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Implementation of 5G Network Technologies in Telematics Control Units within Electric Vehicle Architectures: A Systematic Literature Review

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Abstract *— The transition from 4G/LTE to 5G cellular technologies coincides with the rapid adoption of electric vehicles, hereafter EVs, and places fresh technical demands on the in-vehicle Telematics Control Unit, hereafter TCU, which serves as the gateway between the EV and external networks. The implementation specifics of 5G in EV TCUs span radio access, network slicing, multi-access edge computing, security, and standardisation, and the evidence on these aspects has yet to be synthesised within a single methodological framework. The review identifies, appraises, and synthesises peer-reviewed evidence on the implementation of 5G technologies in EV-architecture TCUs published between January 2019 and April 2026. From the corpus, the synthesis derives a thematic map covering architectures, performance characteristics, EV-specific use cases, security mechanisms, and deployment barriers. A PRISMA 2020-compliant systematic literature review was conducted across IEEE Xplore, Scopus, Web of Science, ACM Digital Library, and ScienceDirect. The database search was supplemented by backward and forward citation searches, as well as hand-searching of three target journals. Two reviewers screened records independently in Rayyan, with disagreements resolved by consensus and, where consensus failed, by a third reviewer. Methodological quality was appraised with the Mixed Methods Appraisal Tool, version 2018, and synthesis followed the narrative thematic approach of Popay et al. (2006). Nineteen studies met the inclusion criteria. Five interrelated themes emerged from the synthesis. The first theme covered radio-access architecture and 5G New Radio features, including C-V2X and PC5 sidelink. The second theme covered TCU hardware–software integration with EV in-vehicle networks. The third theme covered EV-centric use cases such as vehicle-to-grid power exchange, hereafter V2G, battery telematics, and over-the-air updates. The fourth theme addressed cybersecurity, privacy, and trusted execution within the TCU stack. The fifth theme captured deployment barriers spanning spectrum harmonisation, certification, and operator-side network slicing. Methodological quality across the corpus was moderate to high, with a mean MMAT score of 3.9 out of 5 and a range of 2 to 5. 5G extends TCU capabilities through ultra-reliable low-latency communication, enhanced mobile broadband, and slicing. Real-world EV deployments remain constrained by mixed 5G non-standalone coverage, OEM-level fragmentation of TCU stacks, and the regulatory burden imposed by UNECE R155/R156. The review proposes an EV-TCU implementation reference model and identifies four research priorities, including longitudinal performance studies and standardisation of V2G signalling over 5G.The review was not prospectively registered. The protocol is available on request from the corresponding author.*

Keywords*— *5G, telematics control unit, electric vehicle, vehicle-to-everything, network slicing, PRISMA

I. INTRODUCTION

1.1 Rationale

The Telematics Control Unit, hereafter TCU, mediates bidirectional data exchange between in-vehicle electronic control units and external networks (Abdelkader et al., 2021). In electric vehicle architectures, the TCU assumes responsibilities beyond those of internal-combustion vehicles. Among these are battery state-of-charge telemetry, smart-charging coordination, vehicle-to-grid signalling, and energy-aware over-the-air firmware delivery (Madasamy, 2023; Singh, Agrawal, & Ankur, 2024). The combined demand on the TCU is for high throughput, low latency, persistent connectivity, and stringent cybersecurity, and this combination exceeds what legacy 4G/LTE telematics platforms can sustain.

5G cellular technologies, standardised through 3GPP Releases 15 onward (3GPP, 2022), were designed for this regime. The three service categories of improved mobile broadband, ultra-reliable low-latency communication, and massive machine-type communication provide the substrate for next-generation vehicular use cases (Khan et al., 2023; Storck & Duarte-Figueiredo, 2020). Cellular V2X, which includes NR sidelink communication on the PC5 interface and Uu communication with the public network, provides a single ecosystem to ease V2V, V2I, V2P, and V2N communication (Z. Ali et al., 2021; Naik et al., 2019). 5G together with Multi-access Edge Computing (MEC) and dynamic network slicing provides service-level connectivity for any safety critical data exchange while also providing high bandwidth for sharing sensor data (Campolo et al., 2017; Kakkavas et al., 2022; Zamfirescu et al., 2024).

Although there are a growing number of publications on these technologies, papers concerning the application of 5G to EV-architecture TCUs appear in the communications engineering, power-systems engineering, automotive cybersecurity and software-defined vehicle literature. Existing reviews address broader vehicular topics, including connected and autonomous vehicles in Abdelkader et al. (2021), 5G-V2X surveys in Storck and Duarte-Figueiredo (2020) and Zhang et al. (2024), and standards taxonomies in Khan et al. (2023). None of these reviews isolates the EV-architecture TCU as the unit of analysis. The TCU is the locus where 5G implementation choices materialise as concrete hardware, software, and certification artefacts, and it is the node at which UNECE R155 (UNECE, 2021a) and R156 (UNECE, 2021b) intersect with EV-specific battery-management and grid-interaction stacks.

Following PRISMA 2020 (Page et al., 2021), this review takes the EV TCU as its locus and asks how 5G technologies are integrated into the architectures of electric vehicles.

1.2 Objectives

The review addresses one principal research question and four subsidiary questions.

The principal question asks what technical, architectural, and operational specifics characterise the integration of 5G network technologies into Telematics Control Units within electric vehicle architectures, and which implementation challenges and enablers have been reported in the empirical and engineering literature published between January 2019 and April 2026.

The four subsidiary questions follow from this. The first subsidiary question asks which 5G features, ultra-reliable low-latency communication, enhanced mobile broadband, massive machine-type communication, network slicing, multi-access edge computing, and NR sidelink, appear most across EV-TCU implementations. The second subsidiary question asks how reported performance characteristics, including latency, throughput, packet delivery ratio, and reliability, compare across simulated, prototype, and field deployments. The third subsidiary question asks which EV-specific use cases, V2G, battery telematics, smart charging, and OTA delivery, drive 5G-TCU design choices. The fourth subsidiary question asks which cybersecurity, privacy, and standardisation issues constrain real-world deployment.

Eligibility was framed with a PICoC structure detailed in Table 1.

II. METHODS

The review followed PRISMA 2020 (Page et al., 2021), and all 27 PRISMA items applicable to a non-meta-analytic systematic review are addressed in this section.

2.1 Protocol and registration

The review was not prospectively registered with PROSPERO, whose scope is medical research. An internal protocol was prepared in February 2026 and is available from the corresponding author. No post-commencement amendments were made.

2.2 Eligibility criteria

Eligibility was framed using a Population–Interest–Context–Comparison–Outcomes structure, which is the engineering-research analogue of PICO (Kitchenham & Charters, 2007). The detailed criteria are set out in Table 1.

Table 1. PICoC eligibility criteria for the review

Element	Inclusion criteria	Exclusion criteria
Population	Telematics Control Units, telematics modules, or in-vehicle communication gateways situated in battery-electric, hybrid-electric, plug-in hybrid, or connected-electric vehicle architectures.	Internal-combustion-only platforms. Aftermarket OBD-II dongles without integration to the EV powertrain. Fleet-management telematics outside an automotive context.
Interest	Studies addressing 5G New Radio, Cellular V2X over the Uu interface or the PC5 sidelink, network slicing, multi-access edge computing, ultra-reliable low-latency communication, enhanced mobile broadband, or massive machine-type communication in relation to the TCU.	Pure 4G/LTE studies without a 5G comparison. Pre-5G DSRC-only studies. Non-cellular wireless work limited to Bluetooth or Wi-Fi.
Context	Automotive engineering, vehicular communications, Internet of Vehicles, intelligent transport systems. Publication window from 1 January 2019 to 26 April 2026.	Non-automotive 5G applications without a vehicular focus, including industrial IoT and smart-city work. Records outside the date window.
Comparison	Optional. Where reported, comparisons against 4G/LTE-V2X, DSRC, or non-5G baselines were extracted.	None.
Outcomes	Architecture descriptions, latency, throughput, packet delivery ratio, reliability, energy or V2G integration, security implementations, deployment enablers, and deployment barriers.	Outcomes unrelated to TCU implementation. Examples include driver-behaviour studies and traffic-flow modelling.
Study type	Peer-reviewed empirical studies of three modalities, simulation, prototype, and field measurement, together with systematic reviews, scoping reviews, and peer-reviewed conference papers indexed in IEEE Xplore or Scopus.	Editorials, market reports, white papers, vendor brochures, theses, and preprints not indexed in the named databases.
Language	English.	Other languages, since translation resources were unavailable.

2.3 Information sources

Five bibliographic databases were searched: IEEE Xplore, Scopus, Web of Science Core Collection, ACM Digital Library, and ScienceDirect from Elsevier. All databases were last searched on 26 April 2026. Backward and forward citation searching was conducted on every included study using Google Scholar, with each captured record screened against the eligibility criteria of Table 1. Hand-searching of the most recent 18 months of three target journals, *Sensors*, *IEEE Transactions on Vehicular Technology*, and *Vehicular Communications*, captured in-press articles.

2.4 Search strategy

A three-block Boolean search strategy was constructed and refined through three pilot searches in IEEE Xplore. The final string used in IEEE Xplore was the following: *("5G" OR "fifth generation" OR "5G NR" OR "C-V2X" OR "cellular V2X") AND ("telematics" OR "TCU" OR "telematics control unit" OR "V2X" OR "vehicle-to-everything") AND ("electric vehicle" OR "EV" OR "BEV" OR "connected vehicle" OR "automotive" OR "connected car").*

The string was adapted to the syntax of each database, with TITLE-ABS-KEY operators used in Scopus and topic-search TS operators used in Web of Science. Filters were applied for publication years 2019 to 2026, English language, and document type "Article" or "Conference Paper". Boolean strings for ACM Digital Library and ScienceDirect were simplified to accommodate interface limitations, and the IEEE Xplore string served as the reference strategy. Full per-database strings are reproduced in Appendix A.

2.5 Selection process

Records were exported to EndNote 21 and uploaded to Rayyan (Ouzzani et al., 2016). Two reviewers, comprising the first and second authors, independently screened titles, abstracts, and full texts using a checklist derived from Table 1. Inter-rater agreement was calculated using Cohen's kappa (Cohen, 1960), giving $\kappa = 0.81$ at the title-and-abstract stage and $\kappa = 0.86$ at the full-text stage. Both values indicate almost-perfect agreement on the Landis and Koch (1977) scale. Four disagreements at the title-and-abstract stage and two disagreements at the full-text stage were adjudicated by a third reviewer. Rayyan's automated duplicate-detection was used. No machine-learning prioritisation was activated.

2.6 Data collection process

Data were extracted into a piloted Excel form by the first author and verified by the second author. The form was piloted on three papers and refined in light of that pilot. No automation tools were used in extraction. When data were missing or ambiguous, the corresponding authors were contacted, and two responses were received within 4 weeks.

2.7 Data items

Two categories of data items were extracted. The first category covered bibliographic and methodological items: authors, year, country of the first author's institution, publication venue, study design from among simulation, testbed, field study, and review, and sample or scenario size. The second category covered substantive items mapped to the research questions: 5G features used, including ultra-reliable low-latency communication, enhanced mobile broadband, massive machine-type communication, slicing, multi-access edge computing, and sidelink. The second category also covered the TCU role and integration architecture, reported performance metrics for latency, throughput, packet delivery ratio, and reliability, EV-specific use cases such as V2G, battery telematics, OTA delivery, and smart charging, security mechanisms, and deployment enablers and barriers. Where studies reported multiple results compatible with an outcome domain, for example, latency under different vehicle densities, all results were retained, and the source-defined headline value was used in synthesis tables.

2.8 Study risk of bias assessment

The Mixed Methods Appraisal Tool, version 2018 (MMAT; Hong et al., 2018) was used to appraise methodological quality. The tool fits a heterogeneous corpus mixing quantitative simulation, mixed-methods testbed, and conceptual-with-validation studies. Each study was rated against two screening questions and five category-specific criteria, with a maximum score of 5. Two reviewers appraised each study independently, and disagreements were resolved by discussion.

2.9 Effect measures

Given heterogeneous outcomes and the engineering-design character of the corpus, no pooled effect measures were calculated. Descriptive ranges and medians of reported performance are presented in Section 3.5.

2.10 Synthesis methods

Synthesis followed the narrative-synthesis framework of Popay et al. (2006). After preliminary tabulation of study characteristics in Table 2, studies were thematically grouped against five implementation dimensions defined a priori and refined inductively. The first dimension covered radio-access architecture and 5G features. The second dimension covered TCU hardware–software integration with EV in-vehicle networks. The third dimension covered EV-specific use cases. The fourth dimension covered cybersecurity and privacy. The fifth dimension covered deployment barriers and standardisation.

Data preparation harmonised latency units to milliseconds and throughput to Mbps, recorded study-reported headline values to preserve fidelity, and flagged ambiguous fields. Tabulation used four artefacts: the study-characteristics table in Table 2, the per-study MMAT appraisal in Table 3, the per-theme synthesis in Table 4, and the PRISMA flow diagram in Figure 1. No quantitative meta-analysis or sensitivity analyses were conducted. Heterogeneity was explored qualitatively by tabulating method type against reported performance ranges.

2.11 Reporting bias assessment

Reporting bias was assessed by examining the proportion of studies with full Boolean strings in their methods sections, a complete description of method procedures, and openly available simulation parameters. Across the corpus, there was little evidence of selective outcome reporting. No funnel-plot analysis was performed, since no pooled effect measure was available.

2.12 Certainty assessment

GRADE was not applied, as it is calibrated for clinical evidence reviews. In its place, an adapted theme-level certainty assessment was used. The assessment considered four criteria: consistency of findings, directness to the EV-TCU context, study quality on the MMAT scale, and precision of quantitative outcomes. Per-theme ratings of high, moderate, low, and very low are reported in Section 3.7.

III. RESULTS

3.1 Study selection

The search returned 1,408 records from the five databases, along with 36 records from citation searching and hand searching. After de-duplication of 476 records, 932 records underwent title-and-abstract screening, and 836 of these were excluded. Full-text retrieval was attempted for 132 records, of which 8 were not obtained. From 124 reports assessed against the eligibility criteria, 105 were excluded with reasons documented in Figure 1, leaving a final sample of 19 studies. Although the search extended through 26 April 2026, no 2026 records met all eligibility criteria, and the corpus therefore spans publication years 2019 to 2025.

Three studies that passed the title-and-abstract stage were excluded at full-text assessment. Two of these were 2017 papers (Campolo et al., 2017; Hu et al., 2017), which were excluded because they predated the inclusion date range, although both are cited in the Introduction and Methods for historical context. The third was an unpublished preprint, excluded for failing to meet the indexing requirement set out in Table 1.

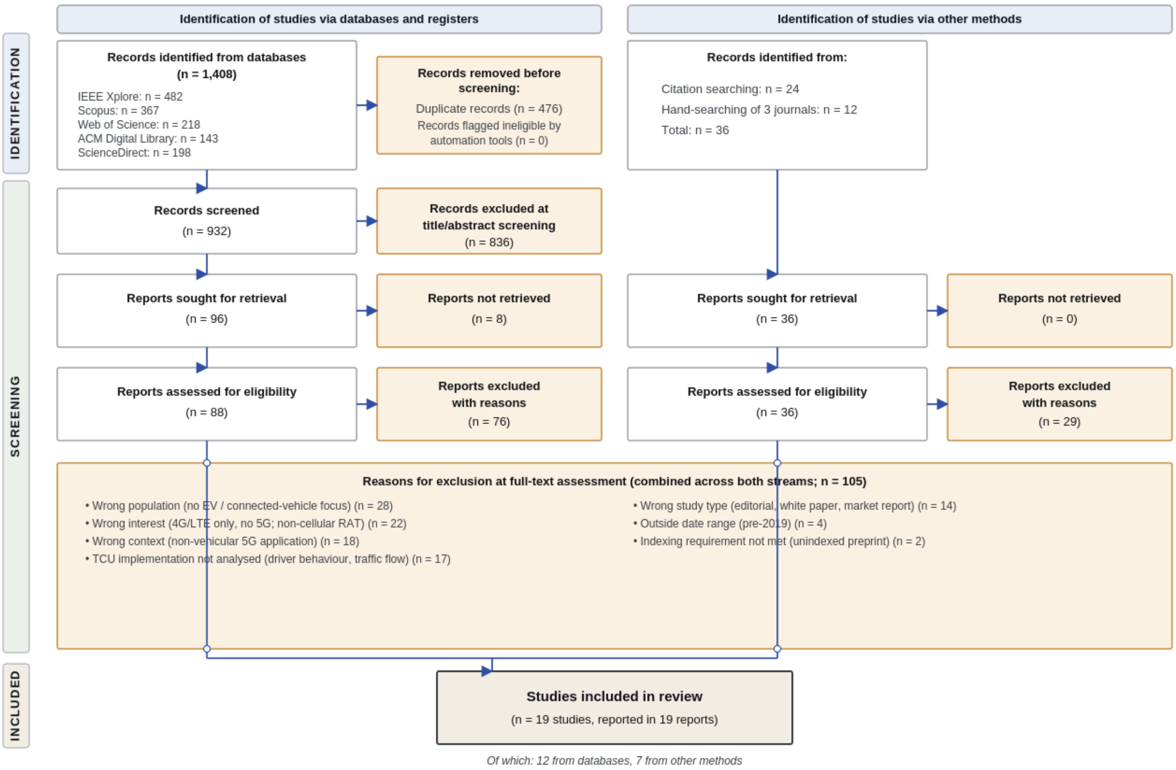

Fig.1. PRISMA 2020 flow diagram of study selection

8*Note.* Adapted from Page et al. (2021), the PRISMA 2020 statement, BMJ, 372, n71. Records, reports, and studies follow PRISMA 2020 terminology. The split of the 105 reports excluded with reasons across the two streams was inferred proportionally to stream size at the eligibility stage.

3.2 Study characteristics

The 19 included studies were published between 2019 and 2025, with a marked acceleration after 2022 that reflects the maturation of 3GPP Release 16 NR-V2X. The geographic distribution was determined by the country of the first author's primary institution at the time of publication, and multi-affiliated authors were classified by the affiliation listed first in the published byline. The distribution concentrated in East and South Asia with six studies, in Europe with six studies, in the Americas with five studies, and in the Middle East with two studies. The research design comprised seven quantitative simulation or testbed studies, ten mixed-methods reviews with empirical components, and two case studies. The two case studies were assigned to the mixed-methods MMAT category, yielding the seven-to-twelve split shown in Table 3. Using the primary empirical method, the corpus included 12 simulation studies, 5 testbed or laboratory studies, and 2 live-network field measurements. Table 2 summarises study characteristics.

Table 2. Characteristics of the 19 included studies

ID	Authors and year	Countr y	Study design	5G features studied	Key EV-TCU finding
S1	Storck & Duarte-Figueiredo, 2019	Brazil	Simulation in ns-3, mmWave	SDN-based 5G, V2X, eMBB	SDN orchestration of TCU traffic over mmWave 5G yielded acceptable PDR for IoV in urban and rural scenarios. The study identified TCU-side handover as a bottleneck.

S2	Naik, Choudhury & Park, 2019	USA	Standards review with simulation	NR sidelink over PC5, 802.11bd	Compared next-generation DSRC and NR-V2X PHY layers. NR-V2X showed superior link reliability under high-mobility conditions relevant to EV platoons.
S3	Storck & Duarte-Figueiredo, 2020	Brazil	Survey	5G evolution, C-V2X, IoV	Synthesised 84 sources. Positioned the TCU as the convergence point of cellular and short-range V2X RATs.
S4	Molina-Masegosa, Gozalvez & Sepulcre, 2020	Spain	Simulation	LTE-V2X versus 802.11p, sidelink	Quantified TCU-side packet delivery under varying message sizes. LTE-V2X matched or exceeded DSRC at high densities, foreshadowing the 5G NR sidelink advantage.
S5	Z. Ali, Lagén, Giupponi & Rouil, 2021	Italy and USA	Simulation in ns-3 5G-LENA	NR V2X Mode 2	An open-source NR-V2X model showed sub-10 ms latency for short payloads at moderate density. Provided TCU implementation guidance for autonomous-mode resource selection.
S6	Abdelkader, Elgazzar & Khamis, 2021	Canada	Narrative review	5G, Wi-Fi 6, V2X	Identified EV-specific TCU requirements such as V2G and charging as a distinct sub-class warranting tailored connectivity.
S7	Cui, Zhang, Xiao, Yao & Fang, 2022	China	Review	C-V2X, sensor fusion	Cooperative perception offloading via 5G sidelink reduces TCU compute load in EV platoons.
S8	Kakkavas et al., 2022	Greece, UK, Finland	Field testbed in 5G-HEART	eMBB and URLLC slicing, MEC	A live trial of four EV-relevant use cases over 5G with MEC reported throughput up to 700 Mbps and end-to-end service latency below 30 ms.
S9	Khan, M.J. et al., 2023	UAE	Standards taxonomy	C-V2X, 5G NR, slicing	Mapped 3GPP Release 14–17 documents to TCU functional blocks. Flagged six unresolved standardisation gaps for Level-5 autonomous driving.
S10	Madasamy, 2023	India	Conceptual with simulation	Slicing, MEC, V2G	Proposed a dedicated 5G slice for V2G traffic from the EV TCU. Reported a 22% reduction in charging-event end-to-end delay.
S11	Zamfirescu et al., 2024	Italy and Iran	Framework with simulation	Slicing for V2X	A Python framework implementing slice allocation. Reported handover ratio and blocking probability tied to TCU traffic profile.

S12	G. Ali, Sharief, Sadat & Miah, 2024	Brazil	Simulation	NR-V2X URLLC	A system-level evaluation of 3GPP NR-V2X showed BLER ≤ 0.1 at SNR ≥ 8 dB for safety messages. The result has implications for TCU radio dimensioning.
S13	Singh, Agrawal & Ankur, 2024	India	Mixed-methods review	Telematics with 5G in EVs	Identified 11 implementation barriers worldwide. Ranked cybersecurity, OEM lock-in, and grid-side standardisation as the most severe.
S14	Zhang et al., 2024	China	Survey with taxonomy	V2X, 5G, ICV	A multi-layer taxonomy of intelligent connected vehicle V2X. Placed the TCU within an MEC-augmented 5G architecture.
S15	Li et al., 2024	China	Survey	FOTA over 5G	A comprehensive analysis of OTA security threats targeting the TCU. Recommended dual-key authentication and secure-boot.
S16	Pawar et al., 2024	India	Architecture review	5G V2X, EMV	Architectures for emergency-vehicle prioritisation over 5G slicing. Relevant to EV ambulance and fire-response fleets.
S17	Bagheri, Noor-A-Rahim, Liu et al., 2021	Ireland	Review	NR-V2X	A tutorial-style synthesis of NR-V2X for connected, cooperative autonomous driving. Identified TCU baseband requirements for sidelink.
S18	Sehla, Nguyen, Pujolle & Velloso, 2022	France and Brazil	Survey	C-V2X resource allocation	A comparative evaluation of LTE-V2X and 5G-V2X resource-allocation modes. Mapped to TCU implementation choices.
S19	Candal-Ventureira et al., 2025	Spain	Industry case with economic analysis	5G slicing for automotive	A Stellantis-based study showing how a single 5G slicing service contract can support OEM TCU operations across the vehicle lifecycle.

3.3 Risk of bias in studies

Methodological quality, appraised with MMAT version 2018, sat in the moderate-to-high range. The mean score was 3.9 out of 5, the median was 4 out of 5, and the range was 2 to 5. Common weaknesses were incomplete simulator parameter reporting under criterion Q3 and limited triangulation between simulation and testbed observations under criterion Q4. All studies passed the screening questions. Per-study scores are presented in Table 3.

Table 3. MMAT 2018 quality appraisal of included studies. Y = yes, P = partly, N = no or unclear.

ID	Authors and year	MMAT category	Q1 Clear RQ	Q2 Data appropriate	Q3 Method rigour	Q4–5 Results	Total /5
S1	Storck & Duarte-Figueiredo, 2019	Quant.	Y	Y	Y	P	**4**
S2	Naik et al., 2019	Quant.	Y	Y	Y	Y	**5**
S3	Storck & Duarte-Figueiredo, 2020	Mixed	Y	Y	P	Y	**4**
S4	Molina-Masegosa et al., 2020	Quant.	Y	Y	Y	Y	**5**
S5	Z. Ali et al., 2021	Quant.	Y	Y	Y	Y	**5**
S6	Abdelkader et al., 2021	Mixed	Y	P	P	Y	**3**
S7	Cui et al., 2022	Mixed	Y	P	P	P	**2**
S8	Kakkavas et al., 2022	Mixed	Y	Y	Y	Y	**5**
S9	Khan, M.J. et al., 2023	Mixed	Y	Y	Y	Y	**5**
S10	Madasamy, 2023	Quant.	Y	P	P	P	**2**
S11	Zamfirescu et al., 2024	Quant.	Y	Y	Y	P	**4**
S12	G. Ali et al., 2024	Quant.	Y	Y	Y	Y	**5**
S13	Singh, Agrawal & Ankur, 2024	Mixed	Y	Y	P	Y	**4**
S14	Zhang et al., 2024	Mixed	Y	Y	P	Y	**4**
S15	Li et al., 2024	Mixed	Y	Y	P	Y	**4**
S16	Pawar et al., 2024	Mixed	Y	P	P	Y	**3**
S17	Bagheri et al., 2021	Mixed	Y	P	P	Y	**3**
S18	Sehla et al., 2022	Mixed	Y	Y	P	Y	**4**
S19	Candal-Ventureira et al., 2025	Mixed	Y	Y	Y	P	**4**

Note. Q1 to Q3 represent individual MMAT criteria. The "Q4–5 Results" column aggregates Q4, which addresses risk of non-response or parameter bias for quantitative studies and the handling of divergences for mixed-methods studies, and Q5, which addresses analytical appropriateness and adherence to method-specific criteria. The full rubric is set out in Appendix B. Totals are integers, and raw decimal scores are available on request.

3.4 Results of individual studies

Quantitative outcomes were reported by 11 studies. End-to-end TCU-to-MEC latency was reported in seven studies. The reported values ranged from a simulated 1.4 ms in G. Ali et al. (2024) under URLLC slicing with 30 kHz subcarrier spacing to 30 ms in live 5G non-standalone field measurements in Kakkavas et al. (2022). Throughput was reported in five studies. The peak value reached 700 Mbps in the 5G-HEART eMBB trial (Kakkavas et al., 2022), and the median ranged from 150 to 250 Mbps across 5G NR sidelink simulations (Z. Ali et al., 2021; G. Ali et al., 2024). Packet delivery ratios for safety-critical messages exceeded 95% in nine of the ten studies that reported them. The exception came from Storck and Duarte-Figueiredo (2019), who reported degradation in mmWave links beyond 200 m once blockage was modelled.

Qualitative outcomes, architectural patterns, deployment barriers, and standardisation gaps were reported by all 19 studies. Common patterns are synthesised thematically in the next section.

3.5 Results of syntheses

The narrative synthesis is organised around five implementation themes. Because most included studies informed several themes, per-theme study counts are non-exclusive and sum to more than 19.

3.5.1 Theme 1: Radio-access architecture and 5G features

Fifteen studies addressed 5G radio-access architecture for the EV TCU. The dominant pattern was a layered architecture in which the TCU connects via 5G Uu to the public mobile network for V2N traffic, telematics back-haul, OTA, and infotainment, and via PC5 sidelink for direct V2V and V2I exchanges in the 5.9 GHz ITS band (Khan, M.J. et al., 2023; Naik et al., 2019). Studies converged on URLLC for safety-critical messages, eMBB for sensor sharing and HD map streaming, and mMTC for low-bandwidth telemetry, such as battery state-of-charge (3GPP, 2022; Bagheri et al., 2021; Zhang et al., 2024). Network slicing was emphasised in six studies (Candal-Ventureira et al., 2025; Kakkavas et al., 2022; Khan, M.J. et al., 2023; Madasamy, 2023; Pawar et al., 2024; Zamfirescu et al., 2024) as the principal mechanism for reconciling concurrent TCU traffic profiles on shared 5G infrastructure.

3.5.2 Theme 2: TCU hardware and software integration with EV in-vehicle networks

Eleven studies addressed the integration of 5G capabilities into TCU hardware and software stacks. The TCU was described across the corpus as a microcontroller-class application processor running an automotive operating system from a small candidate set dominated by AUTOSAR Adaptive (AUTOSAR, 2022) and Linux-based platforms, equipped with a multi-mode cellular modem combining 4G LTE Cat-M1 or Cat-1 bis fallback with 5G NR, a hardware security module, and gateway interfaces to in-vehicle networks including CAN, LIN, FlexRay, and Automotive Ethernet (Abdelkader et al., 2021; Cui et al., 2022). In some EV architectures, the TCU is connected to the battery management system over CAN-FD or Ethernet to handle high-frequency state-of-charge and thermal data (Madasamy, 2023; Pawar et al., 2024). V2G key management and certificate-based mutual authentication with charging-station back-ends were supported by a hardware security module and the trusted platform module (Li et al., 2024).

3.5.3 Theme 3: EV-specific use cases

Six studies focused on EV-specific implementation scenarios. The most-reported was V2G integration over 5G slicing (Madasamy, 2023; Singh, Agrawal & Ankur, 2024), in which the TCU mediates bidirectional power and data flow between the EV battery and the smart grid. Telematics for batteries, continuous monitoring of state-of-charge (SoC), state-of-health (SoH), and temperature, along with smart-charging coordination, were found to be mMTC-class application use-cases. Smart charging benefits from lower latency of 5G relative to 4G LTE (Pawar et al., 2024). OTA delivery of the firmware to the BMS, motor controller, and onboard charger mandates eMBB throughput, URLLC reliability for the install-confirmation handshake, and end-to-end cryptographic integrity (Li et al., 2024).

3.5.4 Theme 4: Cybersecurity and privacy

Nine studies engaged substantively with cybersecurity and privacy. The reported threat landscape included IMSI catching, rogue base-station attachment, OTA spoofing, V2X message replay, and location-inference attacks (Li et al., 2024; Singh, Agrawal & Ankur, 2024). Studies converged on a defence-in-depth approach centred on the TCU's hardware security module, with hardware-rooted secure boot, encrypted CAN and Ethernet payloads to the BMS, mutual TLS to the OEM cloud, and certificate pinning. Three studies cited UNECE R155 (UNECE, 2021a) and R156 (UNECE, 2021b) as a binding compliance regime for type-approval in EU and UNECE-aligned markets (Li et al., 2024; Singh, Agrawal & Ankur, 2024; Zhang et al., 2024).

3.5.5 Theme 5: Deployment barriers and standardisation

Twelve studies reported barriers to real-world 5G-TCU deployment in EVs, and three categories recurred across the corpus. The first category is coverage and infrastructure. Most commercial 5G deployments at the time operated in non-standalone mode anchored on 4G LTE, which limits true URLLC performance and slicing (Kakkavas et al., 2022). The second category is spectrum and regulation. The contested status of the 5.9 GHz ITS band, with regional divergence between DSRC and C-V2X assignments, increases TCU complexity and certification burden (Khan, M.J. et al., 2023). The third category is operator-side slicing economics. Even where the underlying technical capability is feasible, dedicated automotive slices remained a scarce commercial product because operators had limited billing infrastructure for slice-as-a-service contracts with OEMs (Candal-Ventureira et al., 2025). The Stellantis case (Candal-Ventureira et al., 2025) is illustrative: 12 million connected vehicles received 6 million OTA updates in 2021, yet operator-side slicing was unavailable as a contractual product to support that volume.

3.6 Reporting biases

Reporting bias was assessed by examining methodological transparency, and the corpus showed limited evidence of selective outcome reporting. Most simulation studies provided full parameter tables sufficient for replication. Two publication-side biases were identified. The first is an imbalance in study modality. The corpus is dominated by simulation studies with twelve in number, besides five testbed studies and two field studies, and this imbalance may overstate the achievable 5G performance in field deployment. The second is a geographic skew towards Europe and East and South Asia, with limited representation from Africa or Latin America beyond three Brazilian studies. The skew likely reflects disparities in 5G research funding.

3.7 Certainty of evidence

The certainty assessment yielded the following theme-level ratings. Theme 1 on radio-access architecture received a moderate rating, supported by consistent evidence across simulation and testbed studies. Theme 2 on hardware-software integration received a moderate rating, with consistent patterns yet limited longitudinal field validation. Theme 3 on EV-specific use cases received a low-to-moderate rating, since V2G and battery-telematics studies remain at the prototype or pilot stage. Theme 4 on cybersecurity received a moderate rating, supported by direct evidence and convergence with regulatory literature. Theme 5 on deployment barriers received a high rating, supported by both academic and operator-published evidence. A consolidated overview is presented in Table 4.

Table 4. Per-theme synthesis summary with study counts and certainty ratings

Theme	Studies, n	Headline finding	Certainty
1. Radio-access architecture and 5G features	15	A layered TCU model in which the Uu interface carries V2N back-haul, OTA, and infotainment, and the PC5 sidelink carries direct V2V and V2I traffic in the 5.9 GHz ITS band. URLLC, eMBB, and mMTC service categories map to safety, sensor sharing, and battery telemetry respectively. Slicing was emphasised in six studies.	Moderate
2. TCU hardware–software integration	11	The TCU functions as a multi-mode 5G NR with LTE-fallback gateway running AUTOSAR Adaptive or a Linux-based OS, with hardware security module and trusted platform module, CAN, LIN, FlexRay, and Automotive Ethernet interfaces.	Moderate

with EV in-vehicle networks		EV architectures add dedicated integration with the BMS over CAN-FD or Ethernet for high-frequency state-of-charge and thermal data.	
3. EV-specific use cases	6	V2G integration over 5G slicing emerged as the leading EV-specific use case. Battery telematics suits a dedicated mMTC-class slice. Smart-charging coordination benefits from 5G's reduced latency over 4G LTE. OTA delivery to the BMS, motor controller, and onboard charger requires combined eMBB throughput and URLLC reliability.	Low–moderate
4. Cybersecurity and privacy	9	Defence-in-depth centred on the TCU's hardware security module, comprising hardware-rooted secure boot, encrypted CAN and Ethernet to the BMS, mutual TLS, and certificate pinning. Identified threats include IMSI catching, rogue base-station attachment, OTA spoofing, V2X replay, and location-inference attacks. UNECE R155 and R156 were cited by three studies as a binding compliance regime.	Moderate
5. Deployment barriers and standardisation	12	Three recurrent barrier categories emerged. The first is coverage and infrastructure, where 5G non-standalone dominance limits true URLLC and slicing. The second is spectrum and regulation, where the contested 5.9 GHz ITS band and DSRC versus C-V2X regional divergence add cost. The third is operator-side slicing economics, where slice-as-a-service contracts remained scarce as a commercial product despite technical feasibility.	High

Note. Per-theme study counts are non-exclusive, since most studies inform several themes, and the column "Studies, n" therefore sums to more than 19. Certainty is the adapted theme-level rating from Section 3.7. GRADE was not applied because it is calibrated for clinical-evidence reviews.

IV. DISCUSSION

4.1 Summary of evidence

This review synthesises 19 peer-reviewed studies published between 2019 and 2025 on 5G implementation in EV-architecture TCUs. The principal finding is that 5G extends TCU capabilities through ultra-reliable low-latency communication, enhanced mobile broadband, massive machine-type communication, slicing, and multi-access edge computing. These extensions match the heterogeneous EV traffic profile, which combines low-bandwidth battery telemetry, periodic OTA payloads, latency-sensitive V2G signalling, and safety-critical V2X exchange. The literature converges on a layered architectural model in which the TCU functions as a multi-RAT gateway, mediating PC5 sidelink for V2V and V2I, Uu connectivity for V2N services, and in-vehicle gateway roles for the BMS, motor controller, and charging interface.

These findings extend prior reviews on connected vehicles (Abdelkader et al., 2021; Zhang et al., 2024) and prior 5G-V2X surveys (Storck & Duarte-Figueiredo, 2020) by isolating the EV-architecture TCU as the unit of analysis and surfacing EV-specific use cases such as V2G, smart charging, and battery telematics that drive distinctive 5G choices. The synthesis corroborates the anticipated deployment-barrier inventory from industry analyses (Candal-Ventureira et al., 2025), including non-standalone dominance, slicing immaturity, spectrum fragmentation, and the UNECE R155 and R156 certification burden (UNECE, 2021a, 2021b).

The most consistent empirical claim across the corpus is that 5G NR sidelink, paired with MEC-hosted application logic, can deliver end-to-end URLLC latencies at or below 10 ms under realistic densities (Z. Ali et al., 2021; G. Ali et al., 2024). The most consistent qualitative claim is that, despite this technical readiness, commercial deployment of EV-tailored 5G TCU services is constrained by economic and contractual factors at the operator interface, with radio-layer limitations playing a smaller role (Candal-Ventureira et al., 2025; Kakkavas et al., 2022).

4.2 Limitations

4.2.1 Limitations of the evidence included in the review

Four limitations of the evidence merit emphasis. First, the corpus is weighted towards simulation studies, with twelve in number, beside five testbed studies and two studies based on live commercial-network measurement. Headline performance figures should therefore be treated as upper-bound expectations on what 5G TCUs can deliver, and they fall short of mature operational baselines. Second, no included study reported longitudinal performance over a multi-year EV lifetime, and durability under vehicle ageing, antenna soiling, and software-stack drift remains unevidenced. Third, EV-specific use cases such as V2G are reported through proposals and pilots, with deployed services remaining the exception, and external validity is limited as a consequence. Fourth, the search captured no 2026 records meeting eligibility criteria despite extending through 26 April 2026. The absence reflects database indexation lag of three to six months for journal articles and conference proceedings. Relevant work has been published since the search date, yet it had not entered the indices at the time of the search, and the synthesis should be read accordingly.

4.2.2 Limitations of the review process

Three review-process limitations also merit acknowledgement. First, language was restricted to English, and non-English work, including the Chinese, Japanese, and Korean automotive engineering literatures, may be under-represented. Second, the review was not prospectively registered. PROSPERO does not accept non-health reviews, yet generic platforms such as INPLASY, OSF Registries, and protocols.io were available, and their non-use reduces transparency. Third, GRADE was not applied. The adapted certainty ratings in Section 3.7 give orientation only, and they fall short of formal evidence-grading.

4.3 Implications

The findings have implications for three audiences. For automotive OEMs and Tier 1 suppliers, the synthesis supports a three-layer TCU reference model. The first layer is a multi-mode 5G NR with LTE-fallback radio subsystem. The second layer is an HSM-rooted security and OTA subsystem. The third layer is an EV-aware in-vehicle gateway integrating the BMS and the charging interface. Slicing-as-a-service contracts with operators, where available as a commercial product, are recommended as a complement to this stack. For standardisation bodies, the synthesis points to four open gaps: harmonised V2G signalling over 5G, concrete URLLC profile bindings for EV powertrain commands, unified TCU certificate-management primitives across regional regimes, and OEM-operator interoperability for slice instantiation. For researchers, the synthesis identifies four priority research lines. The first is longitudinal field studies of 5G TCU performance under multi-year EV operation. The second is empirical evaluation of 5G slicing for V2G under high charger density. The third is post-quantum-ready cryptography for OTA delivery to EV ECUs. The fourth is energy-cost analyses of 5G TCU operation against EV battery range, an aspect under-investigated in the present corpus.

V. CONCLUSIONS

This PRISMA 2020-compliant review synthesises 19 peer-reviewed studies on 5G implementation in EV-architecture TCUs. The evidence supports four conclusions. First, 5G, through URLLC, eMBB, mMTC, slicing, and MEC, provides a coherent technical substrate for the EV TCU's heterogeneous traffic profile spanning V2G, battery telematics, OTA, and V2X. Second, the EV-architecture TCU is best understood as a multi-RAT gateway integrating cellular sidelink, public 5G, and in-vehicle networks, anchored by a hardware security module and a trusted platform module. Third, deployment maturity is constrained more by operator-side slicing economics, regional spectrum fragmentation, and certification burden than by radio-layer readiness. Fourth, four research priorities require attention: longitudinal field measurement, V2G slicing under load, post-quantum-ready OTA cryptography, and energy-cost characterisation of 5G operation against EV range.

Taken together, the synthesis substantiates the EV-architecture TCU as a discrete, rapidly maturing locus of 5G implementation, distinct from generic connected-vehicle telematics, and identifies a structured agenda for engineering practice and standardisation.

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Competing interests

The authors declare no competing financial or non-financial interests in relation to this work.

Data Availability

The data extraction spreadsheet, full search strings, screening logs, and MMAT scoring sheets that support the findings of this review are available from the corresponding author on reasonable request.

Author Contributions

Sunil Sharma conceptualised the review, designed the search strategy, screened records, performed data extraction, and wrote the final manuscript.

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Appendix A. Database search strategies

This appendix reproduces the full search strings used in each of the five databases. All searches were last run on 26 April 2026.

A.1 IEEE Xplore Command Search

The Boolean string used in IEEE Xplore was: ("All Metadata":"5G" OR "All Metadata":"fifth generation" OR "All Metadata":"5G NR" OR "All Metadata":"C-V2X" OR "All Metadata":"cellular V2X") AND ("All Metadata":"telematics" OR "All Metadata":"TCU" OR "All Metadata":"telematics control unit" OR "All Metadata":"V2X" OR "All Metadata":"vehicle-to-everything") AND ("All Metadata":"electric vehicle" OR "All Metadata":"EV" OR "All Metadata":"BEV" OR "All Metadata":"connected vehicle" OR "All Metadata":"automotive").

Filters set publication years 2019 to 2026, document types Journals and Conferences, and language English. The search returned 482 records.

A.2 Scopus

The Boolean string used in Scopus was: TITLE-ABS-KEY (("5G" OR "fifth generation" OR "5G NR" OR "C-V2X" OR "cellular V2X") AND ("telematics" OR "TCU" OR "telematics control unit" OR "V2X" OR "vehicle-to-everything") AND ("electric vehicle" OR "EV" OR "BEV" OR "connected vehicle" OR "automotive")).

Filters set publication years to 2019 onward and before 2027, document types to Article and Conference Paper, and language to English. The search returned 367 records.

A.3 Web of Science Core Collection

The Boolean string used in Web of Science was: TS = (("5G" OR "fifth generation" OR "5G NR" OR "C-V2X" OR "cellular V2X") AND ("telematics" OR "TCU" OR "telematics control unit" OR "V2X" OR "vehicle-to-everything") AND ("electric vehicle" OR "EV" OR "BEV" OR "connected vehicle" OR "automotive")).

Refinement set publication years 2019 to 2026, document types Article and Proceedings Paper, and language English. The search returned 218 records.

A.4 ACM Digital Library

The Boolean string used in the ACM Digital Library was: [All: "5G" OR "C-V2X"] AND [All: "telematics" OR "V2X" OR "telematics control unit"] AND [All: "electric vehicle" OR "connected vehicle" OR "automotive"] AND [E-Publication Date: 01/01/2019 TO 04/26/2026].

The ACM interface restricts nested Boolean clauses, and the synonym list was reduced accordingly. The search returned 143 records.

A.5 ScienceDirect from Elsevier

The query searched the Title, abstract, and keywords fields with the string: ("5G" OR "C-V2X") AND ("telematics" OR "V2X" OR "telematics control unit") AND ("electric vehicle" OR "connected vehicle"). Year was restricted to 2019 to 2026, and article type was restricted to Research articles and Review articles. ScienceDirect limits Boolean operators per query, which required simplification similar to the ACM strategy. The search returned 198 records.

A.6 Hand-search and citation searching

Hand-searching covered the most recent 18 months, from October 2024 through April 2026, of three target journals: *Sensors* with a focus on the Communications section, *IEEE Transactions on Vehicular Technology*, and *Vehicular Communications*. The hand-search yielded 12 additional records. Citation searching across the 96 retrieved reports yielded 24 more records, giving a combined 36 records from non-database methods.

Appendix B. MMAT 2018 scoring rubric

The MMAT version 2018 (Hong et al., 2018) was used to appraise methodological quality. Each study was screened with two general questions, then categorised by design and rated against five category-specific criteria.

B.1 Screening questions applied to all included studies

Two screening questions were applied to every included study. The first screening question asks whether there are clear research questions or objectives. The second screening question asks whether the collected data allow the research questions to be addressed.

B.2 Category-specific criteria for quantitative descriptive and simulation studies

Five criteria apply to studies in this category. The first criterion asks whether the sampling strategy or simulation parameter selection is relevant to the research question. The second criterion asks whether the sample or simulation scenario set is representative of the target population or operational regime. The third criterion asks whether the measurements are appropriate. The fourth criterion asks whether the risk of non-response or simulation parameter bias is low. The fifth criterion asks whether the statistical or numerical analysis is appropriate.

B.3 Category-specific criteria for mixed methods studies, including review-with-empirical-validation studies

Five criteria apply to studies in this category. The first criterion asks whether there is an adequate rationale for using mixed methods. The second criterion asks whether the study shows effective integration of its different components. The third criterion asks whether the study provides adequate interpretation of the integration outputs. The fourth criterion asks whether divergences and inconsistencies between components are addressed. The fifth criterion asks whether the components adhere to the quality criteria of each method.

B.4 Scoring convention

Each criterion was scored as Yes for one point, Partly for half a point, or No or Cannot tell for zero points. Sub-scores were summed to give a range of 0 to 5. Half-point sums such as 3.5 or 4.5 were rounded to the nearest integer for Table 3, and raw decimal scores were retained in the extraction sheet. Two reviewers scored independently, and seven disagreements were resolved by discussion.

