An Interface Specification for Urban Air Mobility Performance Models to Support Air Traffic Management Research

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Performance modeling of Urban Air Mobility vehicles in support of Air Traffic Management research poses new challenges. These aircraft often rely on a combination of fixed-wing and rotorcraft performance capabilities to enable a new and still-evolving concept of high-volume operations in densely populated areas. These characteristics lead to variability in performance model format and functionality, complicating model development and leading to difficulties for users integrating the models into their applications. This paper describes an interface specification for performance models that is intended to help address this issue. The interface aims to support the core functionality of performance models while also providing the necessary flexibility to both model developers and users. The specification describes the required model documentation, required inputs to the model, and required outputs from the model in general terms that are adaptable to most programming languages. The utilization of an appropriate interface specification will support the development of an Urban Air Mobility performance model database and help to improve interoperability of these models for a broad array of user applications.

I. Introduction

Urban Air Mobility (UAM) vehicles are a unique class of aircraft designed to enable efficient air transportation of people and cargo in densely populated areas [1]. There is substantial interest in studying the incorporation of these aircraft into the Air Traffic Management (ATM) system, necessitating the development of models that accurately capture their flight performance. Distinguishing features of many proposed UAM vehicles are vertical take-off and landing (VTOL) capabilities and unconventional aero-propulsive configurations. These aircraft often utilize an array of enabling technologies such as tiltrotors, tiltwings, stowable rotors, ducted fans, and fixed-pitch or variable-pitch rotor systems in combination with lifting wings and other elements designed to improve cruise efficiency and reduce noise. The complex vehicle designs lead to unique flight envelopes and performance trends that can differ substantially from traditional fixed-wing aircraft and helicopters [2]. Additionally, the UAM concept of operations and applicable regulatory requirements are still evolving, and there is an ongoing need to harmonize these developments with vehicle designs and subsequent performance models [1,3,4]. Taken together, the broad variation in UAM vehicle designs and lack of real-world UAM flight data creates a challenging environment for developing the realistic performance models needed to inform the decision making of regulators and industry stakeholders.

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This paper explores the challenges associated with performance modeling in support of UAM ATM applications and proposes interface specifications intended to improve the functionality and interoperability of these models. The proposed specification should provide flexibility for model users by encapsulating the model's internal structure, such that unique features and assumptions of performance models do not need to be individually accommodated by the user's application. These specifications also offer benefits to modelers by providing guidelines for developing a useful and consistent model interface. This shared interface will then facilitate the creation of a database of UAM performance models that are compatible with a diverse array of applications.

II. UAM Performance Modeling

ATM research often utilizes performance models for vital applications, including traffic management simulation purposes and aircraft trajectory planning and prediction (see generally, Ref. [5,6]). These models provide realistic vehicle performance and typically include details such as nominal airspeed as a function of flight segment and altitude, typical climb or descent rates, fuel consumption as a function of flight condition, and basic envelope limitations. Performance model formats vary significantly, but generally they can be characterized by the underlying mathematical structure and degrees-of-freedom. Common types of models include point-mass models, kinematic models, kinetic models, and some others not fitting these categories [5]. While certain model types are more conducive to UAM performance modeling than others, each of them could be compatible with implementation of an interface specification so long as it does not unnecessarily restrict the model's mathematical structure.

A. Typical Applications of Performance Models

Performance models are utilized for many different purposes. Some of the most common applications are traffic simulations, with some examples including TrafficSim [7], Narsim [8], BlueSky [9], and Airtop [10]. While the focus of traffic simulators is typically on evaluating Air Traffic Control (ATC) functions, the effectiveness of the simulation is often dependent on accurate modeling of vehicle trajectories and performance. However, the details included in many six degree-of-freedom dynamic models are rarely needed for the required level of accuracy, and the additional computational expense of these models is frequently prohibitive. Thus, the lower computational cost of performance models is often desirable as it improves the ability to run large-scale, fast-time simulations. For these reasons, the focus of these models is generally on capturing nominal operations and performance accurately and efficiently. There is often some support for identifying basic performance limitations as well, though this capability varies with the model being used and is often of secondary importance.

Optimization studies are another application of performance models, including those that involve evaluation of ATC procedures or traffic routing. Optimization tasks might include managing trajectories or traffic spacing to minimize fuel burn, reduce time enroute, mitigate noise (see e.g., Ref. [11]), and other objectives. In some cases, an individual vehicle's flight plan might be optimized in terms of cruise airspeed and altitude for given wind conditions. Any limitations or assumptions inherent to the performance model should be carefully considered to ensure that the model has adequate detail and accuracy to produce reliable results. In some cases, optimization applications need to be explicitly accommodated by the structure of the performance model, and in these cases an interface would likely need to facilitate this form of user interaction with the model.

B. Existing Performance Models

There are several existing databases of performance models for traditional aircraft such as commercial airplanes and helicopters. For example, the widely used Base of Aircraft Data (BADA) produced and maintained by EUROCONTROL includes models for over 300 aircraft types. BADA models are separated into families sharing a common structure and include BADA 3 [12] and BADA 4 [13] used primarily to model fixed-wing aircraft, and BADA H [14] which is similarly structured but has performance modeling assumptions adapted to traditional helicopters. Unfortunately, none of these modeling formats are directly applicable to UAM, due to differences in both vehicle performance characteristics and anticipated operations [2]. Efforts to extend the BADA H modeling approach to electric VTOL aircraft have been described but are still under development and appear to have limited coverage of UAM vehicle types [15]. Other approaches to performance modeling such as OpenAP [16] are also available but are similarly not targeted to UAM vehicle performance characteristics and operations.

Dissemination of performance models require a suitable format that provides an effective way of storing and exchanging the data that describes the model. Basic text file formats such as the American Standard Code for Information Interchange (ASCII) are sometimes used to provide model data to users, as are as other formats such as the eXtensible Markup Language (XML), with both used for BADA models [13]. Specialized data structures and languages have been developed specifically for organizing aircraft data, with XML-based examples including the

Dynamic Aerospace Vehicle Exchange Markup Language (DAVE-ML) developed by NASA [17], the Aircraft Design Markup Language (ADML) [18] developed at Virginia Polytechnic Institute and State University, and the Common Parametric Aircraft Configuration Schema (CPACS) developed by DLR [19,20]. None of these examples are specifically designed to support performance models, though they may be extensible to such applications if desired. For example, CPACS is designed to support a broad selection of aircraft design tools in a multi-disciplinary environment and could be extended to include performance models within its data structure. In CPACS, "wrappers" can be used to map parts of the XML data tree to input and output variables accessed or modified by a software application. This suggests a model format like CPACS might be an efficient way to keep performance models and associated aircraft design details organized together and would be especially beneficial if a suitable model interface was implemented to aid users in accessing key performance data associated with the design.

C. UAM Vehicle Performance Characteristics

While there are many proposed designs for UAM vehicles that have been publicly disseminated, detailed performance data for most of these concept vehicles are not widely available. The NASA Revolutionary Vertical Lift Technology project (RVLT) has produced several candidate UAM vehicle concepts intended to offer industry and researchers a realistic basis for assessing UAM vehicle performance and inherent design tradeoffs [21–24]. These UAM concept vehicles are sized to the mission outlined in Ref. [25], and include 6-passenger quadrotor, "lift+cruise", and tiltrotor designs (see Fig. 1), among others, with both fully-electric and hybrid variants. A recent NASA effort to generate performance models for a selection of these UAM vehicles is reported in Ref. [2].

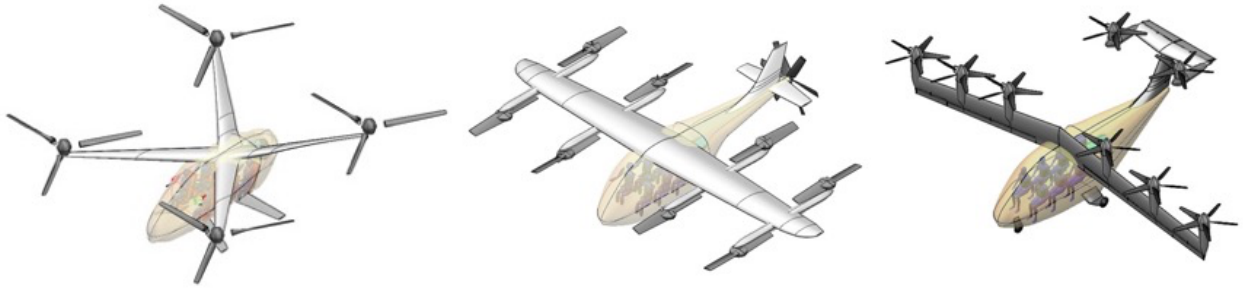


Fig. 1 Examples of the NASA conceptual UAM vehicles. Left to right: the 6-passenger fully electric Quadrotor, fully electric Lift+Cruise, and turboelectric hybrid Tiltwing.

The disparate performance trends between various UAM vehicles are one of the primary challenges to effective performance modeling. For example, Fig. 2 is derived from the performance modeling work described in Ref. [2] and shows the power requirement for the three NASA UAM vehicles shown in Fig. 1. Here, the power requirement for straight and level unaccelerated flight with six passengers as a function of airspeed is shown normalized by the vehicle's battery or fuel capacity. While the specific trends observed would vary depending on details of the vehicle design, it is easy to see that the Quadrotor, Lift+Cruise, and Tiltwing aircraft each possess unique power requirement trends. These differences further extend to the power requirement associated with climbs, descents, and acceleration, illustrating the challenges associated with performance modeling for these vehicles. Thus, flexibility in the performance model is likely required, as a parametric model appropriate for the Quadrotor might not be adequate for the Tiltwing aircraft.

Another challenge posed by the unique performance characteristics of UAM vehicles is the determination of appropriate performance envelope boundaries. All aircraft possess inherent performance limitations, but the complexities of UAM aircraft designs lead to challenges both in establishing appropriate boundaries and representing them in a performance model. For example, UAM aircraft with many individual electric motors might have complex regions of the flight envelope in which the maximum power output of some motors is reached, and these limitations could have numerous dependencies on the flight condition and vehicle configuration that is selected. Such envelope boundaries can sometimes play an important role in certain performance model applications. For example, traffic deconfliction studies may require appropriate envelope limitations on vehicle acceleration to appropriately represent the maneuverability of an aircraft, and trajectory optimization studies may depend on the feasible climb or decent rate, airspeed, altitude, and other performance limitations applicable to the vehicle. In general, different performance modeling methods offer varying levels of detail regarding envelope limitations. Incorporating access to envelope information into an interface specification requires a flexible approach that can be adjusted based on the model and user application.

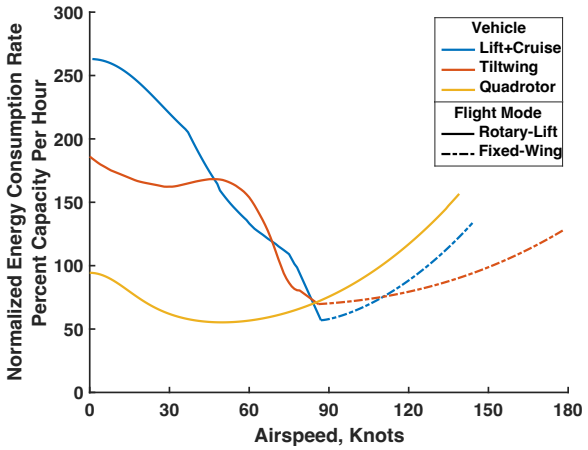


Fig. 2 Comparison of power usage by three NASA UAM aircraft operating in level unaccelerated flight with a payload of six passengers at sea-level ISA conditions.

Detailed dynamic characteristics related to control of the vehicle are often not captured by performance models. For example, a parametric representation of the nominal dynamics associated with heading adjustment, climb rate, or altitude intercept, and other typical flight maneuvers may not be explicitly included in most performance models. In some applications, such details must be assumed by the user based on known operating norms appropriate to the model application. In others, instantaneous transitions between flight segments may even be acceptable. Thus, incorporating detailed information of this kind into the model interface is not generally required, and is avoided here.

D. UAM Flight Segments

It is often the case that vehicle performance varies by flight segment and that these variations must be accounted for by the model. This is because for a routine flight, certain characteristics of the aircraft's operation or performance are changed depending on the stage of flight and operational intent. Assumptions about flight segments can be built into a performance model definition, as is sometimes the case with BADA models [12], or as discussed in Ref. [16] for OpenAP. Such flight segment assumptions are often valuable for simplifying the performance model as they can make specifying aircraft performance characteristics more convenient and understandable to users. Segment definitions are also essential to many performance model applications involving trajectory generation or prediction. However, the uncertainty regarding UAM vehicle operations and designs makes appropriate segment definitions somewhat unclear.

In Ref. [2], segment definitions were based in part on the representative UAM mission described in Ref. [25], with additional segments defined to adequately cover the nominal flight envelope of the vehicle. For UAM aircraft, segments might be used to specify appropriate configuration settings such as wing or rotor tilt angles, stowage or activation of lifting rotors, flap settings, nominal climb or descent rates, speed schedules, power settings or limitations, and other details. The specifics of these might vary substantially with different UAM vehicle designs and the assumed operational environment. For UAM performance model development, flexibility in segment definition is required as UAM operations evolve and the vehicle designs progress. Thus, an interface specification should allow modelers to utilize segment definitions suited to the vehicle and operating environment under consideration, while requiring that the segments be explained in detail to users such that they can appropriately utilize them. As UAM operations and vehicles mature, segment definitions may become more consistently established, and less flexibility may be needed.

E. Performance Model Database

The development of a database containing performance models for representative UAM vehicles would be beneficial to the ATM research community and industry stakeholders. To be practical, this database would require the adoption of a consistent interface to ensure that all models shared a common user-facing functionality, even if the internal structure or assumptions of the models contained in the database differ. This shared interface will also benefit performance model developers and users by ensuring that both the model and the user application are developed from an early stage to be compatible. However, a widely accepted approach to developing performance models in support of UAM ATM applications has not yet been established. This is the result of several factors, including the broad variability in UAM vehicle designs, the difficulty of obtaining reliable and adequately detailed UAM vehicle

performance data, uncertainty about UAM traffic operations and airspace, as well as the lack of established requirements that these models will need to meet to address user needs.

III. Proposed Interface Specification

The notion of an *interface specification* varies by application and among fields but is frequently encountered within the discipline of software development, where related (and sometimes overlapping) concepts are *application programming interface* (API), and *signature* [26]. In this paper, such terminology is used to describe the required interaction and communication capabilities of both the performance model and the user's application. No assumption of a specific programming language or syntax is made, and instead a more general description of the interface is provided. The intention is that performance models adhering to the basic specification will require minimal effort to adapt to the needs of specific user applications and software. The interface is intended to act as an intermediary between the aircraft performance model and the user application, effectively encapsulating the model. Performance models implementing a consistent interface specification would then require minimal effort to be used interchangeably. A notional diagram of the performance model and interface being used in a typical application is shown in Fig. 3. The specifications are chosen to facilitate the core functionality of most performance models while aiming to provide flexibility to both modelers and users. Items which would unnecessarily restrict either the mathematical structure of the performance model or the user's application are avoided. The interface specification for the performance model is described in three parts: documentation, inputs, and outputs.

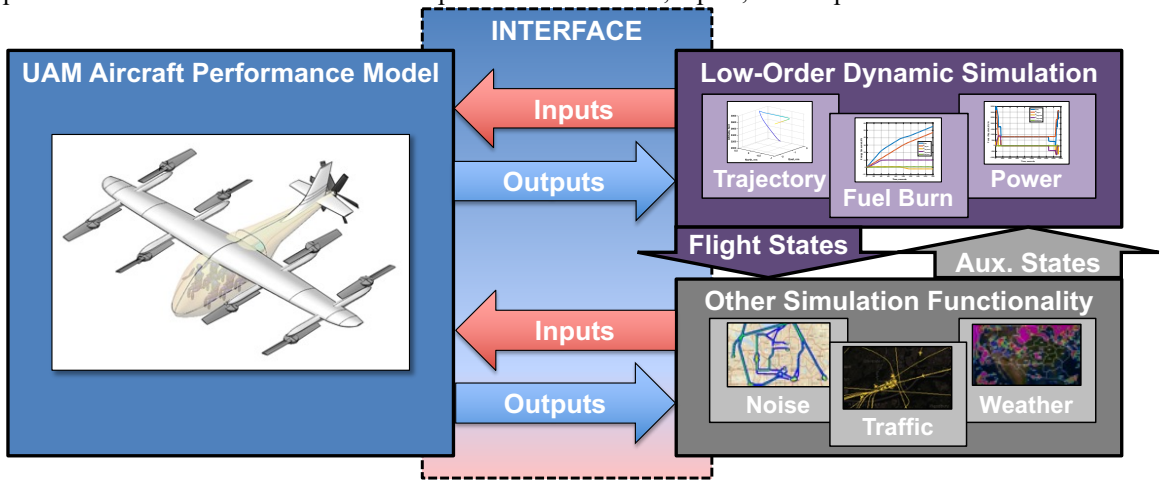


Fig. 3 Notional diagram of a possible use-case for the proposed performance model interface. Noise image adapted from Ref. [11], traffic and weather images adapted from Ref. [27].

A. Required Model Documentation

A minimum set of details describing critical features of the model and interface must be provided to users to ensure that they are able to use the performance model correctly. This information should be supplied with the performance model in the form of documentation. Table 1 lists specific items that must be included, along with their description. All input and output functionality must be explained in detail including the required syntax. Individual methods or calls must be listed and described in detail, as well as any internal parameters or properties stored within the performance model and accessible by the user. In addition, any relevant coordinate systems, inputs, and outputs, including units, used to interact with the model must be explained. For attributes describing the modeled ranges of vehicle payload, fuel tank capacity, and battery storage capacity, all necessary details must be included. For example, the correct accounting for loss of weight due to fuel burn or changes to power availability as a function of battery charge state should be explained. Other parameters of importance unique to the vehicle model should also be described. In some cases, these parameters will be accessible as outputs relevant to the stage of flight or configuration, in other cases they might serve as inputs to the model. The definition and appropriate use of flight segments and flight configurations settings should be described in adequate detail so that even users initially unfamiliar with the performance of the aircraft can use the model effectively in their application. Unique characteristics of the vehicle should also be documented and explained here as appropriate. For example, if the modeled vehicle has a required takeoff profile, the correct application of this in relation to the use of the model must be explained to the user. For some applications it might be appropriate to make a subset of these attributes, or the values related to them, retrievable

through the interface. For example, a data-access method might be included that returns the maximum battery capacity, or a range of available payload settings. However, attributes and constant parameter values reported in the documentation are generally not required to be otherwise accessible through the interface.

Table 1. Required Documentation

Model Attributes	Description
Input/Output Functionality	Performance model interface input and output functionality and syntax. Individual methods or calls must be listed and described in detail.
Input/Output Coordinates, Units, and Data Types	All units for inputs and outputs, as well as coordinate systems used, must be described. Data types for inputs and outputs (e.g., integer, string, Boolean) should also be documented if applicable.
Passenger and Payload Weight Limitations	Valid passenger and payload mass or weight values and settings, as appropriate to the vehicle.
Fuel Tank Capacity	Fuel capacity (typically in terms of mass), if applicable, along with appropriate details describing correct usage.
Battery Storage Capacity	Battery storage capacity expressed in the format used by the model, if applicable, along with appropriate details describing correct usage.
Parameter List	Other parameters, settings, or flags relevant to the model and required for correct model implementation.
Segments or Flight Configurations	Complete description of individually modeled flight segments (e.g., cruise, hover, descent) or special configurations or flight modes (e.g., extended speed brakes, rotor stowage) that are necessary arguments to the model.
Atmospheric Conditions Model	Description of the atmospheric model. For example, ISA conditions might be assumed, or more detailed modeling capabilities supported, but this must be documented and explained to the user.
Model Validity Limitations	A description of the known limitations on the model's fidelity or assumptions that were made during the modeling process must be included. A model-validity envelope can be provided as appropriate (e.g., minimum and maximum altitudes). This should be explained in enough detail that the user can understand how to utilize the model reliably.
Modeled Performance Limitations	Any modeling of the performance limitations of the vehicle, or lack thereof, should be explained. This might include dynamic constraints, power limitations, airspeed limitations, or others supported by the interface.

B. Required Inputs

A list of required inputs is given in Table 2 to ensure that the user develops their application to provide sufficient information to the performance models. Here, V_{TAS} is true airspeed, h is aircraft geopotential altitude, ψ is heading, m is vehicle mass, and first and second derivatives of a value with respect to time are denoted by a single or double dot respectively. It is not required that the model utilizes all these inputs, and many interactions with the model through the interface may require only a subset of them. Inputs such as battery charge and fuel tank level are not necessarily required to be used by the model to compute the output, though for some models they might be needed and should generally be available. Alternative coordinate systems and descriptions of vehicle motion such as Mach number or flight path angle are allowed so long as these are unambiguously defined in the documentation required by Table 1, and all units assumed by the model must always be specified. In many applications, ISA conditions (identical to the U.S. Standard Atmosphere [28] for altitudes below 50 km) may be an acceptable assumption, though more detailed atmospheric modeling is not precluded by the interface specification. Note that while turn rate is specified as an input, bank angle is not. While some performance models incorporate a power-requirement that is dependent on bank angle (see e.g., Ref. [2]), this bank angle is typically computed as a function of required or actual turn rate. Therefore, only turn rate is specified here as this does not in any way preclude the use of bank angle in the user's application or internal to the model.

Table 2. Required Inputs

Inputs	Description
Velocity and Climb or Descent Rate, Altitude, Turn Rate, mass (e.g., $V_{TAS}, \dot{h}, h, \dot{\psi}, m$)	Vehicle state including airspeed, rate of climb or descent, geopotential altitude, turn rate, and mass (including fuel and passengers), respectively
Acceleration (e.g., $\dot{V}_{TAS}, \ddot{h}$)	Specified acceleration. Used in applications where the vehicle state and acceleration are to be input and fuel or battery consumption is computed
Percent Power (e.g., P_{eng})	Specified power to be applied. Used in applications where acceleration is computed for a given power input. Desired share of power applied to velocity or climb typically required as input in accordance with the documentation.
Battery Charge	State of battery charge, if applicable
Fuel Tank Level	Level of fuel remaining, if applicable
Parameter Values	Values of parameters or flags listed as required in the documentation, if applicable. Usage may vary with segment or flight configuration.
Segment or flight configuration	Name of flight segment and configuration of vehicle, as applicable.
Atmospheric Condition	Atmospheric condition description in accordance with Table 1. If ISA conditions are assumed, input may simply be an ISA altitude.

C. Required Outputs

A list of output data accessible through the performance model interface is given in Table 3. Nominal flight conditions for a given segment or configuration that vary with altitude, airspeed, acceleration, weight, or other parameters should be accessible through the interface as an output based on the appropriate inputs. In cases where these values are constant and included in the documentation, the corresponding output might be omitted. For many flight conditions, a key output from the performance model is fuel burn or battery power consumption rate. This must be accessible through the interface as a function of appropriate input variables.

Also required is access to the relevant performance limitations. These might be expressed in terms of acceleration, climb or decent rate, airspeed, altitude, turn rate limits, and maximum motor or engine power limit (P_{eng}). In general, these can be a function of any combination of the inputs, but in some models might be constant values. If these limitations are not available within the model, this should be explained in the documentation and suggestions made to the user on how to obtain realistic performance from the model. The specifics of implementing limitations are left to the modeler, but the advantage of including them with the interface specification is that these choices are made by the modeler rather than an end-user with (typically) less understanding of the vehicle's limitations. Thus, models with low fidelity and very approximate limitations on acceleration or maximum envelope are permitted, but this should be communicated to the users as needed via the documentation.

Table 3. Required Outputs

Outputs	Description
Description of Nominal Flight Condition for Selected Segment	Typical flight conditions for specified segment, usually as a function of aircraft state. For example, nominal cruise airspeed for a given altitude, typical climb rate and associated airspeed for best climb, etc. Type of data provided will typically vary with segment as described in the model's documentation.
Fuel burn	Fuel burn rate, if applicable.
Battery Power Consumption	Battery power consumption, if applicable.
Acceleration Limits	Appropriate limits for acceleration (both horizontal and vertical) due to any modeled limitations, e.g., $\dot{V}_{TAS,min} \leq \dot{V}_{TAS} \leq \dot{V}_{TAS,max}$.
Power Limits	Limits on available power given flight state, e.g., $0 \leq P_{eng} \leq P_{eng,max}$, if applicable
Climb and Descent Rate Limits	Appropriate limits for climb and descent rate due to any modeled limitations, e.g., $\dot{h}_{min} \leq \dot{h} \leq \dot{h}_{max}$.
Turn Rate Limit	Appropriate limits for turn rate due to any modeled limitations, e.g., $\lvert\dot{\psi}\rvert \leq \dot{\psi}_{max}$.
Airspeed limits	Appropriate limits for airspeed due to any modeled limitations, e.g., $V_{TAS,min} \leq V_{TAS} \leq V_{TAS,max}$

IV. Summary and Future Work

The proposed interface specification seeks to promote compatibility of UAM performance models with a broad range of ATM applications by offering guidelines intended to benefit both modelers and users. As UAM vehicles and operations mature, the interface specification proposed in this work will be refined. Upcoming work in this area will focus on implementation of the interface for a variety of representative UAM vehicles. In addition, model optimization compatibility and the development of additional interface specifications to enable this functionality will be explored using the work presented here as a foundation. A successful interface specification is an important step towards the development of a shared database of UAM aircraft performance models, which could improve the ability of ATM researchers and industry to incorporate more realistic vehicle performance into their work. This capability is especially critical in the context of ongoing UAM research, where much of the promise depends on highly capable aircraft being utilized as efficiently and safely as possible within a large and complex traffic network in which automation and trajectory prediction will play a key role.

Acknowledgments

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