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Consumer-Facing Low-Altitude Urban Air Mobility: Energy-Constrained Service Commitment and Trustworthy Access

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***Abstract*—Low-altitude urban air mobility (UAM) is moving toward consumer-facing deployment through electrically powered aircraft, digital platforms, and connected vertiport systems. Yet the central challenge is no longer only whether such systems can fly or be scheduled, but whether they can be offered, maintained, and accessed as credible consumer services through digital platforms and connected infrastructure. This review argues that low-altitude UAM for consumers is best understood not as a vehicle-availability problem, but as a commitment-credibility problem bounded by operational supportability and interface continuity. From this perspective, the key analytical object is the service commitment: a platform-issued, operationally informed promise that a passenger request can be incorporated into a supportable near-term service sequence. First, it offers a compact quantitative synthesis showing that consumer-facing UAM service credibility is shaped by passenger-side safety, noise, trust, and service-quality concerns, time–cost sensitivity, and charging readiness. Second, it analyzes how charging availability, battery state, turnaround energy recovery, and power-constrained dispatch determine whether those commitments remain operationally supportable across booking, departure, and execution. Third, it discusses how operational supportability must be translated into passenger-visible service-state updates, uncertainty communication, disruption handling, privacy-conscious data handling, and secure digital access. The review further outlines future research directions in cross-layer service metrics, service-oriented digital twins, interaction-aware recovery, and energy- and trust-aware service design. Overall, it reorganizes UAM- and eVTOL-specific work on operations, vertiport systems, charging readiness, passenger acceptance, and service reliability, while using adjacent-domain studies only as bounded analogies for interface-level mechanisms such as booking updates, recovery communication, and secure access.**

***Index Terms*—Low-altitude urban air mobility, consumer-facing digital platforms, service commitment, energy-constrained service feasibility, trustworthy access.**

I. INTRODUCTION

LOW-ALTITUDE urban air mobility (UAM) is increasingly discussed not only as an aeronautical or infrastructural development, but as a consumer-facing mobility service embedded in connected urban mobility and service infrastructures[1]. For consumer-facing low-altitude UAM, the central question is not only whether aircraft can fly, be routed, or be accommodated in urban airspace [2], but whether an announced mobility service can be credibly offered, maintained, revised, and accessed under coupled operational and energy constraints. As electrically powered vertical-takeoff-and-landing aircraft, consumer-facing digital platforms, and connected vertiport systems move closer to deployment, the issue is therefore whether such services can be sensed, coordinated, and delivered as usable consumer services through embedded state awareness, real-time data processing, intelligent interfaces, and connected urban infrastructure.

However, the literature remains fragmented[3], [4]. Existing work can be broadly grouped into six main streams according to primary analytical object and service-stage coverage: demand and booking-feasibility studies; state-aware service screening and commitment generation; dispatch and vertiport operations; battery, charging, and grid-constrained supportability; air-ground access and multimodal integration; and passenger trust, acceptance, and service-state communication. A large body of work examines aircraft design, vertiport planning, routing, scheduling, charging, and system operations [5]. Another focuses on passenger acceptance, trust, user experience, and human-machine interaction[6]. Still other studies consider digital platforms, service booking, interoperability, or broader smart-city coordination[7]. These streams are all relevant, but they are still often treated separately. As a result, low-altitude UAM is frequently analyzed either as an operational system to be optimized or as a technology to be accepted, while the service chain linking platform-issued commitments, operational supportability, and passenger interaction remains insufficiently synthesized. To clarify this research landscape, Table I summarizes the major related-work themes in consumer-facing low-altitude UAM and highlights both recent progress and remaining limitations from a service perspective.

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TABLE I
Main Literature Streams and Gaps in Consumer-Facing Low-Altitude UAM

Related work theme	Service-stage relevance	Current progress	Remaining gap
Demand modeling and booking-feasibility studies [7], [9], [10]	Booking	Shifted from broad demand interest toward booking-feasibility analysis.	Links to energy supportability and commitment revision remain weak.
State-aware service screening and commitment-generation studies [11], [12], [13]	Commitment generation	Booking is increasingly treated as supportability screening based on real-time states.	Commitment stability after booking remains insufficiently studied.
Dispatch and vertiport-operations studies [13], [14], [15]	Execution dispatch	Operations are increasingly studied in integrated network settings.	Backend feasibility is rarely translated into passenger-visible service states.
Battery, charging, and grid-constrained supportability studies [16], [17], [18]	Energy feasibility	Energy constraints are increasingly recognized as service constraints.	Commitment credibility is still seldom expressed in passenger-facing terms.
Air-ground multimodal integration studies [9], [19], [20]	Trip-chain continuity	UAM is increasingly modeled as an end-to-end trip chain.	Passenger-facing continuity under disruption and rebooking remains underdeveloped.
Passenger trust, acceptance, and service-state communication studies [21], [22], [23]	Passenger-facing communication	Research is moving from acceptance toward explanation and service-state communication.	Trust continuity during service revision remains insufficiently studied.

This review argues that a consumer-facing service perspective provides a more coherent systems-level entry point for low-altitude UAM[8]. The central claim is that consumer-facing UAM is not principally a vehicle-availability problem, but a commitment-credibility problem bounded by energy supportability and interface continuity. The key analytical object is therefore not nominal vehicle visibility, but the formation and maintenance of a usable service commitment. In this review, a service commitment is defined as a platform-issued, operationally informed promise that a passenger request can be incorporated into a supportable near-term service sequence.

Unlike nominal availability, it reflects interpreted system supportability rather than visible supply alone, and its revisability is governed by subsequent changes in operational state rather than by arbitrary instability. This framing treats low-altitude UAM not as a set of disconnected technical subsystems, but as a consumer service problem in which platform logic, operational feasibility, and passenger-facing communication must remain technically aligned.

This manuscript has a dual role. It is first a structured review of the dispersed literature relevant to consumer-facing low-altitude UAM. At the same time, it advances an interpretive conceptual framework that reorganizes that literature around the staged problem of commitment formation, service feasibility, and passenger-facing service continuity. The contribution is therefore not a new operational optimization model, but a conceptual lens for re-specifying what counts as service deliverability in consumer-facing UAM.

For terminological clarity, four labels are used with distinct functions throughout the manuscript. Service commitment refers to the platform-issued, operationally informed promise made to the passenger. Service feasibility refers to the staged operational supportability of that commitment across booking, pre-departure, and execution. Service-state communication refers to the translation of that staged supportability into passenger-visible states, updates, and recovery information. Trustworthy access refers to the continuity of understandable, authorized, and secure passenger access to those service states across booking, update, boarding, and recovery.

The evidentiary basis of this review is explicitly layered. UAM- and eVTOL-specific studies provide the primary basis for claims about passenger acceptance, demand sensitivity, aircraft operations, vertiport throughput, charging readiness, battery constraints, and dispatch feasibility. Evidence from EV charging, MaaS, multimodal transport, real-time passenger-information systems, and consumer digital-service studies is used only as bounded analogical support for interface-level mechanisms, including conditional booking, uncertainty communication, recovery options, privacy-conscious interaction, and secure access.

To make the evidence base transparent and quantitatively grounded, Table II summarizes representative quantitative findings from UAM- and eVTOL-specific studies and clarifies the transferability boundaries of adjacent-domain evidence. UAM passenger, demand, battery, charging, and vertiport-operation studies are treated as primary evidence for UAM-specific claims, whereas EV charging, MaaS, multimodal transport, and consumer digital-service studies are retained only as bounded analogies for infrastructure and interface-level mechanisms. Because the reviewed studies differ in

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empirical setting, sample composition, stated-preference design, operational scenario, and reported outcome variables, Table II is intended as a structured quantitative synthesis rather than a statistical meta-analysis. It summarizes representative empirical and scenario-based findings to identify recurring passenger-side and technical supportability factors.

TABLE II
Quantitative Synthesis and Transferability Boundaries in This Review

Evidence domain	Representative quantitative / empirical findings	Role in this review	Transferability boundary / implication
Public perception and societal acceptance	Public-perception evidence reports safety concern 55.6%, sound type 49.3%, and sound volume 48.8% as leading concerns [24]. Societal-acceptance evidence reports n = 3,690 across six European cities, 83% positive overall perception, and 71% readiness to try at least one UAM service[25].	Primary passenger-side evidence	Service credibility must address perceived safety, acoustic disturbance, trust, affordability, and accessibility, not only visible vehicle availability.
Adoption, trust, and perceived risk	Quantitative UAM adoption and acceptance studies identify safety, trust, perceived risk, service quality, data concerns, time savings, affective evaluation, and cognitive evaluation as measurable determinants of service acceptance [21], [23], [26], [27]. Additional stated-preference and acceptance evidence further confirms developing-country and public-transport-oriented adoption patterns[28], [29].	Primary passenger-side evidence	Trust, perceived risk, service quality, and uncertainty communication are measurable acceptance factors rather than purely conceptual concerns.
Demand, access, and mode choice	Airport-access stated-preference evidence reports n = 2,604 respondents [30]. Additional eVTOL air-taxi stated-choice and stated-preference studies model choices among conventional modes and air taxi services, showing heterogeneous air-taxi preferences, cost sensitivity, travel-time sensitivity, and the influence of travel satisfaction and attitudes toward existing modes [31], [32]. A Jakarta stated-preference study reports n = 1,000 and identifies travel time and cost among the most influential UAM adoption factors [33]. Mode-choice evidence further identifies access/egress time, waiting/boarding time, in-vehicle time, and monetary cost as significant attributes [34].	Primary demand-side evidence	Booking strength, waiting time, access continuity, departure credibility, and service quality should be treated as measurable passenger-facing service variables.
Travel-time benefit and service applicability	Scenario-based travel-time analysis reports that, under base-case conditions, UAM would reduce travel time for about 3%–13% of motorized trips across the studied scenarios [35]. Demand-impact modeling further examines the short- to long-term transportation-demand effects of on-demand UAM in North America [36]. Stated-choice evidence also shows higher willingness to pay for UAM airport-shuttle services than for city-taxi services, with business travelers willing to pay 31%–44% more than non-business travelers [37].	Primary demand-side scenario evidence	UAM service credibility depends on whether the service offers meaningful time savings in specific trip contexts, not only whether aircraft are technically available.
eVTOL battery, charging, and operations	eVTOL battery and charging studies identify simultaneous requirements for high specific energy, high specific power, fast charging, cycle life, safety, high energy density, and fast rechargeability[18], [38]. These requirement-level findings indicate that charging recovery, turnaround feasibility, and battery safety are measurable technical conditions for whether a visible service option can become a supportable commitment.	Primary technical supportability evidence	Charging readiness, turnaround energy recovery, and battery constraints should be treated as service-feasibility constraints rather than only infrastructure variables.
EV charging, MaaS, multimodal, and consumer digital-service studies	Adjacent infrastructure and interface studies provide representative evidence on charging-service coordination and local power constraints [39], real-time passenger-information updates [40], and consumer digital-service security [41], but these studies generally remain outside aircraft-level UAM operations.	Adjacent bounded analogy	Used only to interpret infrastructure-side power headroom and interface-level update/access mechanisms; not used to infer aircraft-level UAM dispatch, vertiport operations, or operational reliability.

The quantitative evidence summarized in Table II yields three review-level results. First, passenger-facing UAM credibility is repeatedly associated with safety, acoustic disturbance, trust, perceived risk, affordability, waiting time, service quality, and affective and cognitive evaluations of UAM services. Second, demand, willingness-to-pay, and mode-choice studies show that UAM use is sensitive to measurable service attributes, including travel cost, travel time, waiting or boarding time, access and egress time, value of time, booking reliability, departure credibility, and willingness to pay under different trip purposes. Third, eVTOL battery and charging studies show that charging readiness, energy recovery, turnaround feasibility, and battery safety condition whether a visible service option can become a supportable commitment. Together, these results support the central framing of this review: consumer-facing UAM should be evaluated through commitment credibility, energy-constrained service feasibility, and trustworthy access.

On this basis, the review develops a three-part synthesis. First, it examines how real-time operational states are acquired, fused, and converted into passenger-visible booking possibilities through consumer-facing platforms and embedded digital systems. Second, it analyzes how charging availability, turnaround energy recovery, battery state, and

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power-constrained dispatch determine whether those commitments remain operationally supportable across booking, departure, and execution. Third, it considers how such supportability must be translated into service states, uncertainty communication, disruption explanation, privacy-conscious data handling, and secure digital access if automated UAM services are to remain understandable and trustworthy. Passenger-facing communication is therefore treated as the interface-level translation of operational feasibility under dynamic conditions. Fig. 1 summarizes the review's central reframing from isolated subsystem views to a commitment-credible service perspective.

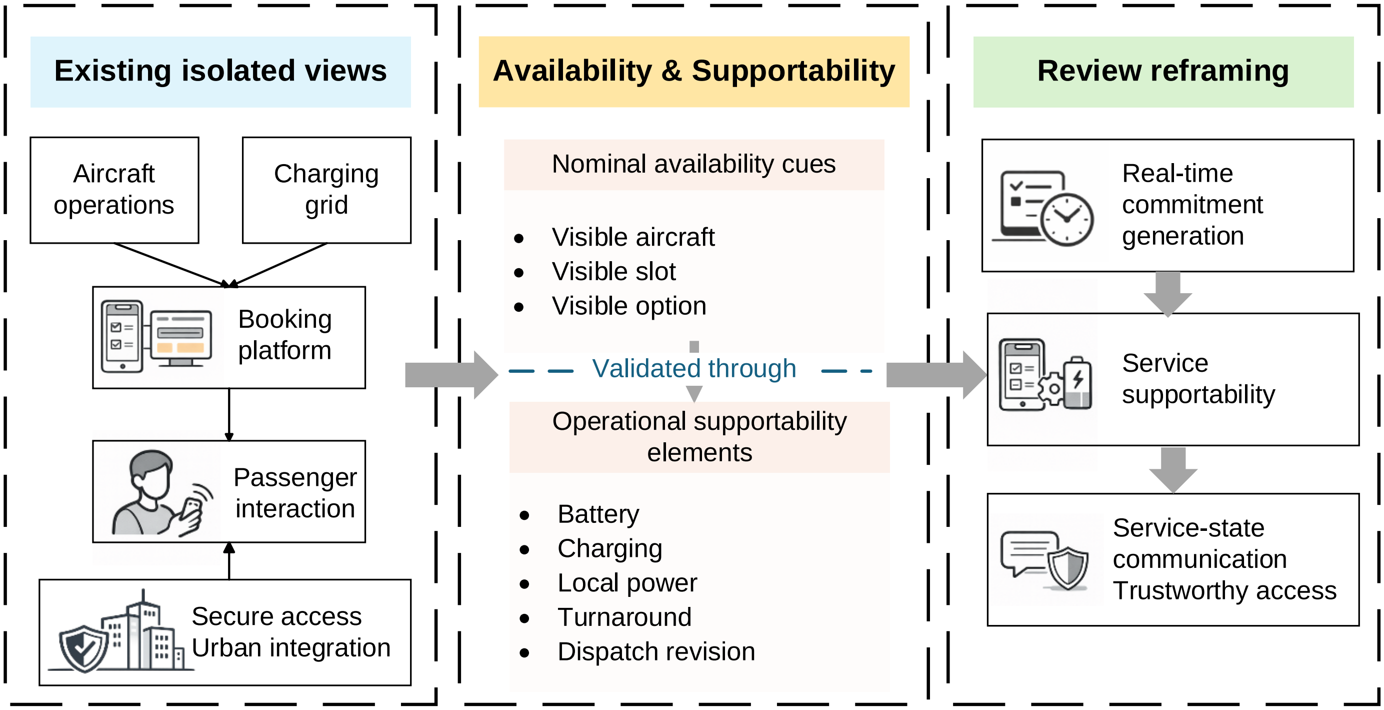

Fig. 1. Reframing consumer-facing UAM through availability and operational supportability

This review contributes in two ways. Substantively, it reframes low-altitude UAM for consumers as a staged service problem linking real-time commitment generation, consumer service feasibility, and trustworthy passenger access across connected urban mobility infrastructure. Analytically, it organizes previously dispersed work on platforms, operations, energy constraints, and passenger-facing systems into a single interpretive structure centered on commitment credibility. Viewed through a consumer-electronics service lens, the practical value of this review lies in showing how backend operational and energy states become passenger-visible service states, platform-side commitment logic, disruption handling, and secure digital access, rather than remaining isolated infrastructure-side variables. The remainder of the paper is organized as follows. Section II examines real-time service commitment generation in consumer-facing UAM. Section III develops energy-constrained consumer service feasibility through booking feasibility, pre-departure readiness, and execution-stage reliability. Section IV discusses passenger-facing communication and trustworthy access under automation and uncertainty. Section V outlines open challenges and future directions for integrated service design across consumer-facing digital platforms and connected smart-city infrastructure. Section VI concludes the review.

II. REAL-TIME SERVICE COMMITMENT GENERATION

In consumer-facing low-altitude UAM, service availability is not determined by published timetables or nominal vehicle presence alone. Before a booking can be issued, the platform and its supporting digital infrastructure must identify and interpret the operational states that determine whether a request can be admitted into a supportable near-term service sequence. These states include aircraft location and rotation, vertiport capacity, turnaround status, charging status, battery state, local power availability, and the downstream network context. Real-time service commitment generation is therefore the process of converting UAM-specific operational states into passenger-visible booking options and platform-issued service commitments. Platform and MaaS studies mainly inform the interface representation of service commitments, whereas the feasibility logic considered here remains grounded in aircraft, vertiport, turnaround, and charging conditions specific to UAM.

This section does not address whether such commitments remain feasible under subsequent charging, turnaround, battery, and power constraints. That problem is examined in the next section. The concern here is earlier in the chain: how the platform fuses relevant states, screens supportability, and generates bookable service states at the time of query.

A. State Fusion and Feasibility Screening

Real-time service commitment generation begins with operational state acquisition. For a UAM platform, the issue is not simply whether data are available, but whether the relevant state variables can be accessed and interpreted for judging near-term service supportability. In practice, these states may be captured through onboard sensing, vertiport-side sensing, charger and infrastructure monitoring, and networked data exchange, and then synchronized through platform-side processing. The review treats this synchronization primarily as a service-screening requirement rather than as a fully specified sensing architecture. The engineering issue is not only whether these states can be collected, but also whether they are timely, synchronized, and reliable enough for real-time commitment screening under rapidly evolving operating conditions[42], [43], [44].

The resulting state description must include aircraft position and assignment status, remaining vehicle rotation obligations, vertiport slot and pad occupancy, turnaround progression, battery state, charger availability, and time-dependent local power availability[45]. In larger networks, it also includes congestion propagation, downstream routing dependencies, and links to ground-access segments and surrounding urban mobility infrastructure[14], [15]. Together, these inputs show that service commitments are formed in a tightly coupled operating environment rather than on separate operational layers.

State visibility alone, however, does not produce a bookable service state. The acquired state must be translated into a feasibility estimate that tests whether a request is temporally and operationally compatible with the system's current operating trajectory [11]. This requires more than identifying a nearby aircraft or an open departure window.

The platform must assess whether a vehicle-slot sequence can be supported, whether the request can be absorbed without violating downstream limits, and whether the relevant vehicle, vertiport, charger, and network resources remain aligned over the planning horizon. Feasibility estimation therefore functions as supportability screening before the platform issues bookable windows, conditional confirmations, or platform-issued departure-related states.

The platform should therefore not treat all visible service opportunities as equally suitable for commitment. A request may appear schedulable at the instant of query yet remain weakly supportable once aircraft rotation, vertiport throughput, charger availability, or infrastructure dependencies are considered[12]. Feasibility estimation determines whether the platform can issue a bookable window, narrow the option set, or withhold confirmation.

B. Commitment Formation and Booking Logic

Feasibility estimation alone does not create a passenger-facing service commitment. A further platform-level decision is required to determine which requests should be converted into bookable options, which should remain conditionally available, and which should be excluded from immediate presentation[46]. This distinction matters because consumer-facing UAM platforms must translate operational feasibility into passenger-visible service states[47]. In this sense, booking logic is the operationally mediated process through which feasibility estimates are translated into bookable windows, conditional confirmations, and platform-issued service states with different levels of confirmation strength[48].

Booking logic transforms underlying feasibility into structured service selection[49]. A visible option is not automatically suitable for commitment because a vehicle appears nearby or a nominal departure slot is open. The platform must judge whether the request fits a supportable near-term sequence compatible with aircraft assignment, vertiport throughput, turnaround progression, and subsequent operations. Some requests may be firmly confirmable, some better represented through narrower windows or alternative itineraries, and others withheld entirely[50]. Platform-based booking logic thus defines the boundary between apparent availability and commitment-worthy availability[51].

This also clarifies what service commitment means at the booking stage. In consumer-facing UAM, a booking confirmation is not merely a commercial transaction but an operationally informed promise generated under current and near-term state estimates[52]. It is stronger than a generic indication of service interest, yet not equivalent to unconditional deliverability under all downstream contingencies[53]. In practice, the interface should show not only whether an option is visible, but also what service state the platform is prepared to stand behind at the time of query[54].

C. State Updates and Commitment Revision

Because consumer-facing UAM services operate under continuously evolving conditions, service commitment should not be understood as a one-time output fixed at booking. The operational states on which commitment formation depends may change as aircraft rotations progress, vertiport conditions evolve, turnaround processes advance, and infrastructure availability is updated[55], [56]. These adjacent transport-control studies are used only to clarify the logic of state updating and service revision, not to infer aircraft-level UAM operational feasibility. Under such conditions, the UAM service platform is not limited to generating an initial commitment; it must also update booking and departure states so that they remain aligned with the latest aircraft, vertiport, turnaround, charging, and local-power states[57], [58]. Dynamic state updates therefore form an essential part of service commitment generation. They ensure that passenger-facing commitments remain linked to the current supportability of the service rather than to an earlier feasibility assessment that may no longer hold[59].

This requirement makes commitment revision an inherent system function rather than an exceptional correction step. When operational states change, the platform may need to revise confirmation status, update a departure state, narrow bookable windows, or replace an earlier commitment with an alternative continuation path[60], [61]. The object being revised is not merely a backend schedule element, but the passenger-visible commitment derived from it. Dynamic updating therefore translates changing operational conditions into revised service states while preserving a clear link between the original commitment and its updated form.

For consumer-facing systems, this revisability has a direct structural implication. Real-time service commitment is not equivalent to static availability disclosure; it is a state-dependent and updatable promise generated under conditions of partial foresight and evolving supportability. Its quality therefore depends not only on timely state estimation, but also on whether charging and power constraints are already internalized in the service-formation logic. Once service commitments are recognized as state-dependent and revisable, the next issue is whether they remain genuinely supportable under charging, turnaround, battery, and power constraints.

III. ENERGY-CONSTRAINED SERVICE FEASIBILITY

As illustrated in Fig. 2, consumer service feasibility is a staged process in which a visible option must remain supportable across booking, departure, and execution before it can become a credible passenger-facing outcome. Booking feasibility concerns whether a passenger request can be admitted under current and anticipated resource compatibility. Pre-departure readiness concerns whether an accepted commitment has reached a mission-feasible departure condition. Execution-stage reliability concerns whether the service remains passenger-credible under real-time dispatch, charging, turnaround, local-power, and recovery constraints. These layers are sequential: a visible option becomes credible only when it can progress from booking-feasible commitment to departure-ready state and then to recoverable execution-stage service.

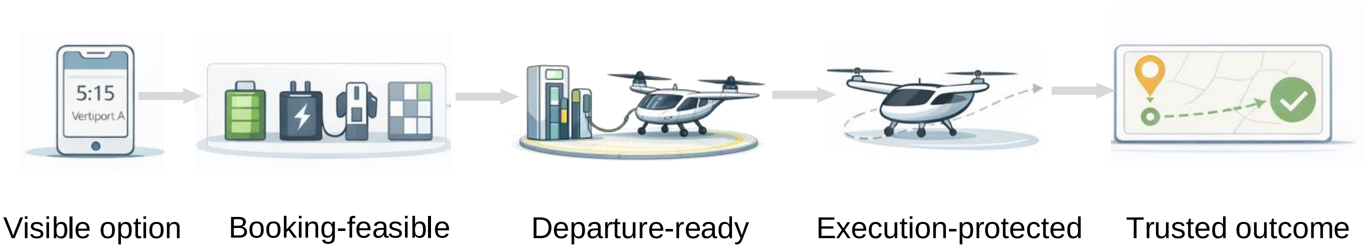

Fig. 2. Staged validation from visible option to trusted service outcome

A. Booking Feasibility under Charging Constraints

Rather than treating charging as a standalone technical subsystem, the reviewed literature supports viewing it as a staged determinant of booking-time feasibility in battery-electric UAM. At the point of booking, the relevant question is not simply whether an aircraft can be nominally assigned, but whether the resulting service commitment remains compatible with downstream charging, turnaround, and network-capacity conditions[9], [20]. In electrical terms, this includes whether the current battery state and reserve margin are adequate, whether a charger can be accessed within the required time window, whether local power availability can sustain the expected recovery process, and whether insertion of the request will erode the energy margin of subsequent rotations[62]. In battery-electric UAM, charging availability therefore functions less as an operational detail than as an admission condition for consumer-facing service commitments and passenger-visible booking availability. This claim is grounded primarily in eVTOL charging, battery, and scheduling studies, rather than in EV charging evidence alone.

Two bodies of work are especially relevant here. The first concerns integrated routing-and-charging formulations, in which recharge decisions materially affect mission continuity, recovery flexibility, and the feasibility of subsequent aircraft movements. The second concerns dynamic scheduling under capacity constraints, in which recharge, vertiport throughput, and time-varying demand are treated jointly rather than sequentially. Taken together, these studies show that a request that appears feasible at the interface layer may cease to be feasible once charger occupancy, recharge duration, local power headroom, and future mission dependencies are taken into account[13].

This conclusion becomes more service-relevant when charging is considered together with local resource bottlenecks. For eVTOL operations, the primary concern is whether charging support can restore mission-feasible energy states within turnaround and dispatch windows; EV charging and power-grid studies are used only to interpret local power headroom as a possible service-facing constraint. Slower charging regimes can materially reduce mission success and effective service supply relative to faster charging or battery swapping. For a consumer-facing system, this means that charging throughput and charger occupancy constrain not only fleet utilization but also which requests can be accepted as robust commitments. Local power limits and simultaneous charging demand tighten this condition further, because apparent aircraft availability does not guarantee that sufficient charging support can be maintained across closely spaced missions[63]. Booking-time feasibility is therefore an energy-aware admission problem rather than a simple question of visible aircraft assignment or nominal departure slots[10].

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B. Pre-Departure Readiness

If booking-time feasibility determines whether a request can be accepted, pre-departure readiness determines whether the associated service commitment can move into execution. In battery-electric UAM, this stage is shaped not only by aircraft presence and schedule position, but also by whether the aircraft has reached a departure-feasible energy state[64]. Departure feasibility at this stage depends on a combination of state-of-charge sufficiency, mission reserve requirements, charger availability, turnaround duration, thermal acceptability, and local power conditions[65]. An aircraft may therefore be physically available at a vertiport while remaining operationally unready for departure.

Here again, two streams of work are especially informative. The first examines turnaround sensitivity in eVTOL operations and shows that charging mode, charging speed, and swapping assumptions materially affect mission success and effective fleet performance[66]. Turnaround cannot therefore be modeled as a fixed ground-handling interval. The second examines battery-aware operation, showing that uncertainty in battery condition and end-of-discharge prediction requires additional operating margins and reduces the confidence with which future missions are assigned[67]. Taken together, these studies suggest that pre-departure readiness is an energy-conditioned operational state rather than a purely logistical milestone. In practice, this readiness state depends not only on nominal state-of-charge thresholds, but also on charging-power trajectory, thermal stabilization time, reserve policy, and uncertainty in battery-state estimation.

This interpretation is particularly important for consumer-facing reliability because it links hidden energy-side variables to passenger-visible departure outcomes. State-of-charge sufficiency alone is not enough. A service commitment may still face weak departure feasibility if charger occupancy delays restoration, if local power bottlenecks slow simultaneous charging, or if thermal conditions require additional stabilization before release. Pre-departure readiness should therefore not be treated as a binary ready-or-not-ready condition, but as a composite service state whose credibility depends on energy recovery, charger availability, local power availability, and thermal acceptability over the remaining turnaround interval.

C. Dispatch Feasibility and Execution-Stage Reliability under Power Constraints

If booking-time feasibility determines whether a request can be accepted, and pre-departure readiness determines whether an accepted service commitment can move into execution, the remaining issue is whether that commitment can remain operationally supportable and passenger-credible once operations are underway. The reviewed literature indicates that this execution-stage problem is governed by real-time dispatch under coupled charging and power constraints. In UAM-specific studies, scheduling, routing, charging, and recovery are increasingly modeled as coupled decisions rather than independent control layers. Real-time dispatch should therefore not be understood merely as the implementation of a precomputed schedule. It is the stage at which previously feasible service commitments are tested against charging contention, energy-margin uncertainty, limited turnaround flexibility, and disturbance propagation.

A first stream of evidence comes from integrated UAM scheduling research. These studies show that real-time dispatch depends on the interaction among flight assignment, vertiport capacity, recharge timing, and recovery logic[16]. Under such conditions, aircraft that appeared viable at the booking stage may no longer remain equally deployable once charging queues lengthen, charger access is reprioritized, or turnaround slack is consumed by earlier delays. A second stream comes from UAM recovery studies, which show that charging activities may be deferred, sequenced, or even canceled to preserve future operational flexibility after disruptions. Taken together, these studies suggest that real-time dispatch is not only a matter of maintaining nominal schedule feasibility. It is also a matter of deciding which service commitments can still be protected when scarce charging opportunities, battery margins, and turnaround resources must be redistributed in real time.

Within this execution stage, power constraints require more explicit attention than charger availability alone[39], [68], [69]. From an operational standpoint, this means that dispatch feasibility depends not only on charger occupancy, but also on feeder headroom, charger power sharing, and the ability to reallocate charging priority without undermining downstream service commitments. Charger occupancy determines whether physical access exists, but local grid limits, simultaneous charging demand, and power sharing across chargers determine how much charging support can be delivered at a given moment[17], [70], [71]. Existing UAM studies often capture these effects through turnaround sensitivity, charging assumptions, or scheduling constraints, whereas adjacent electric-mobility research more explicitly models local power bottlenecks. In this review, such evidence is used only as an infrastructure analogy for service-facing charging delay and recovery flexibility, not as a direct substitute for eVTOL dispatch evidence[38]. Because UAM-specific evidence on passenger-level service reliability remains limited, adjacent work is useful for clarifying how local dispatch disturbances, reduced recharging opportunity, and degraded power support may translate into waiting, delay, weakened recovery flexibility, and lower execution-stage reliability without implying that the underlying systems are operationally identical.

From a consumer-facing perspective, these execution-stage conditions become visible in whether departures remain on time, whether ground-access connections are preserved, whether revised departure estimates remain credible, and whether the system can offer a workable recovery path when disruptions occur. Under power-limited dispatch, some commitments may remain technically executable but become less reliable from the passenger standpoint, while others may

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remain serviceable only through rerouting, rebooking, or cancellation. More specifically, execution-stage reliability is a coupled battery–charging–power–dispatch problem.

D. From Energy Constraints to Service Feasibility

In this review, consumer service feasibility is defined as the staged ability of a UAM system to generate, maintain, and execute a credible passenger-facing service commitment under charging and power constraints. Operational energy constraints in low-altitude UAM should therefore be understood not as isolated technical limitations, but as staged determinants of consumer service feasibility[18], [72], [73]. At the booking stage, charging availability constrains whether a request can be accepted as a valid service commitment. At the pre-departure stage, the ability to recover a mission-feasible energy state constrains whether the commitment can progress into credible departure readiness[38]. During execution, dispatch under charging and power limitations constrains whether the commitment can be maintained with acceptable passenger-level service reliability. Across all three stages, the common implication is that service visibility at the interface layer does not by itself guarantee service deliverability at the operational layer.

Most existing UAM studies do not formulate this problem explicitly in consumer-facing service terms. Their dominant vocabulary remains that of routing, scheduling, turnaround sensitivity, vertiport capacity, and recovery performance. The end-to-end service-chain interpretation is developed primarily from UAM operational and demand studies, while adjacent multimodal service-integration and ground-access studies are used only to clarify how access, transfer, and recovery continuity may be represented to passengers. On this basis, UAM should not be treated as an isolated airborne movement, but as a staged service chain whose credibility depends on whether UAM-specific operational states remain compatible with the commitments issued to the user[74]. In that sense, energy constraints are not merely infrastructure-side restrictions. They are conditions that determine whether the system can sustain a credible trip chain from booking, through departure, to reliable service completion.

Consumer service feasibility should not be treated as binary[75]. A service may be digitally visible but not booking-feasible under current charging conditions. It may be booking-feasible but not departure-feasible because turnaround energy recovery remains incomplete or uncertain[76]. It may be departure-feasible but still lose reliability during execution if dispatch must absorb charger contention, local power bottlenecks, or recovery pressure. This layered interpretation helps explain why nominal availability, confirmation strength, departure credibility, recovery reliability, and user confidence may diverge even when fleet and network resources appear sufficient in aggregate. This leads directly to the next issue: how operationally supportable commitments are translated into passenger-visible states that remain understandable and trustworthy under automation and uncertainty.

Consider a simple end-to-end service sequence. A passenger queries an evening trip through the platform and is first shown a visible but still unscreened option because an aircraft, slot, and vertiport path appear nominally available. The platform then issues a booking-feasible commitment only after screening charger access, battery margin, turnaround compatibility, and local power support. Before departure, the state may be revised from confirmed to departure pending if charging completion slows under local power contention or if turnaround recovery weakens readiness. If a further disturbance occurs during dispatch, the system may preserve execution-stage reliability by offering a revised departure time, a protected alternative connection, or a feasible rebooking path. Throughout this sequence, the passenger-facing requirement is not exposure to raw engineering states, but continued access to understandable booking status, updated departure information, recovery options, and secure digital authorization.

IV. SERVICE-STATE COMMUNICATION AND TRUSTWORTHY ACCESS

Section IV functions as the passenger-interface continuation of the staged feasibility logic developed in Section III rather than as a separate discussion layer. In the present framework, booking feasibility becomes visible to the user as booking availability or conditional confirmation, pre-departure readiness becomes visible as updated departure status or readiness-related delay, and execution-stage reliability becomes visible as maintained trip continuity, disruption notification, recovery options, and boarding-authority continuity. The service conditions developed in the preceding discussion are not directly observable to passengers. What passengers encounter instead are booking confirmations, updated departure states, disruption notifications, and recovery options delivered through digital service interfaces. The technical issue is therefore not only whether a service commitment is supportable under UAM-specific charging and power constraints, but also how such supportability is translated into state categories, departure updates, boarding authority, and recovery options. Adjacent passenger-information and consumer digital-service studies are used only for general interface principles, not for establishing UAM operational feasibility. If the interface fails to reflect these changes, visible availability can drift away from actual service supportability, and even justified operational adjustments may appear arbitrary.

A. Service-State Representation

A central requirement of UAM passenger interfaces is that underlying operational conditions should not be presented in raw engineering form. Variables such as battery state, charger occupancy, local feeder limits, state-of-charge margins, thermal stabilization requirements, and communication-layer contingencies are essential for operational control, but they are not suitable as primary interface elements for passenger decision support. What the interface should represent instead is the service meaning of those variables. In practical terms, this requires a service-state abstraction layer that maps UAM-

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specific operational conditions into passenger-visible states, such as available but conditional, confirmed, departure pending, delayed, disrupted but recoverable, rebooked, or recovery in progress. These state categories must remain anchored in UAM-specific charging, turnaround, vertiport, and dispatch conditions[77], [78], [79], [80], [81].

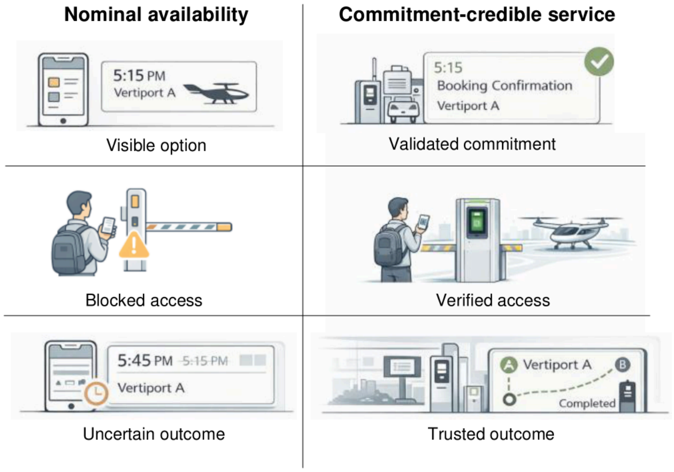

Fig. 3. From nominal availability to commitment-credible service at the passenger interface

Fig. 3 translates this abstraction into interface form by contrasting nominal availability cues with the passenger-facing states of a commitment-credible service.

The goal of this abstraction is not to remove operational detail, but to translate it into interface states that passengers can act on[82]. For low-altitude UAM services, this translation is particularly important because service commitments are formed under tightly coupled charging, turnaround, vertiport, and dispatch conditions, and the interface must remain aligned with those conditions rather than with nominal vehicle visibility alone.

The representation of service states should therefore follow the staged feasibility logic of booking feasibility, pre-departure readiness, and execution-stage reliability. At the booking stage, charging availability should appear as booking availability or conditional confirmation rather than as visible schedule supply alone. At the pre-departure stage, turnaround energy recovery should appear as a departure-readiness state, potentially with an updated departure estimate when readiness remains incomplete or uncertain. During execution, power-constrained dispatch should appear through delay status, recovery status, boarding-authority continuity, and the availability of feasible alternative itineraries[83]. Across these stages, the interface should show service-relevant states rather than isolated technical indicators[84], [85], [86].

B. Communicating Booking and Departure Uncertainty

The representation of service states is closely related to the communication of uncertainty because the conditions behind a booking or departure state can change quickly. A service may remain visible even when charger contention, delay spillovers, battery state, or local power availability have already weakened the underlying commitment. Platforms should therefore avoid presenting all commitments as equally firm when the underlying conditions differ materially. The engineering task is not to expose full operational complexity, but to translate changing supportability into service information that passengers can act on[40], [41], [87].

At the booking stage, uncertainty communication is primarily concerned with whether a visible option should be represented as firmly confirmable, conditionally available, or deferred to an alternative time window. This becomes important when charging compatibility is feasible only within narrow resource margins, or when downstream turnaround conditions remain sensitive to charger occupancy, vertiport delay, and local power contention. Presenting all visible options as equally robust may create a mismatch between interface-level commitment and operational supportability[88]. The aim is not to burden users with optimization detail, but to show which change in operating conditions has weakened booking strength and what that change means for the displayed service state[89], [90].

At the pre-departure stage, uncertainty communication becomes a question of how incomplete or evolving readiness should be conveyed without reducing service communication to raw engineering indicators. Departure readiness in battery-electric UAM is not always a simple ready-or-not-ready condition; it may depend on charging completion, thermal stabilization, charger release, local power availability, and the residual effects of earlier schedule disturbances. Passenger-facing communication should therefore support updated departure states, readiness-related status revision, and reasoned delay explanations when previously expected departure conditions are no longer fully met[91]. What matters is not only informational accuracy, but also revision continuity: passengers should be able to understand what has changed, how it affects boarding, departure, connection, or recovery options, and what immediate course of action remains available.

C. Disruption Explanation and Trip-Chain Recovery

Disruptions in low-altitude UAM should not be interpreted only as operational disturbances internal to scheduling and dispatch. From the passenger perspective, they appear as delayed departure, loss of transfer continuity, itinerary revision, or cancellation of an expected service segment[92], [93]. This distinction matters because execution-stage disturbances are experienced through their effects on service continuity rather than through their operational origin.

Charging contention, local power bottlenecks, turnaround overruns, and dispatch resequencing may all be operationally rational responses to constrained system conditions, yet at the interface they appear as fewer next-step options, revised departure states, weaker connection protection, or the loss of a recovery path[94]. The interface challenge is therefore not only to signal that a disruption has occurred, but to show how it changes the service state that the passenger can still rely on.

This requirement makes disruption explanation closely

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related to recovery support. In consumer-facing UAM systems, recovery should not be treated as a backend rescheduling problem that becomes visible only after a new solution has been computed. It is also an interaction problem in which revised service states are communicated together with feasible next-step options, such as updated departure times, rerouted itineraries, alternative ground-access connections, revised boarding instructions, or explicit cancellation pathways[95]. A revised commitment should therefore be communicated as a recovery state linked to a feasible continuation path.

This issue becomes more important when UAM is interpreted as a UAM-centered service chain connected to access and egress segments, rather than as an isolated airborne movement. A passenger does not consume only a flight segment; the relevant service object is the full journey from origin access to destination arrival. Disruption explanation should therefore not be limited to the airborne leg alone. It should also show whether ground-access coordination remains valid, whether onward connections can still be protected, and whether an alternative itinerary preserves the broader trip[96], [97]. Recovery support is therefore part of the service-control layer through which UAM execution-stage feasibility is translated into continued passenger-facing service, including access, egress, and alternative itinerary information where these elements are operationally available.

D. Trustworthy Interaction, Privacy, and Secure Access

As UAM services become increasingly automated, two related but distinct interface requirements should be separated more explicitly. Trustworthy interaction concerns whether service-state transitions remain understandable, coherent, and behaviorally interpretable to the passenger, whereas trustworthy access concerns whether those states, revisions, and authorizations remain securely and continuously available across booking, update, boarding, and recovery[98], [99], [100]. In highly dynamic operating environments, service commitments may be revised repeatedly in response to charging conditions, turnaround progress, dispatch recovery, or local power constraints. Passengers are not required to observe the full computational logic of these adjustments, but they do require an interaction framework in which service-state changes remain understandable. The relevant standard is not full algorithmic exposure, but sufficient explanatory continuity to show why a commitment has changed, which constraint now governs the service state, and what the revision means for the passenger.

In this sense, trustworthy interaction is achieved through coherent state transitions, timely revision delivery, and interface-level continuity of passenger understanding rather than through explanation alone. Platforms strengthen trust when they keep state categories stable, explain why a booking or departure state changed, and maintain a clear link between earlier commitments and updated ones[101]. Authorization continuity should be treated separately as part of secure access rather than as part of interaction coherence. From an engineering standpoint, the issue is not informational accuracy alone. It is whether confirmation, readiness, disruption, and recovery are updated as a coherent state sequence rather than as disconnected interface events. Trustworthy access is therefore a digital-service continuity problem involving communication coherence, authorization continuity, and secure passenger-facing access across the trip.

Secure passenger access forms the final component of this interaction layer. Access to booking, trip status, boarding authority, itinerary revision, and recovery options must remain dependable under dynamic operating conditions, while passenger identity and service data must be handled in ways consistent with privacy protection, data minimization, and secure system design[102]. When booking, boarding, revision, and recovery all depend on digital identity-bound access, privacy and security failures become failures of service continuity rather than merely data-handling failures[103], [104]. Interoperable digital access also becomes important when disruption handling requires coordination across UAM platforms, vertiport systems, charging infrastructure, and, where applicable, ground-access services. Reliable access control, authorization continuity, and dependable state delivery are therefore prerequisites for credible automated mobility services[105], [106].

V. OPEN CHALLENGES AND FUTURE DIRECTIONS

The preceding sections suggest that low-altitude UAM for consumers should not be studied as a collection of loosely related subsystems. Real-time commitment generation, energy-constrained service feasibility, and passenger-facing communication are analytically distinguishable, but they jointly determine whether a service can be offered, maintained, and understood as a credible mobility option. The next stage of research should therefore move beyond parallel advances in planning, operations, and interfaces toward an integrated service perspective centered on commitment credibility across the passenger journey. The open challenge is not additional optimization within each subsystem alone, but how UAM digital platforms can maintain service-state consistency across aircraft, vertiport, charging, dispatch, and passenger-interface layers under changing operational conditions. Broader smart-city and mobility-platform evidence is relevant only as an adjacent reference for interoperability and service coordination, not as direct evidence of UAM deployment behavior.

A. Cross-Layer Service Metrics

A first requirement for this shift is the development of cross-layer service metrics. Much of the UAM literature still evaluates system performance through disconnected lenses. Strategic and operational studies typically emphasize fleet sizing, vertiport capacity, service profitability, robustness under demand uncertainty, or spatial equity[107], [108], [109].

Passenger-oriented studies, by contrast, place greater weight on acceptance, perceived usefulness, perceived ease of use, trust, and perceived risk[110], [111], but these dimensions still need stronger linkage to measurable service-state consistency and access continuity. Even when these dimensions are considered within the same broad system context, they are rarely organized into a unified service-evaluation framework[112]. This fragmentation makes it difficult to judge whether improvements at one layer strengthen the passenger experience or merely improve subsystem-level performance[113].

For UAM services delivered through digital platforms, future metrics should be organized around booking, departure, execution, and recovery rather than isolated subsystem outputs[114]. At a minimum, future work should distinguish among operational supportability, passenger-visible reliability, and cross-layer consistency metrics[115].

The metrics in Table III do not all have the same operational maturity. Some, such as booking-screening accuracy, readiness-update timeliness, revision latency, and access-continuity failure rate, can be interpreted as nearer-term measurable indicators, whereas others, such as state-consistency error and explainability of service revision, remain future-oriented evaluation constructs requiring further operationalization. Taken together, these categories suggest a layered metric agenda spanning commitment stability between booking and departure, energy-constrained service availability, divergence between announced and delivered states, recovery performance across the broader trip, and the explainability of commitment revision under changing operating conditions[116].

TABLE III

STAGE-BASED METRICS FOR CONSUMER-FACING UAM SERVICE CREDIBILITY

Stage	**Operational basis**	**Passenger-facing state**	**Evaluation focus**
Booking	State fusion, charger access, battery margin, local power, vertiport capacity	Whether the trip is shown as available, conditional, or unavailable.	Booking-screening accuracy, energy-constrained availability, and validity of announced booking states.
Pre-departure	Turnaround progress, charging completion, readiness recovery, feeder/pad support	Whether the trip remains confirmed, becomes pending, or becomes delayed.	Commitment stability, readiness-update timeliness, and revision latency before departure.
Execution	Dispatch feasibility, onboard energy, power-constrained resequencing, trip-chain coordination	Whether the trip is communicated as on time, delayed, rerouted, or still recoverable.	Announced-versus-delivered consistency, execution-stage reliability, and service continuity under changing conditions.
Recovery	Rebooking logic, authorization continuity, multimodal coordination, state consistency	Whether the passenger sees rebooking, an alternative itinerary, cancellation, or ongoing recovery.	Recovery performance, access continuity, state-consistency error, and explainability of service revision.

Table III therefore summarizes a stage-based framework for evaluating commitment credibility across booking, pre-departure, execution, and recovery; where operationalized, these metrics should be measurable at the system level.

B. Service-Oriented Digital Twins

A second requirement for integrated consumer-facing UAM research is the development of service-oriented digital twins for validating service commitments. Existing mobility and transportation digital-twin work provides adjacent methodological support for representing vertiport operations, vehicle movements, disrupted scenarios, and infrastructure-side interactions in real time[117], [118]. What remains less developed is a validation environment explicitly organized around the service commitment chain. Most current digital-twin and simulation frameworks are still centered on aircraft operations, vertiport capacity, or infrastructure performance[119]. Future research should extend these capabilities toward UAM service-oriented twins that test whether a service commitment generated at booking remains supportable through departure, execution, disruption, and recovery. Where UAM is connected to access or egress services, such twins may also evaluate interoperable service-state exchange as an extension of UAM service validation[120], [121].

The significance of such a shift is methodological as well as conceptual. A service-oriented digital twin would not simply reproduce the physical state of vehicles and infrastructure; it would also represent commitment issuance, revision logic, passenger-facing state updates, disruption explanation, and trip-chain continuity under changing system conditions[122], [123]. This would make it possible to evaluate not only whether the network remains operational, but whether the commitments issued to passengers remain credible as charging, turnaround, capacity, and dispatch conditions evolve. The relevant validation target is therefore no longer infrastructure performance alone, but the consistency between announced service states and operationally supportable states over time[124]. Future digital twins should validate commitment credibility, not merely infrastructure performance.

C. Interaction-Aware Recovery

A third requirement for future research is to treat service recovery as a passenger-facing interaction process rather than as a purely backend operational adjustment in the control layer [125], [126]. Much of the current UAM literature still models disruption handling, resequencing, and service correction primarily from the perspective of system feasibility and control. Existing passenger-oriented and multimodal research suggests that revised commitments should not be evaluated only in terms of backend feasibility. Once exposed through passenger-facing platforms and trip-chain interfaces, they may be accepted, deferred, or abandoned through passenger response, and that response can affect whether a recovery strategy remains viable[126], [127]. Passenger response should therefore be treated as a candidate component of future UAM recovery evaluation rather than as a secondary aftereffect.

For this reason, future operational models should incorporate interaction-aware recovery logic rather than assuming that passengers passively absorb revised service states. The relevant question is not only whether a disrupted itinerary can be made operationally feasible again, but also whether the revised commitment remains usable and acceptable once rerouting, rebooking, waiting, or modal substitution is introduced. Recovery models should therefore account for passenger response to commitment revision, the effects of interaction delay on recovery effectiveness, and the role of explanation quality in preserving boarding, transfer, and onward-connection continuity[128]. Future recovery models should therefore solve jointly for operational feasibility and passenger behavioral viability. Within the scope of the present review, however, the emphasis remains on how backend operational supportability is translated into passenger-facing service states and service credibility rather than on fully endogenizing user-behavior feedback within the operational control loop. Incorporating trust-driven demand adaptation, booking deferral, cancellation, and rebooking response into commitment generation, disruption management, and service design remains an important direction for future research.

D. Energy- and Trust-Aware Service Design

A final research priority is the development of service design frameworks that are simultaneously energy-aware and trust-aware[129]. Much of the current literature still treats these two concerns through separate analytical lenses. On one side, operational and infrastructure studies increasingly examine UAM network design, fleet operations, charging coordination, and power-system integration as coupled technical problems[130]. On the other, passenger-oriented studies continue to show that trust, perceived value, safety perception, and perceived risk shape willingness to adopt and continue using UAM services[21], [131]. The resulting gap is the absence of a unified service-design perspective that treats operational supportability and passenger confidence in revised service states as co-determinants of service credibility in digital-platform-based UAM services.

For UAM services delivered through consumer-facing digital platforms, adjacent consumer-electronics security and access-control studies suggest that secure digital access should not be treated as separate from service continuity, although these studies are used here only as interface-level analogies rather than as direct UAM operational evidence[132], [133]. A service that is energy-feasible but difficult to revise or difficult to trust will remain weak at the passenger layer; conversely, a service that is well presented but poorly aligned with charging windows, dispatch constraints, or infrastructure dependence will remain weak at the operational layer. Future work should therefore explicitly co-design four layers: commitment formation, charging-aware supportability, disruption management, and secure passenger-facing access and explanation[134], [135], [136], [137]. In practical terms, this means treating service credibility as a co-produced outcome of power-aware UAM operations, commitment-stability logic, recovery continuity, trustworthy interface behavior, and, where applicable, service-state exchange with connected access or urban-service systems[138], [139]. Power support and trust support should therefore be treated as co-designed conditions of service credibility in future UAM platforms.

VI. CONCLUSION

This review argues that consumer-facing low-altitude UAM should be evaluated not principally as a problem of vehicle visibility or backend flight feasibility, but as a problem of service deliverability under coupled operational, charging, power, and interface constraints. It organizes the field as a staged service problem linking commitment generation, energy-constrained supportability, and trustworthy access. At the service level, credibility depends on whether a passenger request can be formed as a valid booking state, remain supportable under evolving battery state, charging opportunity, turnaround progression, local power conditions, and dispatch-time recovery constraints, and be translated into updated passenger-visible states, preserved access rights, and secure digital access across the trip.

Three findings follow from this framework. First, passenger-visible service options are generated from interpreted system states rather than from nominal vehicle visibility alone. Second, service credibility is bounded by battery state, charging opportunity, local power conditions, and dispatch-time recoverability rather than by schedule visibility alone. Third, operational feasibility becomes usable at the passenger layer only after it has been translated into updated service states, uncertainty communication, disruption handling, and secure access continuity. The quantitative synthesis further indicates that UAM service credibility is shaped by measurable passenger-side factors, including safety concern, noise perception, trust, perceived risk, service quality, travel cost, travel time, waiting time, value of time, willingness to pay, and trip-purpose heterogeneity, as well as technical supportability factors such as charging readiness, battery constraints, turnaround recovery, and dispatch feasibility.

The value of this review lies in reorganizing UAM- and eVTOL-specific work on scheduling, vertiport operations, charging, battery readiness, passenger acceptance, and service reliability, while using adjacent platform, mobility, and digital-access studies only to interpret interface-level service mechanisms. The resulting synthesis reframes consumer-facing UAM as a question of service deliverability under coupled charging, power, operational, and access conditions. More specifically, it shows that the central problem is not simply how to schedule vehicles, but how backend operational and energy states are converted into issuable, maintainable, revisable, and passenger-credible service states under battery, charging, power, and access constraints. Framed in this way, low-altitude UAM should be evaluated not only as a technical possibility, but as a supportable, explainable, and securely accessible mobility service operating across aircraft, vertiport, charging, digital-platform, and relevant urban-access infrastructure. This perspective implies that platform design, service-state communication, secure access continuity, and passenger trust should be assessed together with the operational and energy conditions that determine whether an announced service can actually be issued, maintained, revised, and delivered as a credible consumer-facing service.

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