Safety Targets for Urban Air Mobility Vehicles

From a perspective of Third Party Risk due to UAM operations in the Netherlands

Yuk Shan Cheung, Peter van der Geest, Tom van Birgelen and Jinyoung Choi
Aerospace Operations Safety and Human Performance Department
Royal NLR - Netherlands Aerospace Centre
Amsterdam, the Netherlands
Corresponding e-mails: yuk.shan.cheung@nlr.nl, peter.van.der.geest@nlr.nl, tom.van.birgelen@nlr.nl, jin.choi@nlr.nl

***Abstract*—Urban Air Mobility (UAM) initiatives are developed with the intention to enhance personal transport in congested area of a large city. The UAM vehicles are characterised by distributed, electrically driven propulsion and corresponding advanced flight control systems. The Special Condition Vertical Take-Off and Landing (SC-VTOL) recently published by European Union Aviation Safety Agency (EASA) provides the certification requirements for these new UAM vehicles. The SC-VTOL indicates that the current Certification Standard CS-23 (small aircraft) acceptable means of compliance are no longer considered appropriate for determining the aircraft and system safety objectives. Instead, the system safety objectives for CS-25/CS-29 (large aircraft/helicopters) aircraft should be maintained as a minimum for UAM using VTOL aircraft to address the risks to persons on board and on the ground. An analysis of third party risk (risk to people on ground), based on a use case with a vertiport located in the centre of a city, is made to demonstrate whether or not this SC-VTOL can enable a sizeable volume of UAM traffic over a congested area of a city by taking into account the third party safety objectives. Results of Individual Risk and Societal Risk calculations show that limited traffic volume is only achievable by taking additional measures.**

Keywords: Urban Air Mobility; Third Party Risk; Individual Risk; Societal Risk

I. INTRODUCTION

There are numerous initiatives and on-going developments to enhance the mobility in large and densely-populated cities by means of Urban Air Mobility (UAM). In this means of transport, aerial vehicles used are known for diversity in configurations and technological innovations applied. The vehicles include types like multi-copter, vectored thrust and lift+cruise concepts and they are mostly electrically driven. In general there is a wide variety of configurations available with limited common characteristics except for Vertical Take-Off and Landing (VTOL) capability and distributed propulsion. These vehicles do not fit well in the description of small helicopters or normal category of aircraft, which are certified based on the corresponding European Union Aviation Safety Agency (EASA) certification specifications, which are CS-27 and CS-23, respectively. Therefore EASA developed a Special Condition for small-category VTOL aircraft (SC-VTOL [1]) extensively based on CS-23 Amendment 5 integrating elements of CS-27 and new elements where deemed appropriate.

SC-VTOL has been established to prescribe the technical specifications for the type certification of a person-carrying VTOL heavier-than-air aircraft in the small category, with lift/thrust units used to generate powered lift and control. In order to be proportionate to the nature and risk of the particular activity to be conducted by VTOL aircraft, the SC-VTOL introduces two certification categories. The categories are ‘Basic’ and ‘Enhanced’, which are linked to the intended type of operations.

The link between the categories with the intended types of operations allows proportionality in safety objectives and grants the achievement of the highest safety levels of the ‘Enhanced’ category to protect third parties when UAM vehicles fly over congested areas and when conducting commercial air transport of passengers. This distinction between types of operations clearly indicates that air vehicles designed to provide the UAM service will have to be certified in the ‘Enhanced’ Category.

The SC-VTOL is unique because of the link between third party risk (TPR) and the safety objectives of the certification specification. No other EASA type certification specification specifically mentions this link. In general it is assumed that the internal safety of certified aircraft is sufficient to ensure that the risk for third parties (equivalent to “external safety” here in this context) is acceptable, or even is not considered at all.

In case third party risk becomes a dominant risk, due to a specific operation, it would furthermore be assumed that this is solved by specific measures, as will be elaborated in Section III of this paper. At the same time, it would be difficult or unfeasible to impose the specific measures, such as specifying public safety zones, with limited access for third parties and with the intention to protect them from aviation accidents, in the densely populated area of a major city. This means that acceptable TPR should be an inherent element of the safety objectives of the SC-VTOL certification specifications.

With the prime focus on safety as the highest priority for third parties on ground [2], this study addresses an essential question:

> *Are the current safety objectives of the SC-VTOL (for the 'Enhanced' Category) sufficient to achieve acceptable third party risk for a sizeable volume of UAM operations, without specific operational measures?*

In response to the question above, the present paper aims to present a TPR analysis method, to provide the criteria to assess UAM operations over a densely populated area, and to illustrate the correlation between internal and external safety objectives for UAM. In addition, this study provides insight into the traffic volume that could be accommodated over urban area with acceptable TPR, based on a realistic, challenging scenario for an UAM operation between an airport and a vertiport located in the centre of a city.

II. THIRD PARTY RISK METRICS

TPR concerns the risk to persons that are not involved in the activity that induces this risk. Typically, the third party involves people living and working on the ground who are not involved in the flying activities overhead, but may certainly be exposed to risk due to an aircraft crash.

While air transport is considered an extremely safe mode of transportation, risks still remain. For example, airports generate a concentration of air traffic over the area around the airport. And historically, aircraft accident data show that about 60% of accidents occurred during the initial and final phases of the flight [3], thus in the vicinity of airports. As a result, the risk to people nearby an airport is significantly above average.

The risk caused by aircraft departing from or arriving at the airport to the people residing in the vicinity of the airport is assessed by means of a TPR analysis. Two metrics are used, i.e. Individual Risk (IR) and Societal Risk (SR). Both risk metrics have their own characteristics in expressing risk. They are complementary to each other and are commonly used as basic information for TPR studies and risk communication.

A. Individual Risk (IR)

IR is defined as the "local probability per year that a person, who is permanently residing at this particular location, suffers a fatal injury as a direct consequence of an aircraft accident on or near his/her position" [4].

The characteristics of IR are: (1) it represents a point-location risk calculated for every location around the airport; and (2) it is calculated for a fictive person who is presumed to stay permanently in one location and is independent of the actual population around the airport. IR decreases with increasing distance to the risk source, i.e. the airport, and is commonly visualised by iso-risk contours, plotted on a topographical map.

According to the Act on Aviation of the Netherlands, it is required to determine the 10^{-5} (per year) and 10^{-6} (per year) IR-contours for airports in the Netherlands [5]. These contours are subsequently input to a public safety zoning process. Within the 10^{-5} contour, no houses for permanent living are allowed and existing houses are demolished. Only existing objects for non-permanent usage are allowed in this area. Within the 10^{-6} contours, existing houses are accepted, but no new housing developments are allowed. In theory, 10^{-6} is considered the boundary of acceptable TPR. A slightly higher risk, in the area enclosed between the 10^{-5} and 10^{-6} contours, is only considered tolerable in case of existing houses in that area. Therefore, from a TPR perspective, the following criterion applies:

- $IR \leq 10^{-6}$: acceptable risk.
- $10^{-6} < IR \leq 10^{-5}$: tolerable risk.
- $IR > 10^{-5}$: unacceptable risk

For the present study, TPR resulting from UAM operations is considered acceptable when the resulting IR is $< 10^{-6}$ (per year). This appears slightly stricter than the current practice in the Netherlands, where for existing airport operations and existing houses tolerable risk is also accepted. However, for this new type of operations, that is the UAM in congested areas of the city, it appears prudent to safeguard existing houses from TPR based on an acceptable risk level. In other words, the UAM operation should be designed to avoid exposing any existing houses and its inhabitants to an $IR > 10^{-6}$ (per year).

B. Societal Risk (SR)

SR is defined as "the probability per year that a group larger than a given number of persons (third parties) is killed due to a single aircraft accident" [4].

SR is presented as an FN-curve. The letter 'F' (frequency) stands for the probability per year and 'N' stands for the group size of fatalities. Due to the wide range of values of probability and group sizes, the FN-curve is practically plotted on a double-logarithmic scale. For the purpose of risk calculation, only a selected number of group sizes are calculated, for example, N={2, 5, 10, 20, 50, 100, 200, 400, 1000}. The characteristics of SR are: (1) it depends on the actual population distribution around the airport, so SR would be zero if no population is present around an airport; and (2) it represents the risk over the (study) area around the airport and accumulates the risk contributions for each group sizes selected.

SR is used in the Netherlands to support public safety zoning decisions. However, there are no strict criteria that define an acceptable level of SR due to aviation operations. SR is not a standard, but rather there is an accountability obligation [6]. As part of this obligation, Societal Risk is compared with a so-called Orientation Value for Establishments (OVE). The OVE is used as a SR guideline to which the competent authority must adhere to as much as possible. The OVE is defined as $10^{-3}/N^2$, where N stands for group size. Applying this definition of acceptable SR, it can be established that the risk for a group of two persons or more due to the UAM operations should not be higher than 2.5×10^{-4}.

The essential difference between IR and SR is that SR is dependent of the population density, whereas IR is not. Despite these differences, both risk metrics are important for evaluating third party risk.

III. VEHICLE SAFETY TARGETS IN RELATTION TO THIRD PARTY RISK

As was mentioned before, current type certification specifications do not contain any specific requirement to ensure acceptable risk for third parties. This means that it is basically assumed that the internal safety of a type certified aerial vehicle is sufficient to prevent unacceptable risk exposure to third parties. In general this may be considered as an acceptable assumption, because in the rare case of an aircraft accident usually no third parties are involved.

Nevertheless, based on information from NLR's internal accident database, in the 10-year period between 2009-2018 approximately 150 worldwide fatal accidents with commercial aircraft occurred, with third parties affected in 14 cases, leading to 185 ground fatalities and 70 injuries. These numbers show that TPR should not be neglected, especially not in congested areas close to airports where air traffic streams concentrate. Therefore, it can be questioned whether the hypothesis that the internal safety of a type certified aircraft indeed always ensures an acceptable level of external safety is actually true.

Whether or not the mentioned external safety target in Section II can be achieved with the internal safety level of a type certified commercial aircraft is demonstrated by a simple calculation. The (internal) safety objective is expressed in accident probability per flight hour (FH). The required minimum safety level of a CS-25 certified commercial aircraft is an accident probability of 10^{-6}/FH. Only the take-off and landing operations at an airport are of interest, and a distance of around 6 nautical miles (NM) from the airport is assumed. The exposure time for a take-off or landing would be around 3 minutes. Assuming that the accident probability is equal for all flight phases, the accident probability would then be equal to 5×10^{-8} per movement. However, it is known that the approach/landing and take-off/climb phases are the most risky parts of the flight. Research by Boeing [3] shows that around 12% of the accidents occurred during the take-off and climb and 49% of the accidents during the final approach and landing. Based on an average 1.5-hour flight duration it is shown that during the take-off and climb the accident probability is 4 times higher than the average accident probability per flight hour. For the approach and landing phase it is even a factor of 18. Therefore, the probability for an accident near an airport is roughly 10 times as high as the average probability. The accident probability per movement near the airport would therefore be around 5×10^{-7}.

For a crude estimate, the probability of an accident near the runway for a busy airport that accommodates 100,000 movements per year is then 5×10^{-2} per year, or once per 20 years. So, if the area around the runway were fully populated this would also be the external safety level expressed in IR. Clearly, this is far from the acceptable level 10^{-6} per year. This leads to the conclusion that the internal safety level of a type certified commercial aircraft is not sufficient to ensure an acceptable external safety level, in particular when it is involved in high volume operations of an airport in a densely populated area in a city.

The solution to this problem for safe coexistence of aviation and the populated areas around airports is generally found in the following way. The current internal safety level of type certified aircraft is simply accepted and public safety zones are defined such that exposure to aircraft accidents of persons living around airports is sufficiently reduced in the high risk areas, by simply avoiding the presence of people in those areas. Therefore, in several countries, e.g. the UK, Ireland and Italy, external safety requirements are used for public safety zoning in order to reduce risk exposure of people around airports. In the Netherlands regulations in protecting third parties and safety zoning were established. It requires the application of a specific TPR calculation method, which has been developed by NLR [7], [8] and embedded in the national aviation law [9].

It might be argued that UAM operations cannot be compared with commercial operations at large airports, but rather with general aviation (GA) operations. Reference [10] for instance states that TPR for GA is not statistically significant. It is true that the GA aircraft weight and size are significantly less than commercial aircraft and therefore the potential lethality is significantly less. Nevertheless, GA aircraft still cause fatalities on the ground and therefore it depends again on what is meant with statistically significant and what is considered acceptable. In any case, in the Netherlands it is recognised that GA too may present a certain TPR, and therefore, the public safety zoning requirements do not only apply to the larger commercial airports, but also to the smaller GA airfields and heliports.

So, can we envision that the UAM vehicles, certified according to the EASA SC-VTOL specification, are sufficiently safe to ensure that the required external safety levels are met with?

Here it is relevant to assess what the EASA SC-VTOL-01 [1] mentions in this context. In [1], p. 5, it states, "In order to be proportionate to the nature and risk of particular activity to be conducted by VTOL aircraft, two certification categories are introduced in this special condition, namely 'Basic' and 'Enhanced', linked to the intended type of operations. … Introducing this additional link allows proportionality in safety objectives and enables to apply the highest safety levels of Category 'Enhanced' to protection of third parties when flying over congested areas and when conducting commercial air transport of passengers. The operational rules can then be built on demonstrated aircraft safety levels and adapted as necessary to local particularities." So, actually it is stated that:

- The certification category is linked to the intended type of operations;
- The highest safety level is required for the Category 'Enhanced' to protect third parties;
- Operational rules can be based on the demonstrated safety level and adapted to local particularities.

As for the first bullet, the SC-VTOL covers two different safety standards, based on a specific use case: the lower for the category 'Basic' and the higher for the category 'Enhanced'. The difference is specified as a different response to a failure. The category 'Enhanced' is required to be capable of 'continued safe flight and landing' after a failure, whereas the category 'Basic' needs only to be capable of a controlled emergency landing. This is more or less similar to the discrimination of Performance Classes (1,2 and 3) for regular helicopters.

The second bullet indicates that the higher standard is required to protect third parties. It is however not mentioned what safety standard is required to sufficiently protect third parties. It only relates to the capability of continued safe flight or a controlled emergency landing after a failure. Nothing is stated concerning the acceptable probability of loss of control, or other accident types for both categories, while loss of control is one of the major causes for fatal accidents and thus also for accidents for third parties for instance.

The third bullet indicates that the demonstrated safety level may not be sufficient to achieve the required TPR level and that this may be solved by operational rules adapted to the local particularities. This suggests that some (operational) mitigating measures may be required to achieve the required TPR level. What these mitigating measures could be, in terms of operational rules, is not addressed in the SC-VTOL. For normal airport operations, public safety zoning is a logical solution to deal with third party risks. However, for UAM applications in the congested area of major cities it will be hard to realise. It is the essence of UAM to deliver passengers in the congested city area where it will be not practical to specify such zones as a condition for the UAM operations. Therefore, other measures must be found such that, with the demonstrated safety level of the UAM vehicle, it is possible to conduct the UAM operations with an acceptable risk for third parties. In this context, SC-VTOL provides some interesting statements:

- EASA concluded that the levels of system complexity which are introduced by the distributed propulsion and corresponding advanced flight controls are deemed sufficiently unusual and novel that the **current CS-23 acceptable means of compliance are no longer considered appropriate for determining the aircraft and system safety objective.**
- The current system safety objectives for CS-25 and CS-27/29 aircraft should be maintained as a minimum for the commercial air transport (CAT) operations of passengers **as well as for UAM using VTOL aircraft to address the risks to persons on board and on the ground**.
- The corresponding safety objectives **have been increased by one level compared to CS-23**, due to the higher dependency on systems that are associated with distributed propulsion, VTOL and the possible invalidation of other CS-23 assumptions.

In simple terms it is stated the CS-23 safety objectives are not appropriate, the safety objectives of CS-25/27/29 should apply to UAM vehicles and the safety objectives should be raised with one level relative to CS-23. This means that UAM vehicles are to be certified with the same safety objectives as for large aircraft or helicopters, and that the fatal accident probability should be at least $<10^{-6}$/FH. As explained earlier, this target level of safety is insufficient to ensure a sufficient level of external safety in the congested area around an airport when applied to large aircraft. The question is whether it is sufficient to ensure an acceptable level of external safety for UAM operations with specific UAM vehicles, certified in agreement with the EASA SC-VTOL.

IV. HYPOTHETICAL SCENARIO AND ASSUMPTIONS

The mathematical model applied for the TPR calculation is the same as the one that is currently used in The Netherlands for TPR assessments for airports and heliports and as required by the Dutch rules and regulation for the aviation sector. Specific modifications to the model for application to UAM operations have been introduced. Particular attention is given to the TPR in the en-route phase.

The standard model applies only for the approach/landing and take-off climb phases, because these phases present the dominant risk. For UAM operations, where the en-route phases frequently occur at relatively low altitude over congested areas of the city, this risk contribution cannot be neglected and therefore is also considered in the risk modelling specifically for the hypothetical scenario here. Table I presents the model parameters applied and the relevant references for TPR models [11], [12].

As a starting point, a TPR calculation scenario is devised in which the UAM vehicle is allowed to operate above the city and transport passengers from a location outside the city to the congested city centre area. The hypothetical scenario selected here is an electric VTOL (eVTOL) aircraft used as an air taxi (2 to 4-seater, about 450 kg) operating between Amsterdam Schiphol Airport and Amsterdam Central Station. The route between these two locations is conjectured to be a most-demanding and profitable trip for rapidly bringing (business) travellers from the airport to city centre and vice versa. Four flight routes are defined for departure from and arrival to the vertiport (Figure 1): departure and arrival in the south-west direction, and departure and arrival in north-east direction followed by a turn over the river towards the city centre.

The UAM vehicle is assumed to be certified according to SC-VTOL and controlled by a single, certified pilot. In the future this type of operation might possibly be performed autonomously, without a pilot on board. This type of operation is, however, not covered by the SC-VTOL, which assumes that the vehicle is controlled by a pilot. It should be noted that, in terms of target level of safety, both kinds of operations should be equivalent. In terms of failure conditions and scenarios, both types of operations could be significantly different. For instance, an autonomous operation will be inherently free of pilot-error and pilot-induced loss of control. However, at the same time the type certification cannot rely on pilot intervention credit in case of a system failure. This scenario will require an analysis of all possible system failures, including the failure consequences, in case no pilot is on board to correct them. This might lead to potential failure scenarios, such as fly-away events in case of navigation failure or communication link problems, which may be unique to autonomous operations and which may affect the resulting TPR.

TABLE I. TPR MODELS APPLIED FOR UAM

TPR models applied for UAM (eVTOL)	
Phase of flight	***Models, parameters and references***
departure & arrival	Standard helicopter TPR model [11]
en-route	GA aircraft TPR model [12] modified for following components: (1) Accident rate (*p*): 10^{-6}/FH [1] (2) Accident location; probability distribution function (*PDF*): uniform distribution assumed for loss-of-control in-flight (3) Accident consequences: crash area (*CA*) 145m^2 and lethality (*let*) 0.13 [13]

Figure 1. Departure and arrival routes (red) for the hypothethical Vertiport located at Amsterdam Central Station *(arrows depict the flight directions)*.

V. RESULTS OF THIRD PARTY RISK CALCULATIONS

The TPR calculations for the eVTOL operations in urban area are performed and the results are presented in terms of IR and SR.

The result of the IR calculation is compiled from separate calculation results for en-route risk and for take-off and landing risk. A starting number of movements is chosen for the "basis-calculation" for the scenario. This number is initially set to 10,000 movements per year for reference (i.e. roughly 30 per day). When the result is combined from different en-route and take-off and landing risk results, the result of the basis-calculation is then scaled up or down in order to find the number of movements that can be accommodated with acceptable TPR. The maximum traffic volume is found when no houses or other critical objects are covered within 10^{-6}/year IR contours, or when the probability for a group of two or more persons be killed in an accident by eVTOL is smaller than SR guideline (see Section II).

The result represents a scenario with the maximum number of UAM operations that would be allowable from a TPR perspective, given the safety level that is ensured by the type certification safety objectives. The results of IR calculations are presented as contours (iso-probability lines) on a topographical background. The results of SR calculations are presented as a plot on a double-logarithmic scale presenting the probability against the group of fatalities.

A. Individual Risk (IR)

For the IR calculation (Equation 1) a study area of 15 kilometres by 15 kilometres is chosen which covers the entire flight routes from Schiphol airport to the fictive vertiport located at the Amsterdam railway station. The calculation grid cell size is set to 25 metres by 25 metres.

$$IR = n \cdot p \cdot PDF \cdot CA \cdot let \tag{1}$$

where n = number of movements, p = accident rate, PDF = distribution function, CA = crash area, and let = lethality.

Figure 2 presents the results of en-route and take-off and landing risks combined for 10,000 movements a year. In the figure IR contours are depicted on a map background. According to the criteria used in the TPR around airports in the Netherlands, only the 10^{-5} and 10^{-6} (per year) risk contours are actually of interest. For demonstration purpose the contours of the lower risk values are also presented. It can be seen that the IR contours of 10^{-6} or lower risk values north of the vertiport curve with the flight routes over the water and turn back towards southwest direction. In Section III, it has been assumed that no houses (with permanent residents) are allowed within the 10^{-6} IR contour. As can be seen from Figure 2, a part of the residential area in the inner city of Amsterdam is located within this contour, and even on the other side of the River IJ some houses are covered within the IR contour.

It is evident that this volume of operations to and from the vertiport is not acceptable from a TPR perspective. To avoid that existing houses located within the 10^{-6} IR contour, the number of yearly movements has to be scaled down to around 700, as shown in Figure 3. This amounts to about **one flight (one arrival and one departure) per day**. It is very likely that this volume will not be sufficient to sustain the given UAM operation and certainly would have no impact on relieving other traffic streams (train, bus and car) to satisfy the traffic demand between Schiphol and the inner city of Amsterdam.

So, which measures can be envisioned to achieve an increase in the traffic volume? In practice there are three possible methods. These three have a direct and linear relationship with the traffic volume. In theory, accepting a 10 times higher risk and reducing the accident probability and crash area each with factor of 10 at the same time, will result in a 1000-fold increase of the acceptable traffic volume, and thus boost the traffic volume from 1 to 1000 flights per day. In the following, these methods are addressed to what extent improvements can be realised.

1) Relaxing the TPR safety criterion

In case the TPR safety criterion would be relaxed with a factor 10 the determining IR contour would be at the 10^{-5} level. This would be at the current boundary between tolerable and unacceptable risk (Section III). At present, this level of risk is considered acceptable for existing airport operations and existing houses in the Netherlands. It is however questionable whether it would be acceptable for an entirely new operation in a congested area of a city. It would expose residents to a risk that is clearly not acceptable and that is considered only tolerable. Inhabitants in that particular risk area will perceive this as not being fully protected from a new risk to which they are involuntarily exposed without clear direct benefits to them. Therefore, any relaxation of the TPR criterion is expected to meet resistance from the local residents. In addition, there are other arguments, such as noise hindrance and societal acceptance, to avoid an increase of traffic volume. Thus, it is not likely that any relaxation of the TPR criterion will be accepted in order to increase the traffic volume.

2) Reducing the accident probability

The accident probability used to calculate the IR-contours is based on the already strict certification requirements for UAM vehicles, as presented in the EASA SC-VTOL. As mentioned, these requirements are already an order higher than for normal and utility aircraft as specified in CS-23 and are at the same level as large commercial aircraft (CS-25) and multi-engine large helicopters (CS-29).

In order to reduce the accident probability, the UAM vehicle would have to be certified against an even stricter standard than the current SC-VTOL and thus stricter than CS-25/29. This would be a challenge, in particular for these new types of aerial vehicles with a high level of system complexity due to the distributed propulsion and corresponding advanced flight controls. No commercial air vehicle has been ever designed to a stricter standard than CS-25/29. So, this would be uncharted territory in any case. It is even questionable if accepted design methods and means of compliance are available that would enable the certification of an air vehicle against such a stricter safety requirement. For instance, the well-known CS25.1309 requirement, concerning System Design and Analysis, requires a minimum acceptable probability of 10^{-9}/FH for fatal failure conditions. For flight critical, fly-by-wire and software based flight control systems it is already extremely challenging (and costly) to design such systems and prove that they meet the required safety level. If we would have to certify the UAM vehicle to a tenfold higher safety level, then the system safety requirement would have to increase to 10^{-10}/FH automatically.

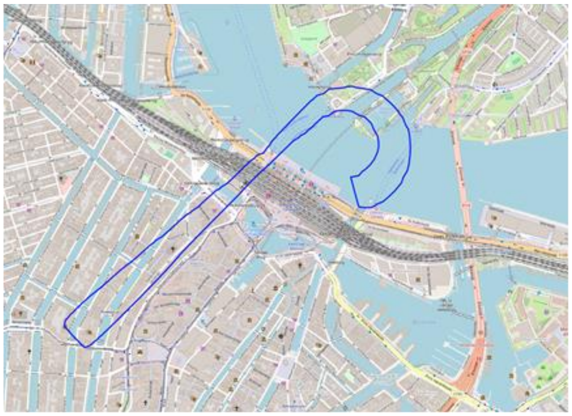

Figure 2. IR contour 10^{-6}/year (blue) for 10,000 eVTOL movements a year.

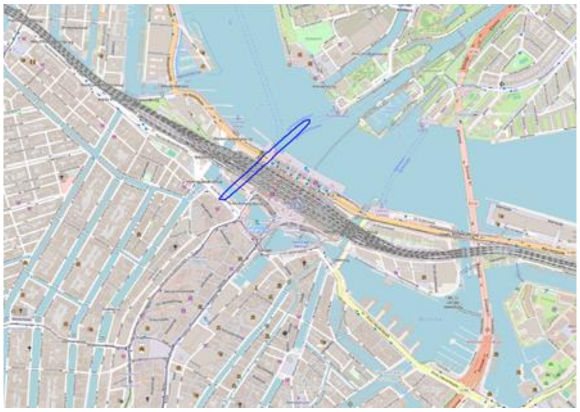

Figure 3. IR contour 10^{-6}/year (blue) for 700 eVTOL movements a year.

It is evident that it would be an extremely challenging task to reach this overall safety objective. Apart from the associated increase of design and certification cost, it may even be questionable whether current state-of-the-art technologies are capable of reaching the required safety level for UAM vehicles with such a high level of system complexity. At least this has never been demonstrated up to now. Therefore, it is concluded that it is not realistic to expect that UAM vehicles could or will be designed to a higher safety standard than currently is required on the basis of the SC-VTOL.

3) Reducing the crash area

The calculation of the IR contours is based on the standard model parameters for a light sport (GA) aircraft: the crash area is 145 square metres and the lethality is 0.13 [13] within the crash area. It is assumed that these parameters are representative for an eVTOL air taxi due to similar size and weight. However, measures may be envisioned that could reduce the lethality and the corresponding crash area. For instance, lethality could be reduced by equipping the vehicle with an emergency parachute system, which would be deployed when a crash is imminent. This will reduce impact energy and therefore may lead to a smaller crash area. With an effective emergency parachute system it may be possible to reduce the crash area to the size of the vehicle itself. Assuming that the vehicle has a dimension of 3 metres by 5 metres, the crash area could reduce to around 15m^2, which is a factor 10 smaller than used in the current third party risk calculation.

A recent study into the effectiveness of emergency parachute systems [14] indicates that these systems have around a 50% effectiveness during the terminal flight phase (approach/circuit). Historical data show that parachute systems are very effective, when deployed above 600ft. However, at lower altitude the effectiveness declines. About one-third of the cases where the parachute was deployed below 600ft led to fatalities, indicating that the emergency parachute was not able to sufficiently arrest the impact. It is also shown that for a typical weight of a UAM vehicle the minimum safe recovery height is around 150ft. Therefore, it is unclear what the total effectiveness of an emergency parachute system could be during take-off and landing phases to reduce the lethality for persons on the ground. Moreover, pilots might be reluctant to deploy the parachute in built-up areas, as the parachute might become entangled with high objects on the ground, or the vehicle could land uncontrolled at very dangerous places, such as on the high voltage power lines of railways. Finally, a parachute device will reduce the payload of the UAM vehicle and add to the cost of the vehicle. Therefore, it can be concluded that it is possible to reduce the crash area by means of a parachute system, but it will go at the expense of increased cost and reduced payload. It is difficult to estimate what the impact on the crash area could be, but likely it will not be a reduction of more than a factor 5, taking into account the system effectiveness at low altitude.

Based on the above-mentioned considerations it is concluded that it will be a challenge to substantially increase the traffic volume for the vertiport above on **average one flight per day**. In conclusion, any business case should take this ultimate traffic volume into account to determine the return on investments (which could be significant to overcome the described challenges).

B. Societal Risk (SR)

In addition to IR, also SR (Equation 2) is computed.

$$SR_k = n \cdot p \cdot PDF \cdot \frac{N_{max}!}{k!(N_{max}-k)!} \cdot let^k \cdot (1-let)^{(N_{max}-k)} \qquad (2)$$

where n = number of movements, k = number of persons killed (group size with k = 1,2,3,… persons), and N_{max} = maximum number of persons that can be killed within the crash area (CA).

To calculate SR, the so-called population density data of the affected area are derived from the cadastral information and population database [15]. The information on the number of persons per object (e.g. houses, offices, shops, schools) is processed into the population densities as calculation inputs.

Figure 4 presents a plot of FN-curves for the reference situation based on 10,000 movements per year and the scaled-down situation with a reduced number of movements. The guideline of OVE is also given for comparison. In the figure, the x-axis presents the group of N or more fatalities whereas the y-axis gives the probabilities (F) for the groups N. Both axes are given in logarithmic scale.

From the figure it can be seen that the FN-curve for the reference situation does not meet with the OVE. A reduction in the number of traffic movements is then applied to lower the risk. This gives a maximum traffic volume of 1850 movements a year, which equates to around 2.5 flights per day.

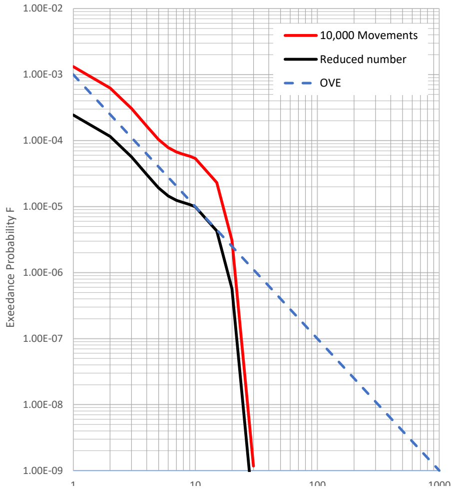

Figure 4. FN-curves with 10,000 movements (red) and 1850 movements (black). Also shown is the OVE reference (blue dashed line).

The number of traffic movements determined with the SR criterion is somewhat larger than that determined with IR criterion. Nevertheless the movements number found for both criteria have roughly of a comparable magnitude (700 versus 1850).

VI. CONCLUSIONS

The safety objectives of an UAM vehicle (eVTOL type) from a TPR perspective are assessed based on a typical, challenging scenario where the UAM vehicle provides direct passenger transport between an airport and a vertiport located at the railway station in the city centre of Amsterdam. This scenario is considered representative for the service that the Urban Air Mobility concept intends to provide.

The TPR metrics and computational model based on specifications in the Dutch regulations for civil airports are modified to the specifics of the UAM concept. The UAM vehicle is assumed to be type certified against the recently published EASA Special Condition for small VTOL aircraft and meets the corresponding (internal) safety level.

The results of the TPR calculation show that with the given (internal) safety level of the UAM vehicle on average only **one flight per day** can be accommodated at the vertiport, without violating the present third party risk criteria.

An increase of the traffic volume at the given location can only be realised by relaxing the TPR criterion, by increasing the (internal) vehicle safety, reducing the crash lethality and crash area, or a combination of these measures. Based on an assessment of the effectivity and feasibility of such measures it is concluded that a substantial increase of the traffic volume would be very difficult to realise.

It is recommended that any entrepreneur who envisions to initiate an UAM service into a major city, as illustrated in this paper, should be aware of the mentioned challenges and should base his or her business plan on a realistic traffic volume, taking into account the TPR involved in the operation. It is further recommended to the (local) regulator to evaluate the public acceptance of (plans of) introducing UAM operations in an urban area, based on the actual risk exposure. Finally, it should be noted that the scenario presented in this paper is just an illustrative example. Other scenarios could lead to different results. However, any operation to a congested area of a large city will likely be faced by similar constraints, limiting the potential traffic volume.

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