AIR TRANSPORT EFFICIENCY AND ITS MEASURES

Alfred Baron
Institute of Aviation

Executive summary

There are various definitions of efficiency of transport and different methods of measurement. This makes it difficult to measure and carry out benchmarking assessment of different modes. This paper presents proposals for measuring the efficiency of transport systems, taking as criteria: travel time, energy consumption, material use, impact on environment, affordability and accessibility. Based on these criteria, a benchmarking analysis of road and air transport was carried out. A new proposal for general definition of efficiency of transport is presented.

1. INTRODUCTION

In ACARE Strategic Research Agenda Efficient Air Transport is defined as "*the movement of aircraft, of all types, and their passengers, through European airports and sky, in a timely and economic manner, without undue constraints on their preferred flight trajectories (aircraft), journeys (passengers) or departure and arrival times*" and the main Vision 2020 Goals are: three times more aircraft movements, punctuality (delays less than 15 min), time spent in airports – no more than 15 min, five-fold reduction in the average accidents rate [1]. This definition of efficiency is limited to the Air Traffic Management level.

At the air travel industry level efficiency is addressed to capital productivity and is measured in two ways [3]:

- The simplest measure is the average aggregate load factor of the airline. This can be taken to measure the approximate capital productivity of the airline Aggregate load factor are defined as the percentage share of seats occupied per year in total aircraft seat capacity on route served by the carrier.
- A more adequate method is to evaluate efficiency by analyzing and comparing the outputs of the decision unit to its inputs. Each output and each input is assigned a weight and the ratio of weighted outputs to weighted inputs yields a global measure of efficiency in given environmental conditions. Outputs include total passengers transported and total passenger-kilometers. Inputs include total personnel, capacity, fleet, fuel and average stage length.

At the route level, standard measures of efficiency are load factors and fares. Load factors express the efficiency in the use of aircrafts on each route. The load factor depends on the structure of the fleet (average size and age of planes), on the economies of scale, passenger flow density, stage length, and on policy and market influences shaping the efficiency of carriers. The efficiency in the use of airline capital increase with average aircraft size and the size of market [3]. That explains the reasons behind the Hub & Spoke system and large airliners development at the expense of direct point-to-point connections and low passengers flows small aircraft service.

From the point of view of vehicle efficiency, the fundamental efficiency indicator of any vehicle are its velocity, payload and energy consumption. These indicators are used to define generic vehicular efficiency that applies to all vehicles.

At the level of European Union and respective Member States, the air transport efficiency evaluation cannot be limited to the level of Air Traffic Management or airline economic efficiency only. The evaluation has to take under consideration social aims, which are targeted by air transport and which were formulated in numerous documents concerning European Union transport policy. They especially concern: securing coherent and sustainable transport development, slowing the dynamics of car transport development down in favor of more environmental friendly modes, extending daily radius of population activity.

The natural measures of transport efficiency in this context at the country level are:

- Origin-Destination time of travel (as a result of mode speed, network availability and traffic management system)
- Energy (fuel) consumption at the level of system (required for 1 passenger-kilometer in given conditions)
- Material use (per 1 passenger-kilometer)
- Externalities – impact on environment (in terms of 1 passenger-kilometer)
- Affordability and Accessibility

As an example of a benchmarking assessment of the effectiveness of passenger transport we compare the road and air transport, particularly passenger cars and small airplanes operating in the European Personal Air Transportation System (EPATS) [14]

2. TIME EFFICIENCY

The travelling public has available a wide choice of modes of transport including car, bus, train, ship and aircraft. By far the most significant advantage of air travel is the time saved by the fast cruising speed. Professor Bouladon of the Geneva Institute aptly described this in his analysis of transport gaps in 1967. The total trip time shown in Fig. 1.7 is a combination of delay caused by the infrequency of the service, the speed of travel and the wasted time due to the interconnection of services.

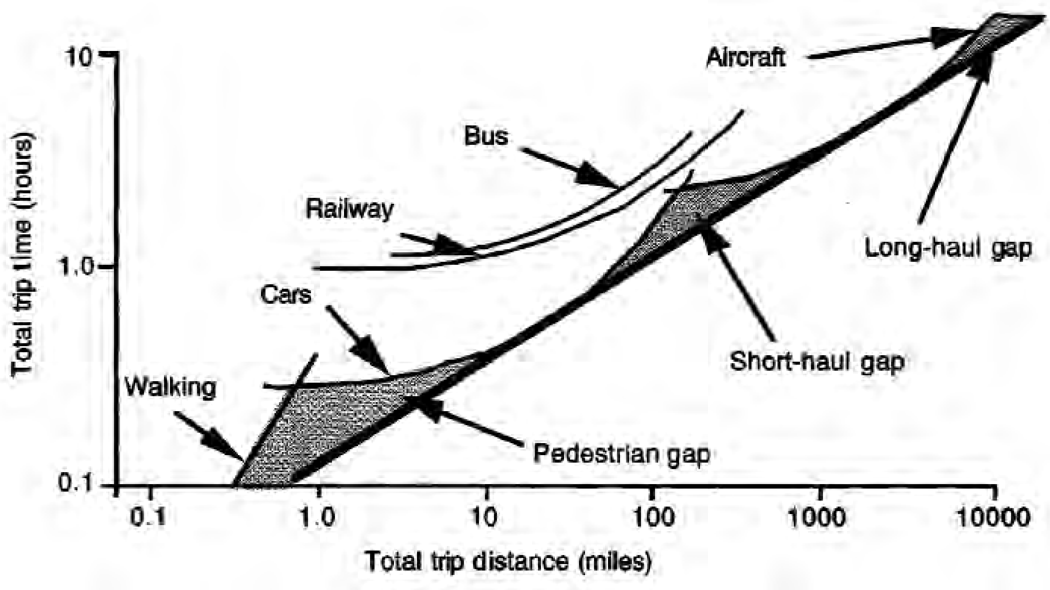

Figure 1. Transport gaps (Source Bouladon)

Of the three “gaps” identified, the short- and long-haul ones are directly targeted by the air transport. Reducing each of the component times contributing to the overall trip time presents opportunities for both operational and technical improvements in new air transport and continues to challenge aircraft designers, airline managers and airport operators. For short stages it is no longer acceptable to have long reporting times prior to boarding. The goal of EPATS Project is shortening reporting time and to fulfill the Short –haul gap.

As we all know, for shorter journeys and where a suitable public transport system is not available the private car is the natural choice of travel. For journeys less than 300 km the car is the dominant mode of transport.

We consider a time effective mode of transport, appropriate for certain groups of population if time of travel is the shortest among other modes. We call time saved by one traveler in terms of O-D travel realization a unitary time efficiency of transport system "m" for "i to j" itinerary in comparison to other available transport systems. Travel time consists of unproductive transport time (including node access, waiting for transport and compulsory rest during travel) and efficient time used for business trip objectives. For this analysis, we assume, typical business trips start during morning hours and trip objectives realization lasts 6 hours, because trip objectives and their time of realization may vary.

Global time efficiency of a new transport system implementation from "i to j" itinerary is measured by aggregating time savings of all passengers traveling using those itineraries per a unit of time (assumed 1 year). Thus, the efficiency depends on which itinerary the system is introduced to and what the flow of passengers is.

The transport time between all regional (16 NUTS-2) capitals using all available modes (except for coach) of transportation and hypothetical EPATS aircraft were analyzed to estimate time efficiency of the EPATS in Poland.

The time data came from train and air transport schedule and the Michelin internet website (http://www.viamichelin.com) for car travel. Data concerning number of business trips in Poland were taken from Polish Institute of Tourism (http://www.intur.com.pl/). The least time consuming mode was found for every itinerary (examples: Figure 2).

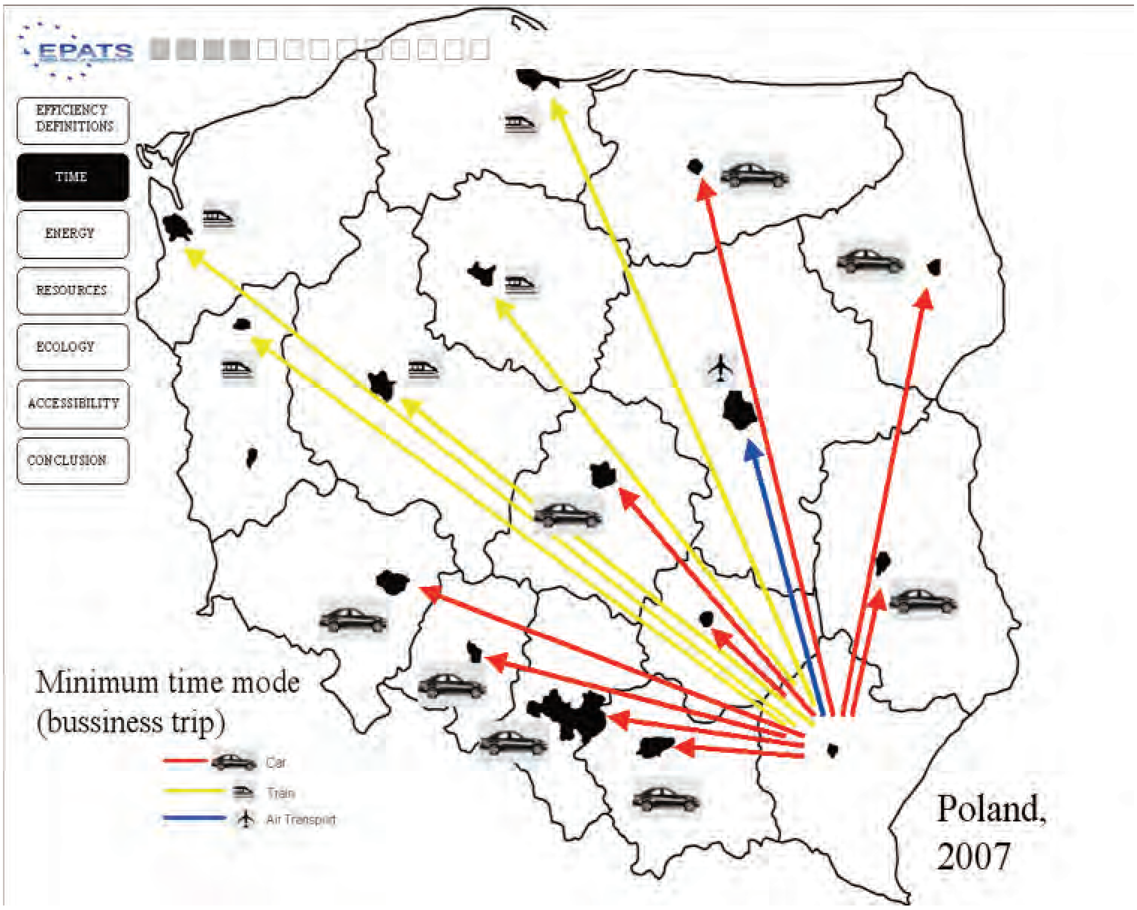

Figure 2. Least time modes on itineraries originating from Rzeszów

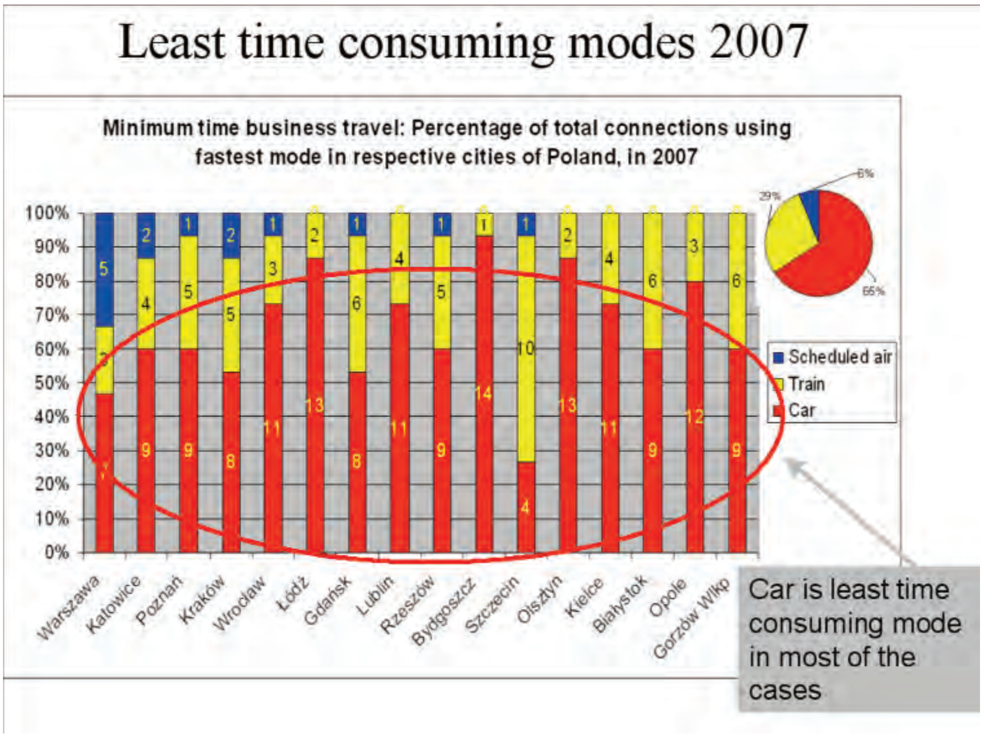

Figure 3. Share of the least time consuming modes among all regions

Calculations show that in 2007, for most business travel in Poland, the shortest time were achieved by using a car. See Figure 3. The implementation of EPATS radically changes the proportions. EPATS is the least time consuming mode in most of the cases. See Figure 4. EPATS possible time savings as a % of average minimum time business trip using modes available in 2007 is shown on Figure 5.

The global time efficiency of EPATS system in Poland is 30 million hours per year with an average of 10 hours on one business trip and number of business trips of 3 million per year.

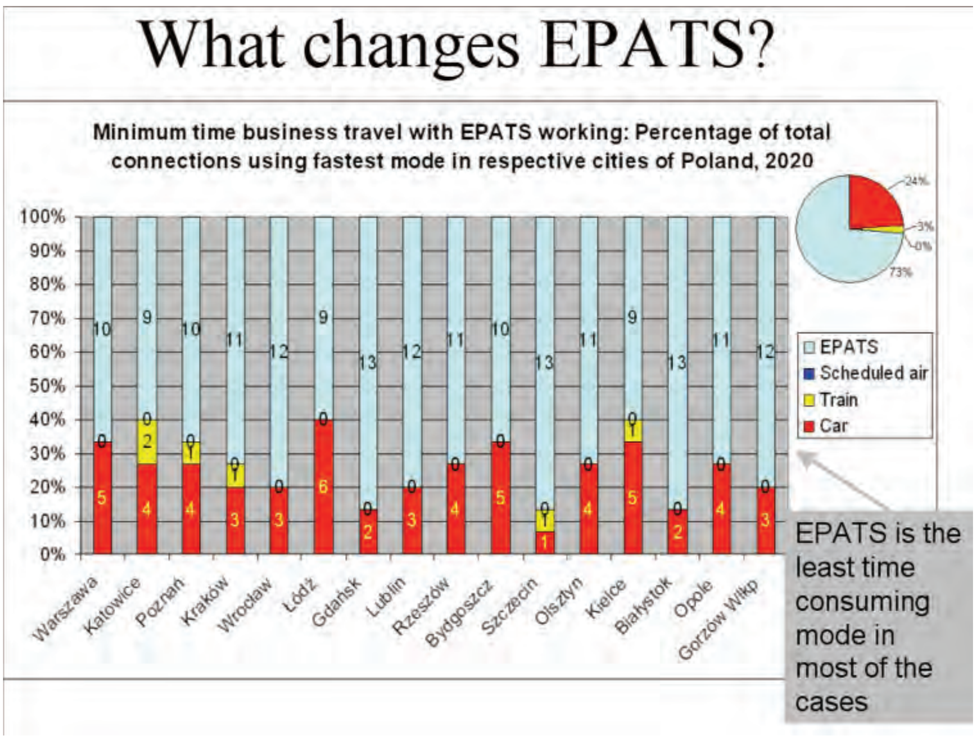

Figure 4. Share of the least time consuming modes among all regions if the EPATS is working

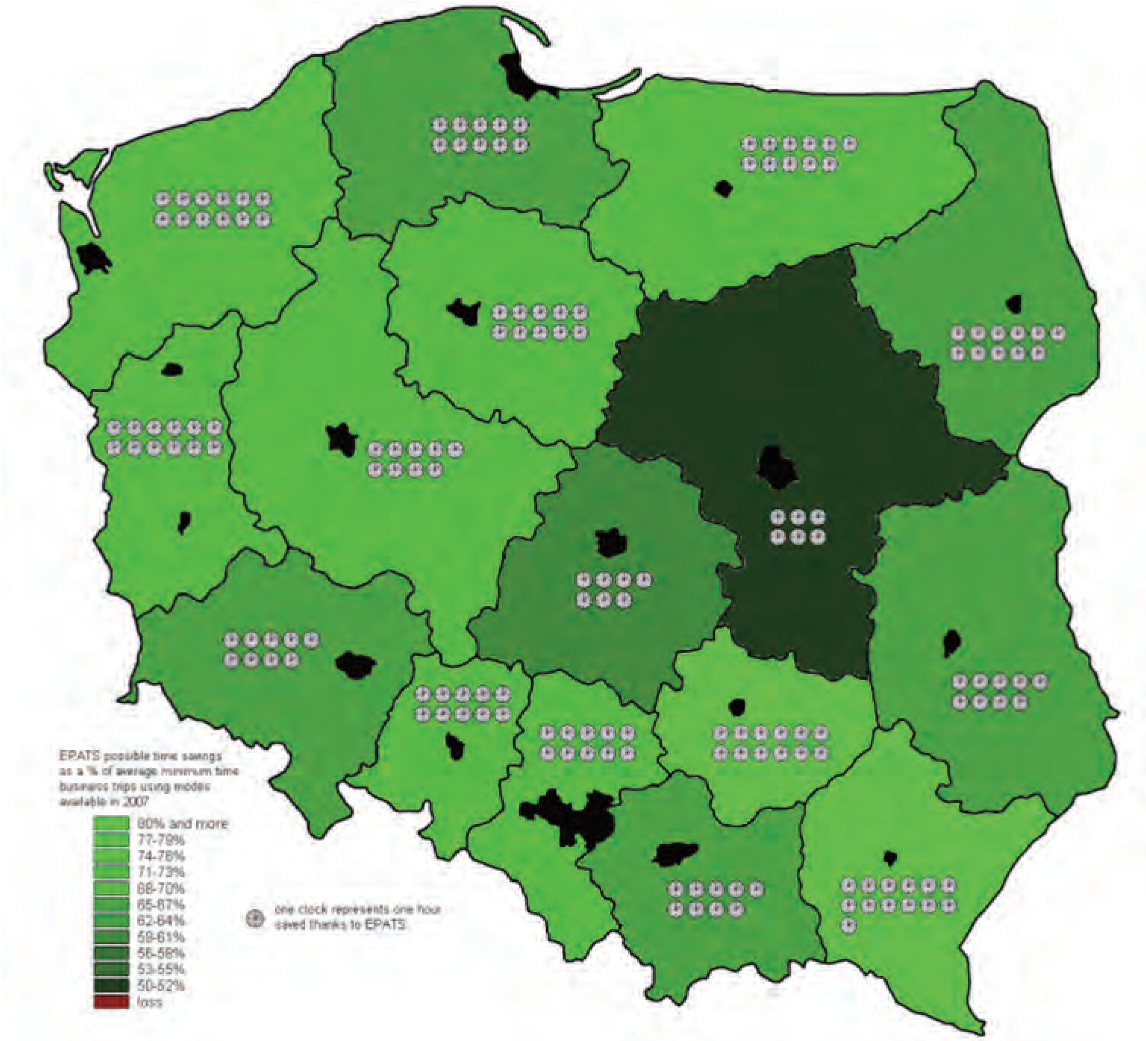

Figure 5. Average time saved during one business trip from one region of Poland to all of the rest after EPATS implementation.

3. ENERGY EFFICIENCY

The words "energy efficiency" are in common use qualitatively, but are difficult to define or even to conceptualize. An engineer may define energy efficiency in a very restrictive equipment sense, whereas an environmentalist may have a more broad view of energy efficiency. Increases in energy efficiency take place when either energy inputs are reduced for a given level of service or there are increased or enhanced services for a given amount of energy inputs. Energy use in the transportation sector is primarily for passenger travel and freight movements and is measured as Specific Fuel Consumption (SFC). The energy input is fuel consumption the given service is passenger transportation from origin to destination in given time and conditions.

In aviation, we can distinguish the following units of fuel consumption: hourly consumption, consumption per kilometer or passenger-kilometer and per unit of effective power, calculated as a product of number of transported passengers and speed. Fuel consumption and theses units values depend on conditions and reference levels, for which they were chosen.

We can list the following levels of reference:

- aircraft technical level, at which various conditions of fuel consumption can be distinguished, especially: flight speed and level condition, longest range condition or during standard mission (according to the requirements), etc. These values are determined by calculations and analysis and are included in the set of aircraft characteristics, given in aircraft manual.
- air subsystem level which includes aircraft of a given airline, airports, air network and air

traffic management, where average fuel consumption is determined on real routes and in real conditions taken under consideration including e.g.: waiting, route change, aircraft load, network geometry, etc.

- air transport system level which includes all airlines and all airports, air network and air traffic management system. Fuel consumption at this level is statistically determined and includes aircraft fleet as well as surface facilities and surface transport
- transport system level which includes consumption of fuel used for airport access and egress operations and airport fuel and material logistics

The example of fuel consumption at air transport system and its comparison to car transport system is given below on the graph Figure 6:

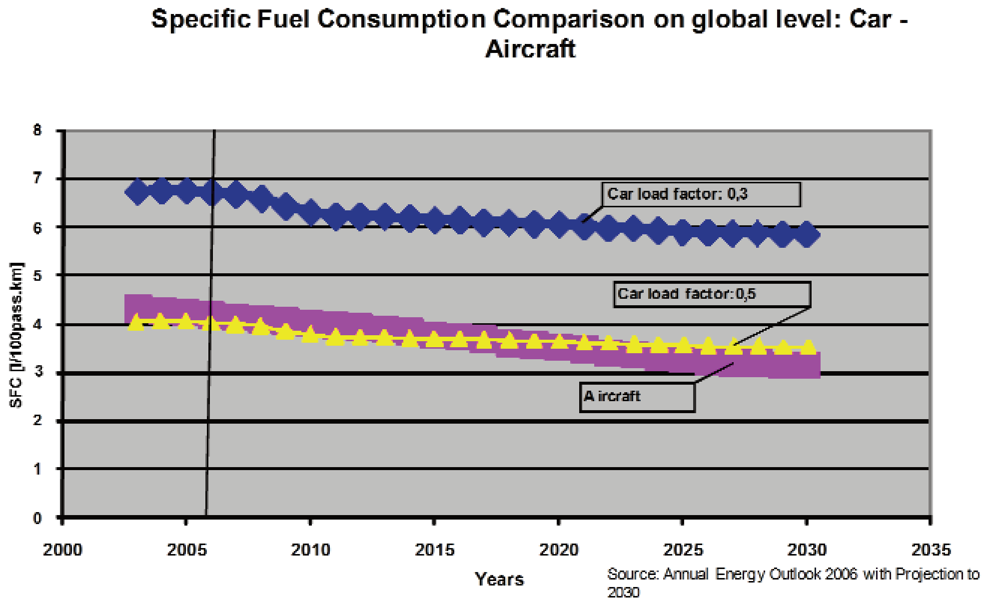

Figure 6. Specific fuel consumption comparison on global level: Car - Aircraft Source: Annual Energy Outlook 2006 with Projection to 2030

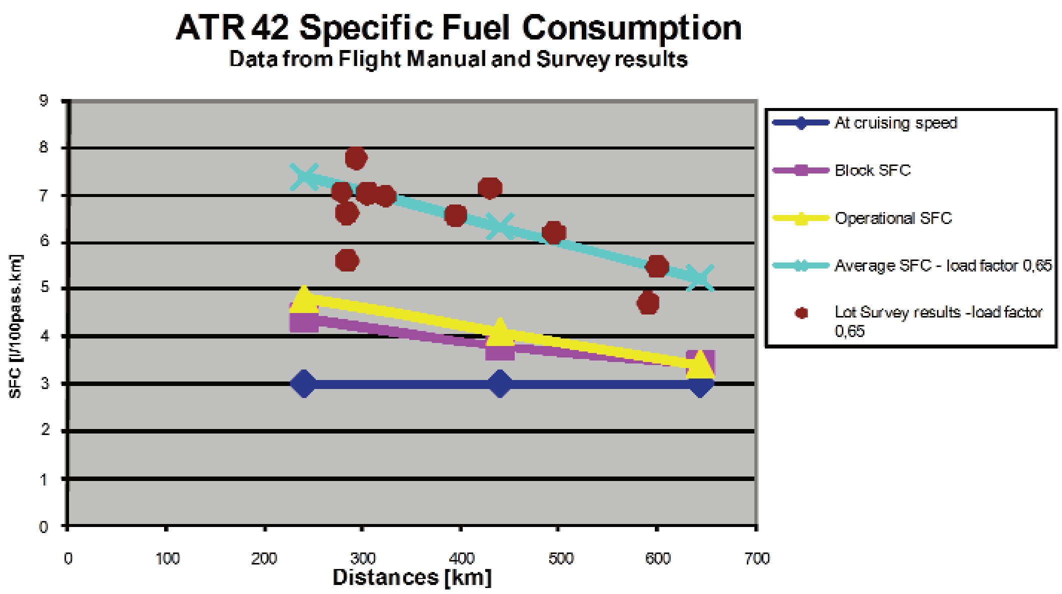

Figure 7. ATR 42 Specific fuel consumption at different conditions

Fundamental differences among the mentioned reference levels can be seen on the example of ATR-42, used by Polish Airlines on regional routes (see figure 7). The statistical specific fuel consumption per unit of this aircraft in real conditions, on distances of 300 km is about 7 liters of kerosene per 100 passenger-kilometers, while this value at block speed in standard conditions is about 3 liters per 100 pkm, that is two times less. It proves that the aircraft technical characteristics are far different from these, reached in the system. It is important not only in terms of fuel consumption, but also speed.

Main factors of specific fuel consumption [l/100 pas.km] increase in air transport system are: empty seats, waiting for start and landing, route extension due to network characteristics, route change due to traffic, etc. The more complete use of airspace and airport, the higher the loses. Increasing number of communication airports and making air traffic management more efficient leads to significant decrease in fuel consumption in air transport. The similar effect is generated by fitting network to directions of O-D(Origin-Destination) travel, simultaneously adjusting aircraft size to passenger flow density.

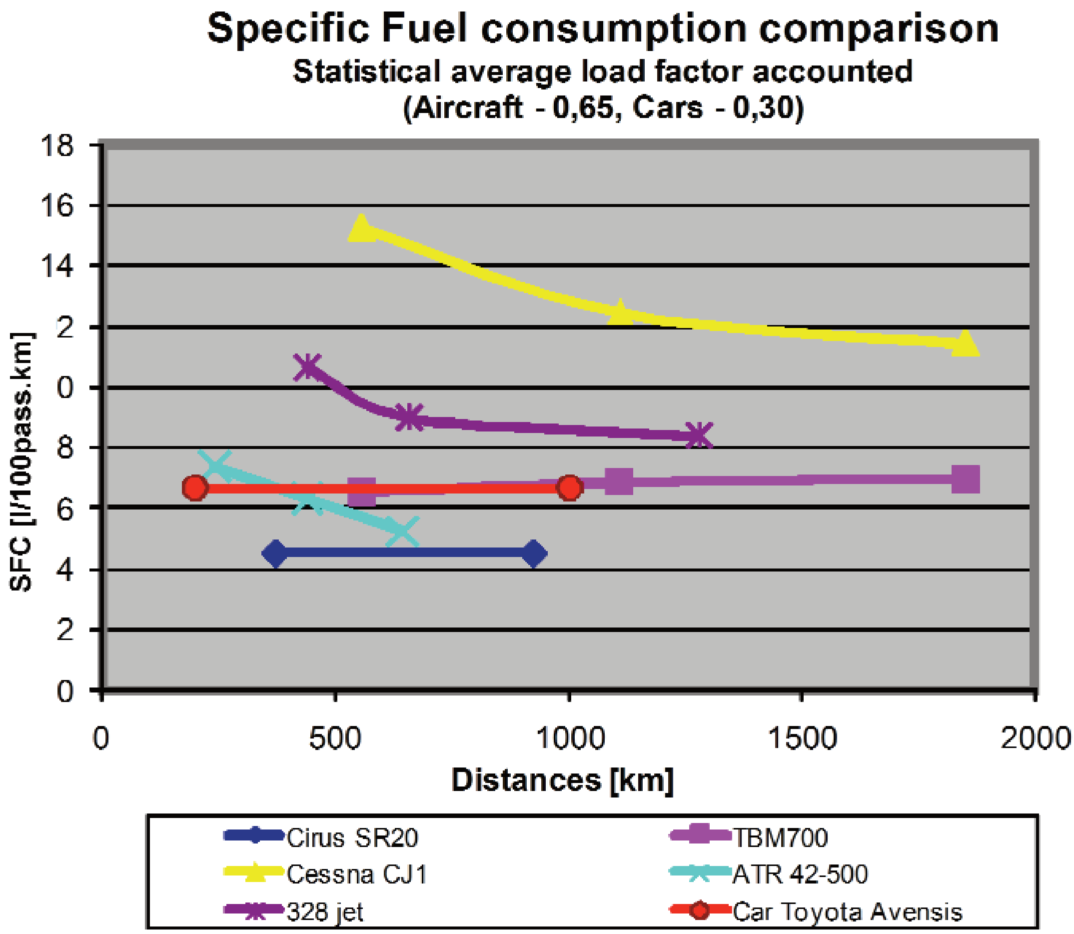

Figure 8. Specific fuel consumption comparison

Comparison of unit fuel consumption, in standard conditions, of car and aircraft of different size and with different propulsion via route distances were shown at the graph Figure 8.

When car statistical load factor is on average 1,2 persons per vehicle, its SFC on one passenger is on average 6,6 liters/100 km, what is, in comparison to 4-seat aircraft, higher by 50%. It is important to note, that the comparison of fuel consumption per unit of transport (passenger x kilometer) of two vehicles of very different speeds is not aligned to the definition of energy efficiency and lead to confusion. According to the definition of energy efficiency of transport mode, the energy put in the transport realization should be referred to the energy required for this transport realization, i.e. to 1 pas.km/hour or pas.speed. In reality, even when load factor is 1, the energy efficiency of car is much lower than aircraft. At an average speed of 80km/h, the SFC per 1 pas.km/hour is 0,025l/pas.km/h, when for aircraft at an average speed of 300 km/h it is, respectively, 0,01 litres/pas.km/h.

There are two, important reasons for that. Car power need is higher at higher speeds, than the need of the aircraft (higher resistance), energy loses for idle gear and for breaking and accelerating are important in total need of power of car. Figures 9 and 10 clearly show it.

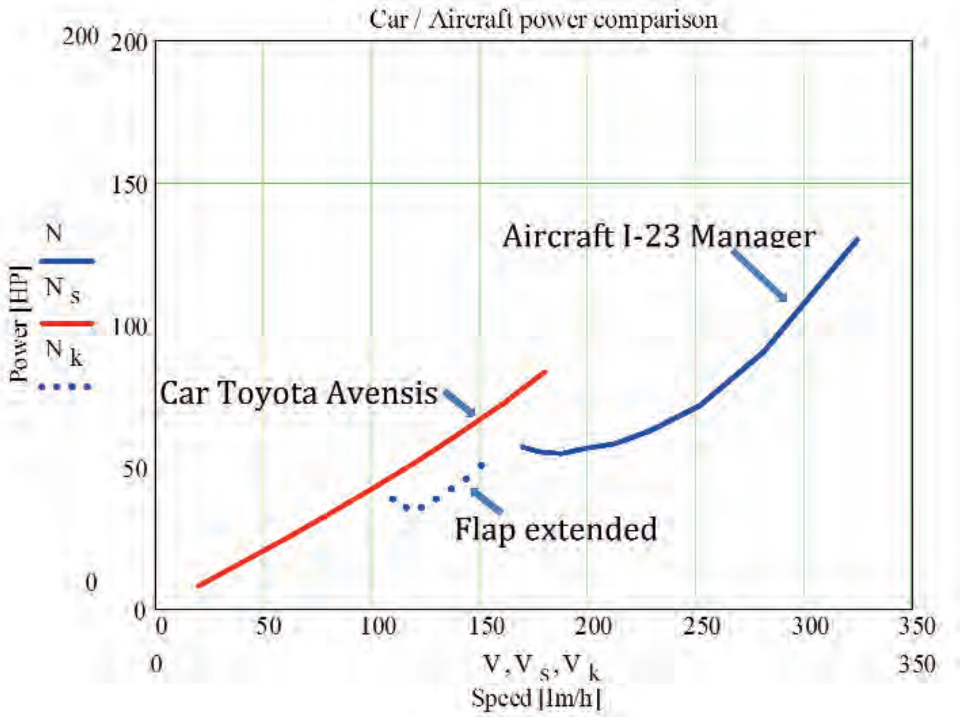

Figure 9. Car and four seats aircraft energy needs via speed

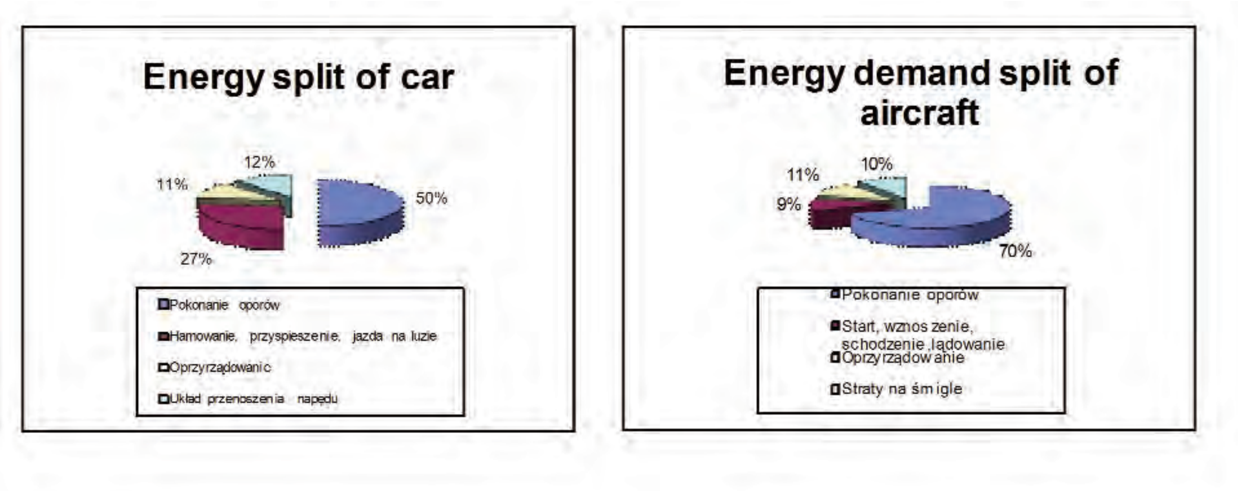

Figure 10. Energy split of car and aircraft

Transport energy efficiency differences of car and aircraft will deepen in favor of aircraft. Assuming a similar development of car and plane propulsion towards more energy saving and ecological solutions, the differences will deepen due to changes in energy demand. Energy loses of car transport caused by road traffic, car mobility resistance and load factor will not be significantly changed and the congestion growth trend will remain disadvantageous. It is opposite in the air transport. There are still large reserves in energy demand at aircraft technical level (aerodynamics perfect ness increase, better material and technology use, lower weight), as well as at the system level (better use of airport network, new air traffic management systems implementation). It is estimated that a unitary need for energy in EPATS system may be decreased in comparison to the present state in aviation by about 30%. It is worth mentioning, that the trend in air transport, focusing on hub-and-spoke system, good to serve large flow of passengers, by large aircraft does not favor energy saving, what is proved by the large disparities between unitary fuel consumption at the level of aircraft and the system. In air transport, transport system energy efficiency should be treated with a great care. It significantly impacts on liquid fuels reserves depletion, air pollution and transport costs. Air network efficiency and air traffic management system, although hard to examine, apart from delay indicator should be measured by energy loses indicators.

Since 1970 the specific fuel consumption of the European passenger fleet has already been cut by 70%. It is intended that this trend should continue. There are a lot of opportunities of reducing further specific fuel consumption - i.e. the amount of fuel necessary to transport one passenger over a certain distance in given time. Further reductions in the specific fuel consumption of aircraft can be achieved not only through advanced engines, improving aircraft aerodynamics. introducing lighter materials, replacing heavy system components with lighter ones, but also by improving ATM – ATC technology, using direct link between nearest local airports and operating the most accommodated capacity of aircraft fleet.

Energy consumption statistics for modern civil aircraft show that air travel is not only a fast but also a fuel-efficient form of transport. The specific fuel consumption of some airliners at cruising speed is now below 3,5 litres of kerosene per 100 passenger-kilometre.

On average, for a long-distance journey, a mean class car with average consumption 8 litres per 100 km and average occupancy 1,3 persons per car will have a specific fuel consumption of 6,15 litres per 100 passenger-km. According to these figures, long-distance car travel requires a higher specific fuel quantity of 25 % more than a propeller aircraft. Only if a minimum of three people is traveling in one car, do they consume less fuel per capita than in an aircraft. Even then, the time, cost and accessibility factors in reaching many destinations are points in favour of air travel.

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

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 forecast of jet fuel prices on the current dollars scale are expected to follow the trends of the previous years, indicating a four percent increase per year over 12 years. In order to achieve improved system efficiency a key requirement is an improved capability to accommodate fuel efficient aircraft operations.

The ideal aircraft would be economical to buy, maintain, have a high cruising speed, short take-off and landing distance, long range (adequate to demand), and be fuel efficient. It's highly unlikely for an aircraft to have all of these characteristics but it is possible to retain the most important for the market The goal in aircraft design is to achieve a rational balance between vehicle performance in combination with affordability.

4. MATERIALS EFFECTIVENESS

We understand material efficiency of a transport mode at the vehicle level as the mass of material used, needed to transport passengers – we assume, that it is relation of useful vehicle weight to total weight (take-off weight). At the level of transport system, we assume, that the weight of material, needed to transport 1 passenger-kilometer in full life cycle is measured in kg/pas.km. Material efficiency was calculated basing on statistical data of aircraft MTOW from 1300 to 28 000 kg and for an average personal car of 1700 kg.

Calculation assumptions:
- Life cycle of aircraft: 20 years, of car: 10 years
- Flight hours yearly of 9-seat aircraft for air-taxi and charter: 600 h, for more than 10-seat aircraft: 1800 h yearly
- Speeds were taken from characteristics
- Load factor of car: 0,3, of aircraft: 0,65
- Average car yearly volume of kilometers: 10 000 km.

Weight and materials effectiveness of car and aircraft are shown in figure 11 and 12.

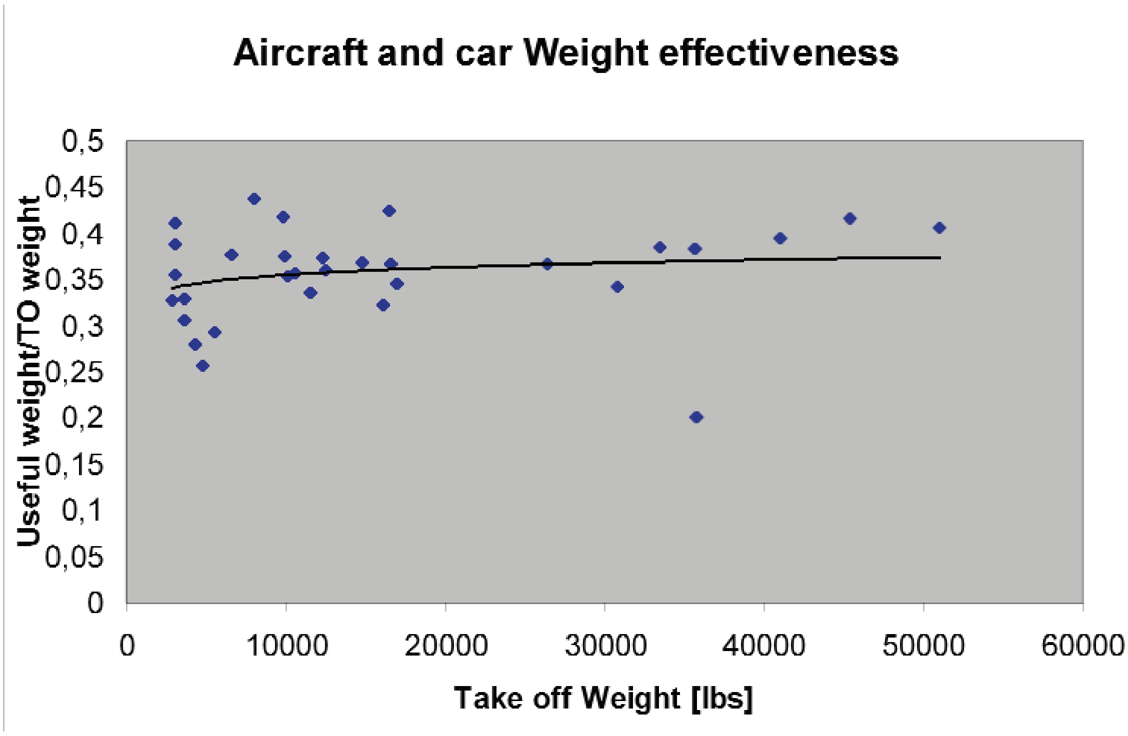

Figure 11. Aircraft and car weight effectiveness

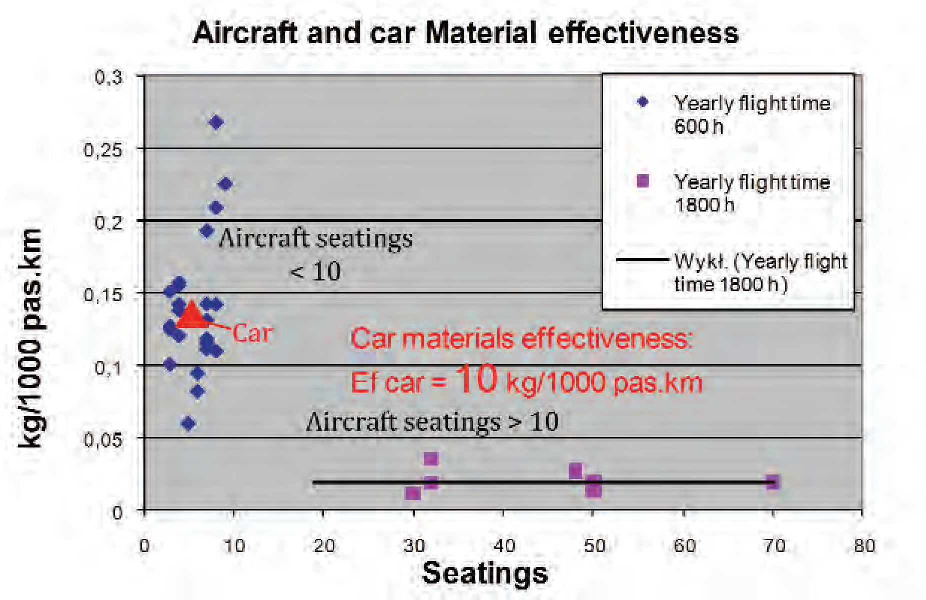

Figure 12. Aircraft and car material effectiveness

Effectiveness = vehicle weight / (life cycle x yearly flight hours x travel speed x number of seats x load factor)

The differences in material efficiency among smaller and larger aircraft comes from different assumptions of yearly flight hours, what is supported by their purpose – small aircraft are mainly used as air-taxis, larger – for regular flights. Average, absolute values are: 0,14 for small and 0,025 kg per 1000 passenger-kilometers for larger. The differences are slight and in comparison to the one of car can be omitted (car: 10 kg per 1000 pas.km, that is 2 ranks higher).

If we total the material use with land consumed by roads, highways, parking places and other materials used for motorization infrastructure, then we clearly see, how great benefits is brought by passenger air transport, if we consider land use

5. IMPACT ON ENVIRONMENT BY COSTS EXTERNALITIES MEASUREMENTS

The impact of air transportation on environment is carry out through costs externalities evaluation. The following data source were used to elaborate external costs of transportation presented in table 1 and figure 13:

1.“The Social Costs of Intercity Passenger Transportation: A Review and Comparison of Air and Highway” by David M. Levinson [10]

2. Efficient Vehicles Versus Efficient Transportation - Comparing Transportation Energy Conservation Strategies By Todd Litman Victoria Transport Policy Institute 6 May 2005 [11]

3.„Sector Operation Program. Transport for years 2004-2006”. Polish Infrastructure Ministry [12]

4. Values assumed for the aeroplanes are based on the comparative analyses, taking mainly into account the difference in: fatalities rate and crash externalities, traffic congestion, street parking, local air pollution, roadway costs and traffic services. [13]

The table 1 and figure 13 show evidently that the external costs of air transport are much lower than road transport, including external costs for environmental damage

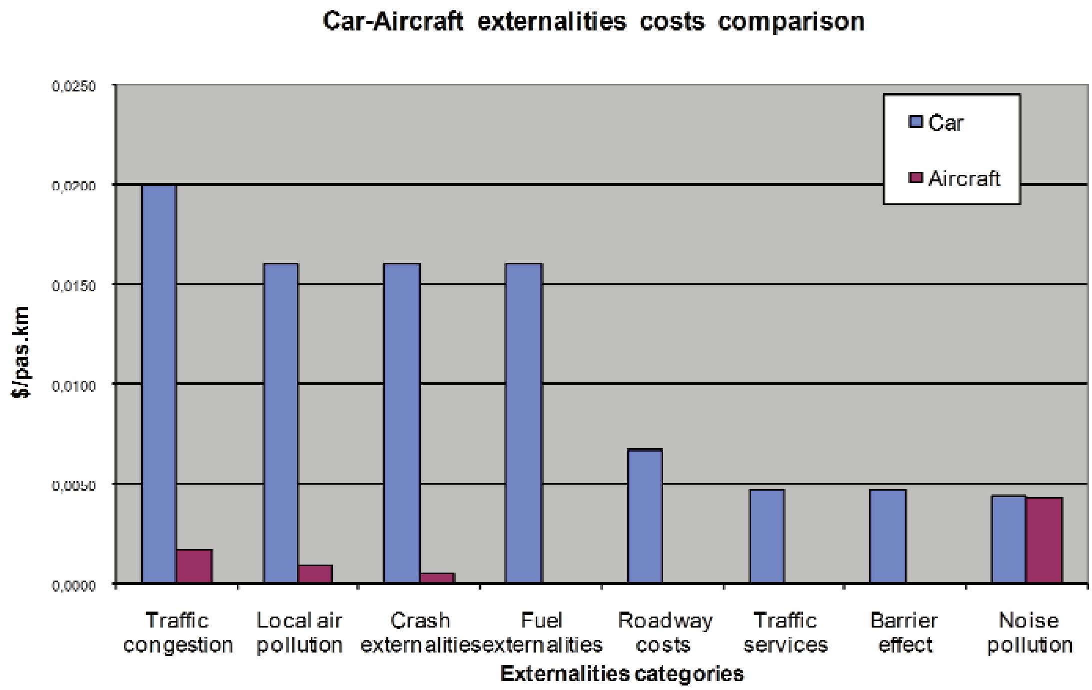

Figure 13. Car-Aircraft externalities costs comparison

According to OECD document “Towards Sustainable Transportation” the externalities of transportation vehicle amount to:

Car – 1,25 USD/km, Train – 0,25 USD/km,Aircraft – 0,45/km

These figures and others, which can be found in the literature, show that there is a large dispersion of statistical data on the impact of transport on the environment, although most data indicate that the most harmful impact has road transport.

Table 1. External costs of transportation
**2004 Dollar per passenger kilometer travelled assuming 1,5 passengers by car*

		EXTERNAL COSTS OF TRANSPORTATION						
		in US dollars per passengers kilometers travelled						
	Vehicles	average Car 1		Car 2		Aircraft 2	Car 3	EPATS 4
		$/vkt	$/pkt *	$/vkt	$/pkt	$/pkt	$/pkt	$/pkm
Users costs	Vehicle ownership	0,15	0,1					
	Vehicle operation	0,09	0,06					
	Off-street parking	0,036	0,024					
	Users costs	0,276	0,184			tbd	0,3	tbd
Externslities	Traffic congestion	0,03	0,0200	0,0069	0,0046	0,0017		0,0005
	Local air pollution	0,024	0,0160	0,0056	0,003733	0,0009		0,0003
	Crash externalities	0,024	0,0160	0,03	0,02	0,0005		0,001
	Fuel externalities	0,024	0,0160					
	Roadway costs	0,01	0,0067					
	Traffic services	0,007	0,0047					
	Barrier effect	0,007	0,0047					
	Noise pollution	0,0065	0,0043	0,0068	0,004533	0,0043		0,002
	Total externalities	0,1325	0,0883	0,0493	0,032867	0,0074	0,06	0,0038
	Total costs	**0,4085**	**0,2723**					

6. AFFORDABILITY AND ACCESSIBILITY

To high speed mode of transport in interregional trips (400 - 2000 km) (inter eu-25 and national), we consider that the mode of transport is:

- **accessible** if the access time to transportation system node is less than 1 hour and
- **affordable** if the generalized cost of travel does not exceed the generalized cost of travel by car.

For these assumptions we evaluate the affordability and accessibility (the share of people) of current high speed mode of transport and EPATS 2020

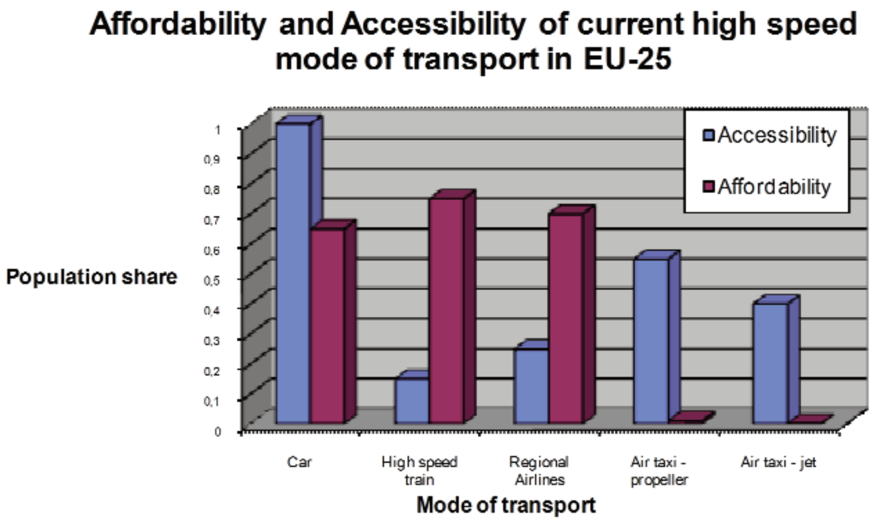

Figure 14. Affordability and accessibility of current high speed mode of transport in EU-25

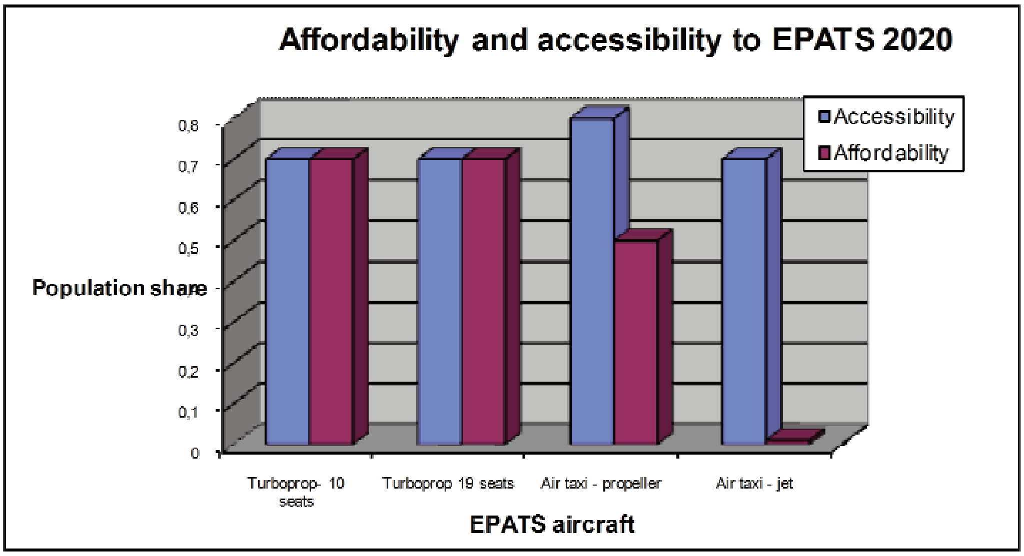

Figure 15. Affordability and accessibility to EPATS 2020

For air transport accessibility can be also presented as the average distance to the nearest airport from where the flight is possible. The figure below shows the distance to different class of airport for a given percent of population.

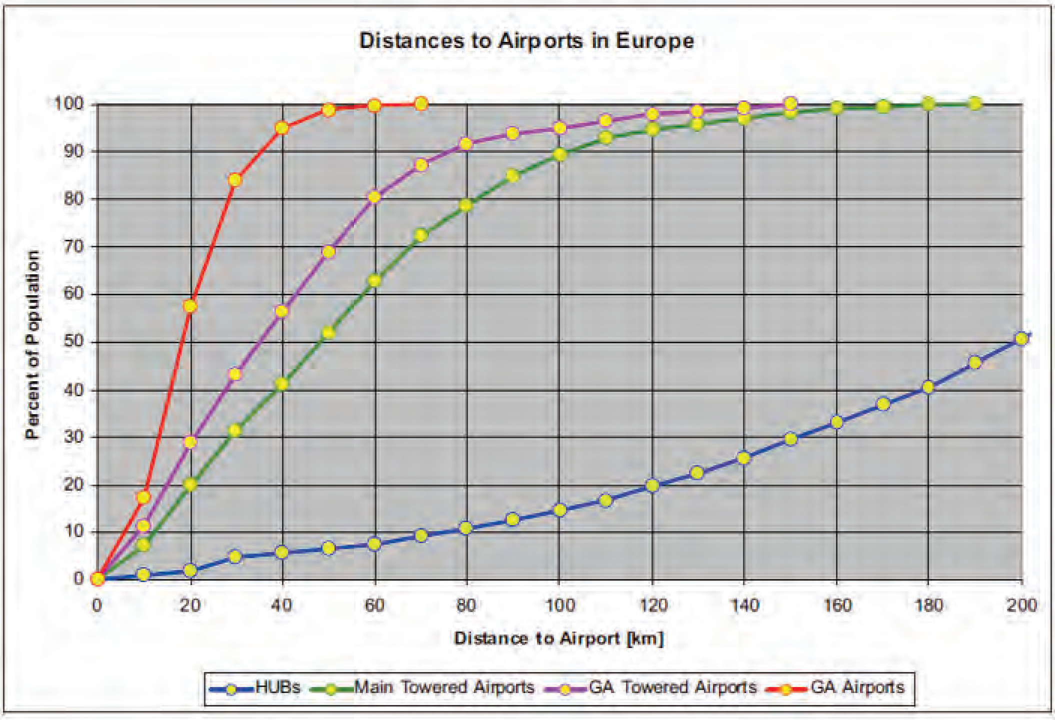

Figure 16. Distance to airports in Europe. Source: EPATS Project

7. CONCLUSIONS

Main natural determinants of personal transportation system efficiency are:

- Traveling time as an effect of a mode speed, infrastructure, traffic management system and accessibility
- Energy used (fuel) on the realization of one passenger kilometer at given speed
- Resources used for the mode of transport and infrastructure production on one passenger kilometer
- Impacts on ecology

The global determinant including all other factors expressed in monetary form is the generalized cost of transport of one passenger-kilometer.

The results of transport efficiency analysis allow the following conclusions:

- Levels of measurement influence efficiency evaluation significantly.
- The shorter distances and larger aircraft, the wider differences.
- Despite the fact, that larger aircraft have better weight ratio and energy consumption characteristics, it is small aircraft, which provide higher efficiency in particular situations.
- Mode efficiency should be measured at the national/European economy level considering social efficiency.
- Air transport is safer, environmentally friendlier and more energy and resource efficient than car.
- The greatest disadvantage of contemporary modes of high-speed transport (scheduled air, hi-speed train) are infrastructure development limitations, low nodes accessibility causing unbalanced regional development as a side effect.
- On the system level Air Transport Efficiency should be define as energy consumption or costs needed to shift one passenger (or kg) on representative (average) origin to destination Great Circle Distance in time according to a fixed plan and complying specifications requirements, including safety and environmental.

BIBLIOGRAPHY

[1] Strategic Research Agenda. Volume 2 October 2002-05-31

[2] Strategic Research Agenda ACARE Volume 1 October 2004

[3] Regulation, Market Structure and Performance in Air Passenger Transportation. Rauf Gonenc and Giuseppe Nicoletti OECD 2001

[4] Energy & Transport Report 2000 – 2004. DG for Energy and Transport EC

[5] Efficient Vehicles Versus Efficient Transportation, Todd Litman ,Victoria Transport Policy Institute May 2005

[6]Modeling aircraft fuel consumption with a neural network by Glenn D. Schilling

[7] Transport performance and fuel consumption. German Airport Association

[8] Business Airplanes & regional Airliners Fuel consumption comparison. IoA Mart 2007

[9] Fuel efficiency of commercial aircraft Fuel efficiency of commercial aircraft Fuel efficiency of commercial aircraft Fuel efficiency of commercial aircraft An overvie of historical and future trends Peeters P.M.1 , Middel J., Hoolhorst A. NLR CR 2005 669

[10] The Social Costs of Intercity Passenger Transportation: A Review and Comparison of Air and Highway by David M. Levinson

[11] Efficient Vehicles Versus Efficient Transportation - Comparing Transportation Energy Conservation Strategies By Todd Litman Victoria Transport Policy Institute 6 May 2005

[12] Sector Operation Program. Transport for years 2004-2006. Polish Infrastructure Ministry

[13] Values assumed for the airplanes are based on the comparative analyses, taking mainly into account the difference in: fatalities rate and crash externalities, traffic congestion, street parking, local air pollution, roadway costs and traffic services.

[14] European Personal Air Transportation System Research Study. EU FP6 EPATS Project