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Energy consumption and environmental impact of Urban Air mobility

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Abstract. Urban Air Mobility (UAM) is a recent concept proposed for solving urban mobility problems, such as urban traffic pollution, congestion, and noises. The goal of this investigation is to develop a backward model for an electric aerial taxi in order to estimate the electric consumption and the indirect emissions of carbon dioxide in a specified mission. The model takes as input the time histories of speed and altitude and estimates the power at the rotor shaft during the mission with a quasi-static approach. The shaft power is used as input for the electric drive where the motor is modelled with an efficiency map and a transfer function while an equivalent circuit model which includes aging effects is used for the battery. The emissions of CO₂ are calculated as a function of the Greenhouse emission intensity and compared with that of a hybrid electric taxi performing the same mission with the same payload. A plug-in Toyota Prius modelled through the software ADVISOR is considered for the comparison. The results show that the air taxi behaves better than the road taxi not only in terms of trip time but also from the environmental point of view if the charging of the battery is performed with the emission intensity factory expected to be reached in Europe in 2025.

1. Introduction

Rapid population growth and urbanization have imposed enormous strains not only on the depletion of fossil energy sources but also on the environment. According to Angel et al. [1], the number of people living in cities keeps growing and it is expected to double from 2011 to 2054. At the same time, the mobility requirement is increasing, leading to the need of forms of transportation, which are faster, cheaper, safer, and cleaner than today [2]. Today transportation accounts for around one-fifth of global carbon dioxide (CO₂) emissions (*ec.europa.eu*). Road travel is responsible for three-quarters of them while aviation accounts for 11.6% of the total transport emissions. Increasing the efficiency of the utilization of energy in transport systems, speeding up the deployment of low-emission alternative energy for transport and moving towards zero-emission vehicles are the main actions to reduce the environmental impact of transportation [3] and fulfill future mobility needs.

In the latest few years, many companies have been developing new delivery and taxi services conceived to work in the air. These services are denoted as Urban Air Mobility (UAM) and Urban Air Delivery (UAD). This investigation focuses on Urban Air Mobility. In this field, large investments have been made, over the past few years, for the development of electric vertical take-off and landing (eVTOL) aircraft. Many issues like the lack of infrastructure, safety (in particular avoiding collisions during the mission) and air traffic management are still open issues [4]-[6]. However, to the authors' knowledge, a detailed energy analysis of this kind of vehicles has never been addressed in the literature, except for a few studies on Urban Air Delivery[7]-[9]. Uber performed a comparison



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between a traditional vehicle and an eVTOL one in terms of time spent, distance covered, and costs without considering the environmental impact [10].

UAM is an interesting application for electric power systems because of the short-range and limited speed that makes possible full electric powertrains even with today's batteries (i.e. despite their moderate values of energy density and power density which are the major bottleneck for larger aircraft). However, ad-hoc flight mechanics analysis tools and design techniques need to be developed for tackling the challenge of sizing and management of hybrid and fully electric aircraft. To this scope, this investigation proposes a new methodology for the analysis of the energy required to complete an air-taxi mission and compares the environmental impact of this kind of vehicle with that of a hybrid electric taxicab using a well-to-wing/wheel approach.

2. Methods

The present investigation compares the two vehicles described in Figure 1. The first one is a hypothetical air taxi with a total mass (including 4 passengers) of 1990kg, equipped with a fully electric propulsion system. The second vehicle is a series/parallel hybrid electric vehicle, the Toyota Prius AWD-i. The reason for the choice of this car is twofold: it is one of the most common vehicles used as a road taxi and also the most studied hybrid electric vehicle with several data available in the literature (see for example [12]). The total mass of the air-taxi was assumed according to what was suggested in the literature, with particular reference to [10] and [11]. However, a more detailed analysis of this important issue will be performed as further investigation. Note that in both cases, the proposed solutions refer to today's technology, but strong improvements are expected in the next years above all in terms of battery energy density. This could help reducing the MTOW (Maximum Take off Weight) in the case of air-taxi and make possible the adoption of fully electric powertrains in the case of road taxis.



	
<p>Hypothetical Air taxi Total mass (4 passengers)= 1990kg Energy battery: 140kWh EM power 240kW</p>	<p>Toyota Prius AWD-i Total mass (2-4 passengers)= 1440kg+Np*75kg Energy battery=13kWh 72kW thermal +53kW EMs</p>

Figure 1. Specification of the air and road taxis

2.1. The route

Using the data reported in [10], the two vehicles were supposed to perform the route between Marina, San Francisco, and Downtown San Jose. For the air taxi the expected distance is about 70km, and the flight time is only 15 minutes. For the road taxi, the distance is 90km while the trip time is strongly affected by the driver style and the traffic conditions.

2.2. Modelling the taxicab

The selected road taxi is a Plug-in Hybrid Electric Vehicle (PHEV), i.e., a type of hybrid vehicle that combines a conventional internal combustion engine (ICE) system with an electric propulsion system (hybrid vehicle drivetrain). The presence of the electric powertrain is intended to achieve either better fuel economy than a conventional vehicle. Being a plug-in hybrid vehicle, the battery is also

substantially discharged during the mission, so this vehicle consumes both chemical energy (fuel) and electricity (battery), that needs to be repleted by recharging the battery from the electric grid.

The taxicab was simulated with the well-known software ADVISOR developed by the National Renewable Energy Laboratory NREL, [12]. Advisor is a set of model, data, and script text files for use with Matlab and Simulink, designed for rapid analysis of the performance and fuel economy of conventional, electric, and hybrid vehicles. The Toyota Prius is one of the vehicle models already included in the ADVISOR library but it was necessary to update some data to simulate the Toyota Prius AWD-I vehicle. The modified model was validated by using the declared data of the vehicle and the fuel consumption on the New European Driving Cycle (NEDC), 4.8l/100km, that was predicted with very good accuracy (2%).

To represent the variability of the traffic conditions two different trips were built. The two trips have the same distance (90km) but a different driving cycle. The first one has an average speed of 77km/h (representative of a rural drive with very low traffic) while the second one represents a congested traffic condition (average speed 34km/h). Moreover, the effect of the number of passengers has been evaluated in the range 2-4.

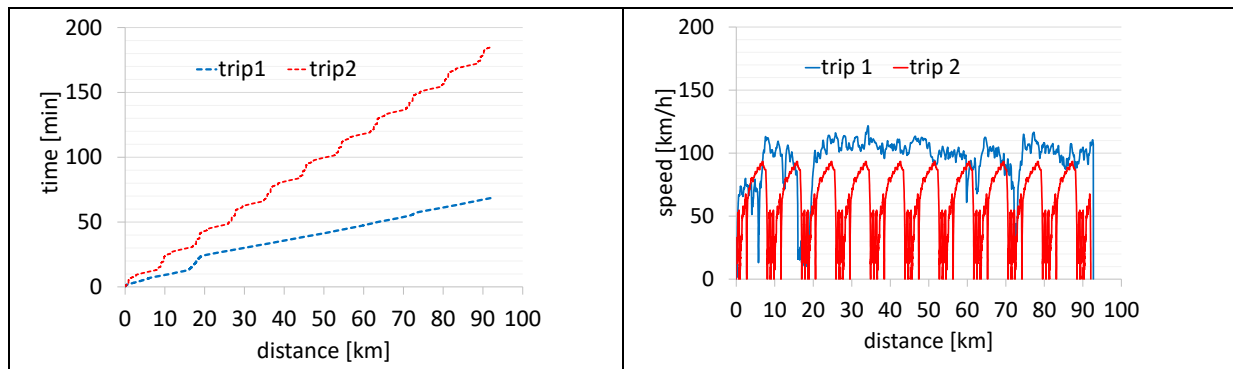


Figure 2. Required time and speed profile for the two trips of the taxicab

2.3. Modeling the air taxi

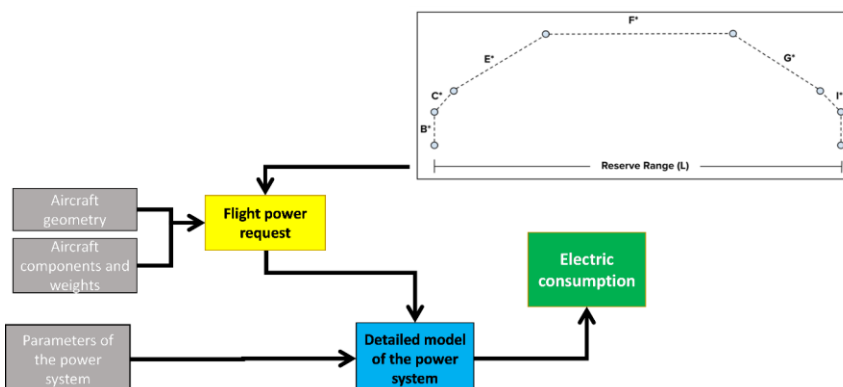


Figure 3. Energy model of the electric air taxi

For the modelling of the air taxi, the following points need to be achieved (see Figure 3):

- Defining a suitable mission.
- Calculating the shaft power request vs time.
- Modelling the electric drive.
- Based on the white paper of Uber [10], a typical mission (see the top-right plot of Figure 3) is considered, consisting of seven blocks which refer to the climb (B,C and E), cruise (F), and

descent (G,I and J) part, respectively. The proposed mission is characterized by a cruise altitude of 458.6m and a cruise speed of 54m/s.

- The shaft power request vs time is estimated using literature methods and data [13] A requested power of 240kW, 165kW and 145kW was considered for take-off, cruise and landing, respectively. Using these values of power and the proposed times of each flight phase, we obtain that the climb/descent phases require about 40% of the cruise energy, a value in accordance with the data reported in [10].

2.3.1. Modelling the electric drive

The required power, together with the selected speed of 6000rpm is used as input for the model of the electric drive consisting of two permanent magnet motors with a nominal power of 125kW. The electric machines are modelled through the curve of maximum continuous torque and an efficiency map. The dynamic behaviour is taken into account with a mechanical time constant [14]. The load is equally distributed between the two electric machines. A third one is used for the back-up operation. The battery is simulated with an electric equivalent circuit [15] where the Open Circuit Voltage *OCV* is mapped as a function of the battery state of charge, while the internal resistance *R* depends on the specification of the battery and varies along with the battery life. Therefore, the battery current, is calculated by solving the following equation:

$$P_{batt}(t) = [OCV(t) - R(t) \cdot I(t)] \cdot I(t) \quad (1)$$

To take into account the Peukert effect (i.e. the reduction of the battery actual capacity when increasing the discharge power), the effective current *I_{eff}* is calculated as:

$$I_{eff} = I \cdot \left(\frac{I}{I_{nom}} \right)^{n-1} \quad (2)$$

Where *n* is the Peukert coefficient of the battery, *I_{nom}* is the current at which the nominal capacity *C* is referred to.

Using the effective current, the state of charge of the battery *SOC* is upgraded, at any time during the mission, as:

$$SOC(t) = SOC(t_0) - 100 \cdot \int_{t_0}^t \frac{I_{eff}(t)}{C} dt \quad (3)$$

Another important characteristic of the proposed battery model is that the values of capacity, internal resistance and Peukert coefficient are updated with the battery cycle life (defined by the number of discharge/charging cycles). For more details about the aging model, please refer to [16].

2.4. Well to wheel emission

To compare the two vehicles, a Well-To-Wheel/Wing approach is considered, i.e. the greenhouse emissions are calculated considering the whole process, from the primary energy source (e.g. crude oil) to the final energy to the wheels/wings. To this scope, for the gasoline fuel, it is possible to assume 3.15kg_{CO2}/kg_{fuel} (which corresponds to 2.35kg_{CO2}/litre) for the Tank-to-Wheel (TTW) conversion, and 0.55 kg_{CO2}/kg_{fuel} for the WTT (Well-To-Tank). This means that the WTT emissions account for 15% of the WTW contribution [17].

Full electric vehicles only produce emissions in the power plants since they use electric energy to move the vehicle. The total amount of electricity depleted from the battery is calculated as the nominal battery energy in kWh multiplied by the Depth Of Discharge (DOD) of the battery in the mission and divided by the overall efficiency of the charging process. The result is multiplied by the Greenhouse emission intensity factor to obtain the overall equivalent emissions of CO₂ (see figure Figure 4). In the present investigation, the DOD is calculated with the proposed models for each taxi while the overall charging efficiency is assumed equal to 80% [18][19].

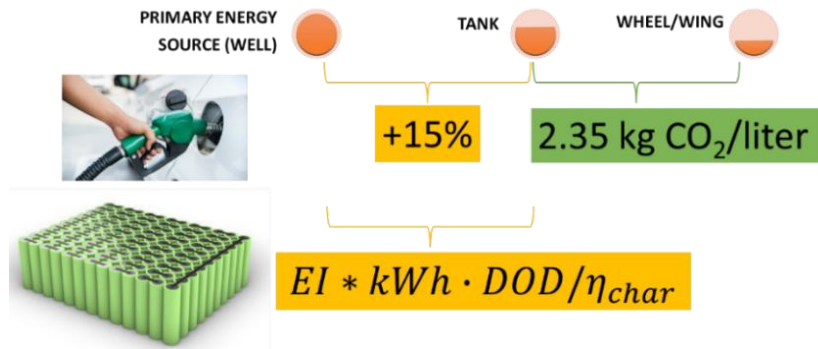


Figure 4. Well-to-Wheel/Wing analysis

For the emission intensity factor, a study about CO_{2eq} emitted due to electricity production has to be conducted. In fact, even if electricity generation from renewable sources has significantly increased in the last years, most of the electric energy is yet produced from fossil fuels [20]- [21].

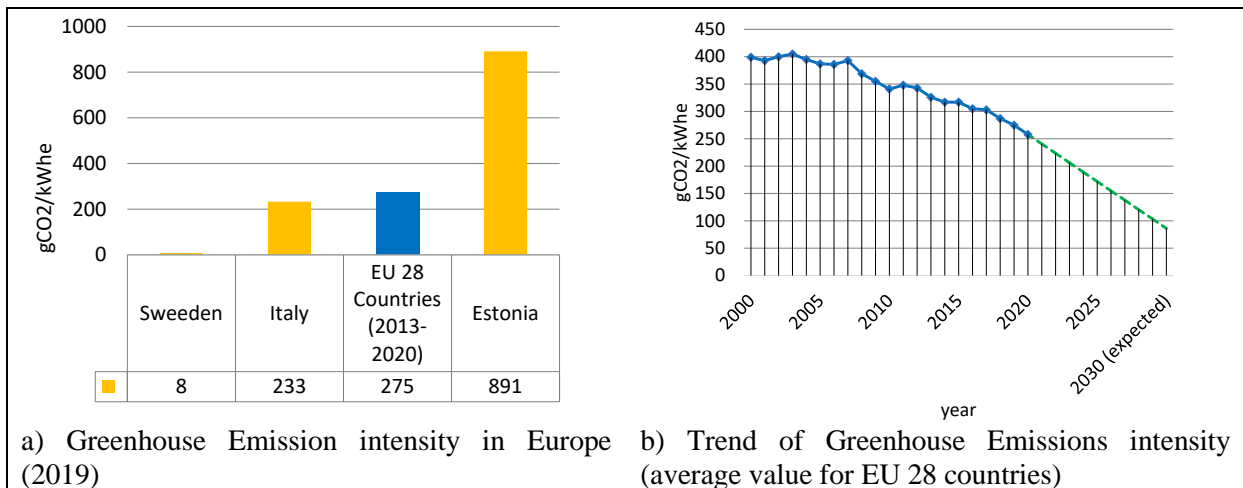


Figure 5. Past, today and future emission intensity of European countries (data from www.eea.europa.eu)

According to the European Energy Agency (EEA [22]), the greenhouse Emission Intensity for EU in 2019 is, on average, 275.0 g CO_{2eq}/kWh with a maximum of 891 g CO_{2eq}/kWh for Estonia and a minimum of 8 g CO_{2eq}/kWh for Sweden as shown in Figure 5a, where the value for Italy is also shown. However, the greenhouse emission intensity is expected to be reduced to 75.49-96.81 g CO_{2eq}/kWh according to the EEA in 2030. In this investigation, we will consider the average value of 172 g CO_{2eq}/kWh as the expected value in 2025 when air taxis are assumed to be introduced in the urban air mobility system.

3. Results

The results of the simulations performed on the two vehicles are reported in this section in terms of electricity and fuel consumption. As explained before, the required electricity is evaluated as a function of the DOD which is calculated as the difference between the initial and the final value of the battery State Of Charge, SOC (see Figure 6a). The overall fuel consumption is obtained by integrating the fuel flow rate (Figure 6b.).

The overall results for the simulations performed on the air taxi are reported in Figure 7. In particular, Figure 7a shows the time history of power request, actual motor power and battery power while Figure 7b reports the plot of SOC as a function of time. Like in the case of the taxicab, this plot is useful to obtain the DOD and, therefore, the electric consumption.

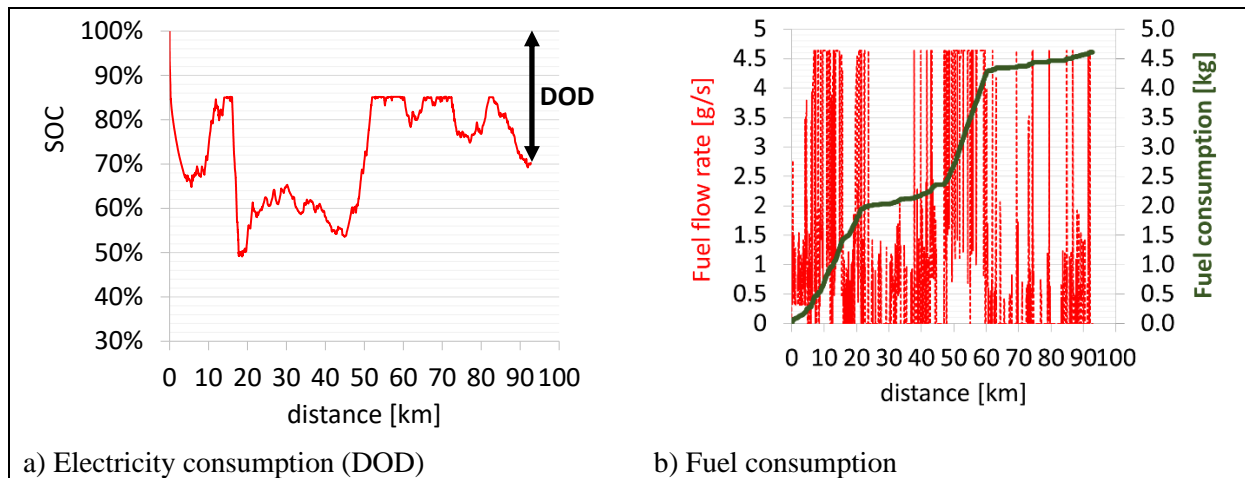


Figure 6. Simulation of the taxicab on trip 1

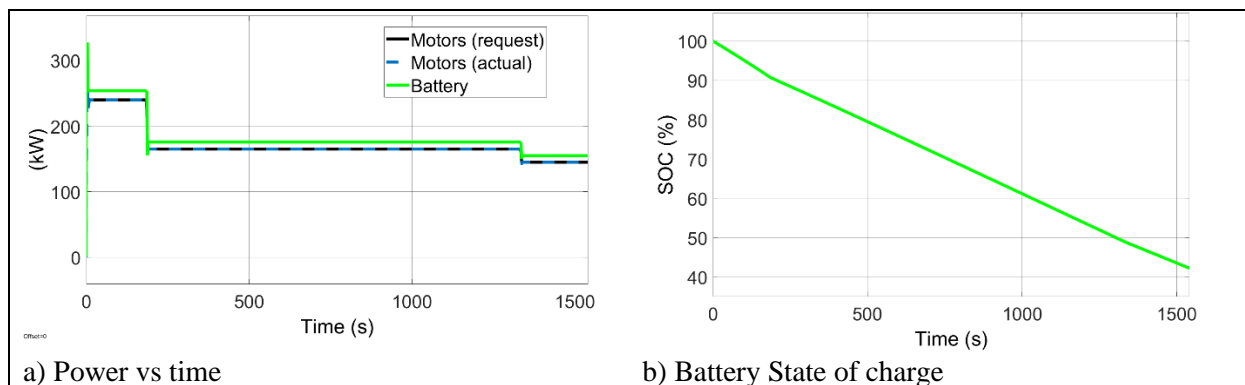


Figure 7. Simulation of the air taxi

Table 1. Overall Results of the simulations

	Distance	Time	Fuel consumption (liter/100km)	Electric consumption (kWh)	Charge electricity (kWh)
Air taxi (4p)	70 km	24 min	-	82	102.5
Road taxi (2p, low traffic)	90 km	1 h 10 min	5.7	3.9	4.9
Road taxi (4p, congested traffic)	90 km	2 h 40 min	6.9	6.5	8.1

The total consumption of fuel and electricity for the two vehicles is reported in Table 1 where the analysis of the taxicab is performed in two cases: 2 passengers and low traffic vs 4 passengers and congested traffic. It is possible to notice the large impact of the traffic conditions and the number of passengers on the taxicab consumption that reaches 6.9 liter/100km in the worst case. Actually, tests performed on the same vehicle [23] revealed that the fuel consumption of the Prius can range between 3 and 6 liter/100km on regulatory cycles (depending also on the version of the vehicle) while a still higher variability is obtained in real driving conditions [24] where the fuel consumption can be as high as 14.8 liter/100km in case of the urban route and aggressive driving style. As for the electric consumption, the battery is more discharged at the end of the trip2 with 4 passengers, so the electric

consumption is 66% higher than in the case of trip 1 with 2 passengers. Moreover, the trip time is much longer in the case of trip 2 because of the lower average speed (Figure 2).

The air taxi allows a very strong reduction of the trip time (which is only 24 minutes) but has a large electricity consumption. Considering the charging efficiency, we have a needed charge electricity of 102.5kWh.

To compare the two systems (with the same number of passengers), the plot of Figure 8 shows the overall emissions of CO₂ as a function of the emission intensity factor. With today's average emission intensity in Europe, the taxicab shows a relevant advantage because of the lower energy needed for the trip. However, with the expected reduction of the emission intensity in 2025, the two solutions are quite similar, with a slight advantage of the air taxi.

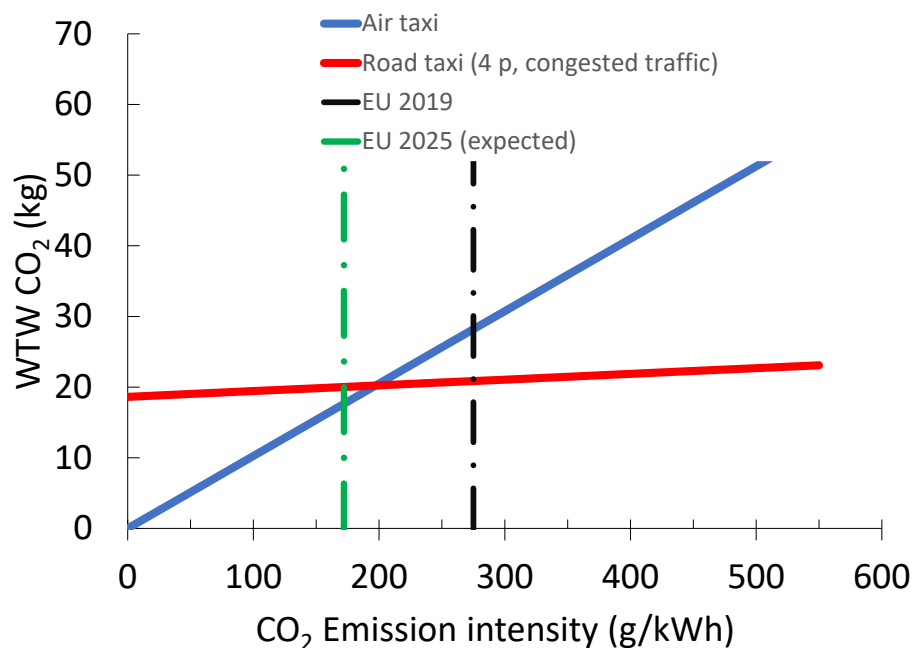


Figure 8. Overall emissions of CO₂ as a function of the emission intensity factor

It is worthwhile to point out that these results are obtained in the case of a battery at the beginning of its life. If the battery aging phenomena are taken into account, the same trip would require a larger charge of electricity (the battery is discharged faster) and the battery could not be able to sustain the selected mission. Moreover, technological improvement in the electric components of the powertrain could reduce, within 2025, the electrical consumption of both vehicles.

4. Summary and conclusions

A methodology has been developed to compare air taxis and road taxis performing the same route. The electric air taxi was modelled with an in-house Simulink model that accounts for battery aging while the plug-in hybrid electric road taxi was simulated with the Advisor software to obtain fuel consumption under realistic driving conditions. The two vehicles were compared in terms of trip time and overall emissions of CO₂. The results showed that the usage of an air taxi can strongly improve the trip time while reducing the congestion of the traffic. However, the overall environmental impact is strongly dependent on the greenhouse emission intensity. With today's average emission intensity in Europe, the taxicab shows a relevant advantage because of the lower energy needed for the trip. However, with the expected reduction of the emission intensity in 2025, the two solutions become quite similar, with a slight advantage of the air taxi. The results presented in this paper refer to today's technologies for each kind of taxi, expected improvement in the next years will be addressed in future works.

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