

From Latency to Value of Information: A Review of Timeliness Metrics for Safe Transportation Systems in the 6G Era

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Abstract—Traffic safety in the 6G era will depend on vehicles exchanging information that is not only timely but also accurate and contextually relevant for cooperative awareness, collective perception, and automated driving. Classic performance metrics such as latency and reliability describe communication behavior, but do not capture how shared data supports situational awareness. Timeliness- and semantic-oriented metrics including Age of Information (AoI) and Value of Information (VoI) provide deeper insight into freshness and usefulness, yet open questions remain on how to assess performance across increasingly complex vehicular functions. This paper reviews the state of the art in timeliness metrics for vehicular networks, surveys the corresponding standardization landscape, and examines the applicability and limitations of AoI-based and related metrics. It highlights persistent gaps in evaluating cooperative and automated driving services and outlines directions toward goal-oriented performance assessment suited to safety-critical 6G transportation systems.

Index Terms—Vehicle-to-Everything, Vehicular Networks, Vehicular Communication, Value of Information, Age of Information, Collective Awareness, Collective Perception, Cooperative Driving, Timeliness Metrics, Public Safety in Transportation, 6G

I. INTRODUCTION

ENSURING public safety in transportation remains a major concern worldwide, with approximately 1.2 million road traffic deaths per year, according to the World Health Organization. Advanced driver-assistance systems, higher levels of driving automation, and Vehicle-to-Everything (V2X) communication are expected to substantially reduce this toll by addressing the primary cause: human error.

Unlike on-board sensors, V2X enables object detection in non-line-of-sight conditions and supports active information sharing among road users, providing richer situational awareness. The core V2X service is *cooperative awareness*, which enables each vehicle to broadcast status information about itself in its immediate vicinity. Despite decades of research, dedicated spectrum, and standardized protocols, V2X adoption – especially of cooperative awareness – remains limited. The introduction of the *collective perception* service – enabling vehicles to share sensor data and detect non-V2X entities such as pedestrians even at low market penetration rates – represents a potential turning point toward large-scale deployment. Finally, the ultimate goal is Vision Zero, supported by cooperative maneuvering, which promotes truly *cooperative driving* through the exchange of intentions and, possibly, the development of joint interaction plans. The gradual adoption of

cooperative mobility is reflected in a widely known Cooperative Intelligent Transport Systems (C-ITS) deployment roadmap ranging from Day 1 cooperative awareness through Day 2 collective perception to Day 3+ cooperative driving.

Evaluating the performance of cooperative awareness, collective perception, and automated driving protocols remains a challenge due to the lack of suitable, standardized, application-oriented metrics. Traditional metrics such as latency and reliability are goal-agnostic: they measure network behavior independently of application content and purpose. Vehicular systems require goal-oriented metrics instead. The Age of Information (AoI) [1, 2] is a major example of this shift, stemming from the recognition that data freshness, rather than integrity, is the focus of cooperative awareness. However, AoI alone does not capture all aspects of timeliness in vehicular systems, and its suitability for highly dynamic and spatially correlated environments remains debated. Three limitations are particularly relevant. First, AoI measures temporal freshness but is blind to semantic correctness: a recent yet inaccurate update is treated as equally valuable as a correct one. Second, being defined per transmitter-receiver pair, AoI cannot assess spatial consistency across the collectively perceived scene. Third, it carries no notion of object-level uncertainty, making no distinction between an update that resolves genuine ambiguity about a nearby hazard and one that merely confirms already-known information. These limitations call for a goal-oriented evaluation framework integrating freshness, correctness, and contextual relevance.

Although several variants of AoI have been proposed – such as Peak Age of Information (PAoI) [1, 2], Age of Incorrect Information (AoII) [3], or Value of Information (VoI) [4] – no prior work has brought these together into a coherent evaluation perspective tailored to vehicular safety functions. Three interconnected gaps remain unaddressed. First, foundational AoI surveys [1] and broader 6G time-perspective works [2] are network-agnostic: they do not map metrics to the use-case groups defined by 3GPP and 5GAA, nor to the C-ITS deployment roadmap. Second, the most closely related vehicular survey [5] treats latency, AoI, and reliability as largely independent indicators, without examining how they relate across deployment phases or connect to application-level notions of information value. Third, current standardization documents define link-layer indicators in isolation from data-centric timeliness concepts, a disconnect no prior work has

examined systematically. This paper addresses all three gaps, offering the following contributions:

- A thorough account of standardization documents and performance metrics defined for vehicular networks.
- A review of AoI and its variants, highlighting their applicability, significance, and limitations.
- A direction toward goal-oriented performance evaluation for public safety and 6G-enabled transportation systems.

II. EVOLUTION OF C-ITS

This section reviews the standard documents and recommendations from 3rd Generation Partnership Project (3GPP), European Telecommunications Standards Institute (ETSI), Society of Automotive Engineers (SAE), CAR 2 CAR Communication Consortium (C2C-CC), and 5G Automotive Association (5GAA). First, it describes the pathway toward cooperative automated mobility through the progressive development phases of C-ITS. Then, it examines ongoing standardization efforts addressing timeliness and reliability performance evaluation of V2X communications.

A. The pathway to cooperative automated mobility

The C2C-CC defines three progressive phases for C-ITS: Day 1 (Cooperative Awareness), Day 2 (Collective Perception), and Day 3+ (Cooperative Driving). Each phase represents a step toward fully cooperative and automated mobility.

Day 1 focuses on exchanging vehicle status and hazard notifications through CAMs and DENMs, enabling driver-assistance applications such as intersection collision alerts and emergency braking notifications. Day 2 incorporates on-board sensor data – from cameras, radar, and lidar – shared via CPMs, enabling awareness of non-visible obstacles and vulnerable road users. It introduces semi-automated functions such as Cooperative Adaptive Cruise Control, supported by enhanced positioning, functional safety, and misbehavior detection. In Day 3+, highly automated vehicles (SAE Level 3–4) share intentions, planned trajectories, and maneuvers via MCMs, while vulnerable road users broadcast their presence via VAMs. Road infrastructure provides active guidance on speed, lane choice, and transition-of-control points. The main features of the three phases are summarized in Table I.

Each transition between phases not only introduces new message types but fundamentally changes the requirements placed on timeliness metrics. In Day 1, per-vehicle freshness captured by AoI or Packet Inter-Reception (PIR) is a natural fit: each vehicle broadcasts its own status, and the evaluation logic is straightforwardly link-centric. This logic becomes insufficient in Day 2, where CPMs aggregate object-level data from multiple sensors, making scene-level spatial coverage and object-level uncertainty the relevant dimensions of timeliness – properties that per-link freshness metrics are blind to. The transition to Day 3+ adds further stress: cooperative maneuver coordination demands that timeliness be assessed relative to control-loop deadlines and decision relevance, not merely update regularity. Real-world deployment further complicates this picture. Sensor disagreement across vehicles reporting the same object, inconsistent object lifetimes across CPM

sources, message bursts at scenario boundaries, and partial deployment effects – where only a fraction of vehicles are V2X-equipped – all introduce variability that latency-only or freshness-only metrics cannot adequately characterize. These phenomena motivate the need for goal-oriented frameworks.

B. Standardization efforts on timeliness evaluation in V2X

The 3GPP service specifications [6] define the scope of V2X: six use case groups – i.e., *General Aspects* (3GPP-UC1), *Vehicles Platooning* (3GPP-UC2), *Advanced Driving* (3GPP-UC3), *Extended Sensors* (3GPP-UC4), *Remote Driving* (3GPP-UC5), and *Vehicle Quality of Service (QoS) Support* (3GPP-UC6) – across four communication types, i.e., Vehicle-to-Vehicle (V2V), Vehicle-to-Infrastructure (V2I), Vehicle-to-Network (V2N), Vehicle-to-Pedestrian (V2P). At the service level, the following definitions apply:

- **Latency** is the end-to-end time from message generation at the source application entity to reception at the destination application entity;
- **Reliability** is the probability that a packet of a given size is delivered within a specified latency bound (a packet is deemed to be lost, if not received within that bound).

The technical report [7] provides link- and system-level metrics for comparative studies.

- **Packet Reception Ratio (PRR)** measures reliability as the fraction of successfully received packets within a distance range or intended receiver set.
- **PIR** quantifies timeliness as the elapsed time between two consecutive successful receptions from the same transmitter.

PIR differs from End-to-End (E2E) delay, as it captures update regularity rather than one-way transfer time. These definitions are broader and more general than those in [6], which specify application-layer reliability and delay requirements, thereby allowing PRR and PIR to be applied consistently across different protocol stack layers.

The 5GAA white paper [8] focuses on direct V2V communication over the sidelink, aiming to establish a realistic methodology for assessing cooperative and automated driving services. Four representative use cases capture the main categories of direct vehicular communication: *Group Start* (5GAA-UC1) for coordinated vehicle departure, *Cooperative Lane Merge* (5GAA-UC2) for negotiation of merging maneuvers, *Vehicle Decision Assist* (5GAA-UC3) for exchanging decision-support messages, and *Sensor Data Sharing* (5GAA-UC4) for transmitting perception data to enhance collective awareness.

Evaluation relies on defined key performance metrics: the PRR measures reliability and successful packet delivery within range. Besides PRR, the white paper [8] defines also

- **Packet Delay Budget (PDB)**, the maximum E2E delay allowed for delivery, including retransmissions.

These two metrics, PRR and PDB, jointly determine service reliability, typically targeted at 95 % within 50–300 m depending on the use case.

An attempt to standardize additional timeliness metrics, including AoI, was made in [9]. The report defines three

Table I
COMPARISON OF DAY 1, DAY 2, AND DAY 3+ DEPLOYMENT PHASES IN C-ITS

Aspect	Day 1 – Cooperative Awareness	Day 2 – Collective Perception	Day 3+ – Cooperative Driving
Shared Data	Vehicle status, events	Sensor-detected objects	Planned routes, maneuvers
Automation Level	Driver-assisted	Semi-automated	Highly automated
Core Messages	Cooperative Awareness Message (CAM), Decentralized Environmental Notification Message (DENM)	+ Collective Perception Message (CPM) (extended CAM/DENM)	+ Maneuver Coordination Message (MCM), Vulnerable Road User Awareness Message (VAM), extensions
Infrastructure Role	Information provider	Sensor and position support	Active coordination and guidance
Supporting Functions	Security authentication	+ Position correction, functional safety, misbehavior detection	+ Automated coordination, trust management
Objective	Situational awareness, collective awareness	Shared environment perception, collective perception	Cooperative automated driving

indicator – Data Age (DA) (equivalent to AoI), E2E delay, and Inter-Packet Gap (IPG) (equivalent to PIR) – for evaluating ITS-G5 and LTE-V2X coexistence within a 0–300 m range.

- **DA** quantifies information freshness as the time between the current moment and the generation of the last successfully received packet, capturing both latency and packet loss effects.
- **E2E delay** represents the one-way transmission latency of received packets, applicable only to delivered packets.
- **IPG** measures the interval between two consecutive correctly decoded packets, describing update regularity.

Despite ongoing efforts, 5G New Radio (NR)-V2X specifications still lack comprehensive timeliness metrics and a clear mapping between link-layer indicators (PIR, PRR) and application-layer requirements for reliability and timeliness in safety-critical services. In addition, the dominance of PRR and PIR in standardization creates an incentive misalignment that goes beyond mere phase coverage: optimizing for packet delivery and update regularity rewards channel-level efficiency regardless of whether the delivered content advances situational awareness or object-level accuracy. In dense environments, this is further compounded, as neither metric can distinguish informative from redundant transmissions. Resolving this disconnect is a concrete open problem for 6G-V2X standardization, which should focus on goal-oriented scenarios that leverage semantic communications.

III. WHY TRADITIONAL METRICS ARE NOT ENOUGH?

Assessing and optimizing timeliness requires suitable performance metrics that go beyond traditional network indicators, such as latency or packet delivery ratio. Useful timeliness metrics must capture how promptly and accurately each vehicle’s representation of the environment reflects reality. The general concepts underlying this gap are presented in the following.

A. Response-centric versus data-centric paradigms

A framework for a general IoT system is composed of the following elements (see Figure 1):

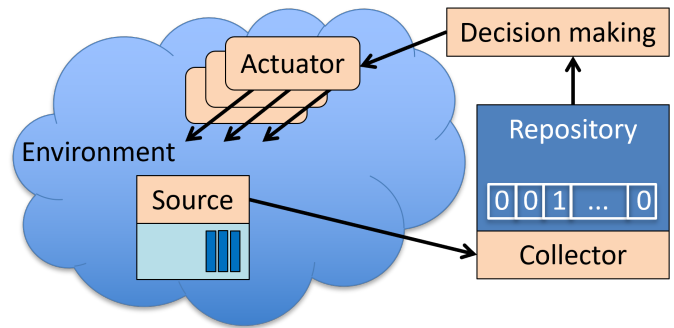


Figure 1. A framework for IoT applications based on distributed sensing.

- **Environment:** The part of the system that is acted upon to achieve the desired objectives. Observations are regularly extracted from this part and sent to one or more collection nodes.
- **Communication infrastructure:** The set of source, destination, and relaying nodes, as well as the communication channels and protocols used to deliver status update messages containing observed data to collecting nodes.
- **Collecting nodes:** Devices that store and possibly process the collected data, making it available to applications.
- **Users/actuators:** End-systems that use the collected data to make estimates of environment state and/or to control systems acting in the environment, to improve its operation.

Two paradigms can be identified with reference to this general scheme: the response-centric paradigm and the data-centric paradigm.

The **response-centric** perspective is typical of control systems, in which users are actuators and data comes from sensors located in the environment. The actuators’ actions are driven by control logic fed by observed data via a communication channel. They periodically request data and act on the system upon data reception. In this case, *reliability* and *delay* are the most relevant metrics, as it can lead to non-trivial dynamics and instability in the control loop. One example of this paradigm in vehicular networking is the formation and control of a platoon of vehicles. Once configured, the platoon leader polls vehicles

belonging to the platoon to collect dynamic data that it will use to regulate the kinematic variables of platoon members.

In the **data-centric** paradigm, applications act asynchronously with respect to the collection of status updates from sensors. A database containing these updates provides the environment view needed by application agents. For example, in cooperative awareness applications, the collecting device is the Local Dynamic Map (LDM) on board equipped vehicles, and the sensors are other vehicles that send CAMs. When an application agent needs to decide on its next action, it queries the database and retrieves the relevant data. This data represents the most up-to-date “picture” of the system status available to the application agent. A background process, *independent* of the application agents, continuously feeds the database by collecting observations from the environment and delivering them to the database. The effectiveness of the application agents’ actions depend on how fresh, complete, and accurate the “picture” of the observed system is in the database at any given time.

The distinguishing feature between response- and data-centric paradigms is whether application agents (users or actuators) directly poll sensors for status updates or if sensors push updates to a collection system (database) that application agents retrieve. The latter approach assumes decoupling between the sensory system and the application agents, meaning sensors do not respond directly to requests but feed a collection system interrogated by application agents when needed. Sensors and application agents are *decoupled*, or better, loosely coupled by means of the data collection entity.

The decoupling weakens ties between the application and environment, generating asynchronous observations that raise issues like optimal sampling, accuracy, timeliness, energy consumption, storage duration, and data relevance. However, decoupling enables new applications to rely on the observation platform without redesigning the status update collection system. Directly polling sensors may be more effective for status update generation and management but creates a rigid, holistic system with strong integration between the observed environment and actuating entities, making evolution and third-party contributions more difficult, though necessary for specific critical systems (e.g., platooning).

It should be noted that the two paradigms are not always sharply separated in practice. Applications such as Cooperative Adaptive Cruise Control with perception sharing combine a response-centric control loop – with strict per-link delay requirements – and a data-centric perception layer, requiring metric selection to account for both timing regimes simultaneously. Furthermore, while the data-centric paradigm offers flexibility and extensibility, its costs must be acknowledged. As the number of tracked objects grows, maintaining a consistent Local Dynamic Map across vehicles introduces state explosion and synchronization complexity. Conflicting observations of the same object from heterogeneous sources require inconsistency handling that current timeliness metrics do not account for. These costs are not incidental: they are structurally tied to the choice of timeliness metric and must directly inform future goal-oriented frameworks.

B. Data-centric paradigm applied to vehicular systems

The data-centric paradigm assumes that the primary purpose of communication is to maintain a consistent representation of the external environment across all network nodes. In vehicular systems, this paradigm can be directly mapped onto the distributed perception and decision-making processes that characterize cooperative driving. Each vehicle acts as a data producer (sensing and generating observations) and consumer (using others’ information to update its local world model and support control). The environment includes static and dynamic road scene elements (e.g., vehicles, pedestrians, infrastructure) whose state must be accurately represented in space and time. Data sources include on-board vehicle sensors (e.g., cameras, lidars, and position sensors) and infrastructure-based sensors (e.g., Roadside Units (RSUs) and traffic cameras).

In this context, V2X communication serves as a data exchange mechanism between producers and consumers. Producers, like vehicles detecting objects, may be unaware of the final application, while consumers, like automated driving functions, may combine information from various heterogeneous sources. This decoupling of sensing and acting distinguishes data-centric vehicular systems from traditional control-centric schemes, in which a single sensor–actuator loop determines the timing constraints.

Data-centric vehicular systems differ from conventional communication networks in several ways:

- Wireless broadcast traffic is the dominant communication paradigm, leading to acknowledgments being unsupported.
- Sensor updates are asynchronous and heterogeneous, causing varying levels of information staleness across vehicles.
- Multiple sources may observe the same object, creating data redundancy and requiring mechanisms that identify and disseminate only novel or higher-quality information.
- Spatio-temporal coverage of the environment is as important as freshness, requiring a balance between update rate and perceived scene completeness.
- The prioritization of information depends on contextual factors such as distance, relative velocity, and risk level.

The data-centric paradigm provides a conceptual basis for defining new performance indicators that capture the ability of the network to sustain this shared situational awareness. The suitability of existing timeliness metrics for such systems and their potential limitations are discussed in the following subsection.

C. Is AoI the answer?

The AoI metric has become a reference for evaluating the timeliness of information updates in networks where nodes periodically exchange status messages. It quantifies the average “freshness” of data at a receiver. Given an update source and the corresponding receiver, AoI at time t is defined as $A(t) = t - g(t)$, where $g(t)$ is the generation time of the most recent update available at the recipient at time t .

While AoI benefits from a reliable communication channel, high reliability is not a strict requirement for achieving

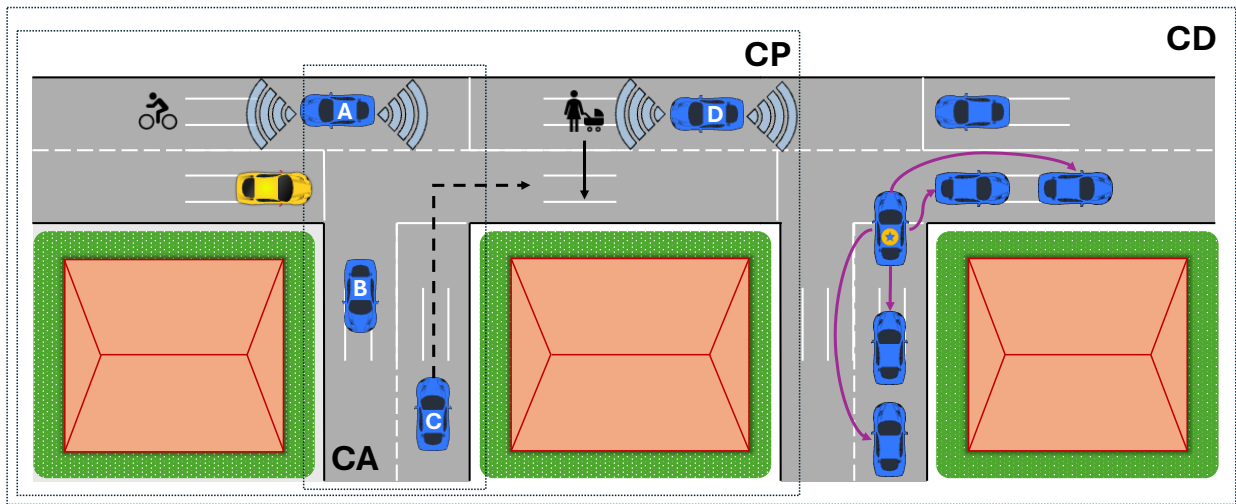


Figure 2. Example of different data-centric application scenarios, in the evolution from Cooperative Awareness (CA), to Collective Perception (CP) and Cooperative Driving (CD).

a satisfactory level of AoI. Random message losses may marginally affect the achieved AoI [10].

In general, AoI provides a highly significant description of the behavior of a data-centric system. However, in vehicular networks, AoI alone does not capture all aspects of timeliness: it measures freshness, but it ignores the accuracy of the information and its contextual value for decision-making. In particular, AoI cannot distinguish between a fresh but incorrect update and an accurate one, leaving critical failure modes such as false object detections, stale object persistence, and delayed disappearance events entirely unpenalized.

Figure 2 provides an illustrative example. It shows a main road (horizontal) with two T-shaped intersections. V2X-equipped vehicles are blue, while yellow vehicles are non-V2X participants. Two Vulnerable Road Users (VRUs) (pedestrians crossing the main road and a bicycle) are shown as well. The scenario is intentionally kept clean and deterministic, as its primary purpose is to illustrate the transition across Day 1, Day 2, and Day 3+ applications and to support the argument that AoI alone is insufficient across these phases.

In a cooperative awareness scenario, blue vehicles exchange only their own status information (CA box in the figure). Hence, vehicle C cannot detect VRUs or other non-V2X vehicles, because they do not transmit messages. Vehicle C is approaching the intersection, planning to turn right, which creates two potential safety hazards: the upcoming yellow vehicle and the pedestrians crossing the main road. Neither of these hazards is addressed by the V2X awareness functions.

In a collective perception scenario, neighboring vehicles share object-level data (CPMs) about relevant objects detected by their on-board sensors (CP box). For instance, vehicle C can learn about the yellow vehicle from data sent by vehicle A. Pedestrians can be signaled to vehicle C by both vehicles A and D. However, vehicle D's messages might not reach vehicle C early enough due to an obstacle (the orange square between the intersections). While the pedestrians are not a safety hazard for vehicle A (which is moving away from them), this information is relevant to A because it can report it to nearby vehicles that

cannot perceive the pedestrians (e.g., vehicle C).

In a cooperative driving scenario (CD box), vehicles share driving maneuvers and trajectories, e.g., to control safe merging of side road vehicles into the main road, as illustrated on the right part of Figure 2.

Strictly speaking, the evaluation of CA, CP, and CD from the point of view of update freshness (and the respective delays) is not complete. Indeed, all three services are based on periodic broadcasting, and the AoI at the receiver ignores the relevance of a specific sender to a specific receiver (e.g., physically separated vehicles driving in different directions on a highway will still receive each other's messages). Such relevance is, however, difficult to handle at the protocol design level in the case of CA, where each vehicle must broadcast basic information about itself, which makes AoI a rather adequate metric. In contrast, in CP each vehicle has to make decisions about which objects to include in its messages, and this brings the notion of relevance to the forefront (e.g., whether to transmit information about an object that has recently been communicated by another vehicle). Moreover, the variety of sensor types, differing confidence levels, and assumptions about the receiver's perception capabilities make the notion of relevance even more critical. Finally, CD may practically require even more than CA and CP, namely not only freshness and relevance but also at least partial consensus on the driving plan, which opens the prospect for new required metrics.

This example illustrates how different aspects should be catered for by a comprehensive assessment of safety-critical vehicular applications, timeliness (e.g., captured by AoI) as well as context-dependent relevance of data. Several extensions to the AoI concept have been proposed and are reviewed in Section IV. These extensions broaden the concept of timeliness, transforming it from a purely temporal attribute into a goal-oriented property that depends on the application context and the impact of the information on control decisions.

IV. ASSESSING INFORMATION FRESHNESS AND VALUE

This section summarizes information freshness and value in V2X systems, covering AoI-based metrics, their variants, and semantic-aware measures such as VoI. It lays the foundation for the following comparison and applicability analysis of timeliness metrics in vehicular cooperative functions.

A. Metrics definition

Since its introduction, AoI has received increasing attention and has motivated a range of related metrics aimed at characterizing information freshness. Alongside traditional performance measures, such as message delivery probability, throughput, and latency, new AoI-related indicators have been proposed to better capture data timeliness:

- **Age of Loop (AoL)** [2] is the “age of the two-way loop” in a networked control system where a sensor/actuator sends its state to a controller and receives a command back; it is measured from the time the state is sent by node η until the corresponding control command is received back at node η .
- **Age of Synchronization (AoS)** [2] measures how fresh a local cache is with respect to its source, while AoI measures staleness with respect to the original generation time.
- **Age of Information at Query (QAoI)** [2] measures AoI only at query instants, i.e., when the application actually requests/reads the information, turning a push-based AoI setting into a pull-based one, where queries sample the AoI process at times when data is actually retrieved.
- **AoII** [2] is a performance metric where “the age increases when the quality of the estimation of node μ about the process at node η deteriorates”; it counts not just time since last update, but how long receiver’s estimate stays wrong relative to the true process state.
- **Effective Age of Information (EAoI)** quantifies the freshness of the information used for decision-making, thus emphasizing staleness only of information if and when it is exploited.
- **Urgency of Information (UoI)** [11] is defined as the product of a context-aware weight and the cost of status estimation inaccuracy. It measures the performance degradation of a system caused by the difference between the actual status and the received status information.

Beyond freshness, *semantic-aware* metrics link timeliness to usefulness. **VoI** is context-dependent and can be defined at the message level or at finer granularity (e.g., per object in a CPM). There is no universal definition of VoI. In [12], it is associated with perceived objects or regions and reflects their contribution to situational awareness, based on how much the information improves understanding by adding relevance, novelty, and reducing uncertainty [13]. More generally, VoI measures the improvement in state estimation by jointly considering relevance and timeliness. In vehicular networks, it supports cooperative intelligence by driving priorities on what information is worth being transmitting, e.g., for context-aware message prioritization [14] and resource scheduling [15].

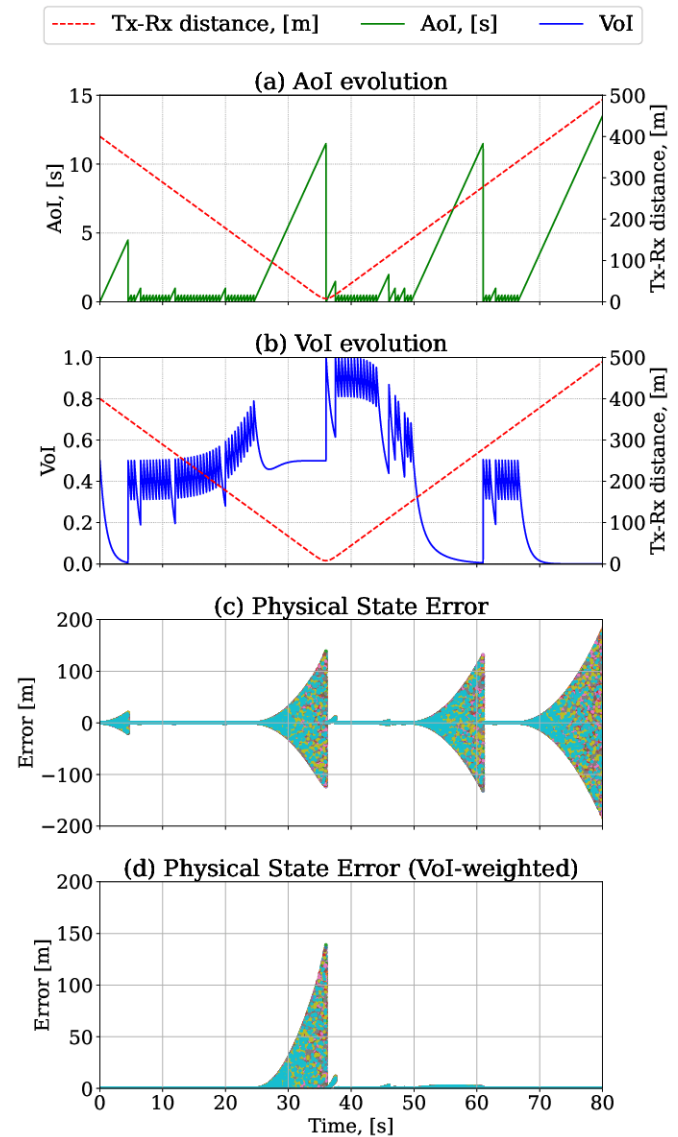


Figure 3. Spatio-temporal evolution of AoI and VoI in a V2V communication scenario.

B. AoI and VoI assessment

In this Section we provide an example based on simulations of a simple, yet rich enough scenario, so as to highlight the added value brought about by VoI-related metrics.

We consider a V2V sidelink scenario to analyze the spatio-temporal evolution of AoI and VoI for CAM messages. Two vehicles approach each other for 36 s, then move apart, modeling overtaking or intersection crossing. The simulation lasts 80 s. Vehicle A travels at 90 km/h, Vehicle D at 130 km/h, with an initial distance of 400 m. Vehicles exchange periodic CAM beacons every 1 s. AoI increases over time and resets upon successful reception of a new CAM. Packet loss depends on distance: communication is reliable within 350 m ($P_{\text{loss}} = 0.1$) and unreliable beyond that distance ($P_{\text{loss}} = 1$). Two collision intervals each lasting 11 s) model communication outages. These outages occur at times $t = 25$ s and $t = 50$ s.

As for the evaluation of the VoI metric, the framework

proposed in [14] is adopted. Equal weights are used for proximity and timeliness ($w_{\text{prox}} = w_{\text{time}} = 0.5$) to isolate mobility effects. The proximity component adopts a logistic function (with parameters $A = 1$, $K = 0$, $C = 1$, $Q = 1$, $B = 0.03$), while timeliness follows exponential decay with $P_{\text{d}} = 1$. The safety distance is set to 72 m.

Figure 3 shows the temporal and spatial evolution of AoI (green curve in top panel) and VoI (blue curve in second top panel) for messages transmitted by vehicle D and received by vehicle A. The red curve superposed to the two top panels represents the distance between the vehicle D and vehicle A, to help interpreting AoI and VoI. The two bottom panels represent position estimation error versus time (difference between predicted position based on latest data available in A and actual position of vehicle D) and position estimation error weighted by VoI.

AoI follows the classical sawtooth pattern, reflecting periodic updates, packet losses, and collision intervals. VoI, instead, captures the combined effect of information freshness and spatial relevance. More in depth, as vehicle D approaches ($t \in [5, 36]$ s), the proximity component becomes dominant and VoI increases. In this phase, recent updates are most valuable, significantly improving safety-critical information held by the receiving node. During the outage starting at time $t = 25$ s, VoI initially decreases due to increasing AoI, then stabilizes. In the absence of new messages, vehicle A relies on the last received CAM to predict vehicle D's motion. VoI reflects this trade-off: although information becomes increasingly stale, due to lack of updates during the outage, thus leading to a gradual increase in estimation error, still this information is deemed to be valuable, because of the proximity of vehicle D. At $t = 36$ s, a new message resets both AoI and the accumulated estimation error, resulting in a sharp increase in VoI. As the vehicles move apart, VoI decreases, since updates contribute to reducing estimation uncertainty, but having accurate estimates of vehicle D trajectory is of diminishing relevance, since it is going away of vehicle A. This highlights that minimizing AoI alone does not guarantee high VoI. A second outage at $t = 50$ s causes VoI to drop to negligible values, as information about vehicle D becomes both increasingly outdated and less relevant as vehicle D moves away of vehicle A. A similar effect is observed beyond 350 m (from $t \approx 68$ s), where packet loss dominates and the proximity contribution vanishes.

It is apparent from Figure 3 that AoI and estimation error do not capture any difference between the two outage periods, while they look quite different through the lenses of VoI. In the first outage the available information (albeit increasingly aged) is important from a safety point of view since it refers to an approaching vehicle. On the contrary, in the second outage it becomes quickly irrelevant. Correspondingly, the weighted estimation error is high in the first outage, triggering an alarm (e.g., calling for actions to acquire more data from other sensors), while in the second outage it is small, highlighting there the error in position estimate is not "worrying" for safety.

C. Applicability of timeliness and value metrics across use cases

Table II maps the different timeliness metrics to 3GPP and 5GAA use-case groups and C-ITS phases, organizing them by approach (response- or data-centric), primary meaning (freshness, delay, or value), standardization readiness, and required information layer. Response-centric or query-driven metrics such as E2E delay, QAOI, and AoL are primarily associated with centralized or control-loop driven functions, but data-centric metrics including AoI, PAOI/PIR, AoII/UoI, and VoI are also relevant when the infrastructure manages resources, fuses perception data, or coordinates maneuvers. These metrics capture freshness, correctness, and information value beyond what delay alone can express. Their role becomes even more prominent under distributed scheduling, where broadcast-based and contention-driven dissemination induces large variability in update regularity, making AoI-like metrics indispensable for performance characterization.

The C2C-CC Phase column shows how each metric's relevance extends across the cumulative C-ITS roadmap from Day 1 to Day 2 and Day 3+. Applicability persists, but operational roles and target thresholds adjust to growing scenario complexity. In Day 1, metrics such as AoI and PAOI mainly assess the timeliness of periodic broadcasts. In Day 2, they additionally influence object-level coverage, spatial correlation, and uncertainty in collective perception. By Day 3+, variants such as EAoI, AoL, AoII, and VoI become central because they link freshness to decision relevance and control-loop timing. As a result, even when a metric spans multiple phases, its interpretation must align with the specific cooperative function and automation level.

Although AoI offers a useful baseline for information freshness, it does not fully capture the timeliness requirements of vehicular systems that exploit collective perception and cooperative automation. Future metrics should therefore be explicitly goal-oriented, integrating freshness, correctness, and relevance to reflect how communication supports an accurate and actionable representation of the environment. Notably, most advanced metrics – including AoII/UoI, EAoI, AoL, and VoI – are not yet standardized and require application- or semantic-layer information, highlighting the gap between current standardization practice and the requirements of goal-oriented vehicular systems.

V. CONCLUSIONS AND OUTLOOK

This paper reviews timeliness metrics for vehicular communications and their role in safety-critical 6G transportation systems. Moving beyond latency-based indicators, we show that AoI and its variants better capture information freshness, while effectiveness in C-ITS applications depends jointly on freshness, correctness, and contextual relevance. Current 3GPP and ETSI standards lack a unified framework linking link-layer metrics (e.g., PIR, PRR) to application-level information value. Data-centric metrics such as AoI, together with semantic-aware measures like VoI, provide a more complete view of system performance across V2X use cases.

Performance evaluation should therefore move beyond packet-level indicators and include metrics capturing both

Table II
MAPPING OF TIMELINESS METRICS TO USE-CASE GROUPS, C-ITS PHASES, AND STANDARDIZATION READINESS.

Metric	Approach	Meaning/Focus	Use-Case Groups	C2C-CC Phase	Rationale / Fit	Standardization Readiness	Required Inform. Layer
E2E Delay / Latency	Response-centric	E2E message generation to reception delay	All	Day 1, 2, 3+	Baseline latency metric for safety-critical services.	Standardized (3GPP, 5GAA)	MAC / Application
AoI / DA	Data-centric	Information freshness	All except 3GPP-UC5	Day 1, 2, 3+	Captures staleness beyond delivery ratio	Partial (ETSI TR 103 766)	Application
PAoI / PIR / IPG	Data-centric	Worst-case freshness / update regularity	All except 3GPP-UC5	Day 1, 2, 3+	Aligns with standard KPIs; worst-case analysis	Standardized (3GPP TR 37 885, ETSI TR 103 766)	MAC
AoS	Data-centric	Cache synchronization freshness	All except 3GPP-UC5	Day 1, 2, 3+	Relevant for LDM consistency	Not standardized	Application
QAoI	Response-centric	Freshness at query instants	3GPP-UC3 & UC5, 5GAA-UC3	Day 3+	Suited for pull-based cooperative driving	Not standardized	Application
EAoI	Both	Freshness at decision / actuation epochs	3GPP-UC3 & UC5, 5GAA-UC3	Day 2, 3+	Links update timing to control actions	Not standardized	Application + Control
AoL	Both	Freshness in closed control loops	3GPP-UC3 & UC5, 5GAA-UC3	Day 3+	Captures full sense-compute-actuate latency	Not standardized	Application + Control
AoII / UoI	Data-centric	Freshness penalized for inaccuracy	All except 3GPP-UC5	Day 1, 2, 3+	Addresses correctness beyond temporal staleness	Not standardized	Application + Semantic
VoI	Data-centric	Information value combining freshness and relevance	All except 3GPP-UC5	Day 1, 2, 3+	Goal-oriented; captures spatial and contextual relevance	Partial (ETSI TS 103 324)	Application + Semantic

timeliness and relevance. A key challenge for standardization is bridging link-layer and application-level metrics, as emerging in Collective Perception. A phased evolution is expected: from packet-level (Day 1), to freshness-aware (Day 2), and finally to semantic- and goal-aware metrics (Day 3+). Scalability and practical implementation remain open issues.

Future timeliness frameworks must be semantic- and goal-aware, evaluating not only when information is delivered but how well it supports decision-making and safe cooperation. Developing unified metrics that integrate freshness, correctness, and context remains a key research direction for efficient and reliable 6G vehicular systems.

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