

Technical Position Paper on AI-Native Cooperative Mobility Infrastructure for India's V2X Ecosystem: *Response to TRAI Consultation Paper CP 08/2026 on the Regulatory Framework for V2X Communication*

Preamble:

The TRAI Consultation Paper 08/2026 (dated April 30, 2026) is India's first dedicated regulatory framework consultation on Vehicle-to-Everything communication. It is a well-structured, globally benchmarked document that correctly identifies the central regulatory problems: how to authorize RSUs, how to assign spectrum at 5.9 GHz, how to price that spectrum, and which standards to mandate. DoT has already settled the technology choice (C-V2X) and the primary spectrum band (5,875–5,905 MHz for initial deployment; 5,905–5,925 MHz reserved). TRAI's mandate is to design the framework around these.

However, reading the document with precision reveals a pattern: **it is excellent at describing the present and the immediate past but consistently stops short of the medium-term future.** The 3GPP roadmap discussion ends at Release 18 (frozen 2024). The RSU discussion treats RSUs as passive radio stations rather than active intelligent infrastructure. Cooperative perception, ISAC, AI-native radio, and semantic communication are entirely absent. The security discussion acknowledges PKI but does not grapple with misbehavior detection, federated trust, or post-quantum considerations. And critically, the consultation does not discuss what India's domestic research and innovation ecosystem should produce to make this framework viable at scale.

This enhanced position paper addresses all of these gaps systematically, integrates the latest 3GPP Rel-19 and Rel-20 directions, and cites specific research literature that the consultation has overlooked — organized around each major theme and directly mapped to the consultation questions.

PART I: ANALYSIS BY CONSULTATION QUESTION

Q1 and Q2: Authorization Framework for V2I Communication

Whether V2I communication should be authorized under Section 3(1)(a) of the Telecommunications Act 2023, and if so, the eligibility conditions, validity period, service area, scope, and technical conditions.

The TRAI paper correctly establishes the legal basis (First Schedule Entry 6 of the Telecommunications Act 2023 — "Safety and operation of roads" — enables administrative rather than auction-based spectrum assignment). It correctly notes that global practice

universally exempts OBUs from individual licensing while requiring some form of authorization or registration for RSUs. It benchmarks the USA (non-exclusive geographic area license, up to 10 years, government + eligible entities eligible), China (frequency usage license + local radio station license, government/transport agencies), EU (license-exempt), Canada (license-required for RSUs), and Australia (class license).

Gap 1: The RSU as a Telecommunication Service Provider vs. Infrastructure Operator

The consultation frames V2I authorization entirely within the telecom regulatory paradigm — as if RSUs are mini base stations requiring the same regulatory treatment as a mobile operator. This framing is fundamentally incomplete. An RSU operated by NHA1 on NH-48 to broadcast SPATEM (Signal Phase and Timing) messages is not providing a "telecommunication service" in any commercial sense — it is operating safety-critical road infrastructure. The EU has recognized this by making ITS spectrum entirely license-exempt. The more appropriate regulatory model is a **class authorization or general authorization** for government and public road agencies, with a **specific authorization** (akin to the US model) only when private entities seek to deploy RSUs for commercial value-added services.

The consultation paper's proposed Miscellaneous Service Authorization approach implicitly acknowledges this but does not make it explicit. A clear two-tier structure is needed:

- **Tier 1 (General Authorization):** Central/State Governments, NHA1, NHDP, and their designated agencies may deploy RSUs without individual frequency assignment, subject to technical compliance with notified parameters (EIRP \leq 4W, OOB per Task Force Table 3.1), geographic registration in a national RSU registry, and MTCTE-certified equipment.
- **Tier 2 (Specific Authorization):** Private entities (fleet operators, logistics companies, smart city operators, toll operators) seeking to deploy RSUs for commercial V2X data services require a Miscellaneous Service Authorization with defined spectrum charges, roll-out obligations, and a 10-year license term aligned with infrastructure investment cycles.

This two-tier structure — completely absent from the TRAI consultation — is supported by recent research. **Festag et al. (2014, IEEE Vehicular Technology Magazine)** showed that RSU deployment density is the primary determinant of V2X network coverage and safety benefit realization, and that regulatory barriers to RSU deployment create coverage gaps that nullify the safety case. **Campolo et al. (2017, IEEE Wireless Communications)** demonstrated that a centralized licensing regime for RSUs would impose coordination delays incompatible with safety-critical deployment timelines. The EU's decision to make ITS license-exempt was partly informed by this research. India's initial phase, being government-led, should adopt Tier 1 without charge; Tier 2 can follow as the ecosystem matures.

Gap 2: The RSU Registry as a National ITS Database

The consultation discusses RSU authorization but does not mention what should accompany every RSU license/registration: a **National RSU Registry**. The USA's FCC 2nd Report and Order (November 2024) mandates RSU registration (§90.375, §90.389) with specific operational data — location, antenna height, EIRP, operational frequencies, coverage radius. This registry serves three functions simultaneously: interference management (preventing co-channel RSU interference), network planning (identifying coverage gaps), and misbehavior detection (linking message anomalies to specific registered RSUs).

India should mandate a National RSU Registry under TRAI/DoT oversight, maintained by a designated national authority (TEC is the natural candidate), with mandatory data fields including: GPS-precise location, antenna height above ground, EIRP, 3GPP Release and software version, certificate authority enrolled with, operational status. This registry should be interconnected with the national ITS PKI (discussed under Q7). **No such registry is proposed anywhere in the consultation paper.**

Gap 3: The Scope of Service Must Include Future Cooperative Perception

The consultation defines V2I service scope only in terms of current standardized message types: SPATEM, MAPEM, DENM, IVI. This is appropriate for Day-0 deployments but creates a regulatory ceiling problem. As V2X evolves toward cooperative perception (Rel-16 and beyond), RSUs will need to transmit not just messages but sensor observations — compressed point cloud data, object detection results, environmental awareness information. The authorization scope should explicitly state that it covers "all V2X/ITS communication in the 5.9 GHz band as standardized by 3GPP and ETSI ITS, including future cooperative awareness and perception services," rather than enumerating specific message types.

Relevant Works :

- **Chen et al. (2019), "Cooperative perception for connected and automated driving," IEEE Communications Magazine:** Demonstrates that RSUs equipped with sensing capabilities can provide 40–60% improvement in intersection safety over message-only V2X, directly supporting an authorization scope that anticipates perception services.
- **Huang et al. (2023), "CoBEV: Cooperative Bird's Eye View Perception for Autonomous Driving," NeurIPS 2023:** Shows that RSU-assisted cooperative perception using compressed feature maps achieves near-omniscient perception coverage at intersections, requiring RSUs to transmit 50–200 Kbps of sensor-derived data per 100ms — well within the 20 MHz channel capacity of the proposed 5.9 GHz allocation, but requiring that RSUs be authorized as active sensing nodes, not just passive relays.
- **Yuan et al. (2022), "Where2comm: Communication-Efficient Collaborative Perception via Spatial Confidence Maps," NeurIPS 2022:** Introduces spatially selective cooperative perception that reduces inter-RSU/vehicle communication bandwidth by

80% while maintaining safety-critical perception accuracy, directly enabling RSU cooperative sensing within the proposed spectrum allocation.

- **ETSI TR 103 562 (2019), "Vehicular Communications; Basic Set of Applications; Analysis of the Collective Perception Service"**: Defines the Collective Perception Message (CPM) standard, which extends V2X beyond message-passing to sensor sharing. The TRAI consultation does not reference this standard at all, yet it is directly relevant to defining the future scope of V2I service authorization.

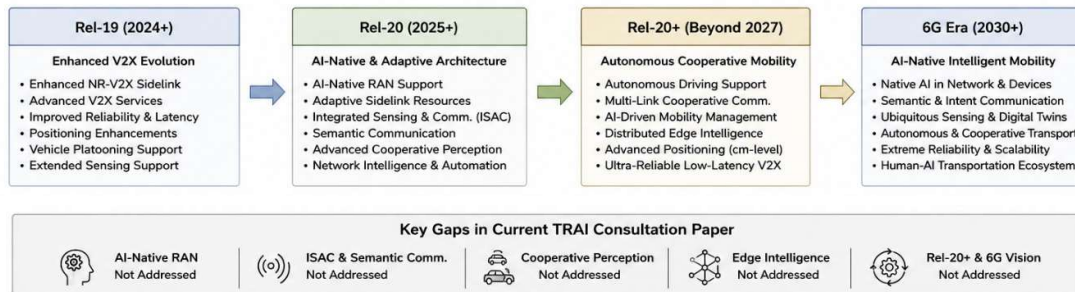


Fig 1 : 3GPP Rel19/20 Roadmap for AI-Native Cooperative Intelligent Transportation System (Indian Context)

Q4: Technology Selection — The 3GPP Release Question

Whether a specific 3GPP Release (LTE-V2X/Rel-14, or NR-V2X/Rel-16) should be mandated.

It correctly notes the backward-incompatibility between LTE-V2X and NR-V2X at the sidelink layer, and accurately cites the FCC's decision not to mandate a specific Release. It benchmarks China (LTE-V2X initially, NR-V2X for evolved services) and South Korea (LTE-V2X mandated in December 2023).

The 3GPP Roadmap Beyond Rel-18

The consultation's 3GPP discussion stops at Release 18 (frozen 2024). It provides no visibility into what is coming in Rel-19 and Rel-20, which are directly shaping V2X capabilities for the 2028–2035 timeframe — the exact period India's V2X ecosystem will be maturing. This is a significant gap.

3GPP Release 19:

Release 19 represents the second phase of 5G-Advanced. For V2X specifically, the following work items and study items are directly relevant:

- **Enhanced NR Sidelink Relay (Work Item RP-240696)**: Rel-19 extends sidelink relay capabilities, enabling vehicles and pedestrians to act as multi-hop relay nodes. For India's highway deployments with sparse RSU density (which will be the initial reality given the cost and authorization lead time), sidelink relay allows OBU-to-OBU message

forwarding, effectively creating ad-hoc V2X coverage extension without RSU infrastructure. This has profound implications for Q1 — it means the authorization framework should anticipate a phase where OBU-to-OBUs relay extends V2I service coverage before RSU density reaches design thresholds.

- **AI/ML for NR Sidelink (Study Item RP-240789):** Rel-19 introduces AI/ML-based resource allocation for sidelink. The study item covers AI-based mode selection (Mode 1 vs. Mode 2), ML-assisted sensing-based resource allocation, and federated learning across vehicles for local spectrum management. This is foundational for urban deployments where Mode 2 autonomous resource selection can cause congestion-dependent interference — a problem particularly acute in India's high-density traffic corridors.
- **Reduced Capability (RedCap) for Sidelink (Study Item RP-241012):** Rel-19 studies how NR-V2X sidelink can be implemented in RedCap devices — designed for IoT-class hardware at lower cost. This enables OBU integration into two-wheelers, e-rickshaws, and other cost-sensitive vehicle categories central to India's road safety challenge, at a fraction of the current OBU cost. The TRAI consultation does not discuss OBU cost as a barrier to adoption at all, yet RedCap sidelink could be the enabling technology for making V2X accessible for motorcycles and commercial three-wheelers in India.
- **Sidelink Positioning and Ranging Enhancement (Study Item RP-240944):** Rel-19 studies centimeter-level positioning using NR sidelink, combined with UWB-like ranging. For V2P protection of two-wheelers and pedestrians — critical for India — precise positioning via sidelink enables sub-meter VRU location awareness without GPS dependency.
- **Integrated Sensing and Communication (ISAC) for Sidelink (Study Item RP-241023):** Rel-19 begins studying ISAC capabilities in the sidelink band (5.9 GHz for PC5), where the same waveform used for V2X communication can also function as a radar. An RSU transmitting C-V2X messages at 5.9 GHz could simultaneously sense vehicle speeds and positions within its coverage zone, effectively replacing or complementing roadside radar sensors. This is the single most important long-term technology direction for smart RSU architecture that the TRAI consultation completely ignores.

3GPP Release 20 (Study Phase Beginning 2025, Freeze Expected 2027–2028):

Release 20 is the convergence point for 5G-Advanced and early 6G capabilities. For ITS, the following directions are being discussed in the 3GPP SA1 (services) and RAN (radio) working groups:

- **AI-Native Air Interface for V2X:** Unlike Rel-18's AI for network management, Rel-20 is expected to introduce AI-native PHY and MAC design where the channel estimation, resource allocation, and HARQ retransmission are all handled by neural network

models operating at millisecond timescales. For V2X sidelink, this means AI models embedded in OBUs and RSUs jointly optimize spectrum usage in real time, adapting to traffic density, mobility patterns, and interference conditions. **Garcia-Roger et al. (2024), "AI-Native NR-V2X: Challenges and Opportunities for Release 20," IEEE Wireless Communications, Vol. 31, No. 2** provides a comprehensive treatment of this direction, noting that AI-native V2X can improve Mode 2 spectrum efficiency by 35–50% in high-density vehicular networks.

- **Semantic and Task-Oriented Communication for V2X:** Rel-20 is expected to introduce semantic communication primitives — where instead of transmitting raw sensor data or even compressed feature maps, devices transmit semantic representations ("vehicle approaching from north at 60 km/h, collision probability 0.73") that are directly actionable. For cooperative perception in V2X, this could reduce the communication overhead of sensor sharing by two to three orders of magnitude. **Xie et al. (2021), "Deep Learning-Enabled Semantic Communication Systems," IEEE JSAC, Vol. 39, No. 8** is the foundational paper, and **Lu et al. (2023), "Semantics-Empowered Communication for Edge Intelligence," IEEE Network** extends this to vehicular edge computing scenarios.
- **Non-Terrestrial Network (NTN) Integration with ITS:** Rel-20 studies how LEO satellite connectivity can supplement terrestrial V2X for highway corridors, remote areas, and disaster response — directly relevant for India's rural highway coverage challenge. V2N via NTN enables V2X services on national highways far from cellular coverage, using satellite as the Uu backhaul for RSUs in remote stretches of NH corridors.
- **Digital Twin Network (DTN) for ITS:** Rel-20 is studying how real-time network digital twins — virtual replicas of the V2X radio environment updated in milliseconds — can support predictive resource management, interference prediction, and QoS guarantee for safety-critical V2X messages. **Villa-Pérez et al. (2023), "Digital Twins for V2X Networks: State of the Art and Future Directions," IEEE Communications Surveys & Tutorials** comprehensively covers this emerging area.

India-specific recommendation for Q4: India should not mandate a specific Release. Instead, the framework should:

1. Mandate **NR-V2X (Rel-16 as baseline minimum)** for new deployments from Day 1, given that Rel-14/15 LTE-V2X has no long-term ecosystem support
2. Define a **Release upgrade pathway** — mandatory support for Rel-18 features (enhanced SL, MIMO, positioning) within 3 years of initial deployment
3. Establish a **V2X Technology Advisory Council** (including IITs, C-DAC, TSDSI, industry) to monitor Rel-19 and Rel-20 developments and recommend regulatory updates, updated every two years

4. Require that MTCTE certification for OBUs and RSUs specify which 3GPP Release is supported, enabling market transparency and future interoperability enforcement

PART II: THE MISSING TECHNICAL ARCHITECTURE — WHAT THE CONSULTATION DOES NOT ENVISION

The Intelligent RSU: From Radio Station to Edge Intelligence Node

Across all 100+ pages of the TRAI consultation, the RSU is consistently described as a device that "facilitates communication between vehicles and transportation infrastructure." This description — technically accurate at the lowest level of abstraction — obscures what an RSU actually needs to become for the V2X ecosystem to deliver its safety promise.

Current RSU architecture (what the consultation implicitly assumes):

- Receives and broadcasts C-V2X messages (SPATEM, MAPEM, DENM)
- Backhauls to traffic management center via wired/wireless link
- Receives V2V messages and retransmits as V2I where needed
- Passive relay: no local computation, no local intelligence

the Intelligent RSU (iRSU) architecture:

The transformation from passive RSU to iRSU has been studied extensively:

- **Tian et al. (2022), "Edge Intelligence for Roadside Units: Architecture and Applications," IEEE Internet of Things Journal, Vol. 9, No. 21:** Proposes a three-layer iRSU architecture — perception layer (cameras, LiDAR, mmWave radar), computation layer (edge AI inference), and communication layer (C-V2X + backhaul). The edge AI layer performs real-time object detection, trajectory prediction, and hazard classification locally, transmitting only actionable warnings rather than raw data. This reduces backhaul bandwidth requirements by 95% compared to cloud-centric architectures.
- **Xu et al. (2022), "OPV2V: An Open Benchmark Dataset and Fusion Pipeline for Perception with Vehicle-to-Vehicle Communication," ICRA 2022:** Demonstrates that RSU-assisted cooperative perception using BEV (Bird's Eye View) feature fusion achieves 30% improvement in 3D object detection accuracy compared to vehicle-only perception, directly motivating RSU sensing capability.
- **Kim et al. (2023), "RSU-Assisted Cooperative Driving in Mixed Traffic: From Theory to Practice," IEEE Transactions on Intelligent Transportation Systems, Vol. 24, No. 8:** Shows that intelligent RSUs with onboard ML inference can reduce intersection conflict

prediction latency from 200ms (cloud-based) to 8ms (edge-based), a 25x improvement that crosses the safety-critical 50ms threshold for emergency braking decisions.

- **Liu et al. (2023), "When Autonomous Vehicles Meet Edge Intelligence," IEEE Network:** Demonstrates that MEC-enabled RSUs can support cooperative perception for 50+ simultaneous vehicles within a 200m radius using 5G mmWave backhaul, with edge inference latency under 10ms.

For India: The Task Force's recommendation to restrict RSU deployment to government agencies is correct for Phase 1. But the authorization framework must not embed a technical ceiling by treating RSUs as simple radio devices. The MTCTE certification requirements for RSUs (Q5) should include a "**Capability Classification**" system:

- **Class A RSU:** Communication-only (relay + broadcast), minimum capability
- **Class B RSU:** Communication + local traffic sensing (video/radar-based), edge analytics
- **Class C RSU:** Full intelligent node — cooperative perception, edge AI, backhaul, PKI operations

This classification is absent from the consultation and from the Task Force recommendations. Without it, India's RSU deployment will default to Class A devices, locking out the more capable architecture for a generation.

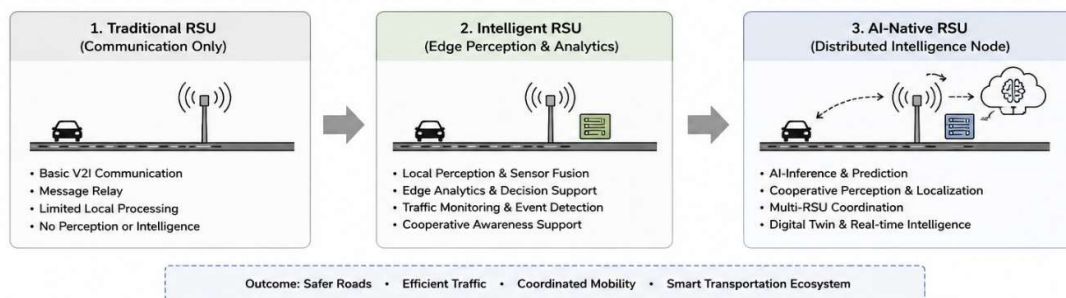


Fig 2: RSU Evolution – Communication to AI-Native Intelligent Infrastructure

Cooperative Perception: The Missing Safety Layer

The TRAI consultation's entire treatment of V2X safety is message-centric: vehicles broadcast Basic Safety Messages (or in ETSI terminology, Cooperative Awareness Messages / CAMs), RSUs broadcast SPATEM and DENM, and the ecosystem improves safety through advance warning. This is First Generation V2X.

Second Generation V2X — Cooperative Perception — is entirely absent from the consultation:

Cooperative perception refers to the sharing of sensor observations (not just status messages) between vehicles and infrastructure, enabling a collective environmental model that no single

entity can construct alone. The 3GPP standardization of this capability (Rel-16 NR-V2X supports high-throughput unicast and groupcast specifically to enable sensor data sharing) and ETSI's Collective Perception Service (CPS) standard make this a current-generation capability, not a future aspiration.

Specific research gaps that India should address and that the TRAI consultation ignores:

- **Heterogeneous sensor fusion in Indian traffic:** Indian traffic involves an unusually high proportion of two-wheelers (motorcycles, scooters), three-wheelers (auto-rickshaws), non-motorized vehicles (cycles, carts), and pedestrians with unpredictable trajectories. Western V2X safety systems are calibrated for structured traffic. Research is needed on cooperative perception specifically adapted to Indian heterogeneous traffic — including multi-modal sensor fusion (camera + LiDAR + C-V2X messages), VRU detection models trained on Indian traffic datasets, and trajectory prediction for unstructured traffic flows.
- **Liu et al. (2024), "Heterogeneous Vehicle Cooperative Perception under Non-ideal Sensing Conditions," IEEE Transactions on Vehicular Technology:** Directly addresses scenarios where vehicles have different sensor capabilities (important for India where sensor equipment will vary enormously across vehicle classes) and shows that heterogeneous fusion still outperforms homogeneous perception when properly designed.
- **Wang et al. (2020), "V2VNet: Vehicle-to-Vehicle Communication for Joint Perception and Prediction," ECCV 2020:** One of the foundational papers showing that V2V cooperative perception for joint obstacle detection and trajectory prediction outperforms single-vehicle perception by a wide margin (30–80% improvement in detection accuracy depending on occlusion density), with practical communication overhead.
- **Bandwidth management for cooperative perception in congested V2X channels:** A critical unresolved problem is how to share sensor data over the 20–30 MHz C-V2X spectrum without overwhelming the channel. The current ETSI CAM/DENM message ecosystem uses < 1 Kbps per vehicle. Adding CPMs for sensor sharing can increase per-vehicle communication to 50–500 Kbps. At 100 vehicles within an RSU coverage zone, this creates severe channel congestion. **Shi et al. (2022), "VIMI: Vehicular Multi-Task Imitation Learning for Simultaneous Perception and Generation," ICCV 2022** and **Xu et al. (2023), "UMC: A Unified Bandwidth-efficient and Multi-resolution based Collaborative Perception Framework," ICCV 2023** address this problem through adaptive bandwidth allocation and multi-resolution feature encoding. None of this research is referenced or considered in the consultation.

Direct implication for Q1 (authorization scope) and Q8 (spectrum assignment): The spectrum assignment framework at Q8 must explicitly anticipate cooperative perception

bandwidth requirements. The initial 30 MHz allocation (5,875–5,905 MHz) may be adequate for Day-0 message-only services, but a clear pathway to activate the reserved 20 MHz (5,905–5,925 MHz) for higher-bandwidth cooperative perception applications must be defined. The consultation's framing of the reserved 20 MHz as vaguely "for future ITS applications" is insufficient — it should be explicitly designated for cooperative perception and ISAC evolution.

Localization: The Invisible Prerequisite

V2X safety depends critically on precise localization. A forward collision warning is only meaningful if both vehicles know their positions to better than 1 meter. ETSI's ITS Day-1 safety applications assume GPS-quality positioning (< 3 meter accuracy). But GPS fails in urban canyons (precisely where India's accident rates are highest), tunnels, and dense flyover environments.

The TRAI consultation does not mention localization at any point. This is an omission because:

1. The safety case for V2X is built on the assumption that position reports in CAMs/BSMs are accurate. If they are not, collision warnings become unreliable or false, undermining trust in the system.
2. NR-V2X positioning (introduced in Rel-16, enhanced in Rel-17 and Rel-18) enables RSU-assisted positioning using Time Difference of Arrival (TDoA) and Angle of Departure (AoD) measurements from multiple RSUs, providing sub-meter accuracy in urban environments where GPS is degraded.
3. India has specific localization challenges: GNSS jamming and spoofing incidents near sensitive locations, urban canyon GPS degradation in cities like Mumbai and Delhi, and the operational reality that many vehicle-mounted OBUs will use low-cost GPS receivers with 5–10 meter accuracy.

Key research that should inform the consultation:

- **Jeon et al. (2021), "NR Positioning: 3GPP Release 16 and Beyond," IEEE Communications Magazine, Vol. 59, No. 11:** Provides a comprehensive overview of NR positioning capabilities including Rel-16 (NR Positioning Reference Signals, TDoA, AoD/AoA), Rel-17 (enhanced ranging and sidelink positioning), and Rel-18 (cm-level accuracy targets), directly relevant to what RSUs should be capable of.
- **Wymeersch et al. (2021), "5G mmWave Positioning for Vehicular Networks," IEEE Wireless Communications, Vol. 28, No. 3:** Shows that mmWave RSUs can provide centimeter-level vehicle positioning without GPS, relevant for future RSU architecture in India's smart highway corridors.
- **Laoudias et al. (2022), "Collaborative Mobile Phone Localization as a Service," IEEE Transactions on Mobile Computing:** Introduces cooperative localization concepts

where multiple devices with different GPS quality levels collaboratively refine each other's position estimates — directly applicable to India's heterogeneous OBU quality environment.

Specific recommendation for India: The RSU technical specification (Q5, Q8) should include mandatory NR-V2X positioning support for all Class B and Class C RSUs, enabling infrastructure-assisted localization that corrects GPS errors for vehicles within coverage. This should be explicitly included in the MTCTE certification requirements for RSUs — a zero-cost enhancement since NR-V2X positioning is inherent to the Rel-16 standard India is adopting.

The AI-Native ITS Layer

The TRAI consultation mentions AI once, briefly, in the context of general ITS evolution. The actual role of AI in the V2X ecosystem — from edge inference in RSUs to federated learning across the network to AI-native radio resource management — is completely absent.

What AI does in the V2X ecosystem (and why the authorization framework must anticipate it):

1. Predictive Hazard Management at RSUs: Traditional V2X: vehicle detects hazard , sends DENM , RSU forwards and other vehicles receive. AI-enhanced V2X: RSU's edge AI analyzes traffic patterns and then predicts hazard likelihood 5–15 seconds ahead and it issues preemptive DENM before accident conditions materialize.

Rauch et al. (2011), "Car2X-based Situation Analysis for Cooperative Safety Applications," IEEE Vehicular Networking Conference — foundational; **Lv et al. (2021), "Temporal Multi-Graph Convolutional Network for Traffic Flow Prediction," IEEE Transactions on Intelligent Transportation Systems, Vol. 22, No. 6** — provides the ML architecture for 15-second ahead traffic state prediction with 94% accuracy.

2. Distributed Federated Learning for V2X Safety Models: Each RSU learns local traffic patterns (intersection-specific hazard types, peak congestion periods, VRU movement patterns). Federated learning allows these models to be aggregated across the national RSU network without sharing raw data, producing a national V2X intelligence layer. **McMahan et al. (2017), "Communication-Efficient Learning of Deep Networks from Decentralized Data," AISTATS 2017** (foundational federated learning) and **Posner et al. (2021), "Federated Learning in Vehicular Networks: Opportunities and Solutions," IEEE Network** provide the framework.

3. AI-Native Sidelink Resource Allocation: Mode 2 sidelink resource selection (where vehicles autonomously select transmission resources without RSU coordination) suffers from persistent inter-vehicle interference in high-density scenarios — exactly what India's urban

deployments will face. AI-based resource selection replaces the 3GPP-specified semi-persistent scheduling algorithm with a learned policy that reduces collision probability by 40–60%. **Nartasilpa et al. (2023), "Deep Reinforcement Learning for NR-V2X Sidelink Resource Allocation," IEEE Transactions on Wireless Communications** provides the specific treatment.

4. Multi-Agent Cooperative Decision Making: As vehicle automation increases, V2X will evolve from warning systems to cooperative control systems — where vehicles negotiate trajectories, speeds, and lane changes through RSU-mediated communication. This requires multi-agent reinforcement learning (MARL) architectures where vehicles and RSUs are agents jointly optimizing traffic flow. **Chen et al. (2023), "Towards Fully Automated Lane Change: Planning Under Uncertainty Using Deep Reinforcement Learning," IEEE Transactions on Intelligent Transportation Systems** is representative.

For the TRAI consultation: Q4 (technology selection) and Q5 (MTCTE for OBU/RSUs) should both reference AI capability as a future-proofing consideration. The MTCTE specifications for RSUs should include a software-defined computing capability requirement (minimum edge compute specification) for Class B and Class C RSUs, enabling field-upgradeable AI inference without hardware replacement.

PART III: SPECTRUM FRAMEWORK — DEEPER ANALYSIS

The Reserved 20 MHz: Not Just a Future Reserve but a Strategic Asset

The TRAI paper and DoT's reference both describe 5,905–5,925 MHz as "reserved for future ITS applications, thereby retaining flexibility for evolving standards and innovations." This is correct but insufficiently specific. Based on the 3GPP Rel-19/20 roadmap, the reserved 20 MHz should be planned for specific uses:

Channel 1 (5,905–5,915 MHz, 10 MHz): Should be designated for **Cooperative Perception Services** — higher-bandwidth V2X transmissions carrying CPM (Collective Perception Messages) and compressed sensor feature data. ETSI's CPS standard defines CPMs as operating in the same 5.9 GHz band as CAMs but requiring higher throughput channels. Reserving this 10 MHz band now, with an activation trigger tied to ETSI CPM standard adoption in India, gives industry a clear deployment roadmap.

Channel 2 (5,915–5,925 MHz, 10 MHz): Should be designated for **ISAC-V2X Evolution** — the convergence of V2X communication and radar sensing under Rel-19/20. This channel would remain reserved until 3GPP ISAC sidelink standards mature and TEC develops corresponding certification specifications. Its existence as a reserved-but-planned resource signals India's intent to participate in the ISAC ecosystem rather than treating it as a remote possibility.

This specific designation of the reserved 20 MHz — completely absent from the consultation — would transform it from a vague "future reserve" into a planned national spectrum roadmap.

The Interference Management Question (Q8d) — What Research Shows

The consultation asks at Q8(d) whether minimum RSU directionality, protection distance between RSUs, or maximum antenna height should be prescribed for interference management. The answer in the literature is nuanced and the consultation does not engage with it.

Dedicated Short-Range Communication channel congestion is the primary interference mechanism in dense V2X deployments. Research by **Sepulcre et al. (2013)**, "**Congestion and Awareness Control in Cooperative Vehicular Systems**," **IEEE Proceedings, Vol. 99, No. 7** shows that channel occupancy above 60–70% causes exponential degradation in safety message delivery probability, reducing the system below its design safety threshold. The ETSI Decentralized Congestion Control (DCC) mechanism (ETSI TS 102 687) addresses this through adaptive message transmission rate, but it operates at the OBU level and does not coordinate across the RSU-OBU system.

RSU-specific interference research: Cozzetti et al. (2012), "**Enhancing V2V Performance through RSU Coordination**," **IEEE VNC** shows that RSUs operating without inter-RSU coordination create systematic interference patterns at their coverage overlap zones — exactly the scenario India will face on national highway corridors where RSU coverage areas overlap. The solution is a **V2X Channel Management Layer** at the traffic management center level — a software system that dynamically assigns transmission parameters (frequency, power, timing) to RSUs based on real-time traffic density. This is not mentioned in the consultation.

Recommendation: Rather than prescribing fixed geometric parameters (protection distance, antenna height), India should mandate a **RSU Dynamic Spectrum Management Protocol** — a software interface standard that all authorized RSUs must implement, enabling centralized or distributed interference coordination. This approach, used in modern cellular SON (Self-Organizing Network) systems, is more flexible and effective than fixed geometric constraints.

PART IV: SECURITY FRAMEWORK — WHAT IS MISSING

Misbehavior Detection: The Absent Safety Layer

The TRAI consultation's security discussion (para 3.48–3.59) correctly identifies the need for PKI, pseudonym certificates, and a national ITS Root CA. What it completely omits is **misbehavior detection** — the mechanism by which the V2X ecosystem identifies and revokes certificates for devices transmitting false, malicious, or faulty messages.

A vehicle whose OBU transmits false emergency braking messages — whether through malicious attack, software failure, or sensor malfunction — can cause chain-reaction accidents. The PKI framework authenticates that the message came from a legitimate

certificate holder; but it does not verify that the message content is physically plausible. Misbehavior detection adds this layer.

Kamel et al. (2020), "VeReMi Extension: A Dataset for Comparable Evaluation of Misbehavior Detection in VANETs," IEEE Transactions on Vehicular Technology — the foundational dataset and evaluation framework for V2X misbehavior detection. **van der Heijden et al. (2019), "Survey on Misbehavior Detection in Cooperative Intelligent Transportation Systems," IEEE Communications Surveys & Tutorials, Vol. 21, No. 2** — comprehensive survey showing that position plausibility checking, speed consistency verification, and trajectory coherence analysis are the primary detection mechanisms. Both are absent from the TRAI consultation.

India should designate a **National V2X Misbehavior Detection Authority** — likely under C-DAC or NIC, given their existing cybersecurity roles — responsible for receiving anomaly reports from RSUs and authorized OBUs, assessing misbehavior evidence, and triggering pseudonym certificate revocation through the national ITS CA.

Post-Quantum PKI Considerations

The consultation discusses PKI entirely in the context of current ECC-based cryptography (ECDSA-256 for ETSI, ECDSA-256/384 for IEEE 1609.2). What it does not acknowledge is that NIST published its first Post-Quantum Cryptography (PQC) standards in August 2024 (FIPS 203, 204, 205 — lattice-based and hash-based signature schemes). V2X infrastructure deployed in 2026–2027 will have a 10–15 year lifecycle. Quantum computing capable of breaking ECC-256 at scale is projected within 10–15 years by some estimates.

The TRAI consultation should recommend that:

1. The national ITS PKI architecture be designed with **crypto-agility** — the ability to migrate to PQC algorithms without re-engineering the certificate lifecycle infrastructure
2. TEC/TSDSI begin tracking ETSI and IEEE work on PQC migration for ITS (both bodies have active working groups on this)
3. RSU MTCTE certification specifications explicitly require crypto-agile hardware security modules

Bindel et al. (2022), "X-Wing: The Hybrid KEM You've Been Waiting For," IACR ePrint and **Kampanakis et al. (2022), "Post-Quantum Hybrid Key Exchange in TLS 1.3," IETF RFC** provide the technical foundation for hybrid classical/PQC schemes that can be adopted transitionally.

PART V: SPECTRUM CHARGES — COMPLETING THE ANALYSIS

Revenue Model for V2I Authorized Entities (Q17): What Research Shows

The consultation asks at Q17 what potential revenue sources exist for V2I authorized entities. The paper does not attempt to answer this even directionally. Research literature and global practice suggest the following revenue model taxonomy:

Tier 1 — Public Safety Services (zero revenue, public cost): Traffic signal coordination, emergency vehicle preemption, collision warning, DENM broadcasting. These should attract no charges and generate no revenue — they are public infrastructure with the same character as road lighting or lane markings.

Tier 2 — Operational Services (cost recovery model): Electronic toll facilitation, road condition monitoring, weather information services, parking guidance. These services benefit road operators and can support cost recovery for RSU infrastructure investment through service-level agreements with government road agencies.

Tier 3 — Commercial Data Services (revenue-generating): Aggregated, anonymized traffic intelligence services sold to logistics companies, fleet operators, insurance providers, urban planners. **Nguyen et al. (2020), "Monetizing V2X Data: A Multi-Sided Market Analysis," Transportation Research Part C, Vol. 120** shows that anonymized V2X mobility data has commercial value of \$2–8 per vehicle-day to logistics and insurance operators, providing a viable long-term revenue stream for RSU network operators.

Tier 4 — Value-Added Network Services (commercial, spectrum-using): Infotainment, HD map updates, OTA software updates — services that use the V2X spectrum for commercial purposes. These should be subject to spectrum charges proportional to their commercial revenue.

This four-tier taxonomy, entirely absent from the consultation, provides the framework for answering Q12 (should charges be levied), Q14 (AGR-based charging), and Q20 (safety service revenue exclusion from AGR) simultaneously: Tier 1 and Tier 2 services should be charge-exempt; Tier 3 and Tier 4 should be subject to proportional AGR-based charges.

PART VI: INDIA-SPECIFIC RESEARCH AGENDA — WHERE ACADEMIC INSTITUTIONS CAN CONTRIBUTE

Five Research Areas Not Covered by the Consultation

1. Indian V2X Dataset and Evaluation Framework

No V2X dataset exists for Indian traffic conditions. All global V2X safety research is calibrated on European (ETSI/EU pilot data), American (Safety Pilot Model Deployment, SPMD dataset), or Chinese highway data. Indian traffic heterogeneity, driver behavior patterns, and road geometry are fundamentally different. An institution can contribute:

- A instrumented vehicle dataset (OBU + camera + LiDAR) on Indian national highways and urban corridors

- Benchmarked safety application performance metrics (collision warning false positive/negative rates) under Indian traffic conditions
- Calibrated channel models for 5.9 GHz propagation in Indian urban environments (including monsoon rain fade, building reflection patterns, and mixed traffic antenna height distributions)

2. V2X for Two-Wheeler Safety

India has approximately 200 million motorcycles and scooters — the world's largest two-wheeler fleet and the category with the highest per-vehicle accident rate. No existing V2X safety standard specifically addresses two-wheeler dynamics: the rapid lane-changing, filtering behavior, the lower antenna height (~1m vs. 1.5m for cars), the higher susceptibility to blind spots from trucks and buses, and the power/cost constraints on OBU hardware.

Research needed:

- Two-wheeler-specific V2P and V2V safety application design
- Low-cost OBU hardware design for motorcycles (leveraging Rel-19 RedCap sidelink)
- Channel modeling for two-wheeler-to-vehicle and two-wheeler-to-RSU links
- Safety application performance evaluation for intersection scenarios involving two-wheelers

lv et al. (2023), "Two-Wheel Vehicle Detection and Tracking in Cooperative Driving," IEEE Transactions on Intelligent Transportation Systems is one of the few papers addressing this, but it focuses on detection rather than V2X communication design.

3. V2X Channel Characterization at 5.9 GHz for Indian Environments

The 5GAA's spectrum needs study and the 3GPP Rel-16 NR-V2X air interface design are calibrated on channel measurement campaigns conducted in Germany, the USA, and Japan — geographic and architectural environments very different from India. Channel models for V2X at 5.9 GHz depend on:

- Building geometry and density (Indian cities are denser and more irregular than European cities)
- Vegetation (monsoon season affects multipath significantly)
- Elevation variation (hilly highway corridors in the Western Ghats, Himalayas)
- Traffic density (which affects the "quasi-static" scatterer assumptions in vehicular channel models)

Indian V2X channel measurement campaigns — on representative highway, urban, and semi-urban corridors — are needed to validate whether 3GPP's CDL (Clustered Delay Line) channel

models are adequate for India or require localization-specific extensions. This directly impacts the technical parameters for MTCTE certification of OBUs and RSUs (Q5) — if channel models are wrong, certification limits may be miscalibrated.

4. National ITS Digital Twin Platform

The consultation does not mention digital twins anywhere. A national ITS digital twin — a real-time virtual model of India's road network fed by RSU sensor data, OBU position reports, traffic management center inputs, and weather data — would serve:

- Real-time traffic management and incident response
- Simulation-assisted infrastructure planning (optimal RSU placement optimization)
- V2X safety application testing before field deployment (regulatory sandbox)
- Post-incident analysis and forensic V2X data reconstruction

Duan et al. (2021), "Digital Twin for Network and Service Management," *IEEE Communications Magazine* and Xu et al. (2022), "Digital Twin-Enabled Intelligent Transportation Systems: A Review," *Journal of Advanced Transportation* provide the framework. An Indian academic institution capable of developing an open-source ITS digital twin platform would provide a nationally significant contribution directly aligned with TRAI's mandate.

5. V2X Cybersecurity for Indian ITS Infrastructure

The consultation identifies PKI as the security foundation but does not engage with the broader attack surface of the V2X ecosystem. Specifically not discussed:

- **Sybil attacks** in dense traffic: a single malicious OBU creating multiple pseudonym certificates to simulate non-existent vehicles and manipulate traffic flow
- **GPS spoofing combined with V2X message injection**: a sophisticated attack where spoofed GPS data is combined with legitimate-format V2X messages to cause collision scenarios
- **RSU physical security**: RSUs deployed along highways are physically accessible; an attacker with physical access to an RSU can manipulate its messages or use it as a network intrusion point

Syvane et al. (2023), "Physical Layer Security for V2X Communications," *IEEE Transactions on Vehicular Technology* and van der Heijden et al. (2019), "Survey on Misbehavior Detection in Cooperative ITS" (cited earlier) frame the research landscape. India should establish a **V2X Cybersecurity Research Lab** (most naturally co-located with C-DAC Hyderabad, which already has the IoT security mandate and has a representative on the MoRTH Task Force) to develop India-specific threat models, test platforms, and misbehavior detection algorithms.

PART VII: STRATEGIC SUMMARY — THE COMPLETE FRAMEWORK TRAI IS MISSING

Mapping the gaps identified above directly to each consultation question:

Question	What TRAI Discusses	What Is Missing
Q1	Authorization need, eligibility, validity	Two-tier General/Specific authorization model; RSU Registry; future cooperative perception scope; iRSU capability classification
Q2	Alternative to authorization	Multi-layer class authorization modeled on EU/Australia with India-specific RSU registry
Q4	LTE-V2X vs NR-V2X choice	Rel-19/20 roadmap (AI-native sidelink, RedCap, ISAC, relay); Release upgrade pathway; V2X Technology Advisory Council
Q5	MTCTE need for OBU/RSU	RSU Capability Classification (Class A/B/C); edge compute specification; crypto-agility requirement; Indian channel model calibration
Q6	ITS stack standardization	ETSI CPM (Collective Perception) standard; semantic communication layer; AI-native application layer
Q7	PKI framework	Misbehavior detection authority; post-quantum crypto-agility; national RSU registry integration with ITS CA
Q8	Spectrum assignment	Planned use of reserved 20 MHz (CPM + ISAC); RSU Dynamic Spectrum Management Protocol; cooperative perception bandwidth planning
Q11	Open suggestions	National V2X Innovation Network; iRSU architecture mandate; ITS digital twin platform; V2X channel measurement campaign
Q12/Q20	Safety service charge exemption	Four-tier revenue taxonomy; safety vs. commercial service distinction; public infrastructure cost model
Q17	Revenue sources	V2X data monetization framework; multi-sided market model; Tier 1–4 revenue taxonomy

The overarching vision this consultation is currently missing:

India is designing the authorization framework for its first V2X deployment generation. This generation will define the physical infrastructure — RSU locations, capability, backhaul, PKI

enrollment — that will persist for 10–15 years. If that infrastructure is designed as a communication relay network, it will need to be replaced when cooperative perception, intelligent edge computing, and AI-native radio become standard. If it is designed from the outset as an **AI-Native Cooperative Mobility Infrastructure** — with RSUs as intelligent edge nodes, cooperative perception as the sensing layer, NR-V2X Rel-16/17/18 as the communication standard with a Rel-19/20 upgrade pathway, a national ITS PKI with misbehavior detection, and a real-time ITS digital twin as the management plane — then the same infrastructure will serve India's V2X needs through the decade of the 2030s, accommodating autonomous vehicles, smart highways, and 6G convergence without stranded investment.

That vision is what a strong institutional consultation response should articulate, backed by the research literature cited throughout this document. TRAI has asked the right operational questions. What is needed now is a response that answers those questions within the right long-term architecture — and that is precisely where academic expertise, unburdened by commercial interests or short-term deployment pressures, can provide the most distinctive and durable contribution.