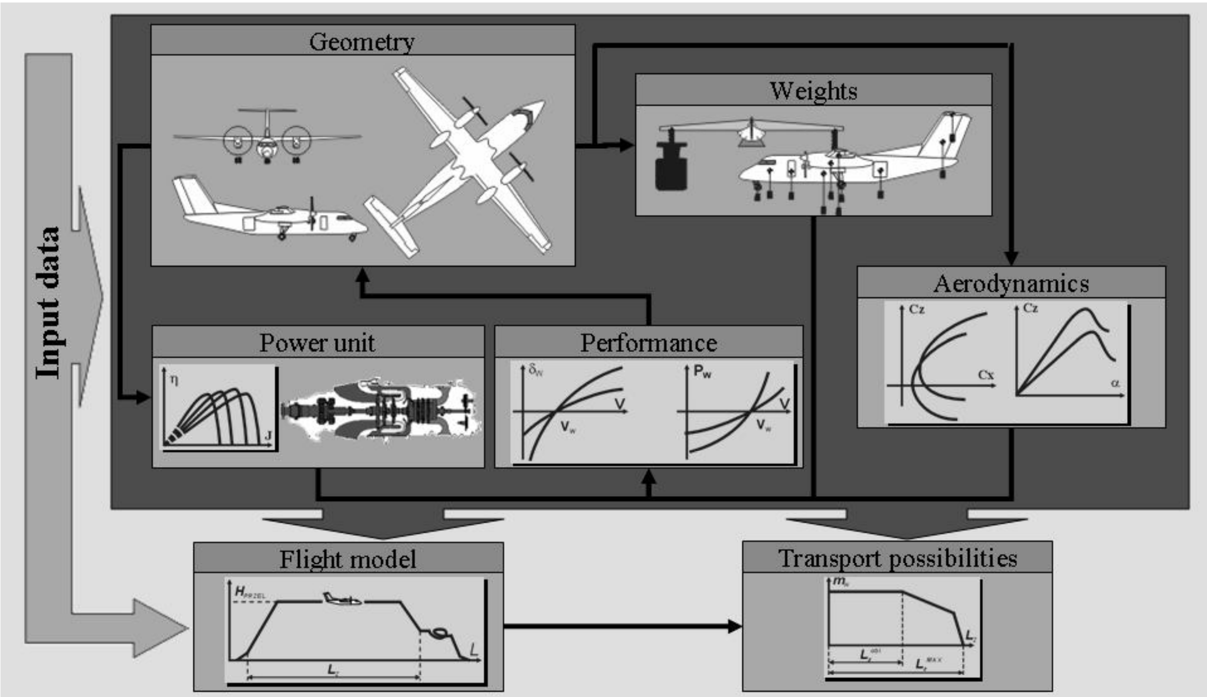


Fig. 3.1 Mathematical model of aircraft

The aircraft fuel consumption model assumptions are based on simplifying the energy balance equation. By simplifying the equation we get point performance.

During level cruise the following is assumed in order to maintain efficient computations without an unacceptable effect on accuracy:

1. The aircraft weight change at a certain flight level is small compared to the total weight, therefore constant weight is used in analyzed cruise segments in the calculations. Number of segments is chosen by software operator.
2. Acceleration = 0 during any flight level.
3. The flight path angle ( ) is small, therefore $\cos\gamma = 1$, or the aircraft weight equals the required lift.

4. Upper wind effects on fuel consumption are not a part of the computational requirement; therefore the velocity [IAS] equals the ground speed.
5. The functional forms used for lift vs. drag, and thrust over fuel flow, are sufficient to obtain a good data fit over the desired speed range.
6. The standard ISO atmospheric conditions apply.
7. Additionally fuel for ground maneuvers, plus fuel for 161 km (100 miles) diversion and 45 min hold at 1 525 m (5 000 ft) was taken into considerations.

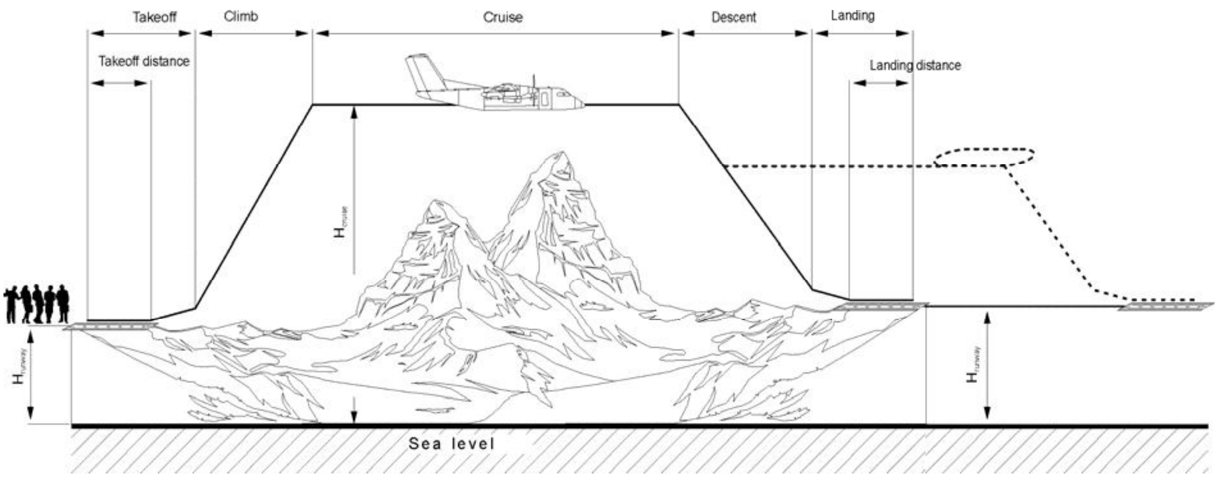


Fig. 3.2 Cruise profile (task model).

4. RESULTS

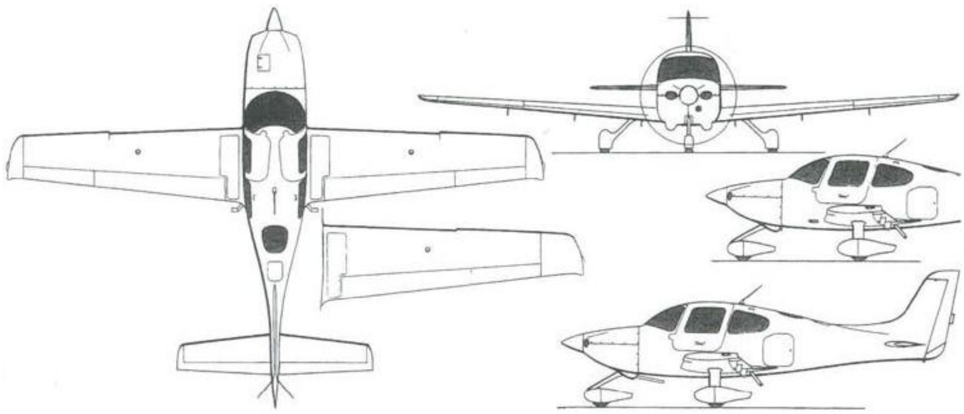
The calculations were done for 9 airplanes:

- Cirrus SR-22, Piper Saratoga II TC – single-engine piston,
- Piper Seneca V – twin-engine piston,
- Pilatus PS-12 – single-engine turboprops,
- Beechcraft King Air 350, BAE Jetstream 31 – twin-engine turboprops,
- Eclipse 500, Cessna Citation Mustang, Cessna Citation Encore – twin-engine jets.

Table 1. Input data

	Pilatus PC-12	BAE Jetstream 31	Cessna Encore	Cessna Mustang	Eclipse 500	Piper Seneca V	Cirrus SR-22	Piper Saratoga	King Air 350
Wing									
B [m]	16.23	15.85	16.48	13.16	11.6	11.85	10.85	11.02	17.65
S [m^2]	25.81	25.2	29.94	19.96	14.16	19.39	12.56	16.56	28.8
τ [-]	0.478	0.347	0.231	0.423	0.224	1.000	0.545	0.691	0.286
Λ [-]	10.21	9.97	9.07	8.68	9.50	7.24	9.37	7.33	10.82
χ_{25} [rad]	0.000	0.017	0.087	0.157	0.035	0.000	0.000	0.017	0.061
Horizontal tail plane									
b_H [m]	4.82	6.66	6.99	6.23	4.15	4.02	3.98	3.86	5.65
τ_H [-]	0.73	0.54	0.47	0.47	0.50	1.00	0.64	1.00	0.43
Λ_H [-]	4.36	6.70	5.36	6.08	5.23	4.68	5.94	4.50	4.90
χ_{25H} [rad]	0.087	0.122	0.087	0.332	0.332	0.000	0.087	0.000	0.314
$S_{H\_}$ [-]	0.197	0.255	0.265	0.320	0.233	0.177	0.194	0.212	0.203
Vertical tail plane									
h_V [m]	2.07	2.83	2.92	2.01	1.59	1.48	1.41	1.29	1.96
τ_V [-]	0.62	0.32	0.40	0.60	0.61	0.41	0.52	0.33	0.65
Λ_V [-]	1.24	1.52	1.60	0.97	1.05	1.23	1.52	1.26	0.90
χ_{25V} [rad]	0.611	0.716	0.576	0.820	0.646	0.646	0.471	0.681	0.681
$S_{V\_}$ [-]	0.127	0.203	0.155	0.208	0.169	0.092	0.096	0.084	0.134
Fuselage									
L_F [m]	14.4	13.4	14.9	12.37	10.2	8.72	7.92	8.43	14.22
D_F [m]	1.82	2.04	1.77	1.60	1.55	1.44	1.53	1.49	1.91
Λ_{FN} [-]	2.11	1.71	1.71	2.10	1.74	2.00	1.36	1.53	1.45
Λ_{FT} [-]	2.38	2.20	3.00	2.26	2.53	2.11	2.43	2.06	2.73
Others									
$x_{w\_}$ [-]	0.393	0.393	0.433	0.449	0.432	0.333	0.324	0.275	0.365
h_{UC} [m]	0.98	1.09	0.52	0.78	0.45	0.55	0.67	0.54	0.98
D_{prop} [m]	2.75	2.68	-	-	-	1.87	2.00	2.25	2.65
Nmax [kW] (Ps0 [kN])	1 197	701	15.12	6.49	4.00	164	231	224	783
M_{FUEL} [kg]	1200	1340	2380	1170	741	380	250	316	1122
npax	9	18	9	4	4	4	3	4	15
M_H [kg]	855	1710	855	380	380	380	190	380	1425

4.1. Cirrus SR-22



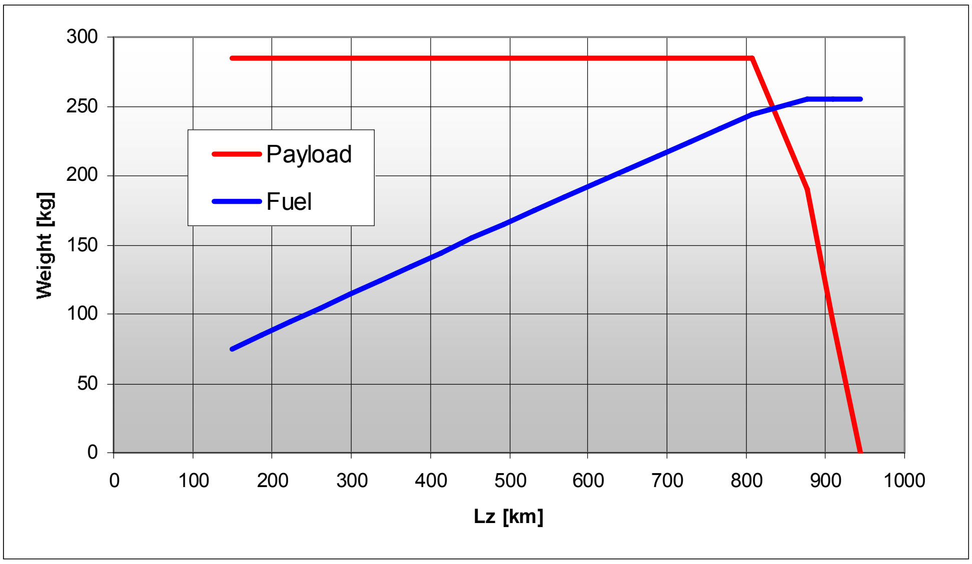


Fig. 4.1.1 Payload (fuel)-range diagram

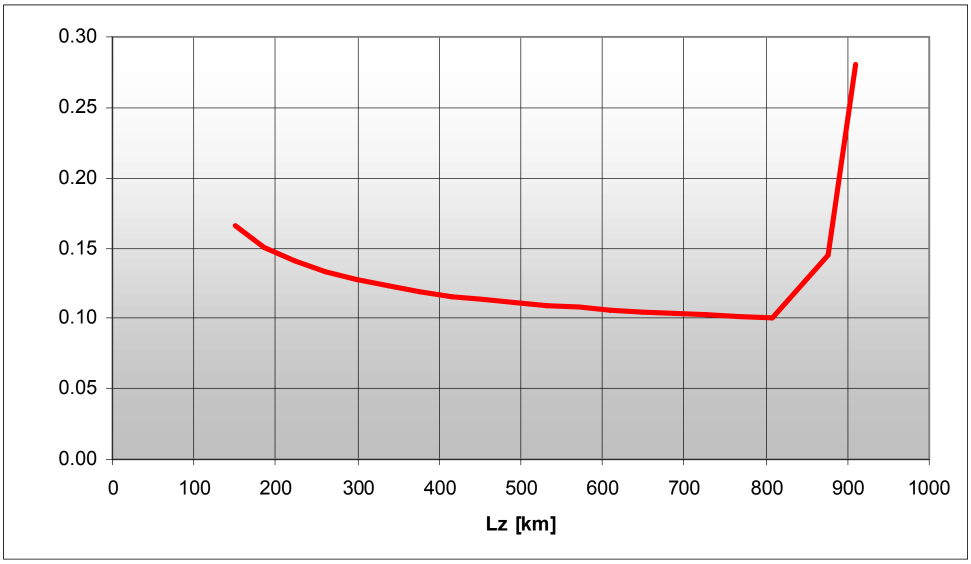


Fig. 4.1.2 Fuel weight per pax per km

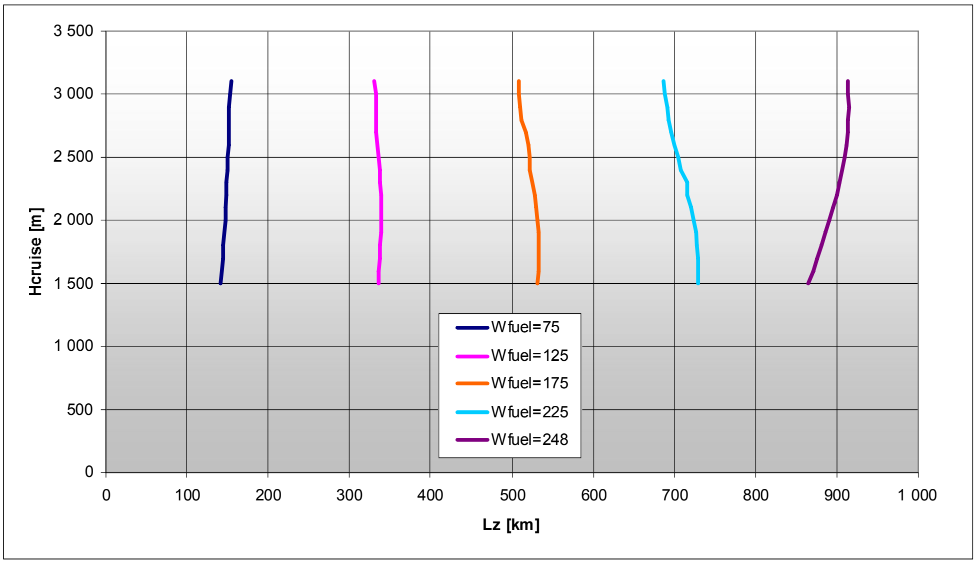
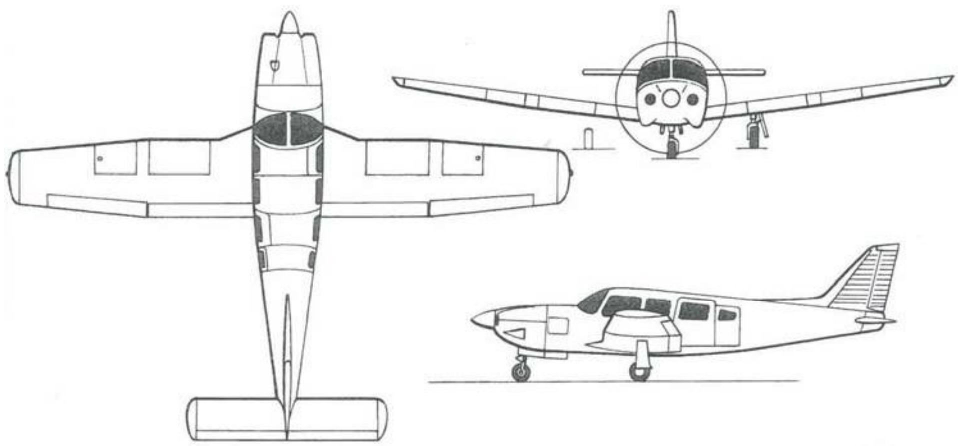


Fig. 4.1.3 Range-cruise altitude dependence for constant fuel weights

4.2. Piper Saratoga II TC



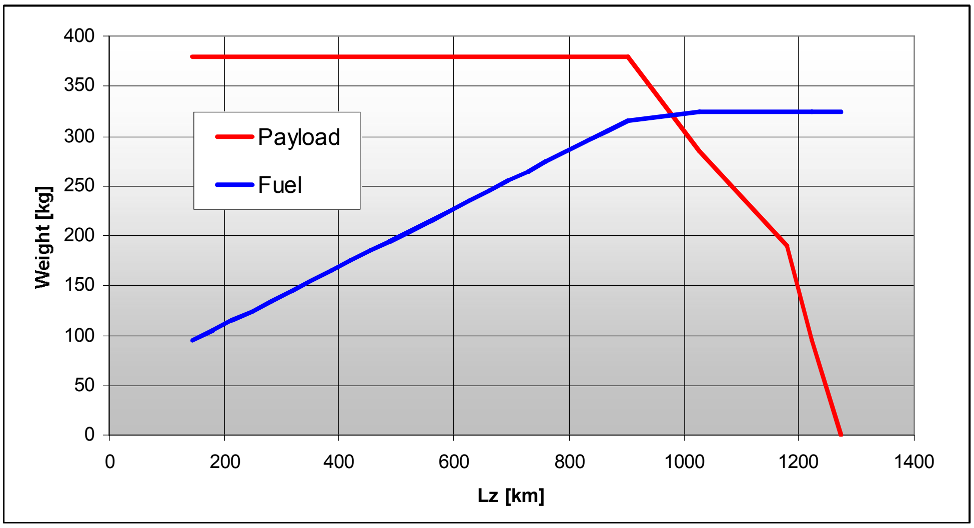


Fig. 4.2.1 Payload (fuel)-range diagram

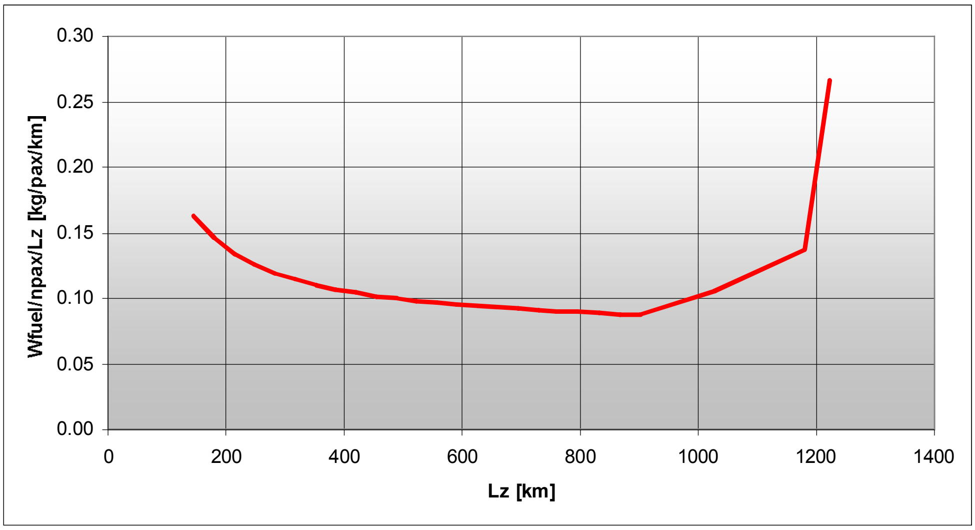


Fig. 4.2.2 Fuel weight per pax per km

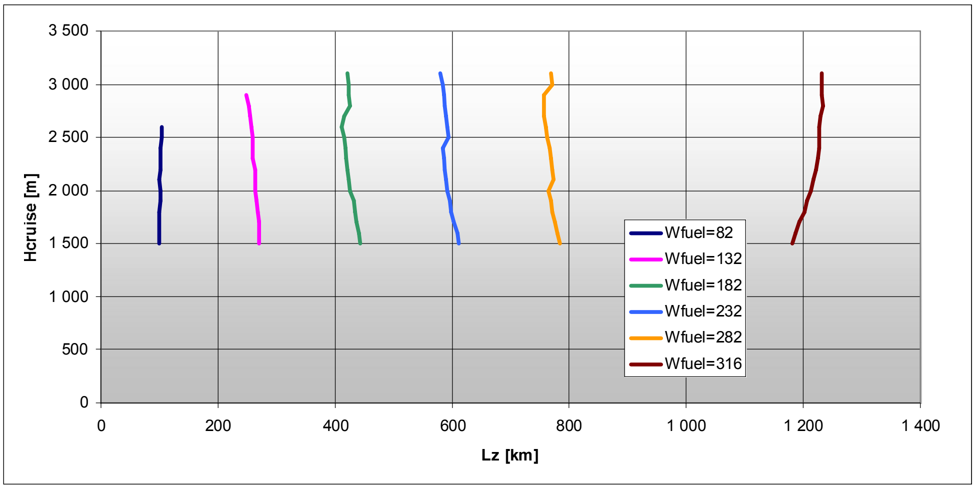
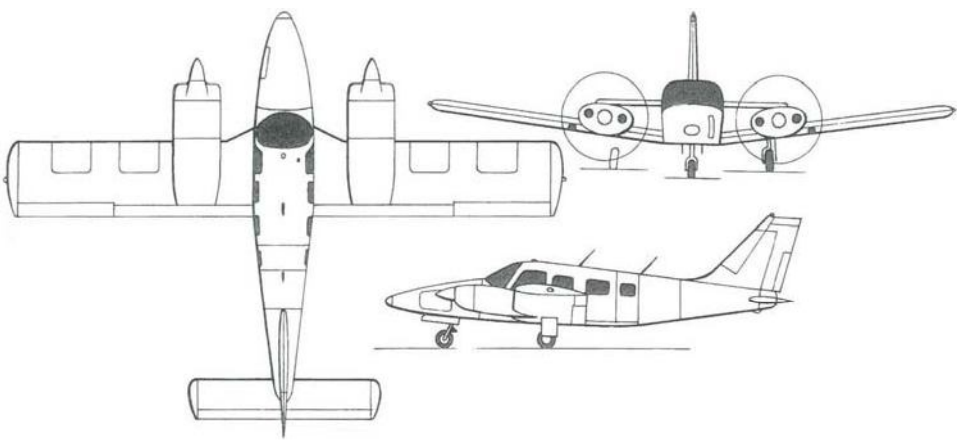


Fig. 4.2.3 Range-cruise altitude dependence for constant fuel weights

4.3. Piper Seneca V



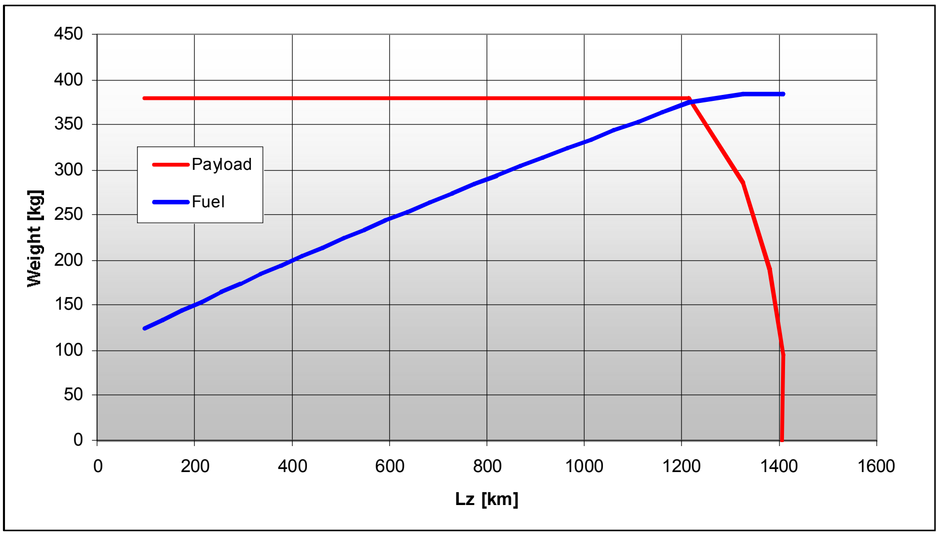


Fig. 4.3.1 Payload (fuel)-range diagram

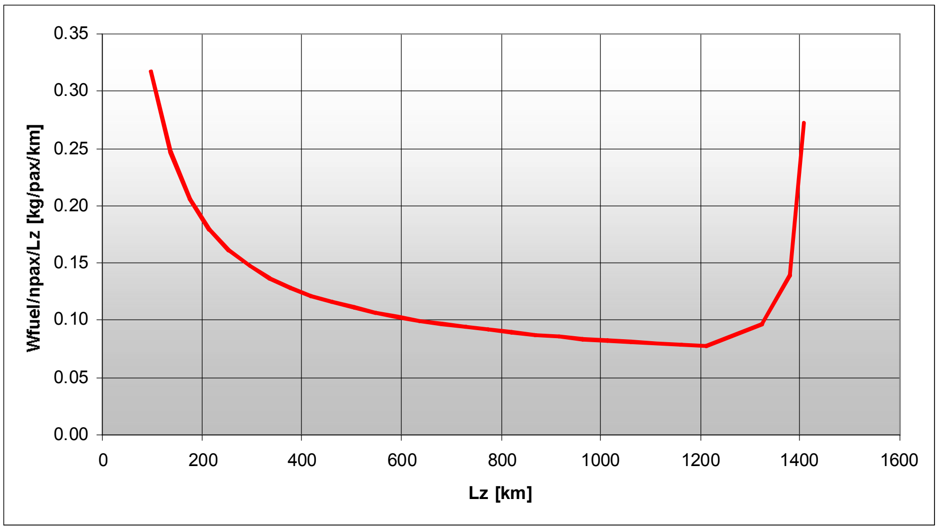


Fig. 4.3.2 Fuel weight per pax per km

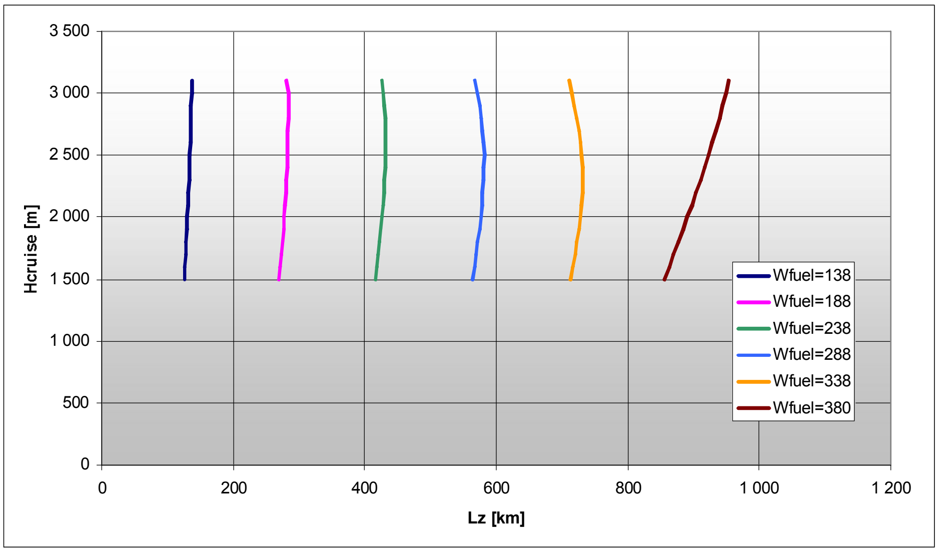
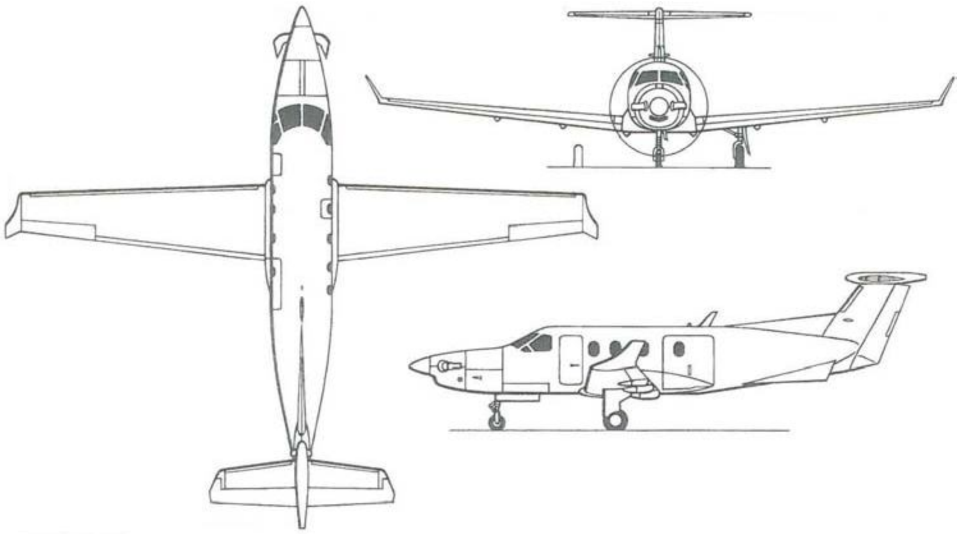


Fig. 4.3.3 Range-cruise altitude dependence for constant fuel weights

4.4. Pilatus PC-12



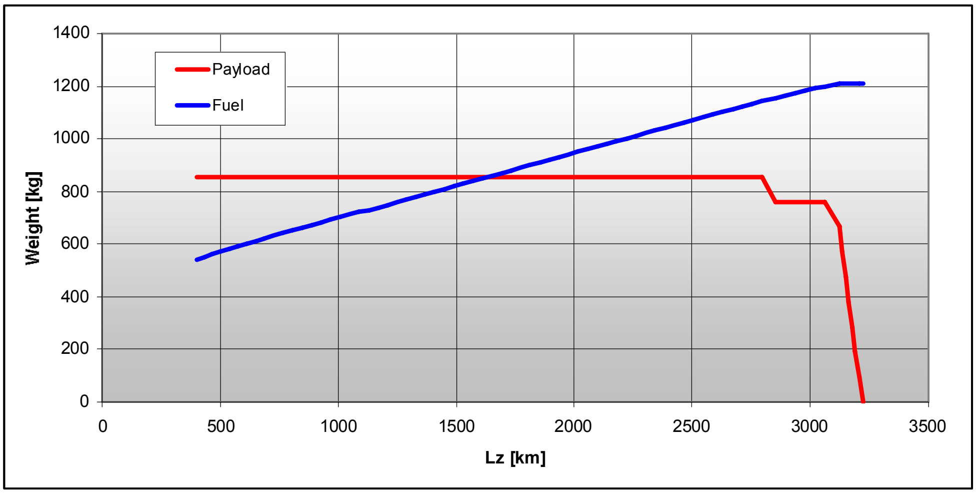


Fig. 4.4.1 Payload (fuel)-range diagram

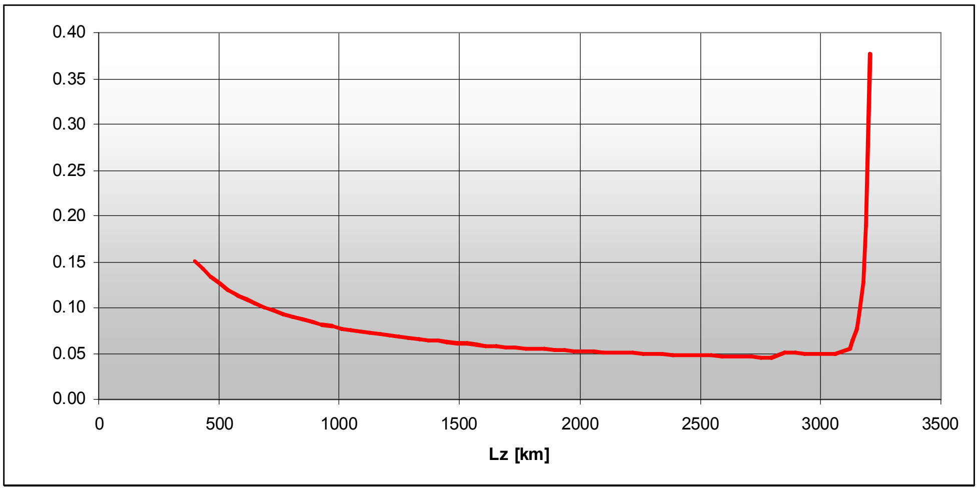


Fig. 4.4.2 Fuel weight per pax per km

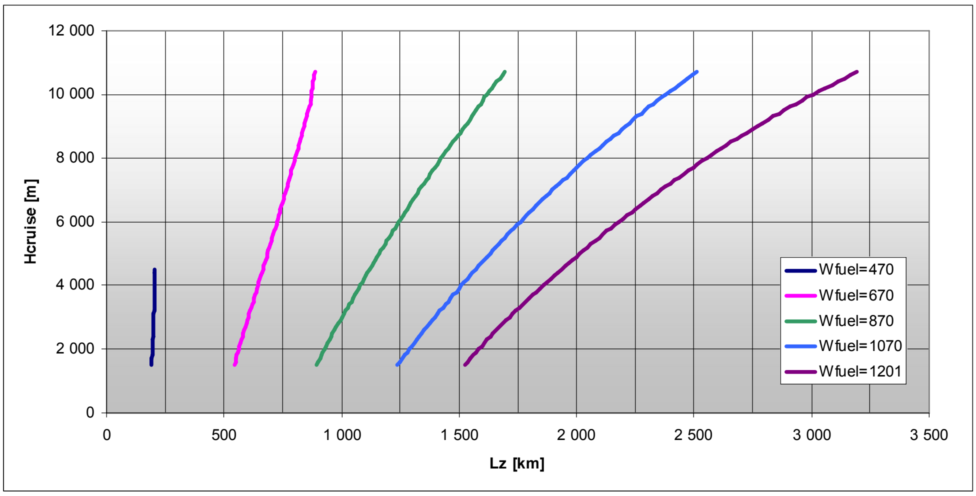
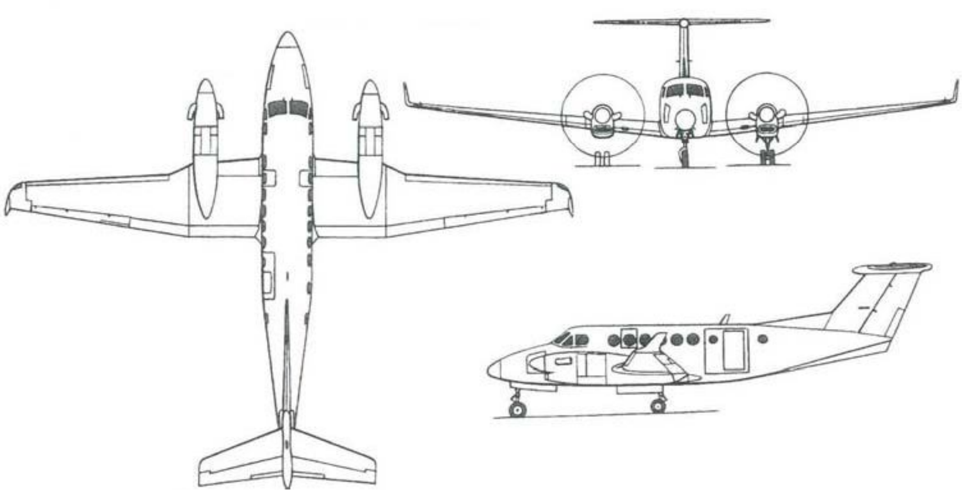


Fig. 4.4.3 Range-cruise altitude dependence for constant fuel weights

4.5. Beechcraft King Air 350



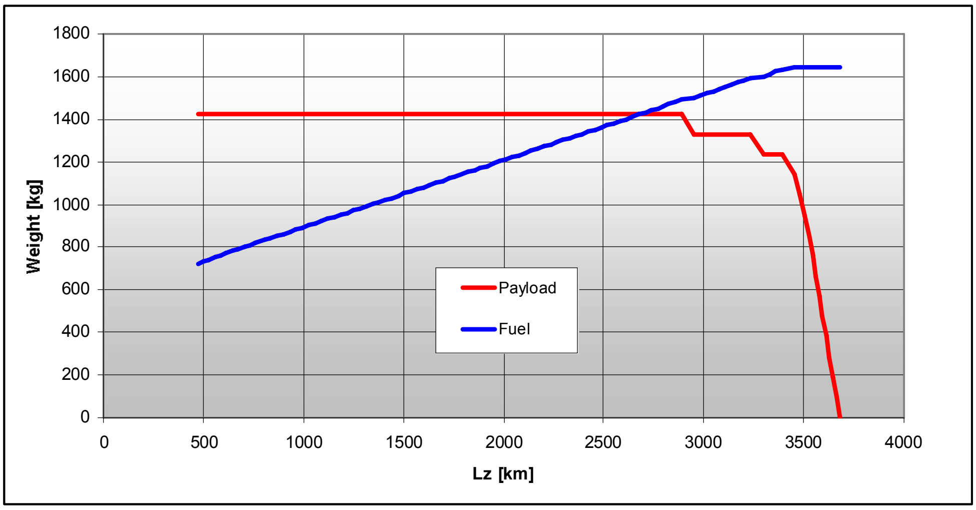


Fig. 4.5.1 Payload (fuel)-range diagram

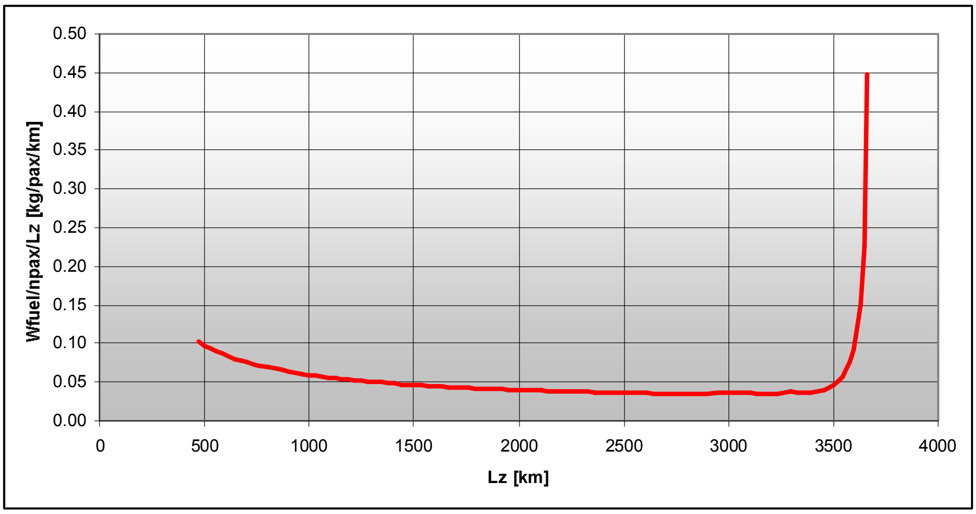


Fig. 4.5.2 Fuel weight per pax per km

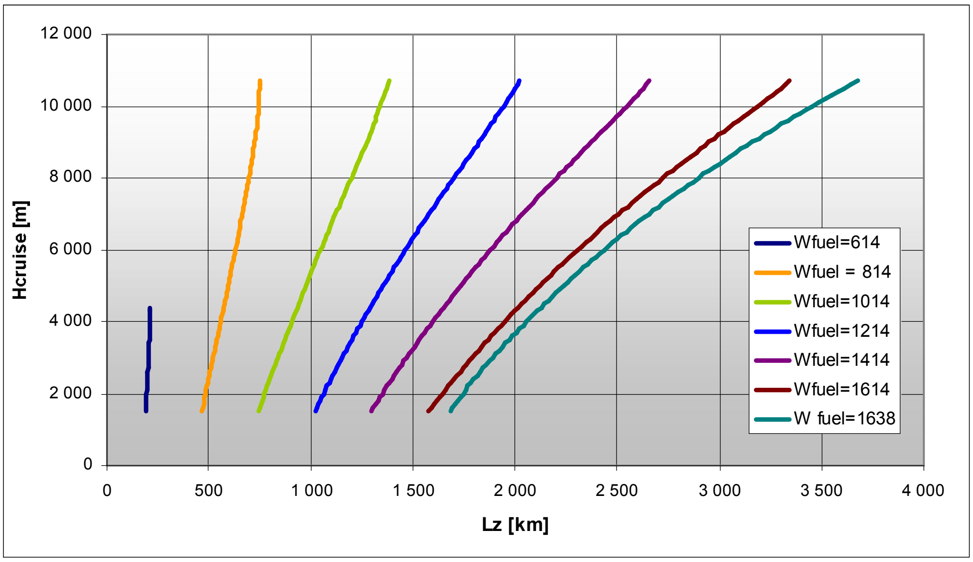
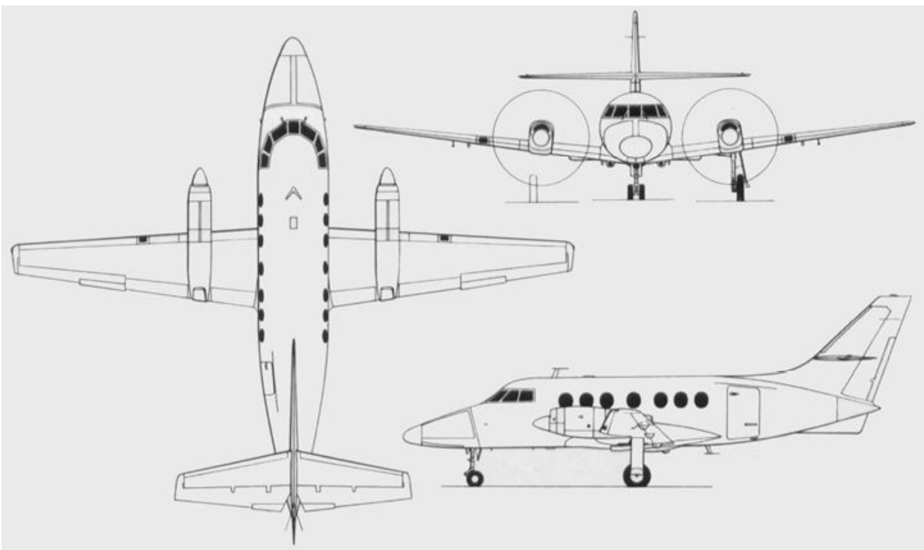


Fig. 4.4.3 Range-cruise altitude dependence for constant fuel weights

4.6. BAE Jetstream 31



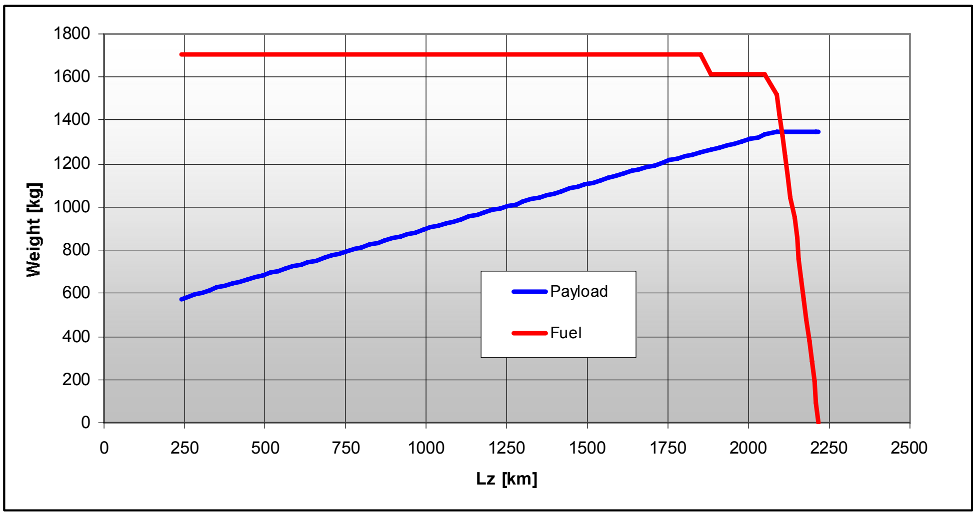


Fig. 4.6.1 Payload (fuel)-range diagram

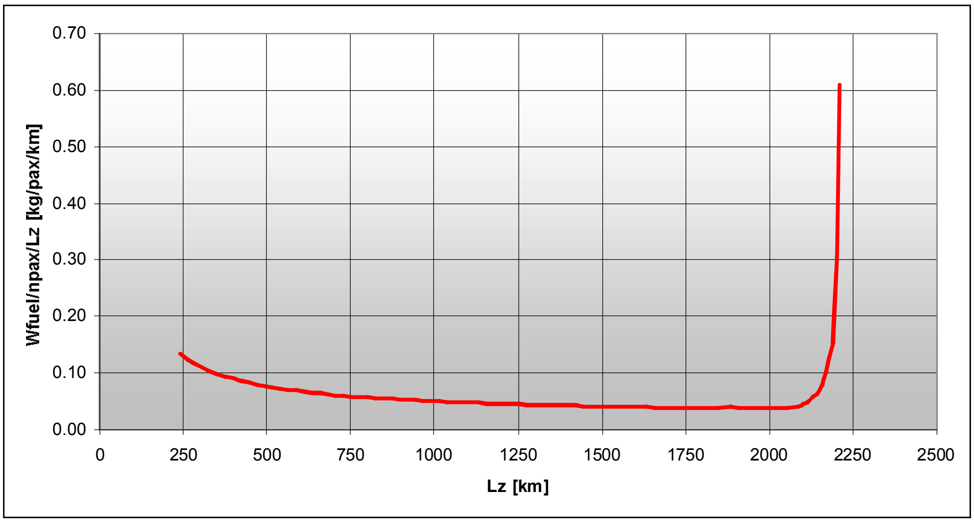


Fig. 4.6.2 Fuel weight per pax per km

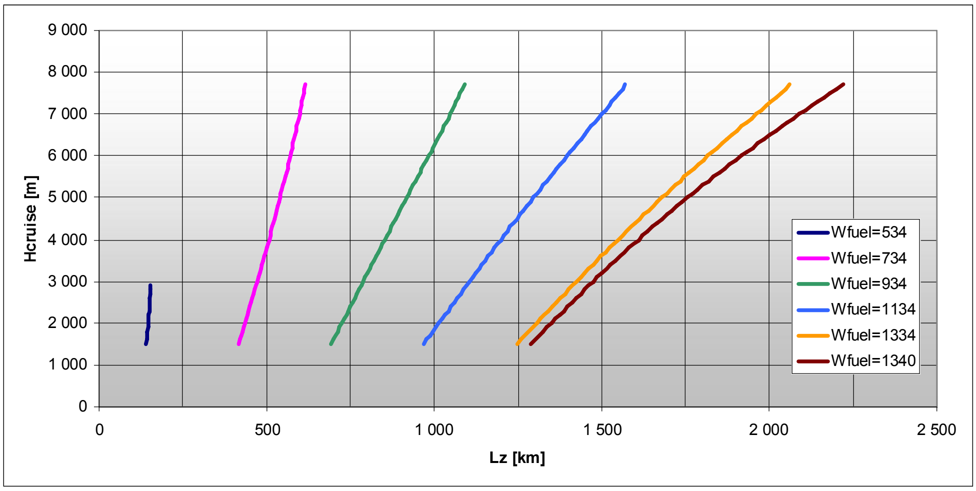
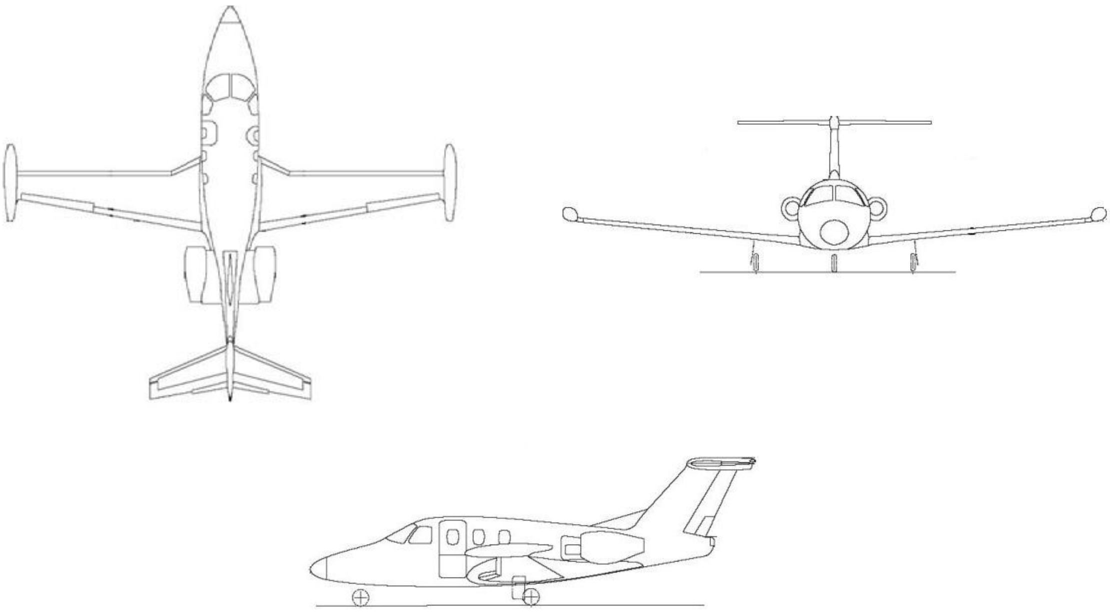


Fig. 4.6.2 Range-cruise altitude dependence for constant fuel weights

4.7. Eclipse 500



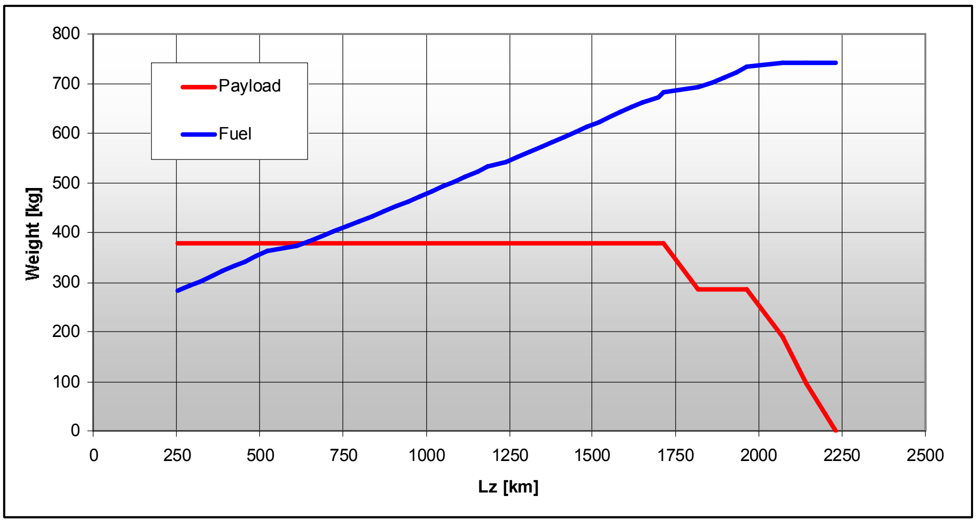


Fig. 4.7.1 Payload (fuel)-range diagram

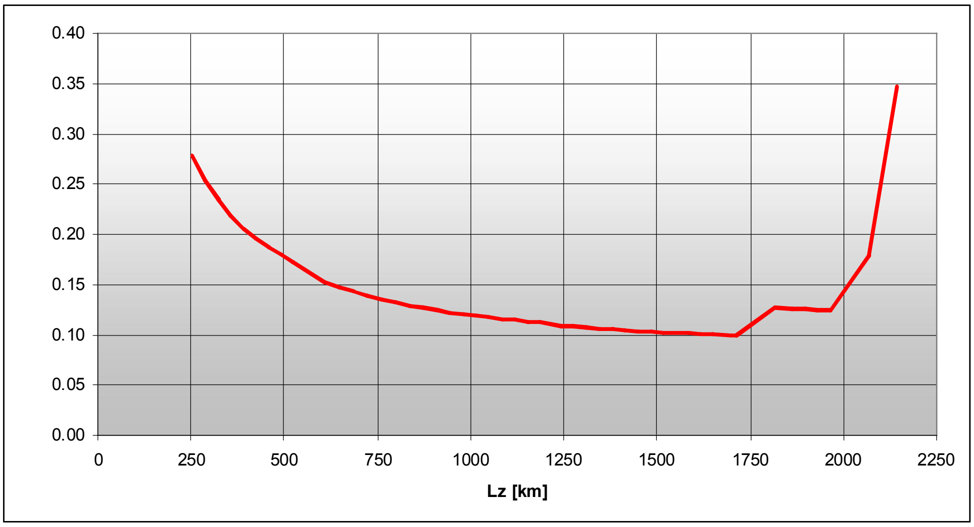


Fig. 4.7.2 Fuel weight per pax per km

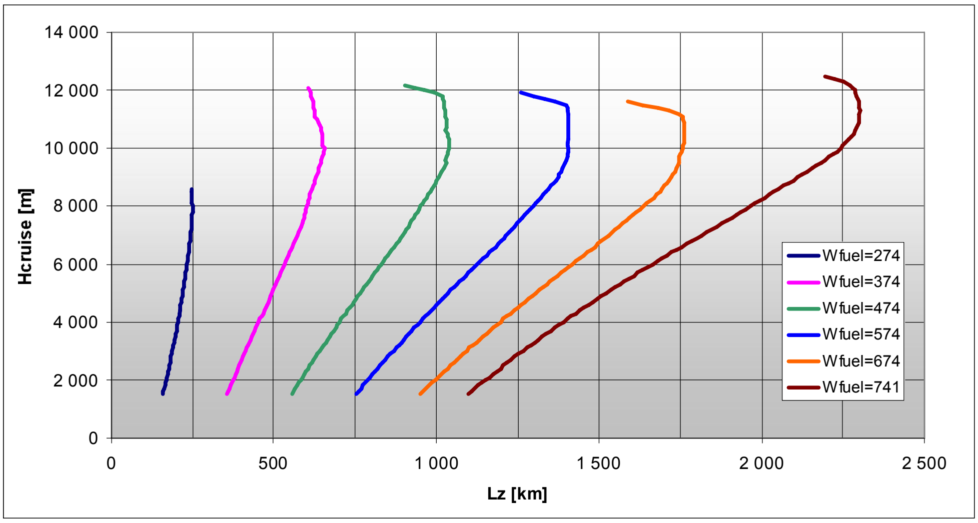
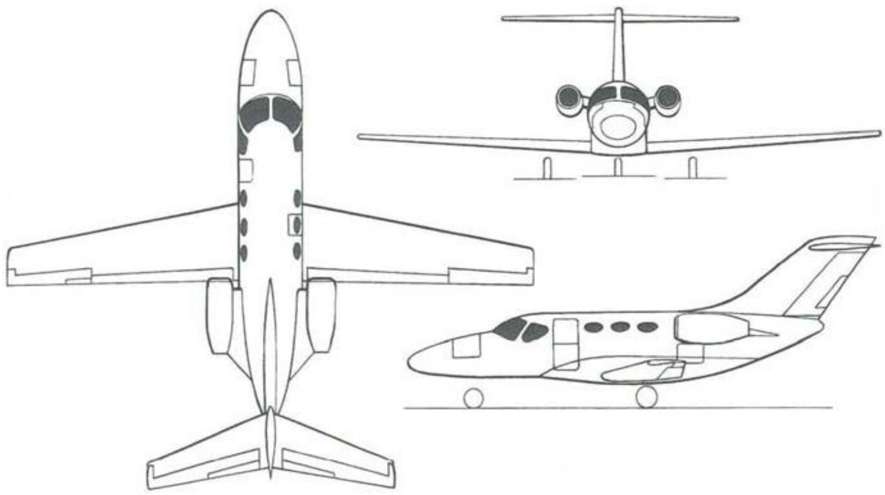


Fig. 4.7.2 Range-cruise altitude dependence for constant fuel weights

4.8. Cessna Citation Mustang



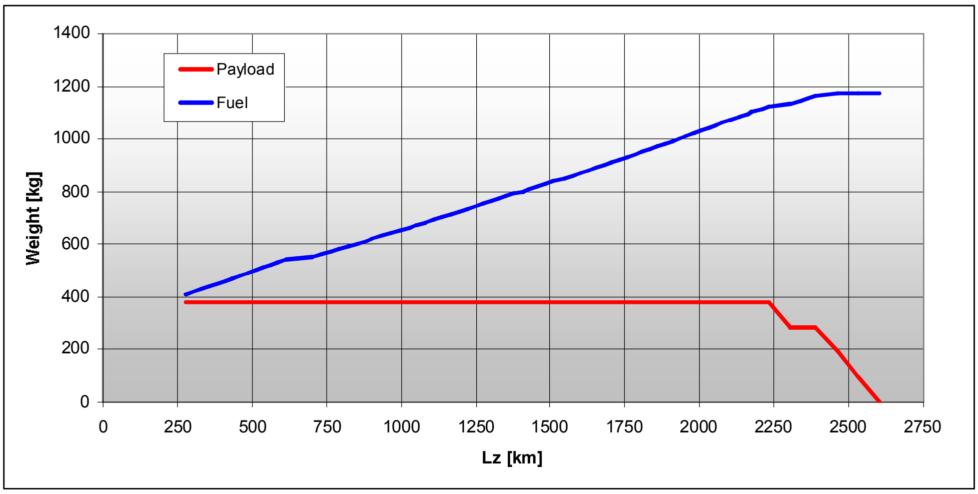


Fig. 4.8.1 Payload (fuel)-range diagram

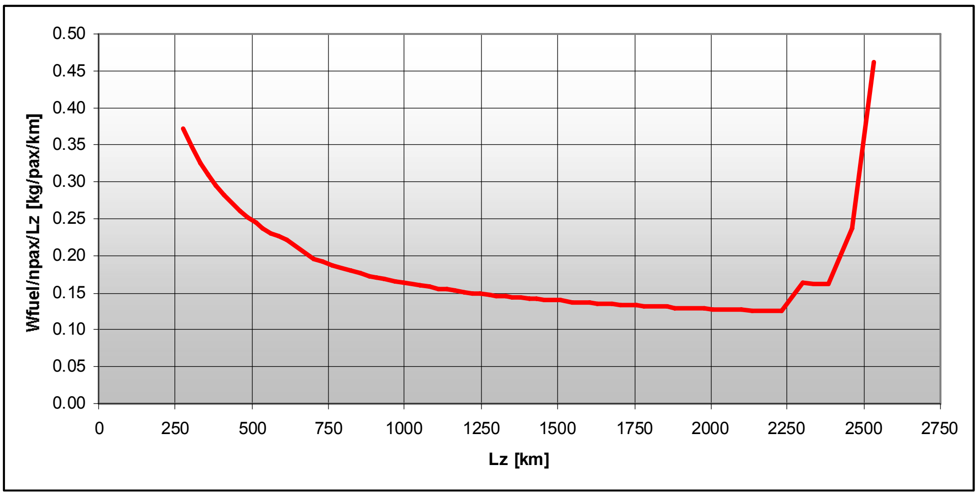


Fig. 4.8.2 Fuel weight per pax per km

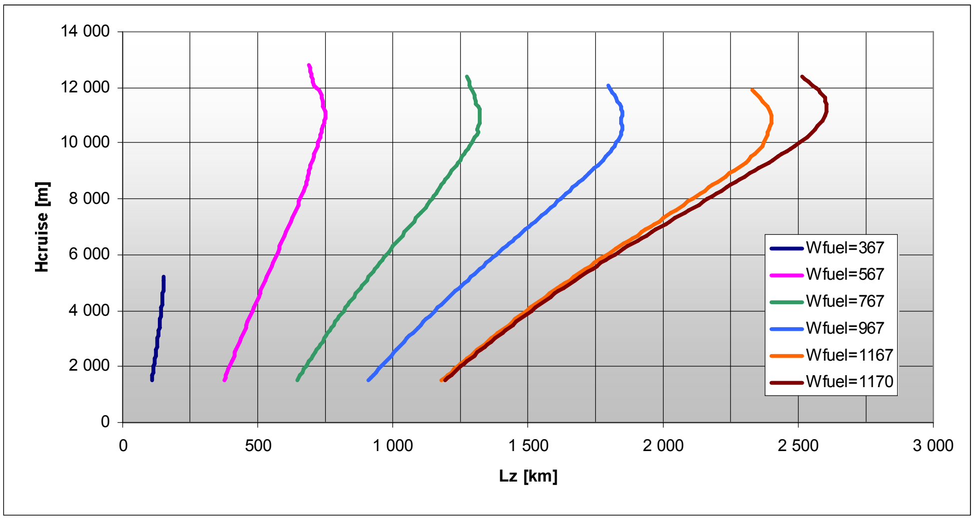
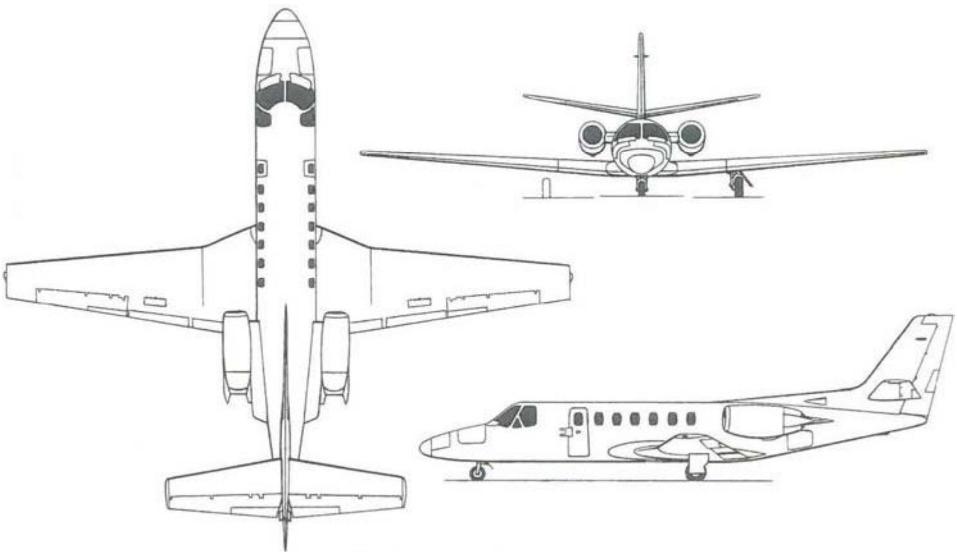


Fig. 4.8.2 Range-cruise altitude dependence for constant fuel weights

4.9. Cessna Citation Encore



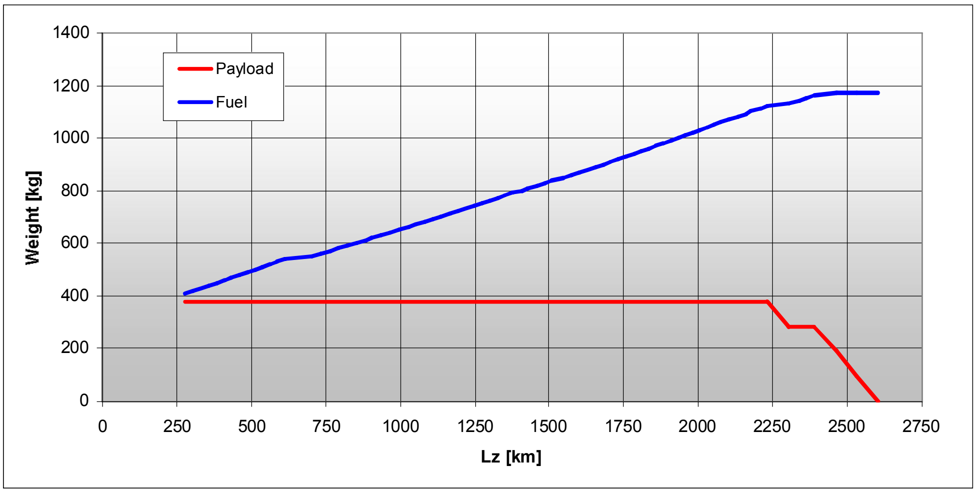


Fig. 4.9.1 Payload (fuel)-range diagram

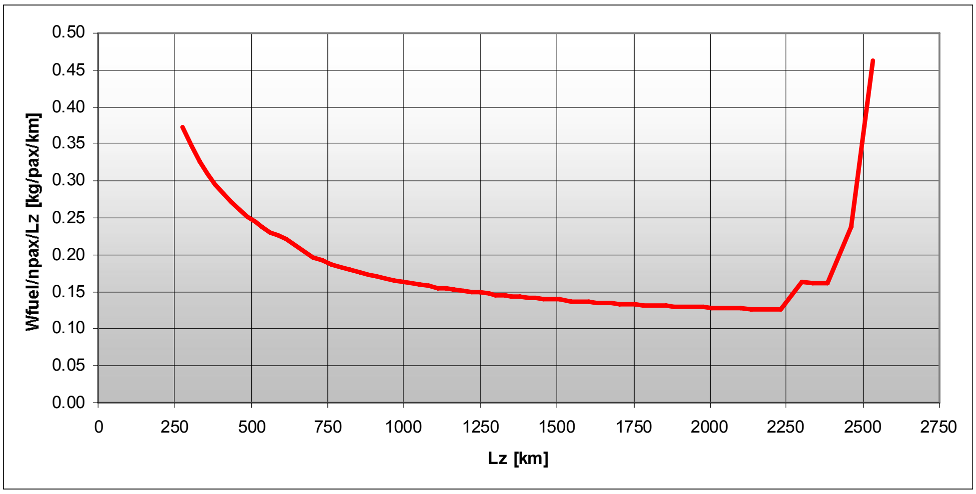


Fig. 4.9.2 Fuel weight per pax per km

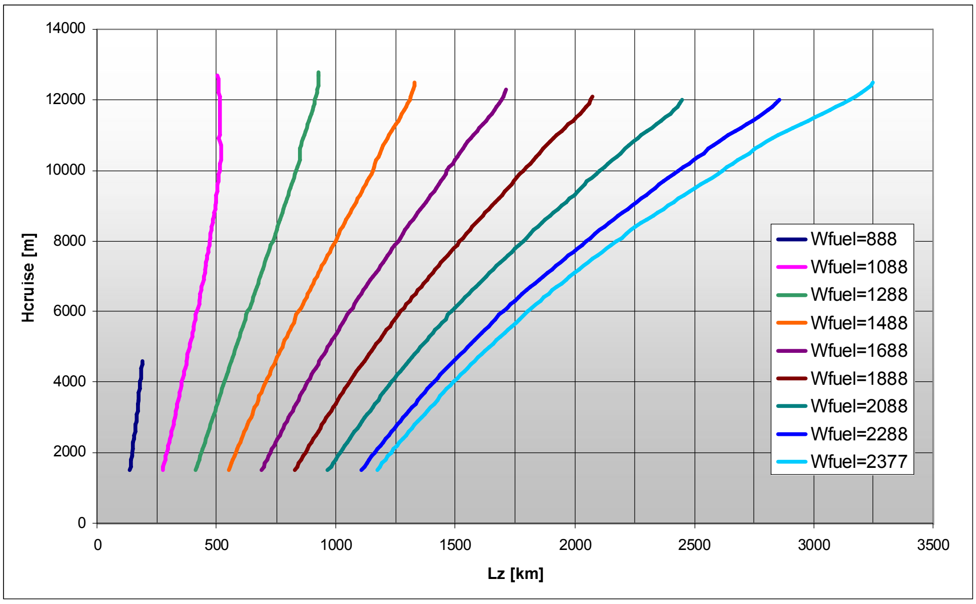


Fig. 4.9.2 Range-cruise altitude dependence for constant fuel weights

4.10. Comparison

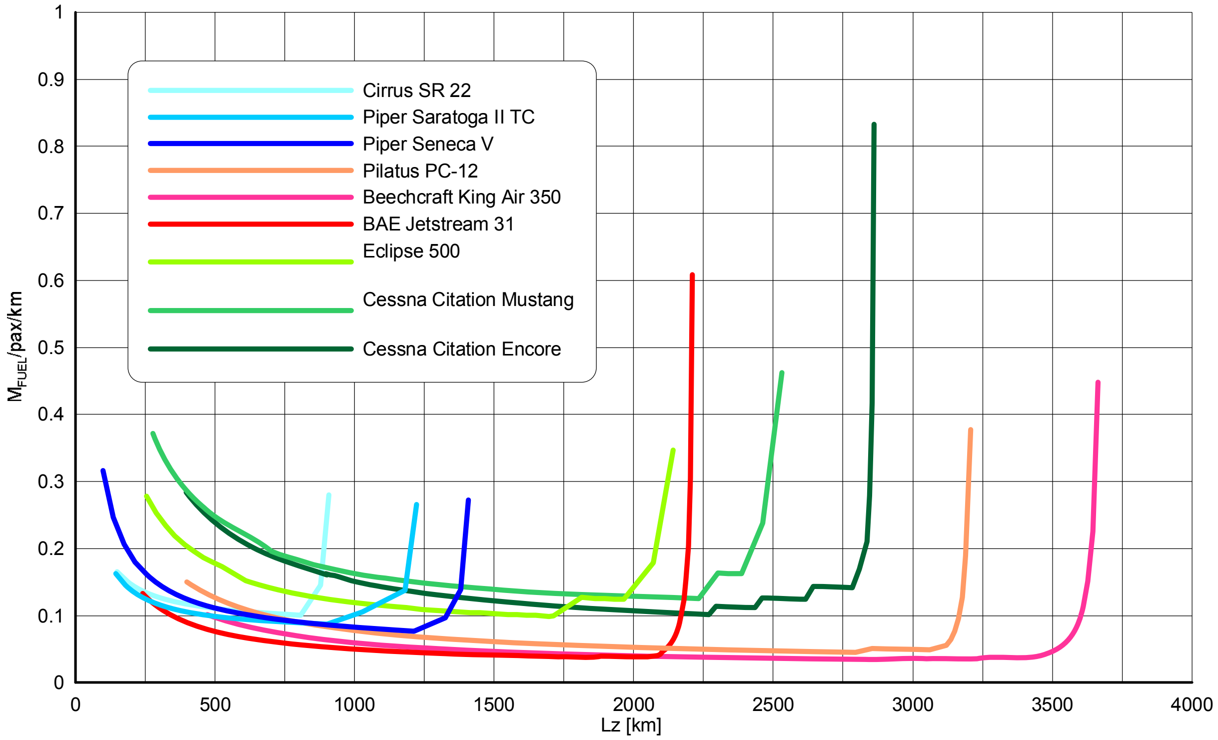


Fig. 4.10.1 Fuel weight per pax per km comparison for all nine planes

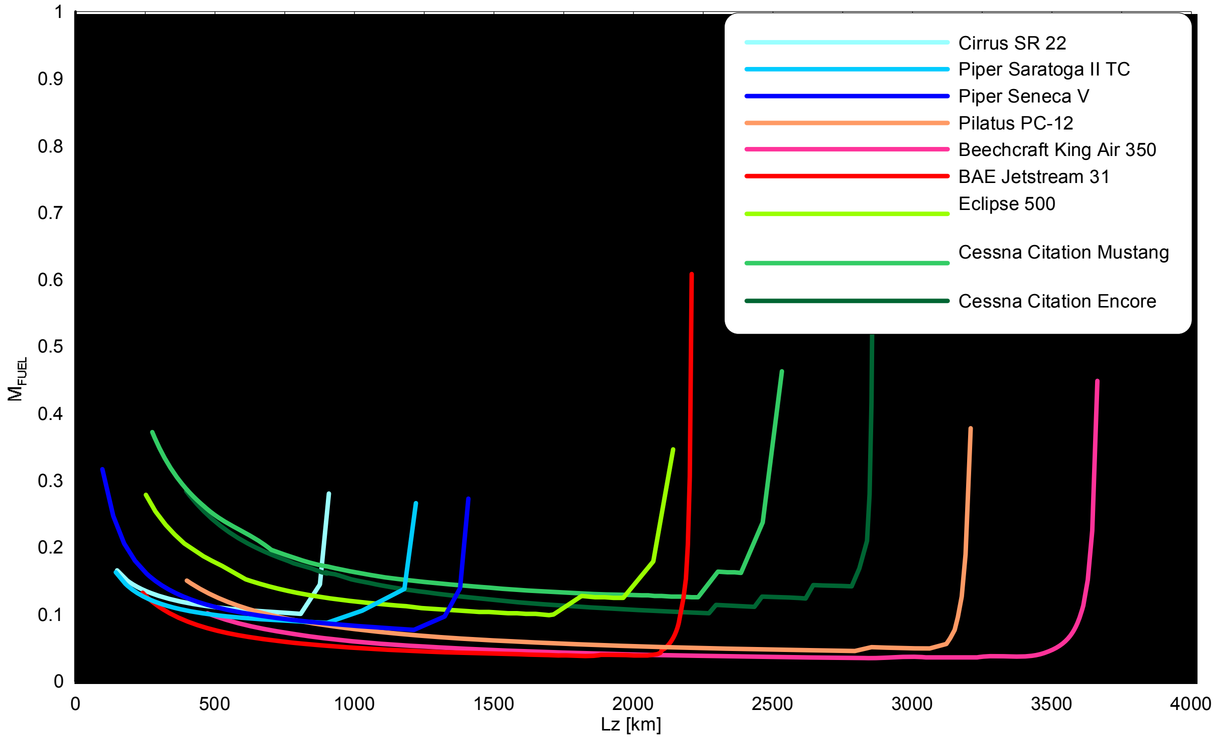


Fig. 4.10.2 Fuel weight per pax per km comparison for all nine planes

(with all European air connections lengths histogram)

7. CONCLUSIONS

Final conclusions and recommendations based on the analysis of fuel consumption and transportation energy effectiveness (as result of "Fuel consumption and transportation energy effectiveness analysis" preparation) are presented below:

- All analyses are based on fuel efficiency, defined as fuel weight per pax per km.
- Calculations were done for three categories of airplanes: piston, turboprops and jets.
- From point of view of fuel efficiency (fuel weight per pax per km), the most efficient are turboprops airplanes, almost for all ranges.
- For ranges shorter then 250 km, more efficient are piston airplanes, from point of view of fuel efficiency (fuel weight per pax per km).
- Fuel efficiency and SFC (Specific Fuel Consumption) for jet planes is much greater then for two other categories of airplanes.
- For piston airplanes (no pressurized cabin, maximum altitude of flight level 10 000 ft) altitude of level cruise flight has no important influence on fuel consumption.
- For turboprops and jets (fully pressurized) for short ranges (less then 250 km) altitude of level cruise flight has no significant influence on fuel consumption, but for long range flights the altitude of level cruise flight has very significant influence on fuel consumption.

Based on the analyses conducted, one can formulate the following recommendations:

- For minimizing fuel efficiency and fuel consumption it is necessary to utilize airplane in limited task area, fitted to its characteristics. Finding of this limited task areas needs optimization of task distribution between various types of airplanes.
- For long range flights (greater than 250 km) the altitude of level cruise flight has very significant influence on fuel consumption. Minimizing fuel consumption needs to find optimal cruise profile.
- Results of these calculations can be used for finding some mission requirements for various ranges and sizes of payload and various types of airplanes.

8. LITERATURE REFERENCES

[1] *All the Worlds Aircraft*, Jane's, 1960 – 2005, London.

[2] *ESDU* (*Engineering Sciences Data Unit*), Aerodynamics Sub-series, The Royal Aeronautical Society, London.

[3] Бадягин . А., Мухамедов Ф. А.: Проектирование самолетов, Машиностроение, Москва 1972.

[4] Barman J. F., Erzberger H.: *Fixed-Range Optimum Trajectories for Short-Haul Aircraft*, Journal of Aircraft vol 13, No 10, 1976.

[5] Cramer E. J.: *Aircraft performance optimization: Design case study*, AIAA Paper, No. 95 – 0465, 6 pp.

[6] McCormick B. W.: *Aerodynamics, aeronautics and flight mechanics*, Wiley, New York, 1995.

[7] Raymer D. P., *Aircraft Design. A Conceptual Approach*, AIAA Education Series, Washington 1989.

[8] Roskam J.: *Airplane Design*, Parts I-7, The University of Kansas, 1990.

[9] Скриниченко С. Ю.: *Оптимизация режимов полета самолета*, Машиностроение, 1975.

[10] Torenbeek E.: *Fundamentals of Conceptual Design Optimization of Subsonic Transport Aircraft*, Delft 1980.

[11] Torenbeek E.: *Synthesis of Subsonic Airplane Design*, Delft University Press, 1976.