ENGINEERING WHITE PAPER

Distributed Environmental Sensing for the Tedford Global Mesh Agent Architecture

A practical, evidence-based design for measuring air temperature, precipitation, wind, and road-weather conditions from fixed and mobile Agents

Prepared for
Government engineering, transportation, weather, and technology evaluation audiences

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A practical engineering assessment of available sensors, mobile measurement limits, and a government-led path to validation.

Executive Summary

A distributed Agent system can support environmental awareness by sampling conditions locally, attaching time and location, reporting measurement quality, and sharing observations through the mesh toward authorized gateways and analytics. A weather sensor does not need a direct satellite link on every Agent: the Agent may relay observations by mesh to a gateway with an available backhaul. Satellite availability, radio access, and the proposed TLTE network implementation are separate engineering questions from whether a sensor can measure weather.

A robust first demonstrator should measure: (1) shielded ambient air temperature and relative humidity; (2) pressure; (3) precipitation occurrence and type using a present-weather instrument or optical disdrometer at a fixed reference; (4) rainfall accumulation at selected reference sites using a calibrated gauge; (5) wind at fixed, well-sited locations; and (6) road-surface temperature/state where road safety is in scope. Mobile Agents should contribute measurements that remain valid while moving, and explicitly downgrade or suppress data compromised by body heat, vehicle wake, splash, vibration, window contamination, or sensor blockage.

The most important truth for the highway scenario is wind. A sensor on a moving car sees apparent airflow: the vector combines ambient wind and vehicle motion, then is distorted by the car body. GNSS/IMU motion compensation can remove vehicle velocity in principle, but does not remove local flow separation and turbulence. A fixed mast, a stopped vehicle with a suitable exposure, or a validated roof/boom installation is required for dependable ambient wind.

Precipitation is similarly difficult on a moving platform. A moving sensor changes collection efficiency and experiences splash, spray, vibration, and airflow; a rain gauge mounted on a moving vehicle cannot be presumed to produce reference rainfall totals. A mobile Agent can reliably report rain presence or particle observations only after its sensor package is tested and its confidence limits quantified. For amount and precipitation type, the preferred architecture is fixed reference sensors plus regional radar and satellite products, fused with mobile corroboration.

The recommended initial component concept is a protected temperature/humidity probe such as Sensirion SHT45-AD1B-R2 for compact electronics prototypes, or a meteorological probe such as Vaisala HMP155 where rugged field integration and maintainability dominate; a WXT536-class multi-weather transmitter for a stationary reference package; a present-weather detector or optical disdrometer such as Vaisala PWD52, OTT PARSIVEL2, or Thies Laser Precipitation Monitor to classify hydrometeors; a conventional weighing or tipping-bucket gauge for accumulation; and a sonic anemometer such as Campbell Scientific CSAT3B or a suitable WXT536 ultrasonic unit for fixed-site wind.

Do not label calculated conditions as direct measurements. Rain/snow/sleet classification, road icing risk, and wind estimates should carry sensor provenance, calibration state, location, time, exposure, and confidence. The mesh/AI layer should preserve uncertainty rather than turn weak observations into certainty.

Status distinction: the listed sensor families and product examples are publicly documented commercial instruments or components. The exact Agent enclosure, mounting, thermal design, calibration workflow, data protocol, satellite/mesh pathway, automated quality control, and multi-sensor fusion described here would require engineering and validation.

1. Scope, Definitions, and Measurement Classes

“Environmental sensing” covers variables in the air, falling precipitation, road or ground surface, and near-surface wind field. A sensor’s name alone does not establish fitness: measurement accuracy depends on siting, exposure, calibration, response time, contamination control, thermal isolation, and platform motion.

Fixed reference Agent: a powered, surveyed, stationary package mounted with appropriate exposure and maintainable sensor access. It may function as a local weather reference and a mesh relay.

Mobile Agent: an instrument package carried by a road vehicle or other moving platform. It samples along a route, but experiences platform-induced heating, airflow, vibration, spray, obstruction, and changing geometry.

Ambient air temperature: temperature of air measured in a ventilated, radiation-shielded location away from vehicle heat sources. A sensor inside the Agent enclosure measures enclosure/electronics temperature, not ambient air.

Precipitation amount: accumulated liquid-equivalent depth over time. It is distinct from snow depth, snow-water equivalent (SWE), instantaneous intensity, and a simple wet/dry indication.

Present weather: a classification such as rain, drizzle, snow, sleet, hail, or mixed precipitation, usually inferred from particle measurements and/or multiple signals. It is not a perfect ground truth in every mixed-phase event.

Wind: ambient air motion relative to Earth. A vehicle-mounted anemometer directly observes apparent airflow relative to the sensor. Correcting the vehicle velocity is necessary but may not be sufficient because the vehicle body distorts the local flow.

FHWA describes Road Weather Information Systems as field environmental sensor stations plus communications and central processing. It groups observations into atmospheric, pavement, and water-level conditions and specifically lists air temperature, humidity, wind, precipitation type/rate, visibility, and related variables [1]. FHWA guidance treats sensors as complementary: air temperature, humidity, precipitation, and pavement sensors answer different questions [2].

2. Recommended System Architecture

Layer	Role	Design requirement
1. Sensor head	Measure a physical quantity at the point of exposure.	Each value must identify sensor model/type, range, units, calibration status, and diagnostic state.
2. Agent edge processor	Time-stamp, geotag, compensate, quality-check, and package measurements.	Keep raw sensor data where feasible; separate measured values from derived estimates.
3. Mesh transport	Move observations among nearby Agents and to a gateway.	Store-and-forward, sequence IDs, time quality, message integrity, and loss/retry metadata.
4. Gateway/backhaul	Forward selected data over an available terrestrial or satellite link.	Do not assume every sensor or Agent has direct satellite connectivity. Link availability and power budget are separate requirements.
5. Fusion / mother AI	Compare nearby observations, sensor histories, radar/satellite products, and forecast context.	Preserve disagreement and confidence; never invent a value when measurements are missing.
6. User products	Deliver maps, alerts, and machine-readable observations to authorized users.	Show source, time, location precision, quality, and whether a result is direct or inferred.

Every observation should have, at minimum: sensor and firmware identity; calibrated units; UTC time plus time-quality estimate; latitude/longitude plus location accuracy; platform state and speed; sensor orientation; mounting/exposure class; raw value or diagnostic; quality flags; and any processing version. For network security, use authenticated devices, signed or otherwise integrity-protected telemetry, replay protection, access control, and a defined update/revocation process. These are requirements for a system design, not claims that a TLTE implementation already provides them.

Global distribution is useful because it increases spatial density, while satellites and AI do not remove the need for valid local measurements. Earth-observation satellites and weather radar provide wide-area context; surface Agents provide near-surface sampling and local confirmation. The network should combine the layers instead of asking a single Agent to replace national observing systems.

3. Temperature: Top 10 Options

The ranking favors practical fitness for a distributed Agent program: measurement quality, packaging, power, fieldability, and complementary value. It is not a universal ranking of sensor accuracy.

3.1 Ranked temperature technologies

Recommended: use two distinct temperature channels where feasible: (a) shielded ambient air and (b) Agent/electronics self-temperature. Add road-surface temperature only when the mission requires it. A vehicle interior or exposed PCB sensor must not be reported as outdoor air temperature.

No.	Option / example	What it senses and why it ranks here	Use limits / engineering note
1	Shielded platinum RTD / Pt100 or Pt1000	Reference-grade resistive temperature measurement when paired with an appropriate probe, excitation, and readout. Strong choice for fixed reference or calibration transfer.	Probe installation and readout dominate performance; use a radiation shield and calibrated assembly.
2	Vaisala HMP155 meteorological probe	Commercial meteorological temperature and humidity probe intended for outdoor weather measurement. Suitable fixed reference candidate. [7]	Larger and more costly than a chip sensor; mount in a proper shield and service per manufacturer instructions.
3	Sensirion SHT45-AD1B-R2	Compact digital temperature/RH component. Manufacturer lists up to ±0.1 C and ±1.0% RH under specified conditions. Good low-power Agent prototype sensor. [5]	Bare component is not a weather station. Enclosure, airflow, solar shielding, PCB heat, calibration, and condensation need validation.
4	Vaisala WXT536 temperature channel	Integrated weather transmitter reports temperature together with pressure, humidity, rain, and wind variables. Useful as a fixed reference package. [13,14]	Multi-parameter package; not a miniature onboard chip. Confirm selected model configuration and specification before purchase.
5	Texas Instruments TMP117	Digital IC with stated ±0.1 C accuracy over -20 to 50 C and 0.0078 C resolution. Useful for board, enclosure, or internal health temperature. [6]	Board-level sensor is not automatically an ambient air sensor; self-heating, PCB coupling, and airflow matter.
6	Thermistor (NTC) probe	Inexpensive, sensitive, compact; useful for internal thermal monitoring or a calibrated contact probe.	Nonlinear response, interchangeability, self-heating, and drift make calibration and circuit design essential.

No.	Option / example	What it senses and why it ranks here	Use limits / engineering note
7	Thermocouple (Type T for cold-range work)	Broad temperature range and rugged probe construction; useful where extreme temperature or fast contact response is needed.	Requires cold-junction compensation and calibrated wiring; less attractive for high-accuracy ambient readings at small thermal gradients.
8	Infrared thermopile surface sensor	Non-contact measurement of a target surface, such as pavement, when field of view and emissivity are controlled.	Measures radiative surface temperature, not air temperature. Reflections, target size, angle, and contamination affect results.
9	Vaisala DST111 remote road-temperature sensor	Commercial IR instrument for non-contact road-surface temperature, intended for road-weather applications. [8]	Road-oriented fixed or carefully mounted geometry; not a substitute for a shielded ambient-air probe.
10	Thermal camera / radiometric array	Provides spatial temperature patterns and scene context for road, equipment, or localized hot/cold surfaces.	Generally less suitable than calibrated point probes for reference ambient temperature; higher power, data volume, and optical-window maintenance.

Air-temperature implementation. Put the sensing element in a radiation shield with free air exchange, physically separate it from processors, batteries, radio power amplifiers, vehicle exhaust, radiator flow, solar-heated bodywork, and enclosed pockets. Log sensor height and exposure. On a mobile Agent, mount away from the vehicle body and exhaust; use a designed probe/aspirated shield if the target accuracy justifies the additional power. Validate with side-by-side reference measurements while parked and across controlled driving conditions.

Cold and heat. Specify a project operating range only after choosing components, housing, battery chemistry, seals, and calibration range. Commercial component operating ranges are not equivalent to end-to-end system operating range. A cold-temperature value also needs sensor response-time characterization and protection from icing, condensation, and snow coverage.

4. Precipitation: Top 10 Options

No single rain sensor answers all precipitation questions. Choose separately for occurrence, type, rate, accumulation, snow depth, and snow-water equivalent.

4.1 Ranked precipitation and frozen-precipitation technologies

The strongest all-around fixed-site precipitation-type option is a present-weather disdrometer, paired with a calibrated accumulation gauge. For a road-mounted Agent, begin with carefully qualified precipitation occurrence and road-surface sensing; do not promise reference rain totals from a moving vehicle before tests establish them.

No.	Option / example	What it senses and why it ranks here	Use limits / engineering note
1	Optical laser disdrometer: OTT PARSIVEL2	Counts particle size/velocity spectra to derive precipitation type, rate, drop-size distribution, and visibility-related measures. Strong fixed-site type/intensity instrument. [11]	Needs stable mounting and unobstructed sampling volume; wind, alignment, contamination, and particle classification affect results.
2	Laser Precipitation Monitor: Thies CLIMA LPM	Optical particle measurement that distinguishes rain, drizzle, sleet, snow, hail, and mixed precipitation categories. [12]	Reference use should include event validation; small sample area and blowing snow/particle artifacts require QC.
3	3D stereo disdrometer: Thies CLIMA 3D	Image-based particle analysis provides richer particle-shape and class information, including rain/snow/sleet and non-weather particles. [12]	More complex optics/data and power; not a default choice for every tiny mobile Agent.
4	Present-weather detector: Vaisala PWD52	Combines precipitation water-content measurement with optical visibility to identify present weather. [10]	Vendor describes a road/meteorological instrument; confirm exact outputs, installation, and operating envelope.
5	Present-weather/visibility detector: Vaisala PWD series	Commercial family of present-weather and visibility products for transportation and meteorological use. [9]	Provides classification/visibility, not necessarily reference accumulation totals.
6	WXT536 RAINCAP piezoelectric precipitation channel	Compact solid-state rain detection/measurement within a multi-weather transmitter; useful for fixed reference or coarse event monitoring. [13,14]	A precipitation pulse/rain measure is not interchangeable with all-weather liquid-equivalent totals or particle-type classification.
7	Heated weighing precipitation gauge (e.g., OTT Pluvio2 family)	Measures accumulated precipitation mass; heating and gauge design can support liquid and solid precipitation measurement.	Stationary, level installation; catch efficiency, wind shielding, heating, siting, and maintenance govern quality.

No.	Option / example	What it senses and why it ranks here	Use limits / engineering note
8	Heated tipping-bucket gauge	Established liquid precipitation accumulation method; can yield event timing and rate at fixed stations.	Solid precipitation needs an appropriate heated configuration; tipping dynamics, clogging, wind undercatch, and intense-rate limitations matter.
9	Snow depth sensor: ultrasonic or laser ranging	Measures distance to the snow surface at a point; repeated readings estimate snow-depth change.	Measures depth, not SWE or snowfall water equivalent. Wind redistribution, surface roughness, and target geometry matter.
10	Snow-water-equivalent sensor: Campbell Scientific CS725	Passive gamma measurement estimates SWE over a surrounding area from attenuation changes. [16]	Fixed-site specialized instrument; it measures snowpack water equivalent, not falling precipitation rate and not a compact mobile Agent sensor.

Rain amount. Report both instantaneous rate (for example, millimeters per hour) and accumulated liquid-equivalent depth (millimeters over a defined interval). Each value needs interval boundaries and a gauge method. A dry/non-dry detector cannot be presented as a rain amount instrument. Optical sensors estimate precipitation from sampled particle size and speed; gauges collect or weigh precipitation. Comparing independent methods helps identify bias.

Snow and sleet. The near-surface air temperature alone cannot classify precipitation: precipitation can melt or refreeze through vertical layers, and mixed phases occur. Use a present-weather sensor that examines particle properties, together with shielded air temperature/humidity and, where useful, vertical radar or national forecast/radar products. National Weather Service materials describe LED-based precipitation identification for rain/snow and intensity; NWS also cautions that radar signatures and melting-layer context have limitations [17,18].

Water, snow depth, and road state. If the mission includes flood or standing-water awareness, add a separate water-level sensor at known sites. If the mission includes road icing, measure pavement/road-surface temperature and surface state; air temperature alone cannot establish that a road is icy. FHWA describes ESS designs combining atmospheric, pavement, and water-level sensors [1,2].

5. Wind: Top 10 Options

The primary distinction is exposure. These technologies can measure wind in suitable conditions; a package on a moving highway vehicle needs a separate validation and correction method.

5.1 Ranked wind-sensing options

For the stated highway case, use fixed ultrasonic wind stations as the dependable local anchor. Treat mobile wind as an experimental derived estimate until the complete vehicle, mounting, GNSS/IMU, and correction model pass an independent comparison campaign.

No.	Option / example	What it senses and why it ranks here	Use limits / engineering note
1	Fixed 2D/3D ultrasonic anemometer	No moving cups; measures wind vector from acoustic transit times. Best practical fit for compact fixed Agent stations. WXT536 includes ultrasonic wind sensing; Campbell CSAT3B provides 3D components. [13,15]	Mount above obstructions with known orientation and exposure; precipitation/icing and flow distortion still matter.
2	Fixed cup-and-vane anemometer	Mature, well-understood wind speed and direction method used in weather stations.	Moving parts require maintenance; response and icing limits; poor siting biases the result.
3	3D sonic anemometer (research/reference class)	Measures three wind components and sonic temperature; useful for turbulent or vertical-motion work. Campbell CSAT3B is a named example. [15]	More size, power, cost, and processing than a minimal Agent; its technical accuracy presumes appropriate deployment.
4	Compact ultrasonic weather transmitter (Vaisala WXT536)	Combines wind speed/direction with pressure, air temperature, RH, and precipitation in one field instrument. [13,14]	Fixed or carefully exposed installations preferred; vehicle wake can dominate wind.
5	Vehicle-mounted sonic plus GNSS/IMU motion correction	Potentially estimates Earth-relative wind by combining measured apparent airflow and platform velocity/orientation.	Requires calibrated coordinate transforms, synchronized high-rate motion data, and vehicle-specific flow calibration; not a drop-in reference wind station.
6	Multi-hole pressure probe / calibrated air-data probe	Can measure local airspeed and direction relative to the vehicle at high rate.	Measures local flow around vehicle, not ambient wind directly; installation and vehicle-flow calibration are critical.
7	Pitot-static airspeed system plus GNSS/IMU	Measures platform-relative airspeed; GNSS velocity and attitude provide ingredients for a vector estimate.	Pitot systems alone do not measure ambient wind. Turbulence, yaw, blockage, and low-speed behavior introduce error.

No.	Option / example	What it senses and why it ranks here	Use limits / engineering note
8	Doppler lidar wind profiler	Remote sensing of wind over a volume; potentially valuable at fixed sites for vertical profile/context.	Large, power-hungry infrastructure, cost, and retrieval limits make this a regional/reference asset rather than an Agent sensor.
9	Weather radar Doppler wind products	Provides regional storm and radial-velocity context over broad areas.	Measures only the radar radial component in sampled volumes; beam height/coverage and geometry limit near-surface local wind.
10	Satellite scatterometer / atmospheric motion products	Regional to global wind context from remote sensing or cloud-motion analysis.	Not a direct, continuous point measurement at every Agent; resolution, revisit, retrieval, and latency vary by product.

Highway truth: an unobstructed road is not an unobstructed sensor. The vehicle creates its own high-speed airflow and wakes. Subtracting vehicle speed from a sensor reading does not automatically recover true ambient wind.

A mobile wind record should include the raw apparent wind vector, GNSS/IMU velocity and attitude, time synchronization, vehicle speed, mounting coordinates, and a calibrated vehicle-specific correction model. During highway operation, label values as “vehicle-corrected estimate” with a tested uncertainty, or omit them from authoritative wind products. A fixed nearby station or external weather observation may be more reliable.

For extreme gust warnings and network alerting, combine fixed sensors, weather radar, and official weather products. A mesh can distribute alerts quickly, but an alert threshold and false-alarm behavior must be specified and tested.

6. Supporting Environmental Measurements

Variable	Recommended sensor class	Purpose / limits
Relative humidity and dew point	Use a calibrated outdoor RH/T probe (e.g., SHT45 for a low-power prototype; Vaisala HMP155 or WXT536 for field package).	Humidity informs fog, frost, evaporation, and heat-stress analysis. Dew point is calculated from temperature and RH; report it as derived.
Barometric pressure	MEMS barometer for compact Agent; meteorological pressure channel in WXT536 for reference site.	Supports weather context and sensor health; pressure trends alone do not identify local precipitation type.
Visibility / obscuration	Present-weather visibility instrument (for example Vaisala PWD family).	Useful for fog, heavy precipitation, and road operations. Optical windows need cleaning and QC.
Road-surface temperature	IR road temperature instrument (e.g., Vaisala DST111) or embedded contact sensor at fixed site.	Separate channel from ambient temperature; geometry and surface emissivity affect IR results.
Road surface state	Road-state sensor or camera-based classifier, paired with surface temperature and precipitation.	Wet/ice/snow inference is a separate validated classifier; no single temperature value proves a surface is icy.
Water level	Site-specific level sensor: radar/ultrasonic, pressure transducer, or float based on installation.	Flood/standing-water observation is distinct from rainfall amount and needs a known datum and siting.
Solar radiation	Pyranometer or photodiode-class irradiance sensor, depending accuracy need.	Helps identify radiative heating of an exposed temperature sensor and supports environmental context.
Agent internal thermal state	Board/battery/processor temperature ICs such as TMP117-class parts.	Protects equipment and helps correct/flag self-heating; never substitute it for outdoor air temperature.

A small Agent should not try to carry every specialist meteorological instrument. The network can distribute instrument roles: dense mobile Agents for local context; a smaller number of fixed reference Agents for calibration-quality precipitation and wind; and external radar/satellite/official feeds for spatial coverage. FHWA's ESS model uses precisely this kind of complementary station and central-processing arrangement [1].

7. Recommended Agent Configurations

The recommended build path separates an initial low-power mobile sensor set from a reference-station set. Exact packaging and electrical interfaces must be selected after environmental, power, and communications requirements are defined.

Configuration	Sensor package concept	Good for	Avoid claiming
Mobile Agent - baseline	Shielded digital T/RH element; separate internal temperature monitor; pressure sensor; GNSS/IMU; optional road-facing temperature/vision sensor; precipitation occurrence input only after test.	Dense route observations of air temperature/humidity trends, location/time context, local road scene, and network status.	Reference wind, reference rainfall accumulation, or guaranteed rain/snow/sleet classification while moving.
Fixed Agent - local weather anchor	Meteorological T/RH probe; ultrasonic wind; pressure; present-weather/disdrometer sensor; accumulation gauge selected for climate; optional visibility and road-surface sensor.	Local validated weather observation and comparison point for nearby mobile Agents.	Global coverage from a small number of stations; measurements outside validated exposure/maintenance conditions.
Gateway / regional node	Data ingestion, timing checks, mesh relay, satellite or terrestrial backhaul where available, persistent buffering, cryptographic device management.	Connectivity and cross-node data assembly.	Direct satellite connectivity for every sensor; guaranteed end-to-end delivery without link qualification.
Specialized snow/flood site	SWE sensor or snow-depth instrument; water-level sensor; reference gauge; temperature/humidity; winterized mounting and power.	Snowpack accumulation, melt, flood, and site-specific hazard monitoring.	Falling-snow amount from snow depth alone; SWE from a generic rain detector.

For highway runs, first install temperature/RH sensors at multiple candidate positions and compare with a traceable reference thermometer in a radiation shield. Then run at stationary, low-speed, and highway conditions to quantify response lag, vehicle heating, solar loading, and location bias. Conduct a separate wind and precipitation trial rather than assuming success from the temperature test.

8. Data Quality, Calibration, and “Mother AI” Rules

The analytics layer should receive data with a quality state, not only a number. Recommended flags include: valid; sensor warming; calibration expired; condensation suspected; icing/blocked; window contaminated; near vehicle heat source; moving-platform correction unavailable; high vibration; precipitation splash; exposure invalid; clock uncertain; location uncertain; stale; and sensor disagreement.

Use a hierarchy of confidence: (A) traceably calibrated, properly exposed fixed reference; (B) fixed field sensor with current calibration and valid diagnostics; (C) mobile measurement with validated platform correction; (D) opportunistic mobile observation without full environmental control; (E) inferred estimate from other sensors or model. Preserve this class through summaries and alerts.

Quality workflow: factory calibration record; incoming inspection; side-by-side acceptance test; field calibration interval based on drift and mission; automated range/rate checks; cross-sensor checks; maintenance/cleaning log; and post-event review. Calibration intervals should be set by an engineering authority and the sensor manufacturer’s instructions, not asserted in advance without drift data.

Fusion rules should detect physical consistency without erasing real extremes. For instance, compare temperature and RH to dew-point bounds; compare local precipitation classification across nearby nodes and radar; compare wind direction to sensor orientation and vehicle heading; compare road temperature to air temperature and surface-state observations. If inputs conflict, retain multiple values with provenance and uncertainty; do not silently average incompatible sensors.

Time and location are measurement attributes. If clock synchronization is lost, mark the observation. If GNSS is unavailable or suspect, retain inertial/dead-reckoned location uncertainty and flag it. These quality fields are necessary for later use in transportation, public safety, environmental monitoring, or government decision systems.

9. Government-Led Engineering and Prime Integration

A government-led program can turn this concept into an auditable demonstrator by providing mission requirements, reference sites, environmental test access, data standards, independent evaluation, and transition criteria. Prime contractors or systems integrators can contribute rugged packaging, vehicle installation, power and thermal integration, cybersecurity, test range coordination, interface management, and integration with government weather, transportation, command-and-control, or data systems. Their participation is a potential role, not a statement that any prime has committed to TLTE.

The government should define the required observation accuracy, time/location integrity, platform types, environmental extremes, service life, maintainability, data rights, classification/security boundary, mesh/backhaul options, and failure behavior. These requirements determine which of the ranked sensors is actually best. The sensor choice should follow the mission specification and comparative test, not branding alone.

Work package	Government / evaluator input	Prime / engineering contribution	Acceptance evidence
Requirements & interface control	Use case, allowable error, formats, alert latency, security boundary.	System architecture, interface control document, power/thermal budgets.	Approved requirements and traceability matrix.
Sensor bench characterization	Reference standards, test protocol, uncertainty target.	Sensor fixture, logging, calibration and diagnostics.	Comparison to traceable reference across temperature/humidity range.
Vehicle integration	Vehicle types, mounting/safety constraints, routes.	Mounts, shielding, vibration isolation, EMC, thermal design.	Repeated parked/road-speed data against reference equipment.
Weather field trial	Representative rain/snow/mixed-phase and wind sites.	Station deployment, maintenance, data pipeline.	Event-based performance report with confusion matrix, bias, missingness.
Network and analytics trial	Operational users, data schemas, backhaul constraints.	Mesh gateway integration, quality metadata, security controls.	Measured latency, loss/recovery, provenance, and uncertainty display.
Transition package	Deployment, sustainment, ownership, and scale criteria.	Bill of materials, service plan, training and manufacturing plan.	Independent test report, configuration baseline, costed transition plan.

Avoid stating that funding, program selection, product certification, military qualification, government endorsement, or prime partnership exists unless an agency document establishes it. A clean concept paper gives evaluators a testable engineering question without implying an award or approved requirement.

10. Demonstration Plan and Measures of Effectiveness

Phase 1 - laboratory and bench. Assemble a compact Agent sensor head and a fixed reference package. Characterize temperature response, humidity response, pressure, power draw, timing, ingress protection, vibration, thermal coupling, and data-health diagnostics. Compare against traceable standards over the operating range selected by the sponsor.

Phase 2 - controlled field comparison. Place fixed reference sensors alongside an established weather station or agency reference. Run mobile units at a stationary location, on an instrumented test loop, and at increasing speeds. Include hot sun, shade, cold start, wet road, spray, rain, snow or mixed precipitation when seasonally available. Preserve raw data and maintenance notes.

Phase 3 - network and fusion. Relay observations through multiple Agents to a gateway. Test local mesh disruption, temporary backhaul loss, buffering, time recovery, duplicate/replayed packet rejection, and restoration. Compare AI classifications with reference instruments and human-verified event records; keep an “unknown/mixed” class when evidence is insufficient.

Recommended measures: temperature bias and RMSE against reference; response time; RH error; precipitation occurrence detection probability and false-alarm rate; precipitation-type confusion matrix; rainfall accumulation bias by event and interval; missing-data percentage; wind vector error by speed/direction and vehicle speed; surface-state classification accuracy; geolocation/time error; network delivery latency and loss; sensor uptime; maintenance time; and energy per observation/relay.

Pass/fail limits should be set with the sponsor and match the use case. For example, a research weather station, a road-safety advisory, and an emergency-response alert have different error costs. This paper does not assign fabricated accuracy grades or overall “effectiveness percentages.”

11. Recommended Initial Bill of Materials by Role

The following is a shortlist for procurement research and a test article, not a final approved bill of materials. Verify current part status, lead time, environmental rating, interface, and exact configuration with each manufacturer before ordering.

Role	Candidate name / model	Recommendation
Compact Agent air T/RH prototype	Sensirion SHT45-AD1B-R2	Use on a thermally isolated board inside a ventilated radiation shield; retain separate internal-board temperature monitoring.
Meteorological T/RH reference	Vaisala HMP155	Consider when a field-serviceable meteorological probe is more appropriate than a bare component.
Integrated fixed weather reference	Vaisala WXT536	Candidate multi-parameter instrument for pressure, T/RH, precipitation, wind speed and direction. Confirm installation conditions/specifications.
Precipitation type / particle distribution	OTT PARSIVEL2 or Thies CLIMA LPM	Choose one for a fixed evaluation site; compare against human observation and gauge data through mixed events.
Present weather and visibility	Vaisala PWD52 or appropriate PWD-series model	Candidate road-weather instrument for classification/visibility. Match exact model to required output and environmental range.
Road surface temperature	Vaisala DST111	Use as a fixed/controlled-geometry road measurement, paired with air and precipitation measurements.
3D wind reference	Campbell Scientific CSAT3B	Consider for a research-quality fixed evaluation point where 3D wind is required.
Snowpack water equivalent	Campbell Scientific CS725	Specialized fixed snow-study instrument; not part of every Agent.

Cost, weight, size, exact mounting, procurement availability, and integration compatibility are not asserted here; published product pages and quotations should be checked during acquisition. There is no single selected or TLTE-qualified product in this paper.

12. Risks, Limits, and Mitigations

Risk	Why it matters	Mitigation
Solar/self-heating bias	Exposed electronics can read hotter than ambient air.	Separate measurement element from processor; shield and ventilate; compare to reference under sun and shade.
Vehicle wake distorts wind	Body and speed alter flow near a mobile sensor.	Fixed wind anchors; validated vehicle-specific correction; label mobile readings as estimates.
Moving precipitation undercatch / splash	Airflow and vibration change collection and contaminate optics.	Use stationary gauges for accumulation; mobile units report only tested quantities and quality levels.
Mixed-phase precipitation misclassification	Rain, snow, sleet, freezing rain, and mixed forms overlap.	Use particle sensor plus temperature/humidity and independent observation; allow unknown/mixed.
Sensor contamination or icing	Windows, shields, and sonic paths can become obstructed.	Heaters only where specified; diagnostics, cleaning intervals, blockage flags, service access.
False precision in AI summaries	A model can overstate uncertain inputs.	Carry source, calibration, confidence, and algorithm version; preserve disagreements and abstain.
Network loss or timing errors	Old/stale observations can mislead downstream users.	Store-and-forward with age limits, sequence/time checks, and explicit stale/offline status.
Thermal or power budget mismatch	Heaters, active aspiration, and satellite uplinks may exceed Agent energy.	Measure per-mode power; use selective reporting, duty cycles, fixed gateways, and site-specific energy budgets.

A compact Agent can achieve a useful sensing role without duplicating a full national weather station. The reliable path is to distribute observations by role, not to demand that every node provide every meteorological quantity equally well.

13. Conclusions and Decision Requested

The available commercial landscape already includes compact digital temperature/humidity ICs; field meteorological probes; integrated weather transmitters; optical disdrometers; present-weather and visibility instruments; road-surface temperature sensors; ultrasonic wind instruments; rain gauges; and specialized snow-water-equivalent sensors. These are mature component classes, but they do not automatically become a validated mobile Agent system.

A government evaluation should begin with a small, instrumented demonstration: one fixed reference station, multiple mobile Agents, a defined vehicle and route, and an independent weather reference. The objective is to quantify which variables each Agent can measure reliably at rest and in motion. The test must establish uncertainty, not merely show that a sensor returns a number.

Recommended government decision: sponsor requirements definition and an independent field trial that evaluates (a) shielded mobile air temperature/RH; (b) fixed reference wind; (c) fixed present-weather classification and rainfall accumulation; (d) road-surface temperature/state where required; and (e) mesh delivery with provenance and confidence metadata. Expand only after results demonstrate accuracy, reliability, power sufficiency, maintainability, and secure data handling.

The defensible story: distributed Agents can add local environmental observations and carry those observations through a resilient communications architecture. Their value depends on honest sensor placement, calibrated references, motion-aware quality controls, and data fusion that reports uncertainty. The proposed program is an engineering pathway to be tested, not a claim that all sensing functions are already developed or government-approved.

Appendix A. Ranked Options at a Glance

Measurement need	Best initial option	Fixed reference backup / complement	Mobile Agent role
Ambient temperature	Shielded, ventilated T/RH probe (SHT45-based prototype or HMP155 class).	Pt100/Pt1000 reference thermometer; compare against HMP155/WXT536.	Dense route measurements after thermal/shield validation.
Precipitation type	Optical disdrometer / present-weather detector.	Second independent method plus human event log and radar context.	Opportunistic particle/wetness observations only after motion tests.
Rain amount	Calibrated fixed accumulation gauge paired with rate/type sensor.	Independent weighing/tipping method for comparison.	Do not report reference totals while moving unless proven in trial.
Snowpack	Snow depth plus SWE instrument at fixed site.	Manual snow course/agency reference.	Report pass-by context; cannot measure local SWE while moving.
Wind	Fixed ultrasonic anemometer with proper exposure.	Cup/vane station or regional radar context.	Experimental GNSS/IMU-corrected estimate with validated vehicle model.
Road icing context	Road surface temperature + surface state + air T/RH + precipitation.	Road weather station and field inspection.	Road-facing sensing with explicit classification confidence.

Abbreviations: Agent = distributed sensing/communications unit; ESS = Environmental Sensor Station; GNSS = Global Navigation Satellite System; IMU = Inertial Measurement Unit; IR = infrared; RH = relative humidity; RMSE = root mean square error; SWE = snow-water equivalent; T/RH = air temperature and relative humidity; UTC = Coordinated Universal Time.

Appendix B. References

Public product information and government guidance reviewed October 2, 2026. Product specifications can change; confirm exact configuration and current status with the manufacturer before procurement.

[1] FHWA, Road Weather Information Systems FAQ
Defines RWIS/ESS and atmospheric, pavement, and water-level observation categories.
https://ops.fhwa.dot.gov/weather/faq.htm

[2] FHWA, ESS Siting Guidelines - Assessing Road Weather Information Applications
Explains complementary roles of pavement, air temperature, humidity, and precipitation sensing.
https://ops.fhwa.dot.gov/publications/ess05/ess0502.htm

[3] FHWA, How Does the Road Weather Information System Work?
Describes field measurements of air/pavement temperature, precipitation, and road conditions.
https://ops.fhwa.dot.gov/weather/resources/publications/tech_briefs/rwis.htm

[4] FHWA, ESS Siting Guidelines - Introduction
Notes ESS may be installed in situ or on a vehicle; document itself addresses stationary systems.
https://ops.fhwa.dot.gov/publications/ess05/ess0501.htm

[5] Sensirion, SHT45 product page
SHT45 humidity/temperature sensor; manufacturer states up to ±1.0% RH and ±0.1 C.
https://sensirion.com/products/catalog/SHT45

[6] Texas Instruments, TMP117 product page
Digital temperature sensor specifications, including stated accuracy range.
https://www.ti.com/product/TMP117

[7] Vaisala, HMP155 documentation/product
HUMICAP temperature and humidity probe family for meteorological use.
https://www.vaisala.com/en/products/weather-environmental-sensors/hmp155

[8] Vaisala, DST111 Remote Road Temperature Sensor
Non-contact IR road surface temperature sensing.
https://www.vaisala.com/en/products/weather-environmental-sensors/remote-road-surface-temperature-sensor-dst111

[9] Vaisala, PWD series present weather and visibility sensors
Present-weather and visibility sensor family.
https://www.vaisala.com/en/products/weather-environmental-sensors/present-weather-detectors-visbility-sensors-pwd-series

[10] Vaisala, PWD52 datasheet
Present weather detector identifies precipitation type using RAINCAP water-content measurement and optical visibility.
https://docs.vaisala.com/api/khub/documents/lkx4y0XfqrcYjN2QYPJTTQ/content

[11] OTT HydroMet, PARSIVEL2
Laser optical disdrometer measures precipitation type, intensity, particle size distribution, and visibility.
https://www.ott.com/products/parsivel

[12] Thies CLIMA, Laser Precipitation Monitor
Laser disdrometer distinguishes rain, drizzle, sleet, snow, hail, and mixed precipitation.
https://www.thiesclima.com/en/laser-precipitation-monitor/

[13] Thies CLIMA, 3D Stereo Disdrometer
Image-based particle analysis can distinguish precipitation and non-weather particles.
https://www.thiesclima.com/en/laser-precipitation-monitor/3d-stereo-disdrometer~5.4120.xx.xxx/

[14] Vaisala, WXT530/WXT536 documentation
Multi-parameter weather transmitter family; WXT536 measures pressure, temperature, humidity, precipitation, wind speed, direction.
https://docs.vaisala.com/r/M211840EN-G/en-US/GUID-6B30C4BA-CEF6-40DF-9F60-41935D25AB9D

[15] Vaisala, WXT536 specs
WXT536 measurement specifications.
https://docs.vaisala.com/r/M211607EN-AA/en-US/GUID-5016B5AD-5086-442C-B943-FBCFDB7DB860/GUID-AD3DAFAA-7537-453B-969B-B3229E311DD7

[16] Campbell Scientific, CSAT3B
3D sonic anemometer specifications and measurement outputs.
https://www.campbellsci.com/products/csat3b

[17] Campbell Scientific, CS725 Snow Water Equivalent Sensor
Passive gamma-based snow-water-equivalent measurement.
https://us.campbellsci.com/cs725

[18] National Weather Service, Present Weather Sensor
Describes automated precipitation identification sensor distinguishing rain/snow and intensity.
https://www.weather.gov/asos/PresentWeatherSensor.html

[19] NWS, Dual-Polarization Radar Applications
Explains radar precipitation classification and limitations during winter weather.
https://www.weather.gov/jan/dualpolupgrade-applications

[20] NWS Radar FAQ
Documents radar precipitation-type categories and observation codes.
https://www.weather.gov/radarfaq/