AURORA

sAfe Urban aiR mObility
for euRopeAn citizens

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Towards sustainable urban air mobility

D1.2 – UAM Sustainable Mobility Indicators Report

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Abstract

Urban Air Mobility has the potential to contribute to a more sustainable mobility system by overcoming challenges in the current mobility system, but also faces some challenges due to worries about environment, regulations and safety. Mobility indicators offers a handhold for a structured, complete and integral evaluation of the various positive and negative impacts of UAM. In this report we develop a set of mobility indicators, which will be applied in the evaluation of the AURORA use-cases. The agreed set of SUMI indicators for Sustainable Urban Mobility is used as a starting point, which is refined in two consecutive steps. First, an overview of relevant literature summarizes the expected impact of UAM on each of the SUMI indicators. Based on these findings, a number of indicators, which are not affected by UAM, are not relevant for the use-cases. In a second step, as AURORA specifically focuses on emergency-related applications, also a number of indicators which do not apply to such applications are omitted. This results in an indicator set consisting of eight aspects of sustainable mobility: Emissions of greenhouse gases, Air polluting emissions, Energy efficiency, Noise hindrance, Traffic safety, Congestion and delays, Net public finance, and Resilience for disaster and ecologic/social disruptions. Two specific indicators are added to account for the specific AURORA objectives: the impact on Public Acceptance, and the Capability of Public Authorities.

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About AURORA

Urban Air Mobility (UAM) has the potential to overcome challenges like congestion and a lack of surface transport whilst saving infrastructure costs and time. However, making it safe, secure, green, quiet and accepted is challenging due to many factors, such as environment, regulations, and safety-critical technologies. Focusing on emergency-related applications, where UAM brings added value on top of current mobility solutions, the EU-funded AURORA project aims at connecting technologies and key actors to foster the adoption of UAM. The project works on development of artificially intelligent, urban autonomous flight solutions for Unmanned Aerial Vehicles (UAVs) and self-piloting passenger-carrying UA (Vertical Take-Off and Landing) aircraft with flight path planning capability using vision and radar environment perception sensors, including autonomous selection of emergency landing sites and landing capability, interactable with Very Low Level Air Traffic Management and Smart City elements, and utilizing GALILEO High Accuracy Service. The overall research and technological development makes use of a digital twin paradigm, effectively combining the physical world with its digital model for the purpose of safety-critical flight testing of autonomous flight solutions for UAM operations. To find out more: http://aurora-uam.eu

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1 Introduction

AURORA's belief in Urban Air Mobility (UAM) stems from its potential to contribute to a more sustainable mobility system by overcoming challenges in the current mobility system like congestion, a lack of surface transport or high infrastructure costs. However, making it safe, secure, green, quiet and accepted is challenging due to worries about environment, regulations, and safety. Because of this balancing of the various positive and negative impacts, a critical, holistic and interdisciplinary approach is needed to come to an overall [1] evaluation of UAM.

A literature overview concludes that the topic of environment and sustainability is mostly characterized by a lack of solid scientific evidence and uncertainties about the environmental impact of drones. A number of surveys have been conducted to understand the public perception of UAM and its impacts on (sustainable) mobility [2], but the lack of public experience with UAM vehicles and UAM operations form an essential limitation to these studies, and make it difficult to accurately evaluate the system. As illustrated in [3], also the context affects the feasibility and impacts of UAM because of the influence of the environment (rural versus urban context), the use-case (transport of goods, delivery of parcels, passenger air transport, emergency applications, …) and the operational organization (scale of operations, scheduled vs. on-demand flights, density of vertiports, …).

Therefore the AURORA work package 1.2 aims at developing a UAM Sustainability Framework, allowing a more integrated and objective evaluation of UAM's impact on the sustainable mobility system.

2 Methodology

Sustainable mobility is a complex term, integrating various impacts of mobility on its environment. This makes it difficult to measure or quantify 'sustainable mobility' directly. Instead it has to be determined by a system of parameters that reflect its various dimensions.

For quantifying such multi-dimensional topics, typically indicator sets -in this case Sustainable Urban Mobility Indicators- can play a key role [4]. Such indicators should cover all relevant aspects -without double-counting- and have to be capable of capturing and illustrating even slight changes concerning sustainable mobility. The indicator set must be accessible by everyone and its structure should be simple and transparent to facilitate the communication of the findings [5] and inform both the experts and the public about a complex phenomenon in a simple way [4].

To this aim, the European Commission has developed a comprehensive set of practical and reliable indicators that support cities to perform a standardised evaluation of their mobility system and to measure improvements that result from new mobility practices or policies [6]. Within AURORA, this existing set of Sustainable Urban Mobility Indicators (SUMI) was adopted as a starting point for developing its own set of UAM-specific indicators. Therefore the SUMI indicators are described in chapter 3.

In a next step, described in chapter 4, the impact of Urban Air Mobility on each of the indicators was inventoried based on relevant literature. This step clarifies which of the indicators are (potentially) affected by UAM, and which are not.

These findings are used in chapter 5 to propose the AURORA indicator set for UAM. By filtering out the unaffected indicators, the set is narrowed down, but on the other hand some specific indicators are added to evaluate the specific AURORA project objectives.

3 The Sustainable Urban Mobility Indicators (SUMI)

The scientific foundation for the SUMI indicators was developed in [6], resulting in a proposed set of 22 indicators, as listed in Table 1. The indicators cover the performance of the mobility system on the one hand, and the effect on the three dimensions of sustainability on the other hand (global environment, economic success and quality of life).

Indicators for the sustainability of urban mobility	Short name	Dimension
Emissions of greenhouse gases	GHG	Global environment
Energy efficiency	Energy efficiency	Global environment
Net public finance	Public finance	Economic success
Congestion and delays	Congestion	Economic success
Economic opportunity	Economic opportunity	Economic success
Commuting travel time	Travel time	Economic success
Mobility space usage	Space usage	Quality of life
Quality of public area	Public area	Quality of life
Access to mobility services	Access	Quality of life
Traffic safety	Safety	Quality of life
Noise hindrance	Noise hindrance	Quality of life
Air polluting emissions	Air pollution	Quality of life
Comfort and pleasure	Comfort and pleasure	Quality of life
Accessibility for mobility impaired groups	Accessibility for the impaired	Mobility system performance
Affordability of public transport for poorest group	Affordability	Mobility system performance
Security	Security	Mobility system performance
Functional diversity	Functional diversity	Mobility system performance
Intermodal connectivity	Intermodal connectivity	Mobility system performance
Intermodal integration	Intermodal integration	Mobility system performance
Resilience for disaster and ecologic/social disruptions	Resilience	Mobility system performance
Occupancy rate	Occupancy rate	Mobility system performance
Opportunity for active mobility	Active mobility	Mobility system performance

Table 1: The proposed list of 22 sustainable mobility indicators

The proposed indicators and measures were adopted by the World Business Council for Sustainable Development (WBCSD) in the frame of the development of the SMP2.0 toolbox [7], [8] for cities to evaluate the sustainability of their mobility system. The practical application of these measures within a global evaluation methodology was evaluated in 6 selected pilot cities. As illustrated in Figure 1, a representation of the results in a spider diagram visualizes the evaluation per indicator.

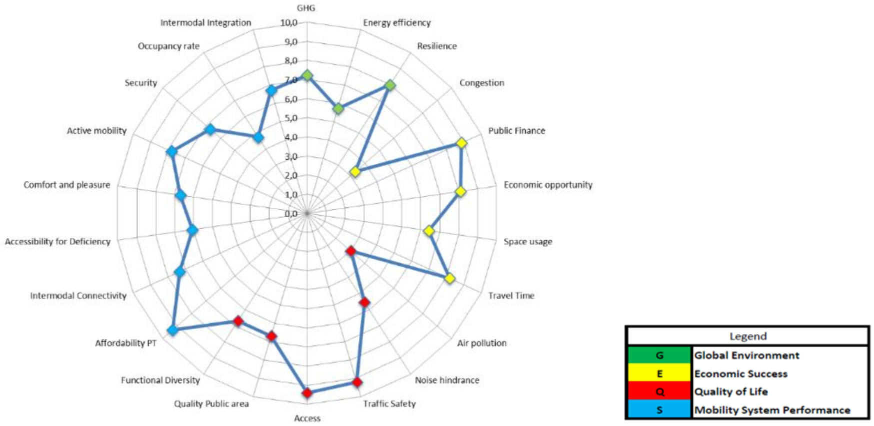

Figure 1: Representation of the indicator evaluation in a spider diagram

In the SUMI-project [9] also the European Commission implemented the proposed methodology for a range of almost 50 varying cities [10], as a test for the practical applicability of the methodology and as a validation of the (partial) results.

Based on the findings of this step, the European Commission modified the initially indicator list, partially for reason of practicality (data availability, data quality, work-intensive survey procedures), partially for reason of content (unclear or overlapping indicators). Note however that these modifications were introduced from the viewpoint of practical applicability, and are not supported by the scientific framework of the indicator set. As a result, some indicators were eliminated (e.g. the financial indicators 'Net public finance' or 'Economic opportunity, 'Occupancy rate', 'Resilience for disaster and ecological/social disruptions'), others were redefined (e.g. 'Comfort and pleasure' was specified into 'Satisfaction with public transport') or grouped (e.g. 'Intermodal connectivity' was integrated into 'Multimodal integration'). Also one new indicator was added, specifically targeting the 'Traffic safety of active modes'.

This has resulted in a list of 18 indicators:

- Indicator 1: Affordability of public transport for the poorest group
- Indicator 2: Accessibility of public transport for mobility-impaired groups
- Indicator 3: Air pollutant emissions
- Indicator 4: Noise hindrance
- Indicator 5: Road deaths
- Indicator 6: Access to mobility services
- Indicator 7: Greenhouse gas emissions
- Indicator 8: Congestion and delays
- Indicator 9: Energy efficiency
- Indicator 10: Opportunity for Active Mobility
- Indicator 11: Multimodal integration
- Indicator 12: Satisfaction with public transport
- Indicator 13: Traffic safety active modes
- Indicator 14: Quality of public spaces
- Indicator 15: Urban functional diversity
- Indicator 16: Commuting travel time
- Indicator 17: Mobility space usage
- Indicator 18: Security

The resulting evaluation method has been adopted by the European Commission as a tool for cities and urban areas to identify strengths and weaknesses of their mobility system when setting up Sustainable Mobility Plans (SUMPs).

In chapter 4 we will evaluate the impact of UAM on each of the SUMI indicators. For this purpose we will a combined set of both the initial theoretical set and the derived practical indicator set, in order to have a complete and broad overview of possibly relevant impacts.

4 Impact of UAM on the Sustainable Mobility Indicators

In this chapter, we evaluate the impact of Urban Air Mobility on each of the SUMI indicators. Based on literature, we summarize how UAM will -positively or negatively- affect the indicator and we detect possible uncertainties about the outcome of UAM.

4.1 Greenhouse gas emissions by city transport

The intention of this indicator is to evaluate the total emissions of greenhouse gases by all passenger and freight city transport modes.

In this regard, expected benefits are mainly related to the fact that drones are a fully electric transportation technology, and are therefore expected to reduce carbon/noise footprint in comparison to fossil-fueled vehicles [1]. This effect is even stronger if the reduction in road traffic is such that also traffic congestion decreases (see 4.4), as congested traffic drastically affects traffic emissions.

However, impacts are complex and dependent on the deployment scenario. For example, in case of freight delivery, drones are more efficient in case of light loads (e.g. single parcels), whereas conventional delivery is more efficient if several parcels need to be delivered or if deliveries can be grouped along routes or if delivery zones are distant. Pukhova [11] therefore considers UAM rather as an alternative for current traditional helicopter flights (e.g. for medical emergencies and VIPs) because of the lower noise and fewer greenhouse gas emissions.

However, the environmental impact of UAM may be almost zero on a local emissions level for battery electric vehicles, but the required electricity still has to be generated and the vehicle components have to be manufactured, assembled and eventually disposed of [12]. Focus should be placed on reducing the overall environmental impact of UAM aircraft during the design phase. Also [1] stresses that the evaluation of electrified mobility should take into consideration factors like the electricity sources, use phase energy consumption, vehicle lifetimes, battery replacement schedules. This requires full life-cycle assessment and comparison to other modes to give insight when drones are the more sustainable option.

Few scholarly analyses have been conducted to determine the actual CO2 reduction when drones are used in cities [13]. In this article, therefore a comparison is elaborated between food delivery service (pizza) by drone vs classic delivery vehicles, based on a Life Cycle Assessment. The estimated GWP (Global Warming Potential) generated by 1 km of drone delivery is found to be one-sixth of the GWP generated by 1 km of motorcycle delivery. The particulate emission of drones is estimated to be about half of that of motorcycles. The environmental impact of drones, based on nine impact categories, was found to be one twelfth of that of motorcycles. Also delivery distance is an important parameter in the comparison: because of the longer delivery distances, the environmental profit is larger in rural areas than in urban areas. It is important to note that the assessment was based on Korean electricity production, which generates more GWP and particulates than US production. Cleaner energy production, e.g. from renewable sources, will even increase the positive environmental impact of drones.

A direct comparison of GHG emissions on a life-cycle bases for a small quadcopter drone and different transportation modes [14] results in following values:

	Fuel GHG emissions (g/km)	Upstream GHG emissions (g/km)	Battery GHG emissions (g/km)	GHG emissions (g/package)
Medium-duty diesel truck	762.8	168.7	-	443.6
Small diesel van	339.8	75.2	-	119.2
Medium-duty electric truck	674.3	83.7	24.5	372.6
Small electric van	293.0	36.4	14.1	98.7
Electric cargo bicycle	17.9	2.2	3.3	23.4
Small quadcopter drone	14.4	1.8	1.3	70.1

The table shows the low GHG emission per kilometer of the drone, on a comparable level to an electric cargo bike. When converting to the GHG emission per package, the lower payload of the drone partially mitigates this advantage, and the emission is closer to the level of a small electric van.

Similar comparisons between different vehicle types and for different use-cases were found:

- In a similar comparison on a vehicle level [15], a 5-seat piloted eVTOL (at 75% load factor) was expected to generate 2 times more well-to-wake (WTW) CO_2 emissions per passenger mile when compared to an all-electric car (e.g., Tesla Model S 75D, 1.54 persons per vehicle occupancy rate).
- [16] summarizes several researches comparing electric aircrafts to other types. An important asset of electric vehicles is the fuel efficiency (97% for electric motor, compared to 28% for hydrocarbon-based, one of the most efficient engines in aviation today). In terms of the total CO_2-emissions the total electric aircraft system efficiency is 5.9 times greater than hydrocarbon-based aircraft system efficiency. The origin of electricity mix plays an important role: a comparison based on the GREET emission model found emissions from hydrocarbon aircraft to be 5 times higher than these from an electric aircraft, based on the U.S. average electricity mix, while they were 10 times higher when using the California electricity mix. comparison (e.g. conventional aircrafts have a very different typical use than urban context).
- Simulations in [16] show that CO_2 emissions per kilometer travelled by Multicopter are 2 to 4 times higher than by conventional diesel-powered cars and 1 to 4 times higher than by petrol-powered road vehicles. However, the difference decreases as travelled distance increases. For short range trips (up to 10-15km) the amounts of CO_2 emissions per kilometer travelled by Multicopter are several times higher than by conventional diesel or petrol powered road vehicles. For longer trips (up to 45-50km) however the amounts of CO_2 gases per kilometer are comparable for Multicopter and conventional road vehicles.
  When considering the total amount of daily CO_2 emissions, the UAM scenarios did not indicate the worthwhile difference, because of the relatively small market share of UAM trips.
  When considering the amount of CO_2 emissions per trip, the UAM scenario results in about the double of the emissions in the business-as-usual scenario (BAU), regardless of the trip length, when also taking into account the access and egress trips to/from UAM. This is caused by various side-effects, such as the fact that sometimes the nearest UAM station is in the opposite direction than the final destination (thus increasing the total distance travelled) or that the UAM station used is not the nearest

(thus shortening the distance travelled by UAM, where emissions per kilometer are higher).

This last example shows the importance of trip distance, which is confirmed in [17], bringing in also the vehicle load as a parameter. This study compares an eVTOL aircraft, a battery electric vehicle (BEV) and a conventional vehicle with combustion engine (not factoring in full life cycle emissions). Traveling 100 km (point-to-point) with one pilot in a VTOL results in well-to-wing/wheel GHG emissions that are 35 % lower than emissions from conventional internal combustion vehicles, but 28 % higher than BEV emissions (both with one occupant). Nevertheless, if the distance considered is shorter than 35 km, eVTOL vehicle is less efficient in amounts of released CO_2-eq gases than both other modes. Comparing fully loaded VTOLs (three passengers) with ground-based cars, VTOL GHG emissions per passenger-kilometer are 52% lower than ICEVs and 6% lower than BEVs, which also have a lower average occupancy of 1.54. Therefore pooled flights (with multiple passengers) are an important means to achieve emission savings.

Because of the role of trip distance, also related aspects come into consideration, like the physical infrastructure (spatial distribution of charging infrastructure, depot infrastructure for logistics, and vertiports for passenger transport), flight planning (terrain, obstacles) and regulation (flight routes, no-fly zones, altitude, …).

A recent evaluation, considering life-cycle assessment, is based on simulations for different scenarios with varying assumptions for aircraft parameters (fleet size, weight and payload, cost), trip parameters (speed, altitude), operational parameters (type of service, number of flights) and infrastructure parameters (number of landing pads, cost) [18]. Some finding for the GHG emissions are:

- The smaller the load, the less the drone pollutes,
- Carbon emissions are strongly related to the electricity mix in a country of operation. The greater the contribution of fossil fuels in electricity mix, the greater the carbon footprint. Therefore the location makes a difference in terms of energy mix. It is essential that the green transformation of transportation should go in pair with energy generation means to make it truly environmentally friendly.
- For both passenger and cargo transport, in total terms, small drones have a greater carbon footprint related to kilogram-kilometre or passenger-kilometre than conventional, larger aircraft that carry more cargo and passengers on a single flight.

Another Environmental Life Cycle Assessment of Electric VTOL Concepts for Urban Air Mobility [19] names a number of requirements for a scenario meet the environmental potential of battery electric vehicles (BEV):

- The provided energy comes largely from renewable energy sources;
- the eVTOL seats are utilized to a maximum, implying a pilotless, and thus fully autonomous operation;
- the UAM mission profile implies rather long-ranged missions with a short share of hover time and -most importantly- as much distance saving as possible compared to road-bound mission;
- batteries have an effective energy density of at least 400Wh/kg, and are rechargeable for at least 1000 cycles.

In conclusion, the examples above show how comparing studies about environmental performance is difficult because of different assumptions on vehicle type, energy type (e.g. source and composition of electricity), type of usage (trip distance, load), and vehicles used for comparison (e.g. comparing to vehicles with different purpose, like conventional aircrafts or helicopters). On al local level, a positive impact is expected because local emissions are reduced to zero. However, the impact is unclear if evaluation is made on a global level and taking into account the complete lifecycle assessment.

4.2 Energy efficiency of city transport

The primary interest of this indicator is the total energy consumption by urban transport including petroleum products, natural gas, electricity, and combustible renewable and waste. The evaluation is complex because it can be made on various levels.

Firstly, on a vehicle level, comparison to other modes in terms of net energy consumption per kilometer travelled should give insight when drones are the more sustainable option. For example, a comparison between a Multicopter eVTOL vehicle and electric vehicle [20] shows that an EV consumes 5 times less energy per kilometer, and thus also the related emissions and pollutants are 5 times lower. Considering electricity mixes with higher shares of electricity from renewable sources reduce the absolute amounts of related gases, but nevertheless the Multicopter still emits more than EV.

Given the energy-intensive take-off and landing operations UAM's efficiency would benefit from longer trip distances [20], which is however contrary to the mainly short-range UAM trip demand. High base usage fees would make UAM less attractive for short -range trips.

A complication in this comparison is that evaluation of electrified mobility should also take into consideration factors like the electricity sources, use phase energy consumption, vehicle lifetimes, battery replacement schedules [1]. Full life-cycle assessment would need to be performed. Reuse or recycling of batteries is needed to reduce impacts.

Secondly, the evaluation can be made on an operational level, in order to evaluate not only the performance of the vehicle in itself, but also how it functions within the mobility system. The UAM performance of UAM, but also the related energy consumption depends on various technical, processual, logistic and infrastructural aspects [1], such as the distribution and density of hubs or vertiports, battery capacities (limiting the flight length and urging the need for recharging), regulations (speed, altitude, restricted or no-fly zones, …). A simulation of a UAM system [21] tests the influence of UAM parameters on UAM transport performance. The results show that UAM adoption is strongly influenced by the travel time reduction perceived by potential passengers. UAM infrastructure and ground-based UAM processes have elemental influence on UAM leg trip duration and, thus, on passenger adoption. However also the maximum range and the requirement for charging/refueling (frequency, duration) have a major impact on the system performance.

The impact of route planning on energy consumption is simulated in [22], comparing different strategies for planning 3-dimensional trajectories avoiding obstacles in the field. Overall, current emissions (kg CO2-equivalents) by Internal Combustion Engine Vehicles (ICEVs) are estimated 4.7 times the estimated emissions from passenger drones. Over all simulated trips, drones used an average of 0.39 kWh of energy per 1 km, which gives a reference to compare UAM to other modes. For example, values in the Electric Vehicle Database [23] show an average consumption of 0.195 kWh/km for electric cars, but for direct comparison also the travel distance and load factor should be taken into account.

A direct comparison of energy consumption for a small quadcopter drone and different transportation modes [14] results in following values:

	Energy consumption in MJ/km	Energy consumption in MJ/package
Medium-duty diesel truck	11.00	5.24
Small diesel van	4.90	1.41
Medium-duty electric truck	3.80	1.81
Small electric van	1.65	0.47
Electric cargo bicycle	0.10	0.10
Small quadcopter drone	0.08	0.33

The table shows how the lower payload of the drone compared to the other modes, mitigates the much lower energy consumption per kilometer. In other words, more flights are needed to transport a similar amount of freight.

An evaluation, considering life-cycle assessment, is based on simulations for different scenarios with varying assumptions for aircraft parameters (fleet size, weight and payload, cost), trip parameters (speed, altitude), operational parameters (type of service, number of flights) and infrastructure parameters (number of landing pads, cost) [18]. Some findings for the energy efficiency are:

The energy efficiency of UAS increases when the load factor and distance travelled rise;

In the best-case scenario, when maximum 4 people are travelling, the energy efficiency is comparable to or better than fossil fuelled cars, petrol fuelled motorcycle, mini bus during off-peak hours, metro or tram/light rail during off-peak hours;

Compared to the electric or hybrid cars, the electric UAS have worse energy efficiency, which is related to the greater amount of energy required to lift the UAS;

Transportation of great number of people in buses, trains, especially during the peak hours, is incomparably more energy efficient than any UAS;

Finally, the evaluation can also be related to the individual behaviour to take into account rebound effects, given travelers' tendency to spend achieved time savings on additional or longer trips which may lead to latent demand which compensates the desired impact on traffic flows and the related environmental or energetic costs.

In conclusion, the impact of UAM on energy consumption is unclear because of various uncertainties related to lifecycle performance, UAM system design and rebound effects. The simulations in [18] conclude that UAM is less energy effective compared to ground transportation, but adds that it is expected to become more competitive with further development of UAM services.

4.3 Net public finance related to city transport

This indicator expresses to which extent the urban mobility system is financially sustainable, by comparing the net result revenues and expenditures related to city transport.

On the expenditure side, literature stresses the investments needed to adapt existing infrastructure or construct additional physical and digital infrastructure in order to integrate drones into urban space [1]. Important aspects are charging infrastructure, depot infrastructure (for logistics) and vertiports (for passenger transport). The location choice and spatial density of these elements are also key determinants for delivery routes and flight planning, and thus for sustainability, efficiency, profitability.

The infrastructural quality is essential as well-connected hub infrastructure is a precondition for the UAM business model [1]. For example, modelling in [11] suggests that for the majority of origin-destination pairs, UAM does not provide a reduction in travel times when also travel time for access and egress, boarding time and potential waiting time are included. In several ways, this is affected by infrastructural conditions like the process time (for boarding, vertical ascent and descent, alighting), the limited fleet size and vehicle capacity (possibly introducing new congestion issues in the UAM system) and the need to recharge vehicles during operations (closely related to flight distance, and thus density of hubs). For this reason UAM reduces the travel time only for limited and specific origin-destination pairs (mainly between remote areas, where other transport infrastructure is limited). From this analysis it is concluded that UAM could potentially offer more benefits in rural areas (e.g. mountainous regions where topography requires large detours for ground transportation, connecting remote areas with airports or services, replacing inefficient ferry services to or between islands, …).

On the revenue side, we refer to the Affordability indicator in chapter 4.15, describing the variable willingness to pay in different population groups. Price differentiation between target groups may optimize revenues, but introduces the discussion of social inequity or exclusion.

A study for different markets [15] shows that the type of use-case has an impact on the challenges and evaluation of UAM. Three potential UAM markets are considered: Airport Shuttle, Air Taxi and Air Ambulance. The study found that the Airport Shuttle and Air Taxi markets are viable, with a significant total available market value in the U.S. of $500 billion, for a fully unconstrained scenario. In this unconstrained best-case scenario, passengers would have the ability to access and fly a UAM at any time, from any location to any destination, without being hindered by constraints such as weather, infrastructure, or traffic volume. Significant legal and regulatory, weather, certification, public perception, and infrastructure constraints exist, which reduce the market potential for these applications to only about 0.5% of the total available market, or $2.5 billion, in the near term. However, it was determined that these constraints can be addressed through ongoing intra-governmental partnerships, government and industry collaboration, strong industry commitment, and existing legal and regulatory enablers. The Air Ambulance market was found not a viable market if served by electric vertical takeoff and landing (eVTOL) vehicles due to technology constraints, but may potentially be viable if a hybrid VTOL aircraft are utilized.

A recent evaluation, considering life-cycle assessment, is based on simulations for different scenarios with varying assumptions for aircraft parameters (fleet size, weight and payload, cost), trip parameters (speed, altitude), operational parameters (type of service, number of flights) and infrastructure parameters (number of landing pads, cost) [18]. Some findings for the Environmental Life-Cycle Cost (ELCC) are:

- Investment cost are strongly dependent on the number of vertiports. Also the use of smaller drones reduces the investment cost due to the initial cost of both aircraft and landing infrastructure. In most scenarios investment costs amount to infrastructure rather than aircrafts.
- Energy costs expand with shorter distances travelled, with smaller cargo transported and with increasing size of vehicles.

Finally, the evaluation can also be related to the individual behaviour to take into account rebound effects, given travelers' tendency to spend achieved time savings on additional or longer trips which may lead to latent demand which compensates the desired impact on traffic flows and the related environmental or energetic costs.

In summary, the resulting financial feasibility of the system is unclear and limited by several issues. No total evaluation is found for this indicator.

4.4 Congestion and delays in city transport

This indicator calculates the impact of congestion and delays in the urban mobility system. The reduction of traffic congestion and the shortening of (commuting) travel times is one of the most frequently addressed societal benefits of UAM [1]. Delivery and passenger drones could relieve the pressure on already congested streets. This way, drones would allow faster commuting in the air, but indirectly also on the ground. This would result in a more robust and more reliable mobility system, reducing travel times uncertainty.

At the same time, however, some authors caution that Urban Air Mobility will also adversely change consumption and mobility patterns [1], for example:

- Drones are not (yet) able to perform complex multiple deliveries. Therefore, currently the UAM potential is mostly found in remote areas or in humanitarian (emergency) scenarios, which represent only a marginal share of trips, and thus have only a small potential for (urban) traffic reduction.
- Adversely, to realize a significant traffic reduction would require immense drone fleets. This is even more true given low capacity of UAM vehicles in applications for passenger or goods transportation. Such scenarios may cause new issues of airspace congestion.
- A model study for the Bavaria area in [11], applying a four-step model with UAM as an additional travel mode, forecasts that 49% of all UAM users would have chosen transit if UAM were not available. Therefore the success of UAM only partially results in a reduction of car traffic.
- Even in case of a reduction of traffic flows and thus traffic congestion, people and companies will adapt their behavior accordingly. As a substitution effect, they will be more likely to use motorized transportation modes, thus mitigating the effect of the freed road capacity.

- UAM, e.g. for freight transport, may overcome issues in last-mile deliveries, resulting in cheaper and more reliable deliveries, which in turn may cause an increase of demand for transportation, compensating the intended traffic reduction. Such rebound effects may(over)compensate the expected positive impact.

Several studies investigated UAM potential to replace conventional traffic and reduce congestion:

- In a simulation study [24], a potential of 123,449 UAM passengers per day has been calculated compared to the 14 million daily trips within the study area, resulting in a share of around 1%. Only for longer distances, the modal share increases significantly to 3–4% for distances exceeding 30 km. These number indicate that Urban Air Mobility will not significantly change the daily mobility situation in general, but will mainly complement the current transport offer by a fast, flexible mode of transport. On short distances (< 10 km), UAM has a modal share of 0.5%. In absolute terms, UAM demand is concentrated (84%) on short distances under 40 km; 55% of demand is on routes < 10 km. It could be shown that two important parameters for UAM potential are the passenger processing times at the vertiports and the number of vehicles per vertiport.
- An agent-based simulation in [16] finds a total UAM market share of 0.03%. An important constatation is that the agents switching to UAM also generate considerable flows of new ground-based trips to travel to and from the UAM stations. An overview of literature in [20] found similar UAM potential market shares.
- A model study for the Bavaria in [11], applying a four-step model with UAM as an additional travel mode, shows that the share of UAM trips is relatively low with 0.14% to 0.61% of the total number of trips, depending on the UAM fleet size. The scenario with UAM resulted in a total Vehicle Kilometers Travelled (VKT) of 48.94 million VKT. In the base scenario without UAM, the substituted trips required a performance of 49.39 million VKT. However, UAM access and egress trips created an additional 0.59 million VKT, leading to a grand total of 49.53 million VKT for the UAM scenario. This means the UAM scenario generated in total approximately 0.14 million more vehicle- kilometers than the base scenario, an increase of 0.27%.
  The increase in VKT for the UAM scenario is counterintuitive at first sight, as UAM was expected to reduce auto travel. However, the nesting structure of the mode choice model drew more UAM trips from transit than from auto. Also, access and egress trips were done by car more often than by transit or non-motorized modes. While the net impact on VKT is very small, UAM could not be shown to reduce auto travel.

[25] notes that the efficiency of a UAM system is closely related to two problems in flight planning. The “Pooling and scheduling” describes the grouping of passengers demands into common flights taking into account their expected arrival time at origin vertiports and potential constraints on arrival time at destination, minimizing the waiting times at the vertiport and the total number of flights required to fulfil the demand. The “Routing and recharging” deals with the routing and battery recharging of the aircrafts, minimizing operational costs taking into account the duration for charging and the energy rates (considering slow or fast charging modes, which affect battery performance because of e.g. capacity and power fade). Both problems were modelled in order to evaluate the impact of specific parameters on the system performance. The importance of this case is that the UAM system capacity and performance depend to a large extent on the travel demand profile (origins, destinations, departure and arrival times, …) and on operational parameters (vertiport capacity, vehicle characteristics, charging performance, …).

In conclusion, the consulted literature indicates rather low UAM shares, which limit the potential to reduce traffic and traffic congestion. In contrary, secondary substitution effects may even (over)compensate the positive effects.

4.5 Economic opportunity of city transport

This indicator intends to quantify the direct economic contribution from the city transport sector to the welfare of the metropolitan area.

In the literature review in [1] economic benefits form almost half of the quoted benefits of drones. Especially drone-supported logistics are expected to lead to lower costs for companies in the rapidly growing and price sensitive logistics sector.

However, at the same time, some sources warn for potential job losses, especially in logistics sector [1].

On the other hand, the deployment of UAM requires considerable investments in physical infrastructure (charging infrastructure, depot infrastructure (for logistics) and vertiports (for passenger transport), maintenance centers, …) and a digitized, automated control system enabling safe and efficient access to lower airspace for a large number of drones [1]. As described under indicator 3 'Net public finance related to city transport', this infrastructure forms a key determinant for flight planning (and thus for sustainability, efficiency, profitability) and for integration with existing road and transit networks. Modelling in [11] suggests that for the majority of origin-destination pairs, UAM does not provide a reduction in travel times when also travel time for access and egress, boarding time and potential waiting time are included.

No quantified evaluation of the economic opportunity of UAM was found in literature. Both positive and negative impacts are described, where the required investment in UAM infrastructure is named as an important concern. Performance is highly depending on infrastructural aspects like density (access and egress time), processing (boarding, alighting), air traffic management (ascent, descent, regulations like no-fly zones, …), fleet size and recharging. Especially in urban context these conditions are under pressure, but at the same most critical.

4.6 Commuting travel time

Commuting travel time is recognized as an important sustainable mobility indicator across the literature, mainly as an economic aspect of sustainable mobility but also as a part of accessibility analysis and the role of public transport in a more sustainable modal shift. This indicator evaluates the time needed to commute from home to work or to an educational establishment (for students).

Note that most researches consider 'travel time' in general, rather than specifically 'commuting travel time'. One can expect that UAM has similar impact on both, although commuting travel time typically occurs during rush hours, when the mobility system is functioning more at capacity and thus less reliable.

For UAM applications in the field of emergency services, the indicator could be given a broader interpretation in the sense of reducing the response time in case of emergency [12].

Some general impacts on travel time are summarized in [1]. Delivery and passenger drones could relieve the pressure on already congested streets, so that drones would . allow faster commuting both in the air, and the ground [1]. In relation to indicator 4 'Congestion and delays in city transport' we however described that it would require immense drone fleets in order to realize a significant traffic reduction, to such an extent that such scenarios may cause new issues of airspace congestion. On the other hand, also the role of technical, processual and infrastructural aspects is stressed:

- Distribution and density of hubs or vertiports is critical, as transportation to and from hubs increases with lower density.
- Limited battery capacities limit the flight length and urge the need for recharging.
- The space needed for infrastructure may limit its density, especially in dense urban areas.
- Statically or dynamically defined no-fly zones or the establishment of flight corridors, which may be required to reduce the environmental impact, can highly affect delivery routes and flight planning, and therefore reduce the efficiency of the UAM system.
- Travelers' tendency to spend achieved time savings on additional or longer trips may lead to latent demand which increase traffic flows and environmental or energetic costs.

An overview of studies [26] comparing door-to-door travel times between UAM and conventional modes shows that access and egress times, processing time (waiting time, times to board and disembark the aircraft, for safety procedures, for lift-off and landing and aircraft cruise speeds as crucial parameters. Travel distance needs to be at least 15 to 25 km in order to compensate for access and egress losses and to provide travel time savings over existing modes.

A simulation of a UAM system [21] tests the influence of UAM parameters on UAM transport performance. UAM adoption is strongly influenced by the potential travel time reduction perceived by potential passengers. The results show that UAM infrastructure and ground-based UAM processes have elemental influence on UAM leg trip duration and, thus, on passenger adoption. The industry's current focus on UAM vehicle capacity and speeds should therefore be extended with UAM accessibility and short process times.

Simulations in [20] estimate that under base-case assumptions, UAM could provide travel time savings for 3-13% of motorized trips. Because of the need of accessing/egressing UAM stations, UAM is still affected by road traffic congestion, but 51-82% less than motorized traffic.

Further modelling in [11] similarly suggests that for the majority of origin-destination pairs, UAM does not provide a reduction in travel times when also travel time for access and egress, boarding time and potential waiting time are included. This is further affected by the process time (for boarding, vertical ascent and descent, alighting), the limited fleet size and vehicle capacity (possibly introducing new congestion issues in the UAM system) and the need to recharge vehicles during operations. For this reason UAM travel time reductions only for limited and specific origin-destination pairs (mainly between remote areas, where other transport infrastructure is limited).

The above researches add some nuance to the generally expected travel time reduction by UAM. This reduction may apply to the travel time between hubs (although the profit of UAM may be limited by regulations in terms of speed, altitude, flight corridors or no-fly zones, …), but is compensated when comparing door-to-door travel times, because of the various additional time loss access trip, waiting time, boarding and alighting, egress trips).

4.7 Quality of public area

The quality of the public area describes the presence of streets and squares in the city that offer opportunities for individual contact and social interaction, and that have a good image.

Several aspects of urban quality are linked to other indicators such as noise hindrance (indicator 3), air quality (indicators 1 and 2) and traffic calming (indicator 5).

As described in indicator 19 on space usage, the introduction of UAM requires additional infrastructure for landing (hubs, vertiports), charging and maintenance. The additional space usage may also put pressure on the quality of (public) space, especially because the density of these facilities highly impact operational aspects of the UAM system.

Also the visual aspects of UAM highly affect the (quality of) public space [12]: both the aircraft and infrastructure have a visual impact that should be limited to preserve the city landscape. The presence of UAM vehicles also affects people's sense of privacy, blurring the boundaries between public and private spaces [1].

A specific point of attention are locations with intense vertical movements, such as hubs or vertiports (specific infrastructure to embark and disembark air taxis) or charging points. These locations form concerns in terms of noise (take-off, landing) and safety, followed by visual pollution and privacy [12].

An review of UAM infrastructure studies in [26] describes some other quality aspects:

- Vertiport placement, design and airspace integration:
  This aspect includes opportunities to integrate infrastructure into cities (e.g. on rooftops, near highway or interchanges, …); optimal location to serve different types of demand (e.g. required density, relation to socio-demographic attributes, …); vertiport lay-out (optimizing capacity, processing time). This aspect includes a link to urban planning (accessibility, active mobility, mixed land-use, …) and regulation (noise, safety, …).
- Battery and electric grid:
  This aspect is a trade-off between battery size (and weight) versus mission length. Use of UAM inevitably comes with the issue of (partial) recharging the battery after each mission. Charging times are an essential issue for operational reasons (unavailability due to charging), but also determine the required number of charging stations and vehicles (fleet size). Policies and strategies to manage the impact of charging on the electric grid are needed (time of day, normal or fast charging, jointly designed charging station and solar power plants, use of replaceable batteries, …).
- Integration with existing modes and ground transportation:
  Hereto it is essential to understand whether UAM will complement or compete existing modes. Effects include rebound effects (new technologies resulting in increased travel) or -on the longer term- impact on car ownership or residential location choice. Parking availability and congestion are mentioned as factors impacting the integration with car, but this can be extended to accessibility by bike or public transport for accessing/egressing the vertiport.

For this indicator, literature mainly mentions various threats to be taken into account in (urban) planning.

4.8 Mobility space usage

This indicator represents the proportion of land use, taken by all city transport modes, including direct (e.g., roads, rails) and indirect uses (e.g., parking space). Whereas the previous indicator evaluates the quality of public space, this indicator focuses on the amount of space consumed by mobility infrastructure.

It is therefore essential for this indicator that the integration of drones into urban space requires adaption of existing infrastructure and construction of additional physical and digital infrastructure[1]. Similarly, [2] refers to the extensive infrastructure needed such as a network of vertiports; charging/fueling stations (including power grid improvements) and maintenance stations; communications, navigation, surveillance and IT infrastructure.

Some of the quality aspects, described in [26], also relate to the space usage:

- Vertiport placement, design and airspace integration:
  Not only do vertiport (and other types of infrastructure) consume space. For an optimal accessibility they require a close integration with origin and destination areas (i.e. dense zones in terms of population, offices, shops, …) and with urban transport, which are exactly optimal zones for urban development. These areas are also more susceptible to possible negative aspects of UAM (noise, visual hindrance, …).
- Integration with existing modes and ground transportation:
  UAM stations generate additional trips for accessing/egressing the vertiport. Parking availability and congestion are mentioned as factors impacting the integration with car, but this can be extended to accessibility by bike (e.g. parking facilities) or public transport. On the other hand, a good integration with active modes (bike, foot) and public transport and a smart urban planning (see indicator ‘Functional diversity’) may as well contribute to a less car-oriented travel behavior.

Similar conclusions are found in [20], evaluating the impact of some UAM system parameters on travel time. This is essential as travel time savings in comparison to other modes are considered one of the main drivers for UAM.

- The density of UAM stations (hubs) is crucial as it determines the availability of UAM stations in terms of ease to reach a UAM station. However, the primary effect of an increased number of stations is that more short-range trips come into consideration for UAM. The exact placement of UAM stations (hubs) has been researched either based on GIS multi-criteria approaches (defining location criteria for high suitability for UAM station), either on the demand-driven approaches (identifying concentrations of trip origins and arrivals).
- The process time duration has an important impact on total travel time, specifically for short-range trips.
- The impact of cruise speed is only relevant for longer trips, and is therefore of secondary importance.
- An optimal travel time occurs when a direct flight path can be followed. However, regulations to avoid safety issues and hindrance (e.g. no-fly zones over populated areas) may steer UAM towards indirect (routed) flight paths, e.g. following ground-based infrastructure. Simulations [20] show a ratio difference of 0.06 for median travel times between direct and indirect UAM flight paths. Similarly to the cruise speed, these indirect flight paths do not overly impact the total travel times. Therefore the benefits in terms of noise-avoidance and safety seem to outweigh the slightly prolonged travel times.

A possible strategy would be to locate facilities in less valuable spaces such as near highways or in interchanges, but these locations conflict with the interest of UAM to land close to origin and destination locations. A high density of vertiports with close integration to urban activities is essential for the efficiency of the UAM system (access and egress trips, flight distances, recharging, …).

For the mobility space usage, literature expects negative effects because of the space needed for additional infrastructure, and the required density and location of hubs (dense urban areas, near population, shops, offices, …).

4.9 Appropriate access to mobility services

This indicator shows whether people have a sufficient access to the urban mobility services, in order to fulfill their travel needs. In this sense UAM, as an additional transport mode, complements existing modes, offering opportunity to improve accessibility to less serviced areas or population groups.

Some aspects of the physical infrastructure are key determinants for the integration with existing road and transit networks, and thus for the access to the UAM system. Therefore clearly defined requirements are needed [1], e.g. for the spatial distribution of charging infrastructure, depot infrastructure (for logistics) and vertiports (for passenger transport).

An essential parameters for access to UAM is the density [20] of vertiports, as it determines accessibility in two senses. The primary effect of a higher number of stations is that more (very) short-range trips come into consideration for UAM, while -on a secondary level- also shortening the overall access and egress distances to/from the stations (transportation to and from these hubs increases with lower density).

Other technical, processual and infrastructural aspects to be taken into account in the UAM system design [1] include:

- Limited battery capacities limit the flight length and urge the need for recharging.
- The space needed for infrastructure (stations, charging) may limit the density of hubs, especially in dense urban areas.
- Travelers’ tendency to spend achieved time savings on additional or longer trips may lead to latent demand, increasing traffic flows and related (environmental, energetic) costs.
- Especially for short-range trips, the impact of process time at the station heavily outweighs UAM’s cruise flight speeds. This affirms that future UAM operators should focus on station placement and processes (efficiency), rather than on vehicle speed.

The exact placement of UAM stations (hubs) has been researched either based on GIS multi-criteria approaches (defining location criteria for high suitability for UAM station), either on the demand-driven approaches (identifying concentrations of trip origins and arrivals).

Also urban planning can have an important role in supporting UAM development [2], e.g. by requiring an additional level of development standards around vertiports (e.g. higher density or mixed-use developments), or by limiting building heights to preserve the airspace access to the facility.

In conclusion, UAM has the potential to positively impact this indicator, but is depending on a number of essential system parameters.

4.10 Road fatalities in urban transport

This indicator reflects the damage caused by road and rail accidents in the city. It plays an important role in public perception. For example the literature review by Kellerman [1] found that roughly a third of the quoted objections against UAM referred to physical safety, collisions, crashes, accidents and injuries.

It is important to note that the safety is often considered in a much broader sense. [12] clarifies that it refers to safety of passenger as well as safety of pedestrians underneath the flights. Indeed a survey across four countries (Los Angeles (U.S.), New Zealand, Switzerland, Mexico) [27]found that the most important factor affecting the public perception was the concern about the safety of individuals on the ground. In [1] also the threat of potential misuse of drones by criminals and terrorists are mentioned as safety issues.

Therefore a highly digitized, automated control system is needed [1] for enabling safe and efficient access to lower airspace for a large number of drones. The system requires smallscale planning of the lower airspace, taking into account terrain specificities and obstacles. Further challenges to the U-Space management are posed by the safeguarding of statically or dynamically defined no-fly zones and the establishment of flight corridors, which may be crucial factors in minimizing the effects of drone traffic for the population and the environment (noise, visual pollution, etc.).

[2] refers to safety of UAM users, other airspace users as well as bystanders (people flown over on the ground). Key areas include issuing and enforcing of regulations, advisories, guidance means of compliance and minimum standards in relation to:

- Governing the manufacturing, operation and maintenance of aircraft
- Certifying pilots, aircrew, maintenance and other personnel
- Certifying aviation facilities
- Operating a network of air navigation, airspace and air traffic management facilities.

From the specific perspective of (urban) transport safety, it is striking that mentions of benefits of drones in the field of safety and security mostly refer to the use of drones as sensory devices and not as a transportation technology. This indicates some uncertainty as to the safety of UAM as a new means of transportation, compared to conventional modes.

Lessons could be learned from the development of aviation safety, where four consecutive approaches have been distinguished [28]:

- Initially the focus was on technical deficiencies, resulting in technical improvements and regulatory measures
- Later focus shifted to human factors and avoiding individual’s errors
- In a third phase organizational and operational optimalisations took place, resulting in more proactive and predictive methodologies
- Finally a total system consideration leads to a more systematic safety approach.

This last step shows the complexity of the aviation system, given the interactions between people, processes and technologies.

Finally, also the impact of drones on wildlife, in terms of collisions with birds, can be considered an aspect of traffic safety [1]

In conclusion, the impact of UAM on this indicator is somewhat unclear. Most sources stress the importance of the indicator for the acceptance of UAM, but seem rather unsure about the actual safety of the new transportation mode, compared to conventional modes.

4.11 Noise hindrance by city transport

This indicator expresses the impact of the noise, generated by city transport, on people's well-being.

A survey across four countries (Los Angeles (U.S.), New Zealand, Switzerland, Mexico) [27] found that the second and third important factors affecting the public perception (safety of individuals on the ground being the most important one) were the type of sound and the volume of the sound generated by UAM vehicles. Also the fourth to sixth most important mentions relate to noise hindrance: the time of day, the flying altitude of the aircrafts and the duration of the noise.

An elaborated evaluation on noise hindrance in [12] mentions some important findings about noise hindrance by UAM:

- There is a clear separation between the noise hindrance by drone/air taxi and road vehicles, even when played at the same sound level, with a more negative rating for UAM sounds.
- This may be caused (partially- by the (un)familiarity of the sound: a known sound may be perceived as less hindering.
- Also elements of tonality at certain frequencies (the different sound characteristics of the aircrafts) play a role.
- Also speed of pass-by is a factor, as a slow pass-by is perceived as more annoying than a quick one.

Cohen [2] is uncertain about how future evolutions may affect the perception of UAM noise. On the one hand, technological improvements may mitigate the noise emissions, while on the other hand larger-scale operations may actually reenforce the noise levels. A potential reduction of ambient urban noise (e.g. because of electrification of ground traffic) may make the UAM noise even more perceptible in the future.

Vertiports may be specific points of attention: due to the additional power need during vertical take-off and landing, noise levels are at least 10 dB above the noise levels during flyover [29]. Moreover, concepts to hide noise emissions from vertiports (e.g. by locating them in industrial zones or highway cloverleafs) and from corridors (e.g. by clustering them above highways or major roads, or by protecting living areas as no-fly zones) increase the travel distance to/from vertiports (access and egress trips) and the flight distances between them [29]. In terms of efficiency, vertiports need to be in the vicinity of people's origins/destinations, thus increasing UAM noise hindrance.

Because of the uncertain impact on noise hindrance, Pukhova [11] considers UAM rather as an alternative for current traditional helicopter flights (e.g. for medical emergencies and VIPs) than for motorized traffic.

Finally, it is noteworthy that also the environmental impact of noise on wildlife can be considered part of this indicator.

The above elements show many uncertainties: the actual noise impact of UAM (as the different soundscape may be even more hindering, even at lower noise levels), but also the relation to the system organization (distribution and density and location of hubs) and regulation (flying restrictions, altitude, speed) in regard to other criteria like energy efficiency, travel times, …).

4.12 Air polluting emissions of city transport

The impact of urban air mobility on air quality is mainly related to the fact that drones are a fully electric transportation technology and are therefore expected to reduce (local) carbon/noise footprint in comparison to fossil-fueled helicopters[1].

However, as described by EASA [12], "the environmental impact of UAM may be almost zero on a local emissions level for battery electric vehicles, but the required electricity still has to be generated and the vehicle components have to be manufactured, assembled and eventually disposed of. Focus should be placed on reducing the overall environmental impact of UAM aircraft during the design phase." Also Kellerman [1] stresses that evaluation of electrified mobility should take into consideration more factors like the electricity sources, use phase energy consumption, vehicle lifetimes, battery replacement schedules.

Full life-cycle assessment would need to be performed, to allow a complete and fair comparison to other modes and to give insight when drones are the more sustainable option.

Pukhova [11] therefore considers UAM rather as an alternative for current traditional helicopter flights (e.g. for medical emergencies and VIPs), because of the lower noise and fewer greenhouse gas emissions.

Simulations in [16] show that for short range trips (up to 10km) the amounts of NOx emissions per kilometer travelled by Multicopter are higher than by conventional diesel powered road vehicles. However, for trip distances of 15 kilometers or longer the differences become negligible, and for distances of 25 kilometers and higher, the amounts of NOx emissions per kilometer for Multicopter are lower than for conventional diesel powered road vehicles. When considering the total amount of daily emissions, the UAM scenarios did not indicate the worthwhile difference, because of the relatively small market share of UAM trips.

When considering the amount of NOx emissions per trip, the UAM scenario results in amounts about three to four times the emissions in the BAU scenario, depending on the trip length, when also taking into account the access and egress trips to/from UAM. Other side-effects are that sometimes the nearest UAM station is in the opposite direction than the final destination (thus increasing the total distance travelled) or that the UAM station used is not the nearest (thus shortening the distance travelled by UAM, where emissions per kilometer are higher).

This overview shows the complexity of evaluating the impact of UAM on air quality because of the distinction between local and global effects, the inclusion of life-cycle impacts and the relevance of travel distance and of access and egress trips. Because of these latter aspects, also the type of use-case (number of flights, trip patterns), its context (urban versus rural) and the system design (density and location of hubs, regulations, …) will affect the evaluation.

4.13 Satisfaction with public transport

This indicator evaluates the physical and mental comfort of transport and services for all users. No sources were found describing user's satisfaction of UAM comfort or performance.

4.14 Accessibility for mobility-impaired groups

This indicator refers to the accessibility for mobility-impaired target groups, such as wheelchair users, disabled people or elderly people. UAM, as an additional transport mode, complements existing modes, offering opportunity to improve accessibility to less serviced areas or population groups.

Essential parameters for this indicator are the spatial distribution [1] and density [20] of vertiports. The density of UAM stations (hubs) is crucial as it determines accessibility in two senses. The primary effect of a higher number of stations is that more (very) short-range trips come into consideration for UAM, while also shortening the overall access and egress distances to/from the stations.

Urban planning can have an important role for this indicator [2], e.g. by regulating the access for mobility-impaired groups both to and from the UAM stations, but also inside the stations and vehicles (boarding, alighting), and by a spatial distribution of UAM station in the vicinity of important locations.

4.15 Affordability of city mobility for the poorest group

The affordability indicator evaluates the ability of transportation system users to pay for their transportation needs.

Straubinger [30] investigates the distributional effects of UAM for passenger transport. Given the high travel speeds and high prices this mode demands for a user group with high willingness to pay for travel time savings. A comparative statics analysis, comparing the benchmark situation without UAM and the base scenario with UAM, showed that in the base scenario with UAM, high-income households achieved welfare gains due to UAM introduction, while low-skilled households faced welfare losses. Interestingly, the results show that the direction and magnitude of welfare effects do not differ between two city-types considered (the so-called 'US-type city' with low-skilled households living close to the city centre, and the 'EU-type cities' where low-skilled households live further away from the city centre). Changes in marginal cost or pricing schemes had the biggest impact on mode choice and welfare. The impact of changes in travel time, induced either by changes in cruise speed or access and egress time, only had a minor impact. Similar distributional changes in location behavior of households have also been reported in [31].

These effects are confirmed by simulations [32], [33] concluding that respondents consider travel time savings the primary reason for using UAM, rather than travel cost savings. As expected, respondents with a higher VOT (value-of-time) are willing to pay more for these travel time savings and thus for using UAM services. This suggests that market penetration rates for UAM may be greater among respondents with following charateristics:

- Younger-aged respondents (between 18 and 35 years old)
- Older-aged respondents (between 56 and 65 years old) with high income and relatively high propensity to use an AT
- Respondents with children (0 to 17 years old) living in the household

A simulation of a UAM system [21] tests the influence of UAM parameters on UAM transport performance. UAM adoption is strongly influenced by the potential travel time reduction perceived by potential passengers. The results show that UAM infrastructure and ground-based UAM processes have elemental influence on UAM leg trip duration and, thus, on passenger adoption. The industry’s current focus on UAM vehicle capacity and speeds should be extended with UAM accessibility and short process times. Future research in the field of potential transport performances of UAM should also implement UAM pricing differentiation and additional UAM vehicle parameters, such as maximum range and the requirement for charging/refueling.

One of the aspects modelled in [25] is the impact of passenger classes, i.e. distinguishing Regular users from Premium users. For Premium users a lower value is applied for the maximum waiting time at the origin vertiport, and their waiting time is weighted by a factor in the objective function in order to account for the different value of time for Premium users. The results show that Premium demands enjoy a lower average and a lower variability in expected waiting times than Regular demands. This finding could be monetized through appropriate premium pricing, which however raises fairness and affordability issues.

Literature sources therefore explicitly suggest an imbalance within the population based on education level, income, willingness to pay. Price differentiation based on Premium service, further exploiting these differences, may even be a necessity to make a UAM system profitable.

On the other hand, Cohen [2] draws a parallel to the eventual democratization of air travel, although it took decades for the industry to achieve mass market affordability. At this moment it is very uncertain how much UAM will ultimately cost, how much time it will take to reach this cost level, and what (public) investment will be needed to support the evolution of UAM, but this does not mean this point will never be reached.

4.16 Security in city transport

Security covers the risk for crime in mobility.

The literature review [1] broadens the ‘safety’ aspect beyond threats to physical safety, collisions, crashes, accidents and injuries, to include also e.g. the threat of potential misuse of drones by criminals and terrorists. Also [2] distinguishes several aspects of security: not only personal security of passengers (including hijacking, violence, …), but also physical security of UAM infrastructure and cybersecurity of all enabling IT systems. Therefore the need for a highly digitized, automated control system enabling safe and efficient access to lower airspace for a large number of drones is stressed [1].

However, no sources discuss the social security in UAM, likely because it highly depends on very local context.

4.17 Urban functional diversity

The indicator on functional diversity measures the mobility impact of the city’s spatial structure. Large monofunctional areas (housing, industry, commercial activities) urge people to travel for other activities. Mixing several functions within one area creates proximity, allowing people to realize more activities with travelling less frequently or for shorter distances. This indicator describes how well different functions are spatially intermixed.

Literature mainly describes the important role urban planning can have in supporting UAM development, e.g. by requiring an additional level of development standards around vertiports (e.g. higher density or mixed-use developments), or by limiting building heights to preserve the airspace access to the facility [2].

On the other hand it is signaled [29] that the vertical movements (take-off, landing) at vertiports, requiring additional power, cause noise levels to be at least 10 dB above the noise levels during flyover. Developing exactly these areas as multi-functional urban concentrations may even increase the impact of noise hindrance (but also other types of hindrance) and thus affect other indicators.

In conclusion, UAM is not expected to directly affect the urban functional diversity. However, this indicator, focusing on dense and mixed urban functions nearby UAM hubs, seems contradictory to other aspects of environmental impact (such as noise hindrance or visual hindrance).

4.18 Multimodal integration of city transport

This indicator evaluates the availability of different mobility subsystems, and their ability to function as a whole. Essential is the (physical) opportunity to interchange between different travel modes, but the level of comfort of these transfers.

Some aspects of the physical infrastructure are key determinants for the integration with existing road and transit networks. Therefore clearly defined requirements are needed [1], e.g. for the spatial distribution of charging infrastructure, depot infrastructure (for logistics) and vertiports (for passenger transport).

However, studies on the potential of taxi services [34] show that on-demand trips were transit-competing rather than transit-complementing, a conclusion which may be applicable to similar systems like UAM.

This finding is confirmed by a model study for the Bavaria area [11], applying a four-step model with UAM as an additional travel mode, shows that UAM has the greatest relative impact on transit modes (train, tram/metro, bus) and shared AV. The model forecasts that 49% of all UAM users would have otherwise chosen transit if UAM were not available. Regarding access and egress to the UAM station, it was estimated that 52% of UAM access and egress trips would be made by either automobile or AV, which is similar to the results of the main mode choice model in which 59% of all trips were made by these modes.

These cases illustrate the importance of multimodal integration of UAM as a well-considered complementary system.

4.19 Resilience for disaster and ecologic /social disruptions

Measures for resilience in literature cover two aspects of resilience. One is resilience to extreme weather events (heavy rainfall, windstorm, hurricanes, droughts, etc.), which regularly occur in the current and in the future climates, even though likelihoods and intensities may be modified. The second is resilience to long-term climate change, which influences average weather conditions, and thereby can reduce infrastructure service quality, quantity or reliance, and can require infrastructure retrofit.

Given the purpose of the indicator set, measuring the sustainability of the city's urban mobility system, the focus is on the current mobility system, and therefore the focus is on the first aspect of resilience, the capability to face sudden perturbations from hazards.

Cohen [2] notes that weather impact does not necessarily refer to critical safety risks, but can also result in operational and reliability challenges (e.g. in terms of offering dependable and consistent service with minimal delay). Strategies that are typically used in commercial aviation, like delaying or rerouting flights, are not convenient for UAM as they affect the very UAM values of convenience (proximity) and time savings.

Concern about weather constraints are evaluated in [15]: weather can influence many components of UAM, including operations, service supply, passenger comfort, community acceptance, infrastructure, and traffic management. "Impact scores" per hour were calculated describing how weather conditions influence UAM vehicles to evaluate the number of 'impacted hours'. The number of impacted hours were summed across the UAM operational day. Evaluations were based on data for 10 cities in the U.S [35]. The number of impacted hours was highest in winter and spring, averaging 6 to 7 hours per day, opposed to 2 to 3 hours per day in summer and fall. However, large differences were noted between cities, with e.g. an average of 11 to 12 impacted hours per day in winter and spring in New York, Washington, Dallas and Denver, opposed to 0 to 1.5 impacted hours per day in Miami, Phoenix and Los Angeles .

In conclusion, the resilience to weather conditions may affect the performance of UAM, but is highly dependent on the local meteorological conditions.

4.20 Occupancy rate of city transport

This indicator intends to quantify the average load factor of all modes of city transport, both for passenger and freight transport, expressed as the ratio between the actual performance of the mobility system and its maximum capacity. The indicator refers to the efficient usage of available (vehicle) capacity in terms of occupancy of cars, buses, trams, … for person transport, and to the load factor for freight (trips by empty or underused trucks).

In literature no mentions were found about UAM affecting occupancy rate of person cars, public transportation or goods vehicles.

4.21 Opportunity for active mobility

This indicator expresses how good the city creates friendly conditions towards walking and biking in the city. Therefore the indicator closely depends on the integration of the UAM network within its spatial context.

Spatial distribution of charging infrastructure, depot infrastructure (for logistics) and vertiports (for passenger transport) are therefore named [1] crucial for the integration with existing road and transit networks.

The density of UAM stations (hubs) is crucial [20] as it determines the availability of UAM stations in terms of ease to reach a UAM station, but an even more important effect is that more (very) short-range trips come into consideration for UAM.

Not only the density, but also the location choice of UAM stations contributes to the accessibility by active mobility in terms of the connectivity to active mobility networks and the functional density (potential of nearby origins and destinations). The exact placement of UAM stations (hubs) has been researched either based on GIS multi-criteria approaches (defining location criteria for high suitability for UAM station), either on the demand-driven approaches (identifying concentrations of trip origins and arrivals).

In conclusion the opportunity for active mobility is mainly determined by the density and location choice of the UAM stations.

5 AURORA Indicator set

5.1 Indicators for UAM services

In chapter 4 we evaluated the impact of UAM on each of the SUMI indicators. Table 2 summarizes the findings per indicators, describing the effect as positive (+), neutral (0), negative (-) or uncertain (?).

Indicators for the sustainability of urban mobility	Effect	Background
Emissions of greenhouse gases	+ to ?	GHG emission excluded on a local level, but unclear impact based on a global life-cycle assessment
Energy efficiency	?	Uncertainty about lifecycle performance, UAM system design and rebound effects
Net public finance	?	Uncertainty both on the cost (infrastructure, operations, …) and revenue side
Congestion and delays	0 to +	Positive impact in terms of reliability, but very large fleet needed for significant impact on congestion level
Economic opportunity	?	Both positive (e.g. in logistics) and negative effects (e.g. job losses, investment cost)
Commuting travel time	0 to +	Positive impact in terms of reliability, but very large fleet needed for significant impact on congestion level
Quality of public area	0	UAM may affect this indictor indirectly via other indicators.
Mobility space usage	-	Integration of additional infrastructure (with high density in dense areas)
Access to mobility services	+	Depending on the integration with the
Traffic safety	?	Depending on regulation (certification), integration with other modes and urban context
Noise hindrance	?	Depending on regulation (speed, altitude, …), system design (fleet size, number of flights) and context (urban vs. rural). Uncertain because of the different soundscape (perception, unfamiliarity, vertical movements, …).
Air polluting emissions	+ to ?	Emissions excluded on a local level, but unclear impact based on a global life-cycle assessment. Depending on system design (trip length).
Comfort and pleasure	0	No effect expected.
Accessibility for mobility impaired groups	0 to +	Depending on distribution and density of vertiports.
Affordability of public transport for poorest group	?	Uncertainty about price settings, but risk of distributional effects.
Security	0	No effect expected.

Functional diversity	0	No direct effect expected, although urban planning may affect other indicators.
Multimodal integration	?	Important for access and egress trips to/from UAM hubs, but risk that UAM is transit-competing instead of transit-complementing.
Resilience for disaster and ecologic/social disruptions	?	Highly dependent on local meteorological conditions.
Occupancy rate	0	No effect expected.
Opportunity for active mobility	0	No (direct) effect expected, depends on integration with existing mobility system.

Table 2: Overview of the impact of UAM on the SUMI indicators

Based on this evaluation, six of the SUMI indicators appear to be irrelevant for UAM, as no(direct) impact is expected. Therefore these are omitted for the further evaluation of UAM (Quality of public area, Comfort and pleasure, Security, Functional diversity, Occupancy rate, Opportunity for active mobility).

5.2 Indicators for emergency-related UAM services

A second limitation is that the AURORA project specifically focuses on emergency-related applications of UAM (e.g. intervention on emergency locations, urgent medical deliveries, …). Because of the specificity of these applications some of the proposed indicators become irrelevant for the AURORA purpose:

- Emergency-related applications involve a limited fleet size with a low number of flights. Therefore no significant impact on 'Economic opportunity' is expected in case of emergency-related UAM services.
- For the same reason no substantial effect is expected in terms of lowering traffic and congestion levels. This means that the indicator 'Commuting travel time' will be unaffected and can be deleted from the AURORA indicator set. The indicator 'Congestion and delays' however is withheld, but with a specific focus on the reliability of emergency services, in terms of faster and reliable travel times (intervention times, delivery times).
- The emergency-related UAM services are targeted to specific locations (hospitals, medical services and companies, …), limiting the density and space usage of required UAM infrastructure, often integrated with existing infrastructure (e.g. heliports). Therefore the indicator on 'Mobility space usage' is omitted.
- Because of the specificity of the emergency services, the indicators on the integration with the existing mobility system become redundant. The indicators 'Access to mobility services', 'Accessibility for mobility impaired groups', 'Multimodal integration' and 'Affordability of public transport for poorest group' are therefore omitted.

On this basis the 7 forementioned indicators are not withheld in the AURORA indicator set.

5.3 Specific indicators for the AURORA project

AURORA explicitly aims at expanding the project scope beyond the technical aspects of UAM, and also consider the environmental and societal aspects of UAM. As raised by Kellerman [1], the (urban) population will be most exposed to the adverse effects of the widespread use of drones. In order to create a public acceptance of UAM, it is necessary that the benefits of UAM outweigh the adverse effects. An important note is that these effects may depend on the type and size of the use-case, and the context it is situated in (urban vs rural).

Kellerman [1] indicates that there is a problem in policymaking, as expertise and involvement are restricted to a small number of experts and stakeholders. Two specific worries are the lack of awareness at municipal level and the low acceptance of citizens.

Relating these findings to the AURORA objectives on public acceptance, additional indicators are proposed for the two target groups:

- The impact of the AURORA project on the public acceptance;
- The capacity building within the AURORA project.

Especially on public acceptance, extensive evidence is reported.

EASA [12] found in a literature review that the most mentioned social acceptance factors by far were noise and safety. Safety mostly refers to safety of an occupant of an air taxi, but also includes safety of people on the ground.

Kellerman [1] relates the lack of public acceptance with invasions of privacy, safety concerns and noise levels. Privacy issues are one of the key issues for public acceptance, linked with data privacy. Even when exclusively used as transport device, there is need for sensing and surveillance technologies (prevent collisions, but also needed for drop-off and take-off process), causing potential of causing privacy infringements. He mentions information and process transparency as instruments to create acceptance, combined with more participatory approaches.

A survey amongst over 2500 consumers [36] reports 5 major categories of concerns: safety (autonomous technology, safety systems), privacy (camera equipment), job security (obsolete jobs across multiple industries), environmental threats (waste from batteries, impact on wildlife, energy usage), noise and visual disruption (disturbances in residential neighborhoods). Safety records and demonstrations are cited as factors that would increase their level of comfort with UAM.

Also another survey in Prague shows some aspects of public acceptance [37]:

- No impact was found of personal characteristics (age, gender, familiarity with UAM). Younger people are not more inclined to UAM.
- Environmental pollution from transport is a major issue for most respondents: 35% decided different mode when knowing the emissions during their journey.
- UAM is more attractive for longer journeys (when bicycle is no alternative, and difference in transport time compared to public transport is significant)
- People who are dissatisfied with their currents means of transport would welcome UAM most. It is therefore important that the chances of improving land transport have been exhausted first.

Also [38] contains a survey on the willingness-to-fly in a UAM aircraft. This study finds a higher willingness among male respondents and young respondents, and respondents with higher familiarity with UAM. Other factors relate to travelling with other passengers (preferably with people they know) and the level of automation (presence of flight attendant creates trust).

5.4 The AURORA Mobility Indicator set

In the previous steps, the SUMI indicators were evaluated in three consecutive steps:

- A first step evaluated the impact of UAM on the indicators, based on an overview of literature. For most indicators, some impact is expected, either positive or negative or uncertain. For 6 indicators, however, the conclusion was no (direct) impact was expected, and thus that these indicators were not relevant for the evaluation of UAM.
- In a second step, the remaining indicators were considered from the specific viewpoint of emergency-related UAM services, which are the focus of the AURORA project. 7 indicators were found to be irrelevant for these specific applications, and therefore omitted from the indicator set.
- In order to reflect the objectives of the AURORA project correctly, two specific indicators were added, describing the impact of the project on the capacity building of public authorities, and on the public acceptance of UAM.

The resulting indicator set consists of 10 indicators:

- Greenhouse gas emissions by city transport;
- Air polluting emissions of city transport;
- Noise hindrance caused by city transport;
- Fatalities in urban transport;
- Congestion and delays in city transport;
- Energy efficiency of city transport;
- Resilience for disaster and ecologic /social disruptions;
- Net public finance related to city transport;
- Capability of public authorities;
- Public awareness/acceptance.

6 Conclusions

The AURORA indicator set

In this report we develop a set of indicators for evaluating the impact of UAM on sustainable mobility.

We started from the SUMI indicators, a set of sustainable mobility indicators, that has been adopted by the World Business Council for Sustainable Development (WBCSD) for assessing sustainable urban mobility in cities, and by the European commission for evaluating Sustainable Urban Mobility Plans (SUMP) in cities.

In a first step, the impact of UAM on the indicators was researched in literature. For most indicators, some impact is expected, either positive or negative or uncertain. For 6 indicators, however, the conclusion was no (direct) impact was expected, and thus that these indicators were not relevant for the evaluation of UAM.

In a second step, the remaining indicators were considered from the specific viewpoint of emergency-related UAM services, which are the focus of the AURORA project. 7 indicators were found to be irrelevant for these specific applications, and therefore omitted from the indicator set.

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- Noise hindrance caused by city transport;
- Fatalities in urban transport;
- Congestion and delays in city transport;
- Energy efficiency of city transport;
- Resilience for disaster and ecologic /social disruptions;
- Net public finance related to city transport;
- Capability of public authorities;
- Public acceptance.

Expected impact of UAM on the indicators

For the indicators on *'Greenhouse Gas emissions'* and *'Air polluting emissions'*, a positive effect is expected when considering the local emissions. However, literature raises the question on the impact on a global level, especially when the complete life-cycle assessment is considered.

A similar uncertainty is found for *'Energy efficiency of city transport'* as the impact depends on life-cycle performance (batteries), possible rebound effects and specific parameters of the UAM system (trip length, regulation, flight planning).

The effect of UAM on *'noise hindrance'* is still unclear because of the very different sound characteristics of UAM vehicles. Surveys indicate that UAM noise may be perceived as more hindering than motorized traffic, but this may be due to people's unfamiliarity with the sound. Hindrance also largely depends on the character of the flights (frequency, speed, altitude), the people's exposure (urban versus rural context) and the related regulations (flight planning, no-fly zones, …).

The indicator on *'Fatalities in urban transport'* is important as safety is an often mentioned obstruction in public perception of UAM. It refers directly to the safety of both passengers and pass-byers on the ground, but also indirectly to the quality the emergency service (safe and fast trip to the emergency location, safe and performant intervention at the emergency location).

For the indicator *'Congestion and delays in city transport'*, no significant impact on the city's congestion level is expected, given the relatively low number of emergency flights, and thus limited substation of motorized traffic by UAM. A positive impact however is expected on the reliability of emergency services, as interventions do not suffer from congestion, resulting in faster and more stable intervention times.

Very limited information was retrieved on the '*Net public finance'* of UAM, both on the cost (infrastructure, operational cost, …) and revenue side (price setting, willingness-to-pay).

In terms of *'Resilience for disaster and ecologic /social disruptions'*, literature refers to UAM's dependency on weather conditions. The performance for this indicator therefore largely depends on the local meteorological conditions.

For the specific AURORA indicators on *'Capability of public authorities'* and *'Public acceptance'*, a positive impact is expected from the AURORA project. Demonstrations create involvement of both local instances and population, and give insight in the social and environmental impact of UAM, but also in the potential mobility services by UAM.

Indicators for the sustainability of urban mobility	Effect	Uncertain factors
Emissions of greenhouse gases	+ to ?	global life-cycle assessment; rebound effects
Air polluting emissions	+ to ?	global life-cycle assessment; UAM system design; rebound effects
Energy efficiency	?	global life-cycle assessment, UAM system design; rebound effects
Noise hindrance	?	UAM system design; regulation; perceived hindrance
Traffic safety	?	Regulation, UAM system design
Congestion and delays	0 to +	Regulation
Net public finance	?	Expected costs and revenues
Resilience for disaster and ecologic/social disruptions	?	Local meteorological conditions

Table 3: Expected impact of UAM on AURORA mobility indicators

Factors affecting UAM impact

For several indicators, the eventual impact of UAM is to some extent unclear. Important determinants are:

- Life-cycle effects on emissions and energy consumption (production, renewal and recycling of vehicles and batteries, energy production, …).
- Rebound effects because of new mobility capacity creating new mobility demand, compensating the expected positive impact.
- UAM system design: several parameters of the UAM system impact the travel time reduction, compared to other ground-based modes; such as the density and exact location of hubs (origin and destination locations), the process time duration, fleet size, vehicle characteristics (battery), charging infrastructure, …
- Regulations: restrictions, imposed to mitigate environmental impacts (e.g. no-fly zones above public buildings, correctional institutes, hospitals, specifically protected locations, etc. for reasons of safety, noise hindrance, …) may limit the airspace available for UAM, and therefore the performance of the UAM system.

Research, technical development and demonstrations should contribute to clarify the weight of these factors.