SIAM

Society of Indian Automobile Manufacturers

Building the Nation, Responsibly

STRENGTHENING AUTOMOTIVE MATERIAL COMPLIANCE ACROSS THE VEHICLE VALUE CHAIN

Global Benchmarking, Digital Systems, and Industry Readiness

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1 Executive Summary

Automotive material compliance is undergoing a structural shift. What was once treated as a technical or documentation led function is now emerging as a board-level capability that directly affects market access, export continuity, supply-chain resilience, and the credibility of sustainability disclosures. As vehicles become more material intensive and sustainability driven, the ability to demonstrate what materials are used, where they come from, and how they are governed across the lifecycle has become central to automotive competitiveness.

Globally, regulators and customers are moving from intent based compliance to evidence-based compliance. Requirements such as restricted substance communication, traceable material disclosure, and product-level information mechanisms are pushing the industry away from certificates and declarations toward auditable, data-backed proof. Digital Product Passports expanded chemical restrictions, and the convergence of material compliance with product carbon and sustainability reporting reinforce this shift. In this environment, compliance risk is no longer confined to late-stage regulatory checks; it now influences early design choices, sourcing decisions, engineering change management, and supplier governance.

This paper frames automotive material compliance as a system, not an activity. It proposes a lifecycle-based compliance framework structured around four reinforcing pillars: (i) substance restrictions, (ii) material disclosure and declaration depth, (iii) traceability and chain-of-custody, and (iv) documentation, auditability, and reporting. Together, these pillars shift compliance from post-hoc checking to proactive governance embedded across design, sourcing, industrialization, operations, and end-of-life considerations.

India's automotive ecosystem stands at an inflection point. The regulatory anchor exists through CMVR and AIS standards, including AIS-129 provisions related to restricted substances. Export programs already impose higher evidence expectations, making global compliance maturity a leading indicator for future domestic needs. However, supplier capability remains uneven. While large and export-linked suppliers often have structured systems, many tier-2 and tier-3 MSMEs face constraints in digitization, tools, and trained resources. A compliance transition that ignores these realities risks supply disruption and loss of localization resilience.

The way forward, therefore, lies in a phased, risk-based, and enablement driven roadmap. This paper outlines priorities across policy alignment, digital compliance infrastructure, supplier capability building, and readiness for emerging requirements such as substance-class governance and product-level sustainability disclosures. By strengthening material compliance as a shared industry capability rather than a punitive obligation India's automotive sector can protect export competitiveness, improve audit readiness, enable circularity and ELV outcomes, and build long-term trust across the vehicle value chain.

In this context, Automotive Material Compliance & Sustainability (AMCS) is positioned not merely as a conference, but as a platform to align stakeholders on the systems, data, and governance required to future-proof the automotive industry while enabling circularity, audit defensibility, and sustained global competitiveness.

2 Introduction

The automotive industry is entering a phase where material choices, substance governance, and supply-chain transparency are becoming as strategically important as cost, quality, and performance. Vehicles are increasingly complex material systems, incorporating advanced polymers, coatings, electronics, recycled content, and bio-based inputs to meet efficiency, safety, and sustainability objectives. At the same time, regulatory expectations and customer requirements are shifting from certificate-based assurance to evidence-based proof. This change is redefining how automotive material compliance is understood and managed across the vehicle lifecycle.

The core problem facing the industry is that existing material compliance practices were designed for a slower, less transparent regulatory environment. Compliance is often treated as a late-stage documentation exercise, relying heavily on tier-1 declarations and fragmented evidence. In multi-tier automotive supply chains, this approach creates structural blind spots, particularly at tier-2 and tier-3 levels where material formulations, additives, coatings, and processing chemicals are decided. As regulatory scrutiny intensifies and sustainability disclosures expand, these blind spots translate into systemic risks, including audit findings, shipment delays, forced material substitutions, and loss of market access.

For India's automotive ecosystem, the challenge is especially acute. While regulatory anchors exist through CMVR and AIS standards, and export programs already impose higher compliance expectations, supplier capability remains uneven. Large and export-linked suppliers often operate structured disclosure systems, while many tier-2 and tier-3 suppliers face constraints in tools, digitization, and compliance expertise. The problem, therefore, is not a lack of intent or standards, but the absence of a scalable, evidence-driven compliance system that aligns global requirements with domestic feasibility. Addressing this gap requires reframing automotive material compliance as an integrated system, one that combines lifecycle governance, digital data infrastructure, and phased supplier enablement, rather than as a standalone regulatory obligation.

3 "Sustainable Materials" in Automotive

3.1 What Are "Sustainable Materials" in Automotive

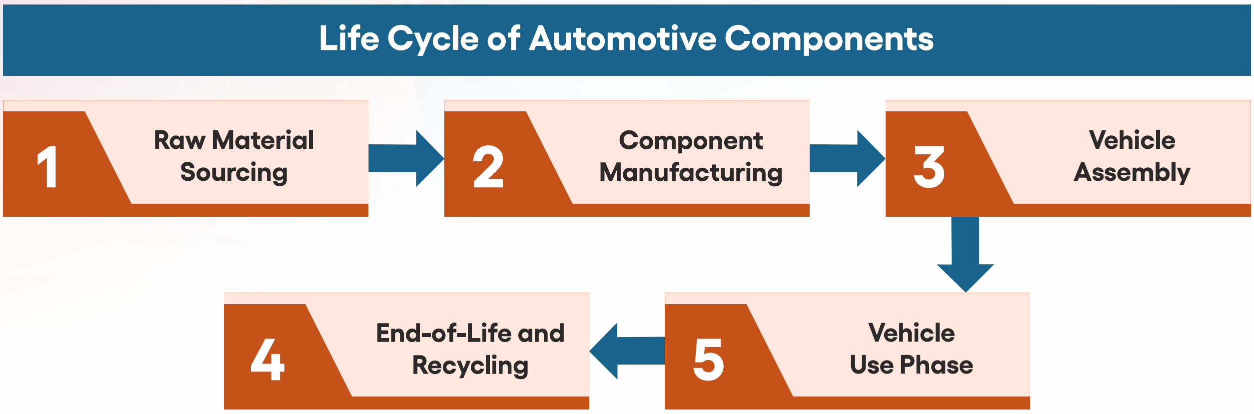
In the automotive industry, sustainable materials refer to materials selected to reduce lifecycle environmental impact while continuing to meet safety, durability, cost, and regulatory compliance requirements. The sustainability of a material is not judged solely by whether it is "green" at origin, but by how it performs across the full vehicle lifecycle, from sourcing and manufacturing to use, service, and end-of-life recovery.

In practical automotive terms, a material is typically considered sustainable when it improves one or more of the following outcomes:

- **Lower lifecycle carbon footprint,** particularly for high-mass materials such as metals and polymers
- **Higher recycled or renewable content,** without compromising quality or performance
- **Reduced toxicity and safer chemistry,** aligned with evolving substance restrictions
- **Responsible sourcing and traceability** across upstream supply chains
- **Improved circularity at end-of-life,** enabling reuse, recycling, and material recovery at scale

Common examples include recycled metals, recycled polymers, bio-based polymers, low-carbon material variants, and design-for-recycling material strategies. Importantly, sustainability in automotive materials is therefore not a single attribute, but a system-level outcome shaped by composition, sourcing, processing, use, and end-of-life behavior.

As automakers increase the use of recycled, bio-based, and low-carbon materials, the vehicle material system becomes more complex and harder to control across supply tiers. Sustainability-driven material choices made during design and sourcing often introduce new additive packages, coatings, and multi-material assemblies, many of which sit upstream and evolve over time as suppliers, processes, and alternates change. As components move through the vehicle lifecycle, from design and supplier nomination to manufacturing, service, and eventual end-of-life, material compositions can shift in ways that are difficult to track without robust governance.



3.2 Benefits of Sustainable Materials and Alignment with National and Global Goals

The adoption of sustainable materials delivers benefits across environmental, climate, and policy dimensions, but only when implemented at scale and governed effectively. From an environmental perspective, increased use of recycled and low-impact materials reduces resource extraction, lowers waste generation, and improves end-of-life recovery outcomes. High-quality material circularity also strengthens scrap quality and supports more efficient recycling systems.

From a climate perspective, material choices significantly influence a vehicle's embedded emissions. Low-carbon metals, recycled materials, and improved material efficiency can materially reduce lifecycle greenhouse gas emissions, directly supporting long-term decarbonization pathways. These outcomes align with India's national objectives, including Net Zero by 2070, the Circular Economy Action Agenda, and Mission LiFE, which emphasizes resource efficiency, responsible consumption, and sustainable production.

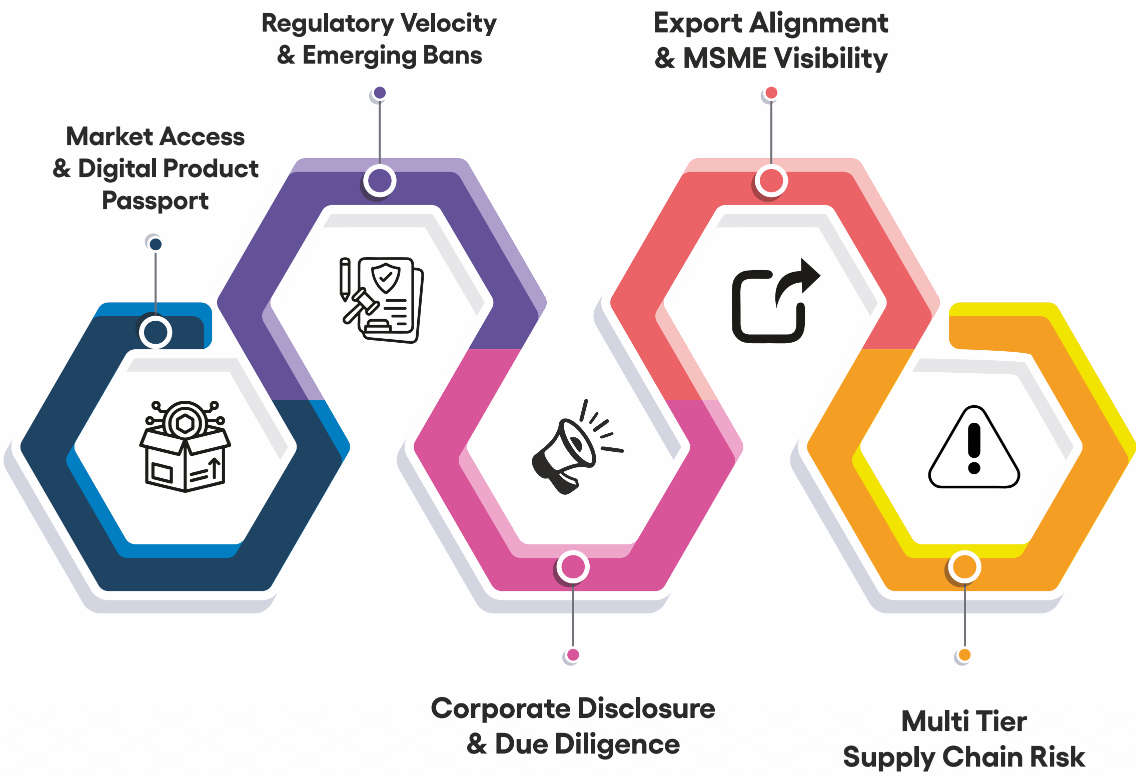
At a global level, sustainable material adoption contributes to international commitments such as the UN Sustainable Development Goals (SDGs) particularly those related to climate action, responsible consumption and production, and sustainable industrialization. However, these benefits are not automatic. Without robust material compliance, traceability, and evidence systems, sustainability claims cannot be validated, and circularity ambitions risk being undermined by contamination, hazardous substance carryover, or inconsistent recycled content quality.

Sustainable material adoption can be scaled only when OEMs can prove, through structured and auditable evidence, what is in the vehicle and how material decisions are controlled across the full lifecycle. In this context, material compliance becomes a strategic capability that underpins sustainability credibility, regulatory defensibility, circularity outcomes, and long-term competitiveness, making it an increasingly board-level issue for the automotive industry.

4 Why is automotive material compliance now a board-level issue

For the automotive industry, material compliance is no longer a narrow check on restricted substances at the part level. It is rapidly becoming a board-level issue because it now directly affects market access, legal defensibility, supply-chain continuity, and corporate disclosure credibility. The scale and complexity of the automotive sector make this problem unique. For Indian OEMs, the strategic challenge is to protect competitiveness while ensuring compliance expectations are met consistently across multi-tier supply networks.

Reasons Behind Material Compliance Becoming A Board Level Issue



4.1 Market access now needs proof, not just certificates

Across major markets, regulators are moving from intent-based rules to evidence-based compliance. Companies must be able to prove through structured data and auditable documentation what substances are present in products, where they are, and under what conditions. This changes the risk equation: if material data is incomplete or inaccurate, compliance failure becomes a practical barrier to selling into that market.

At the same time, automotive is increasingly expected to supply product-level information. The EU's Ecodesign for Sustainable Products Regulation introduces the concept of a Digital Product

Passport (DPP). DPP is a digital identity for products, components and materials that stores relevant information to support sustainability outcomes and strengthen legal compliance. [2] This is significant because it shifts compliance from "meeting requirements at approval" toward "maintaining traceable product information through the lifecycle."

In this new environment, the strategic question is no longer only whether a vehicle is compliant today, but whether the OEM and its supplier network can demonstrate compliance continuously as materials, suppliers, and designs change.

4.2 Faster regulation means earlier design and sourcing decisions

Another reason for material compliance becoming board-relevant is the speed and breadth of regulatory change is rising. Traditional models in which material restrictions are checked late in development phase or treated as documentation formality are increasingly exposed.

Per- and Polyfluoroalkyl Substance (PFAS) developments illustrate the scale of this shift. PFAS are widely used in industrial applications due to performance properties. But the regulatory direction in Europe signals increasing scrutiny and restriction potential across large categories of uses. [3] For OEMs, the implication is practical: substances that were historically managed as niche concerns can become strategic risks requiring redesign and substitution.

This creates a board-level reality: compliance risk is no longer only regulatory; it becomes an engineering and procurement timeline risk. The earlier compliance is embedded into material selection and sourcing decisions, the lower the cost and disruption of change later.

4.3 Multi-tier supply chains make failures systemic

Automotive supply chains are multi-tier and fast-moving, shaped by alternates, localization shifts, continuous cost engineering, and frequent supplier changes. OEMs typically interact directly with tier-1 suppliers, who deliver complete components or systems, while the underlying material composition of those parts is largely determined further upstream. Tier-n suppliers, primarily tier-2 and tier-3 provide raw materials, sub-components, additives, coatings, and processing inputs that ultimately define what substances and materials enter the vehicle.

Because these upstream tiers operate at a distance from the OEM, material visibility often diminishes as one move beyond tier-1. Many critical decisions, including polymer formulations, additive packages, surface treatments, and electronic material choices, are made at tier -n (tier-2, tier-3 and beyond) levels with limited direct oversight. This makes tier-n the most common point of compliance vulnerability, where declarations can weaken over time, upstream changes may go unreported, and traceability becomes inconsistent. As regulatory and customer expectations shift toward evidence-based proof, such gaps can translate into audit findings, shipment holds due to non-compliance, forced material substitutions, and program delays.

This structural challenge explains why global automotive ecosystems are moving toward interoperable, data-driven compliance models. Platforms such as Catena-X reflect this direction by enabling structured data exchange across the value chain while preserving data sovereignty for participating companies4. Although still evolving, this approach signals a decisive shift away from fragmented documents and trust-based declarations toward scalable, evidence-backed compliance systems. For Indian OEMs, the implication is clear: compliance maturity will increasingly be judged by the ability to manage tier-n material evidence at scale, rather than relying solely on internal compliance statements or tier-1 assurances.

4.4 Disclosure and due diligence are pulling compliance into reporting

Material compliance is now linked to company-level expectations on disclosure and due diligence. Firms are increasingly expected to show value-chain accountability and provide high-quality evidence data to support credible reporting and audit response. For automotive, this becomes a simple governance question: Can companies defend product and supply chain decisions using verifiable material data, clear audit trails, and documented controls?

This is not only about chemical restrictions. New product transparency expectations are also expanding to product-level sustainability data. For example, Product Carbon Footprint (PCF) ecosystems strengthen tier-to-tier data exchange discipline and improve governance of calculation methods. ? The key insight is that material compliance and sustainability disclosure are converging into the same operating requirement: evidence-grade product data, managed through lifecycle governance.

4.5 India must align globally without breaking suppliers

India's standards framework provides a domestic anchor for the compliance narrative. AIS-129 includes provisions related to End-of-Life Vehicles and, importantly, limits on heavy metals. This makes restricted substances a formal compliance requirement within India's automotive standards system. ? This creates a base for building stronger material governance that aligns with global expectations.

However, the board-level challenge for Indian OEMs is twofold. They must develop compliance capabilities that meet global norms. This requires stronger data depth, multi-tier traceability, and audit defensibility. But the compliance system also must make sure the transition is practical for the supplier ecosystem, especially tier-2 and tier-3 MSMEs. If compliance upgrades are driven only by penalties or tools, they risk reducing supplier diversity, weakening localization resilience, and increasing costs. If approached as capability building with phased readiness, they can improve both export competitiveness and domestic governance.

The board-level conclusion is therefore simple: material compliance is no longer a back-office task. It is now a strategic capability that shapes market access, program stability, and reputational protection.

5 The Automotive Material Compliance Framework

Material compliance becomes manageable only when it is treated as a system. It should have a defined scope, standardized datasets, clear responsibilities, and an auditable evidence trail rather than as ad-hoc declarations or late-stage checks. The practical objective is to ensure that every vehicle program can demonstrate at scale and across tiers that materials and substances are known, controlled, traceable, and defensible under evolving regulatory and customer expectations.

5.1 Material compliance across the vehicle lifecycle

In automotive, a component's compliance risk rarely starts only from the initial design. It is shaped by what happens after design stage, during supplier nomination, engineering changes, localization, service parts supply, and substitutions which are made to manage either cost or availability. A workable compliance framework therefore links material compliance to a lifecycle control model, not a one-time certification event, especially as product-level information mechanisms such as digital product passports expand. 2

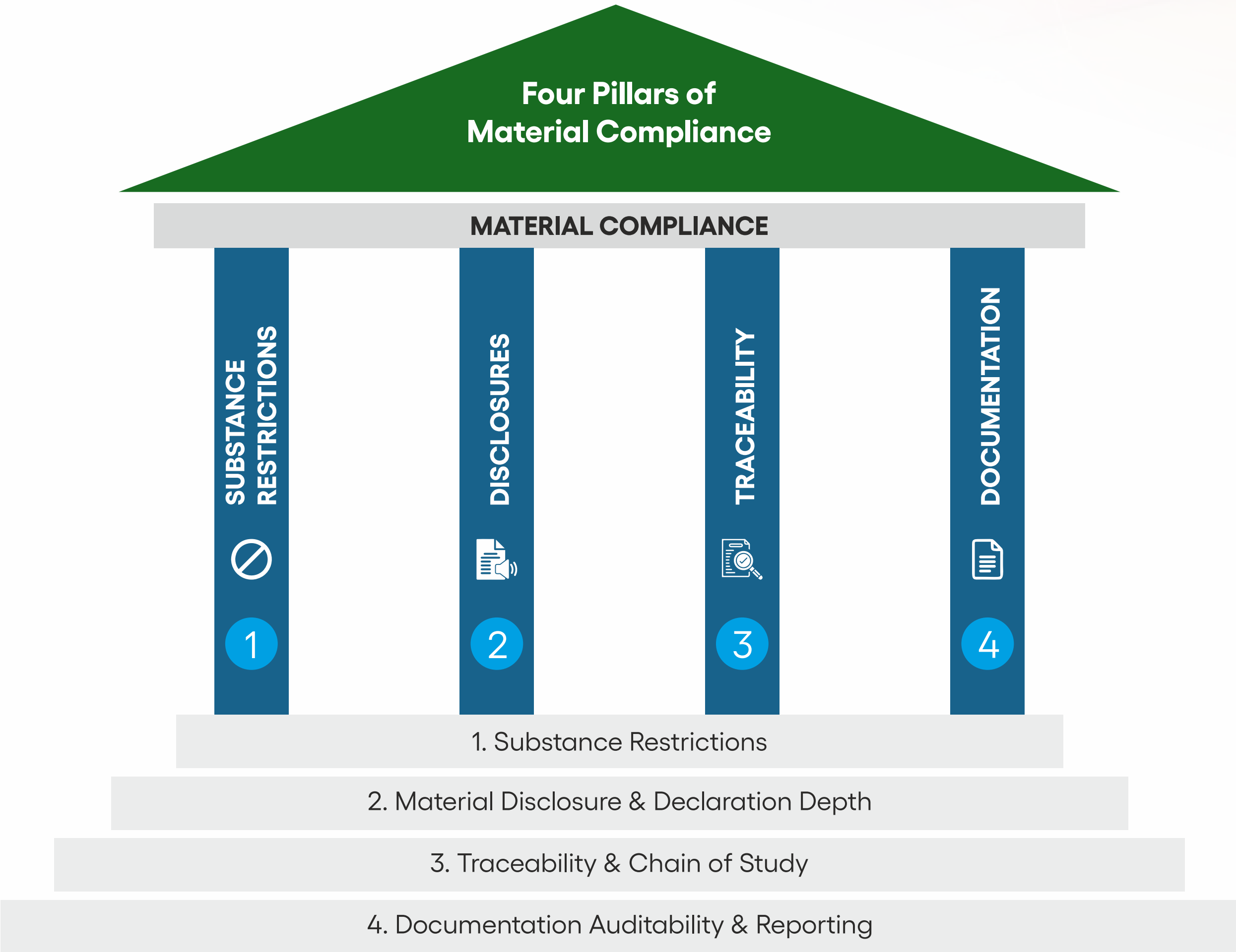
A lifecycle-based compliance model creates clarity on why each stage matters:

1. **Design & material selection (risk creation stage):** Choices on polymers, coatings, adhesives, flame retardants, plasticizers and surface treatments decide downstream restriction and reporting exposure.
2. **Sourcing & supplier nomination (data availability stage):** Requirements for compliance must be converted into enforceable commercial terms, expected disclosure depth, and evidence obligations.
3. **Industrialization and production (control and discipline stage):** Uncontrolled alternates and process changes can shift substance content; change management must trigger re-declaration and re-approval where required.
4. **Operations and service parts (persistence stage):** Documentation must remain retrievable and version-controlled over time and across service supply.
5. **Downstream information obligations (evidence stage):** Markets increasingly expect structured product information, reinforcing the shift from compliance statements to data-backed evidence.

This lifecycle framing leads to one operational conclusion: material compliance must be governed as master data, with ownership, versioning, and auditability.

5.2 The four pillars of compliance

Four Pillars of Material Compliance



Pillar 1: Substance restrictions

This pillar focuses on identifying and controlling restricted or declarable substances. Under obligations such as Article 33 in Europe, supply chains must communicate SVHC information in articles above defined thresholds. [1] These requirements matter not only because they restrict substances, but because they force the OEM to build upstream visibility and strong documentation discipline.

For OEMs, this requires a restrictions governance model built into early stages:

- Restricted substance lists integrated into engineering specifications and design standards,
- Gate checks during development,
- Supplier requirements fixed at nomination, and
- A live process to track and apply regulatory updates.

The strength of this pillar depends on how early restrictions shape sourcing decisions-not on late-stage verification.

Pillar 2: Material disclosure and declaration depth

Restrictions alone are not enough when markets and customers want visibility into material composition and traceability. This is why automotive uses standardized disclosure systems. International Material Data System (IMDS), for example, is widely used to capture material and substance composition at scale across the supply chain. ?

Disclosure governance must answer three practical questions:

- What declaration depth is required by category (e.g., polymer additives vs metallic alloys vs electronics)?
- What qualifies as evidence when confidentiality applies?
- What rules apply to changes and alternates, so declarations remain valid over time?

Global standards also support machine-readable declarations. IEC 62474 defines a framework for material declarations and links to a database of declarable substances, along with an XML schema for data exchange. ? This matters strategically because it shows the direction of travel: compliance expectations increasingly assume data can be exchanged, checked, and audited through structured formats.

Pillar 3: Traceability and chain-of-custody

Disclosure tells what is inside the part; traceability tells whether that declared data can still be trusted over time especially when substitutions happen. A defensible traceability model requires OEMs to link declared material data to:

- Specific part identifiers and revision levels,
- Supplier and manufacturing sources,
- Approved alternates and substitutions, and
- Decision records that show why and how changes were approved.

This traceability discipline is increasingly being enabled through interoperable data exchange. Catena-X is one example of ecosystem-level infrastructure being developed for cross-value-chain exchange while protecting participant data sovereignty.[4] The point is not the platform itself, but what it signals: multi-tier traceability is becoming a structural expectation, not a nice-to-have best practice.

Pillar 4: Documentation, auditability and reporting

Auditability turns compliance into a board-defensible capability. It requires evidence packs, retention rules, internal controls, supplier audit readiness, and clear accountability across engineering, purchasing, supplier quality, and compliance.

Importantly, auditability is no longer only about regulatory response. It is increasingly tied to broader corporate and product-level reporting expectations. Product Carbon Footprint (PCF) governance frameworks strengthen tier-to-tier data exchange, calculation rules, and evidence discipline.[5] This convergence is important: the same infrastructure used to defend substance compliance will increasingly support credible product-level disclosure.

5.3 Digital systems: making compliance scalable

The framework above cannot be executed reliably through manual processes. Automotive compliance is fundamentally a scale problem:

Scale of Automotive Value Chain								
Parts	X	Variants	X	Suppliers	X	Engineering Changes	X	Markets

Digital systems are therefore not an enhancement but are the infrastructure that makes compliance repeatable.

A fit-for-purpose compliance backbone should provide:

- Single source of truth for material data linked to part IDs, supplier IDs and revisions
- Workflow governance with role-based approvals and traceable decisions
- Automated validation for completeness, plausibility, and rule-based checks
- Version control and change governance, separating SOP declarations from later changes
- Interoperability capability so data exchange across tiers can be scaled in structured formats

When executed properly, this transforms compliance from a "checking activity" into an institutional capability: one that reduces audit shocks, prevents data drift, and enables faster response to regulatory change.

6 Global Benchmarking: How Mature Systems Operate

Global benchmarking is necessary to understand how material compliance is implemented in markets where enforcement is increasingly evidence-based, supply-chain expectations are mature, and product-level transparency is becoming normal. Across Europe, North America, and advanced Asian markets, compliance is increasingly treated as compliance infrastructure with standardized datasets, auditable trails, and interoperable digital systems. It is not treated as a one-time declaration.

The core lesson from global benchmarking is that "Mature systems do not rely on post-hoc checks. They build compliance as a repeatable operating system."

6.1 Regulation is moving from rules to proof

In mature markets, regulators increasingly expect compliance to be proven through verifiable product information, not through generic certificates or broad declarations. This is clear in how chemical information obligations are designed.

In Europe, Article 33 requires suppliers to share information on Substances of Very High Concern (SVHC) in articles above set thresholds. This creates an upstream obligation to identify, record, and pass substance information through the supply chain. [1] While this is often seen only as a communication rule, its real operational impact is bigger. It pushes companies to build structured internal evidence. Organizations must be able to show what they knew, what they communicated, and the basis on which it was done.

The EU's Ecodesign for Sustainable Products Regulation (ESPR) strengthens this direction through Digital Product Passports, which link product information to structured digital identities for products and components. [2] The impact on compliance is that regulators and customers are shifting from accepting "assurance" to demanding traceable data.

For automotive, this means enforcement pressure is increasingly focused on:

- Dataset integrity,
- Reproducible evidence trails, and
- Strong change-governance discipline over time.

6.2 Why IMDS became foundational

Automotive created global-scale material reporting systems earlier than most industries because vehicle complexity and regulatory exposure made them necessary. International Material Data System (IMDS) is widely used to enable structured reporting of material composition and substance data across supply chains. ?

In practice, IMDS operates as a supplier-to-OEM disclosure workflow. Each supplier builds a structured material tree for every part, capturing materials, substances, and reportable thresholds using standardized substance and material lists. These submissions are linked to part numbers and revision levels, allowing OEMs to track compliance across changes, alternates, and localization updates. OEMs then apply formal review logic accept, reject, or request correction before the data is released for program use.

What differentiates mature systems is not only the fact that IMDS is used. It is the discipline of the ecosystem around it:

- Clear declaration depth expectations,
- Validated material trees and plausibility checks,
- Formal acceptance/rejection logic, and
- Controlled governance for updates.

The benchmark insight is simple: Data quality becomes a strategic capability. OEMs that treat IMDS only as a submission workflow, without enforcement discipline, often build "compliance debt". For them declarations exist on paper but cannot stand up to audit scrutiny. Mature systems treat structured reporting as governance: suppliers are trained, validation standards are applied consistently, and acceptance depends on quality, not convenience.

6.3 Tier-n visibility: governance beyond tier-1

A key benchmark difference in mature markets is how companies manage multi-tier visibility. Leading practices accept that compliance risk often sits upstream, especially in additives, coatings, electronic assemblies, and process chemicals. These are usually at tier-2 or tier-3 levels.

Mature ecosystems therefore put in place:

- Supplier segmentation by risk and maturity,
- Declaration depth rules by component type,
- Enforceable compliance clauses in contracts,
- Audit routines for high-risk materials and suppliers, and
- Engineering change triggers force re-declaration.

In practice, mature systems do not assume tier-n visibility is perfect. Instead, they build operational control loops that reduce the chances of unknown risks staying hidden. Compliance is treated as a managed risk system.

6.4 Interoperability: toward ecosystem data exchange

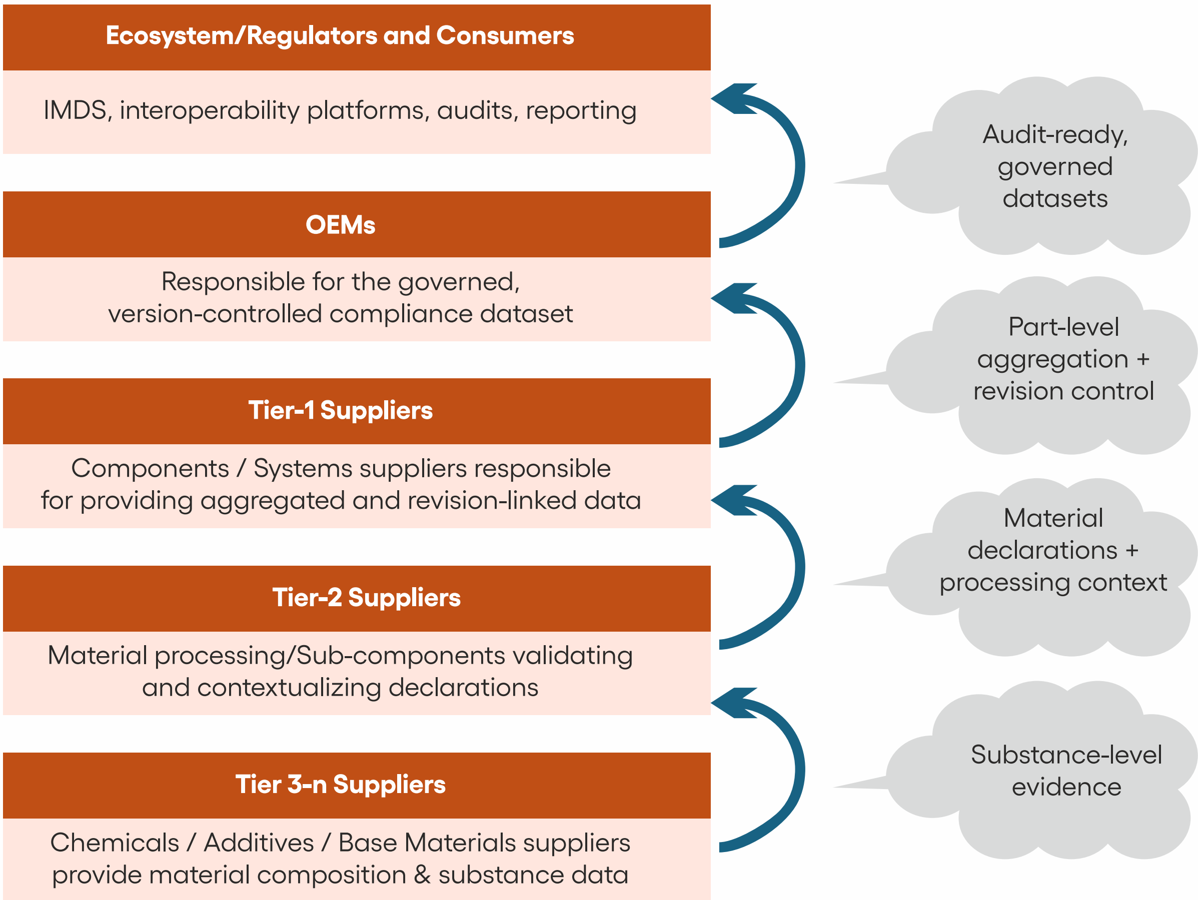
The next benchmark frontier is interoperability. Compliance is moving away from isolated tools and toward multi-party exchange networks, where data can be shared securely and selectively across supply chains.

Catena-X shows this direction: an ecosystem model for cross-value-chain data exchange while keeping data sovereignty and standardization intact. ? These ecosystems are still evolving, but they reflect a clear shift: compliance is increasingly seen not as internal paperwork, but as shared supply-chain infrastructure.

For material compliance, interoperability matters because:

- Tier-n data cannot scale through manual evidence exchange,
- Change management needs updated data flows across partners, and
- Audits increasingly demand traceability across parties.

Tier-n to OEM Data Flow for Automotive Material Compliance



This benchmark is critical for India: even if adoption happens in phases, compliance frameworks should be designed so they can connect to such ecosystems when needed-especially for export programs.

6.5 PCF is linking compliance and sustainability reporting

Material compliance is increasingly linked with product-level sustainability reporting. Product Carbon Footprint (PCF) initiatives strengthen the same discipline needed for chemical compliance: controlled datasets, tier-to-tier evidence exchange, and governance of calculation integrity.

Catena-X PCF governance reflects the global direction: credible reporting increasingly needs not only carbon numbers, but proof of how those numbers were calculated and under what rules. ? This convergence matters because it expands the compliance from "restricted substances" to credible product-level disclosure. For OEMs, it means the same infrastructure used for substance compliance will also support broader reporting credibility and export requirements.

6.6 Emerging restrictions: compliance must be proactive

A major differentiator in mature systems is proactive handling of emerging restrictions. Companies build horizon scanning, structured screening, and substitution planning into compliance governance. The reason is simple: late identification of upcoming restrictions often leads to expensive redesigns and supply disruption.

PFAS (Per- and Polyfluoroalkyl Substance) is a strong example of substance-class risk governance. As policy action grows and restrictions tighten, organizations are being pushed to identify PFAS exposure early, map use cases in a structured way, and plan substitutions that align with platform cycles. [3]

Compliance is becoming an anticipatory capability, not a reactive function.

Comparative Assessment of Global Automotive Material Compliance Systems and Indian Standards

Dimension	International Material Data System (IMDS)	Catena-X	Indian Standards (CMVR /AIS framework
Core focus	Material composition and restricted/declarable substances	End-to-end data interoperability (materials, PCF, traceability, diligence)	Conformance to notified standards and rules
Supply chain coverage	Supplier OEM (primarily ter-1, with upstream dependency)	Multi-tier (tier-n) value chain participation by design	Largely OEM and tier-1 centric
Tier-n visibility	Indirect; depends on supplier discipline and declaration depth	Explicit objective; designed to enable tier-n visibility	Not explicitly defined or enforced
Data structure	Standardised material trees and substance lists	Standardised data models with interoperability principles	Predominantly document- and certificate-based
Change management	Managed through part revisions and re-submissions	Designed for continuous updates across ecosystem participants	Change tracked mainly through type approval and internal OEM processes
Auditability	Strong when data quality and validation are enforced	Strong by design through traceable, shared datasets	Varies; depends on internal OEM documentation
Link to sustainability	Indirect; material data can support sustainability analysis	Direct, PCF, traceability, and circularity use cases built-in	Emerging; limited explicit linkage
Regulatory alignment	Strong alignment with global chemical regulations	Designed to support evolving global regulatory and reporting needs	Anchored in domestic regulations (CMVR, AIS)

7 Indian Automotive Material Compliance Landscape

India's automotive material compliance landscape is at an inflection point. The regulatory building blocks exist through CMVR type approval and AIS standards, but system-level execution across multi-tier supply chains remains uneven. The priority is to strengthen compliance capability in a way that supports exports and domestic trust while remaining feasible for India's supplier ecosystem.

7.1 Policy and standards: the anchor exists

India's vehicle regulatory system is anchored in the Central Motor Vehicles Rules (CMVR) and supported by Automotive Industry Standards (AIS) through the type approval framework. ? This structure sets a clear principle: vehicles must meet defined regulatory requirements at the approval stage, supported by certified processes and test agencies.

Within this framework, AIS-129 is especially relevant for material compliance because it provides a direct anchor for restricted substances, including requirements linked to heavy metals.? While AIS-129 is often discussed mainly in the end-of-life vehicle context, it also signals something bigger: India's standards system already reflects the expectation that substances and materials must meet defined restrictions and compliance conditions.

The key implementation question is not whether this anchor exists. It is whether the compliance evidence system: supplier declarations, data depth, traceability, and audit readiness, can be executed consistently across the supply chain

7.2 Exports set the compliance bar

Indian OEMs operate in a dual compliance environment:

- Domestic AIS / CMVR anchored requirements, and
- Export market expectations, especially in Europe and global OEM supply chains.

Export programs increasingly demand structured material disclosure and compliance evidence, often through systems such as IMDS.[6] Even if domestic enforcement does not always require the same level of structured digital evidence, export programs often do because compliance is treated as proof-backed capability, not a declaration.

This creates a structural reality for Indian OEMs: global expectations become the highest standard, and compliance maturity in export programs becomes a leading indicator for future domestic needs.

In practice, this means compliance governance cannot remain split. The compliance "engine" built for export programs becomes the template for ecosystem-wide maturity across domestic supply chains as well.

7.3 Governance: execution depends on operating systems

India's institutional compliance framework is supported by MoRTH notifications, AIS standards development, type approval authorities, and test agencies. However, material compliance is not delivered only through regulation. It is delivered through operational governance systems, such as:

- Engineering standards and material specifications,
- Procurement requirements and contractual enforceability,
- Supplier quality programs and audits, and
- Change control routines linked to re-declaration expectations.

This is where the governance challenge appears. Automotive material compliance is cross-functional. If engineering, purchasing, supplier quality, and compliance do not work through a single evidence system, material compliance becomes fragmented especially across complex platforms and high-change categories.

Therefore, India's compliance maturity is shaped not only by regulatory ambition, but by how effectively the ecosystem executes:

- Declaration discipline,
- Traceability across tiers, and
- Audit defensibility

7.4 Supply chain maturity is "two-speed"

India's supplier ecosystem is best described as two-speed:

Export-linked and large suppliers (higher maturity)

Large tier-1 suppliers and export-linked programs often have structured reporting discipline. This includes stronger documentation practices, trained compliance personnel, and structured declaration workflows, including IMDS readiness. ?

Tier-2/3 and MSME-heavy supply chains (uneven maturity)

Many tier-2/3 suppliers face limits in digitization, training, documentation, and structured data governance. This leads to inconsistent declaration depth, weaker evidence packs, and limited readiness for audits and regulatory updates. The issue is often not intent, but feasibility: limited resources, limited tools, and uneven interpretation of requirements.

The compliance risk is systemic: even when tier-1 submissions exist, tier-2/3 inputs may be weak, creating data credibility gaps. This is the same mode of global failure: compliance systems break when tier-n visibility and evidence discipline are not structurally supported.

7.5 New material shifts are raising complexity

India's automotive industry is not only scaling in volume but also shifting rapidly in material complexity.

- **Smart and engineered materials increase compliance complexity**

  As vehicles adopt more engineered polymers, specialized additives, coatings, and functional materials, compliance becomes harder because restricted or declarable substances often sit inside additive packages, not the base material category. Research on polymer systems shows how additives drive functionality and performance, while increasing complexity for substance governance.[18]

- **Lightweighting increases material change velocity**

  Lightweighting trends push substitution from traditional metals toward polymers, aluminium alloys, composites, and multi-material designs. These shifts can improve efficiency, but they increase material variability and supplier churn. Lifecycle studies on lightweighting highlight the need to manage trade-offs carefully through a compliance lens, this means stronger declaration depth, traceability, and change governance.[17]

- **Bio-based and sustainable materials create new diligence requirements**

  As bio-based materials enter vehicle interiors and parts, the compliance question shifts from "is it sustainable?" to "is it traceable and defensible?" Bio-based sourcing can introduce variability in inputs and processing aids, increasing the need for controlled declarations and long-term evidence retention.

8 Industry Practices in Automotive Material Compliance

Material compliance is not achieved through standards alone. It is achieved through operating models:

- How OEMs set governance,
- How suppliers are enabled and controlled,
- How engineering changes are handled, and
- How data quality is enforced at scale.

In mature organizations, compliance is cross-functional by design. It connects engineering intent, purchasing controls, supplier execution, and audit-ready evidence retention.

The global benchmark insight is clear: strong compliance regimes build compliance into the product lifecycle and supplier governance, instead of treating it as a late-stage documentation task.

8.1 How OEMs run compliance

Effective OEM operating models treat material compliance as an enterprise control system, with clear accountability across functions. The compliance function typically sets requirements and risk frameworks, but real execution depends on controls embedded in engineering, purchasing, supplier quality, and manufacturing.

A key differentiator is change governance. In automotive, substitutions and revisions are unavoidably driven by cost, localization, availability, and platform changes. If engineering change management does not trigger compliance checks and re-declaration, compliance becomes assumed, not proven.

Research on automotive part change management shows how complex the change environment is, and why structured governance is needed to prevent data drift and uncontrolled alternates.[1]? In compliance terms, the lesson is operational: the strength of the compliance system is shaped less by what is declared at SOP, and more by how deviations are managed after SOP.

Therefore, mature OEM models typically put in place:

- A compliance framework embedded in engineering standards,
- Procurement controls that convert requirements into enforceable supplier obligations,
- Supplier quality routines to verify compliance processes, and
- Evidence retention rules for audit readiness.

8.2 Supplier enablement and data control

Mature material compliance practices do not assume every supplier is equally ready. Instead, they segment suppliers based on:

- Material and component risk (e.g., coatings, polymers, electronics),
- Export exposure,
- Supplier maturity and systems capability, and
- Change volatility

A strong engagement approach balances enforceability with enablement. Compliance demands without supplier capability often lead to low-quality declarations, delays, or supply disruption. In contrast, staged requirements with training and clear guidance improve both supplier retention and compliance depth.

In practice, well-executed OEMs typically establish:

- Standardized compliance onboarding for suppliers,
- Documented declaration depth expectations by category,
- Supplier training programs (especially for tier-2/3), and
- Targeted audits for high-risk categories and suppliers

This is especially important for India because supplier ecosystem viability is strategic. Compliance maturity must be built as a capability upgrade pathway, not as a punitive barrier.

8.3 IMDS data quality: what works

IMDS is now a foundational mechanism for structured material and substance reporting across automotive supply chains. ? But its effectiveness depends entirely on data quality governance. IMDS submissions that exist but lack correct structure, depth, or plausibility often fail audits, creating compliance debt instead of reducing risk.

Mature ecosystems enforce data quality through:

- Clear acceptance criteria and rejection reasons,
- Validation checks for completeness and plausibility,
- Supplier guidance and training, and
- Feedback loops that steadily improve submission quality

OEM rulebooks and supplier guidance show how this discipline is applied in practice. Supplier rejection guides and structured data-entry standards define what counts as acceptable declarations, how common errors are handled, and how "template compliance" is avoided where composition is oversimplified or masked without proper controls.[11 12]

IMDS is not just a tool. It becomes an ecosystem operating standard only when OEMs enforce:

- Declaration depth expectations,
- Realistic material trees, and
- Consistent rejection of low-quality submissions

Without this discipline, IMDS adoption can increase risk by creating a false sense of compliance while evidence quality remains weak.

8.4 Beyond IMDS: interoperable ecosystems

IMDS mainly supports structured disclosure of substances and material composition. But emerging global practice is pushing beyond single reporting databases toward interoperable ecosystems. Compliance is moving toward multi-party evidence infrastructure, where data can be shared across entities without exposing confidential information.

Catena-X reflects this direction. It is an ecosystem approach designed to enable interoperable data exchange across the automotive value chain while protecting data sovereignty. ? This matters for compliance because the hardest challenges: tier-n visibility, traceability across alternates, and audit defensibility cannot scale through manual document exchange.

The strategic conclusion for OEMs is practical: even if IMDS remains the core reporting tool, the ecosystem must move toward interoperability principles, so compliance evidence can scale efficiently across multi-tier networks.

9 Key Challenges in Implementing Material Compliance

The practical question for India's automotive ecosystem is why execution remains difficult even when intent is clear. Across markets, failure is rarely caused by missing standards. It happens because material compliance depends on multi-tier data, change discipline, and audit-grade evidence and these break under scale, complexity, and uneven supplier capability.

This section outlines the main execution bottlenecks that OEMs and suppliers must solve to move from compliance intent to compliance infrastructure.

Key Challenges in Implementing Material Compliance

- **A** Tier-n Visibility Limits
- **B** Data Quality Failures
- **C** MSME Capability Gaps
- **D** Regulatory Change, Audits & Trust Deficits

9.1 Tier-n visibility is hard to sustain

Automotive supply chains are multi-tier by design. Chemical composition, additives, coatings, and processing aids are often decided several tiers upstream from the final component supplier. As a result, OEMs often rely on tier-1 declarations that are only as strong as tier-2/3 inputs. When upstream information is missing or inconsistent, compliance becomes "best effort" instead of a defensible control.

Research on multi-tier transparency in automotive-related supply chains shows that building transparency is difficult even with active interventions. Mapping and auditing can improve visibility, but it is complex work and hard to sustain without institutional routines and structured data systems.[1]? The material compliance implication is direct: tier-n visibility must be built into supplier governance using standardized data exchange, not treated as an occasional audit activity.

In practice, the biggest tier-n breakdowns happen in high-variation areas like polymers and masterbatches, coatings, adhesives, and electronic assemblies. These are the points where formulations change often, confidentiality is common, and supplier networks shift. Without clear declaration depth rules, change triggers, and supplier discipline, tier-n visibility collapses under normal commercial change.

9.2 Weak validation creates systemic data problems

Once a reporting mechanism exists (for example, IMDS workflows), the next bottleneck is data quality. It includes incorrect classifications, generic material trees, unrealistic weights, and the frequent use of placeholders that pass submission requirements but fail audit defensibility.

This is why mature ecosystems treat validation as governance, not clerical checking. IMDS quality guidance follows this logic: warnings are signals that require review, and acceptance/rejection practices must be disciplined so weak declarations do not become embedded across the supply chain.[19] If low-quality submissions are accepted to "keep programs moving," compliance debt builds up and later becomes audit risk, redesign pressure, or supplier disruption.

In India, this challenge becomes bigger due to uneven supplier digitization. If tier-2/3 suppliers lack trained staff and standard declaration practices, the quality burden shifts upward to tier-1 or OEM teams creating bottlenecks, rework cycles, and inconsistent outcomes across programs and OEMs.

9.3 MSME capability and cost constraints

Material compliance requires trained people, tools, documentation discipline, and time. In MSME-heavy ecosystems, this capability is often limited. Empirical work on company size and REACH compliance capability shows that smaller firms are more likely to lack systems and tools to manage requirements, and they often rely on upstream suppliers to understand chemical composition and impacts. This is exactly the dependency that weakens tier-n visibility.[15]

For India, the implication is both strategic and operational. If compliance is implemented mainly as a mandate meaning "submit declarations or lose business", the transition may push sourcing toward a smaller set of digitally mature suppliers. This can raise costs and weaken localization resilience. A sustainable pathway needs capability-building at the base: shared rulebooks, training, low-cost tool options, and phased adoption. This will make sure that compliance upgrades do not become a supplier continuity risk.

9.4 Change, audits, and trust gaps

Even when a baseline system exists, two forces repeatedly destabilize it: regulatory change and audit pressure. New restrictions require controlled updates to restricted/declarable substance lists, supplier requirements, and evidence packs. Without strong versioning and change governance, organizations cannot answer audit-critical questions: What was declared at SOP? What changed later? Who approved it?

Interoperability adds another execution layer. As global ecosystems move toward multi-tier data exchange, the challenge shifts from managing a single tool to securely connecting datasets across parties. Catena-X and other interoperability demonstrations show that cross-ecosystem data exchange is increasingly possible, but it requires technical systems, governance standards, and trust foundations to operate at scale.[13]

Industry research also highlights a persistent trust gap: OEMs and suppliers often do not fully trust one another's data, weakening sustainability and compliance initiatives that depend on credible reporting.[1]? This gap is practical, not theoretical. This shows up in supplier disputes, audit escalations, and slow correction cycles.

For India's OEMs and suppliers, the takeaway is clear: These bottlenecks are not isolated issues. They are system characteristics. Building material compliance capability therefore requires parallel action on tier-n visibility, data quality governance, supplier capability, and interoperable evidence trails.

9.5 ELV and Material Circularity

End-of-Life Vehicles (ELV) and material circularity present a growing challenge for the automotive industry as material complexity increases faster than recycling and recovery systems can adapt. Modern vehicles contain a wide mix of metals, polymers, composites, coatings, and additives, often sourced across multi-tier supply chains. Without robust material compliance covering composition, substance restrictions, and traceability vehicles reach end-of-life with limited visibility into what they contain. This undermines the ability of dismantlers, recyclers, and regulators to manage ELV safely and efficiently at scale.

Material compliance is directly linked to scrap quality, which is the foundation of effective circularity. High-quality recycling depends on predictable, contamination-free material streams. When material composition is poorly documented or upstream substitutions are not traceable, recycled scrap risks being downgraded, rejected, or diverted to low-value applications. Inconsistent compliance data leads to mixed or contaminated scrap, reducing recovery rates and weakening the business case for using recycled materials in new vehicles.

Compliance is equally critical for controlling hazardous substances and enabling safe use of recycled content. Restricted or legacy substances embedded in vehicles can re-enter material loops if not identified and managed properly, creating regulatory, environmental, and reputational risks. As OEMs increase recycled and bio-based content, sustainable material control becomes more complex, not less. Effective circularity therefore depends on compliance systems that can track materials across lifecycles, ensuring that recycled inputs are safe, compliant, and suitable for high-value automotive applications rather than becoming a barrier to circularity ambitions.

10 Way Forward: Strengthening Automotive Material Compliance in India

The next phase of material compliance in India must be positioned as an industry readiness and competitiveness agenda, not only as a regulatory response. The practical goal is to build a capability that is:

(i) Export-aligned and audit-defensible,

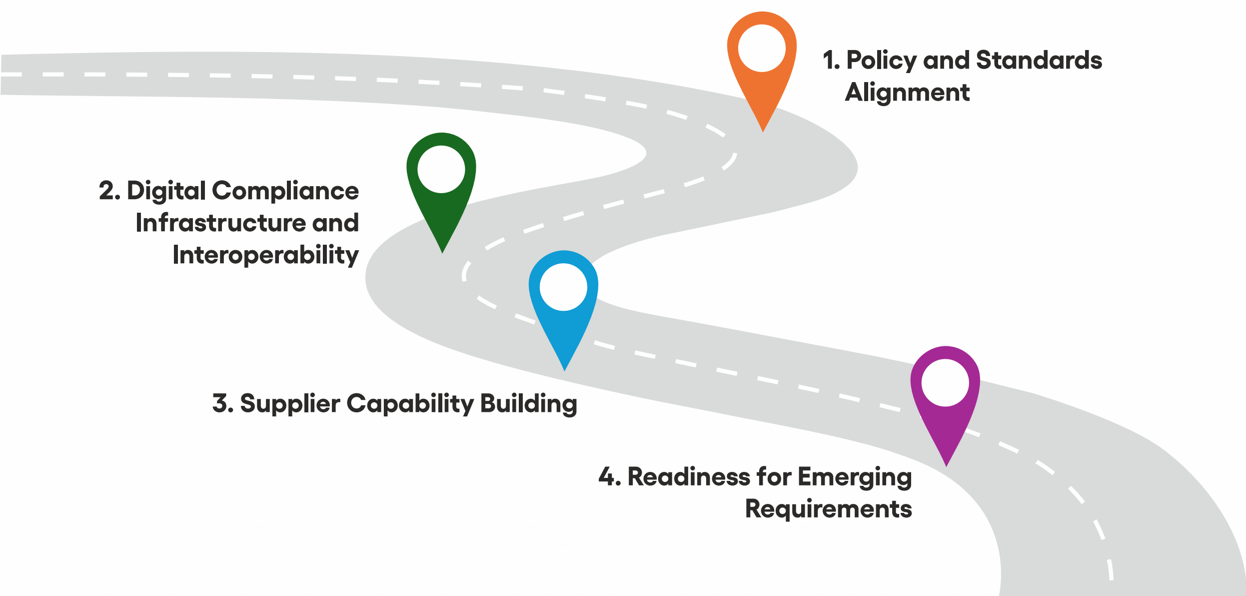
(ii) Digitally governed and scalable across tiers

(iii) feasible for India's supplier ecosystem especially tier-2/3 MSMEs

This requires a roadmap that balances ambition with implementation realism.

A practical way forward can be structured around four reinforcing pillars: policy alignment, digital infrastructure, supplier capability, and readiness for emerging requirements. These are delivered through phased rollout with clear accountability across OEMs and supply chain partners.

Way Forward: Strengthening automotive Compliance in India



10.1 Policy and standards alignment priorities

India does not need a new intent narrative. It needs clearer interpretation and consistent execution guidance so OEMs and suppliers can implement requirements predictably across programs.

Priority actions (high feasibility):

1) Standardize interpretation of material compliance requirements

A common friction point is inconsistent interpretation across OEMs about what counts as acceptable disclosure depth, what evidence is sufficient, how confidentiality is handled, and when re-declaration is triggered. The near-term need is of aligned guidance that converts standards into clear supplier expectations.

2) Operationalize AIS-129 substance restriction expectations through evidence discipline

AIS-129 provides a compliance anchor, including restrictions on heavy metals.? The implementation focus must be turning this intent into evidence discipline: traceable declarations, consistent documentation, and retained approvals through engineering and supplier changes.

3) Define a Minimum Material Compliance Dataset (MMCD) for India

An MMCD creates a baseline of what every supplier must provide: material category, declarable substance presence/absence, market-relevant compliance flags, evidence references, and change history. Evidence-based systems increasingly depend on standardized datasets, not unstructured documents.[27]

Looking from a feasibility lens these actions are mainly alignment and standardization. They are low capex, fast to implement, and highly effective in reducing rework, inconsistent expectations, and audit friction.

Stakeholders, Compliance Mandate, and Regulatory Interfaces in Automotive Material Compliance

Stakeholder	Typical Compliance Status	Primary Roles in Material Compliance	Relevant Regulatory/ Institutional Bodies
OEMS	Ultimately accountable for vehicle-level compliance	Define compliance requirements and disclosure standards, Govern tier-n traceability and evidence retention, Defend compliance across audits and markets	Ministry of Road Transport and Highways (MoRTH), Type Approval framework, Export regulators
Suppliers (Tier-1 to Tier-n)	Uneven maturity across tiers	Provide material, substance, and process. data, Control restricted substances and material changes, Support traceability and re-declaration obligations	OEM contracts, Chemical regulations, IMDS governance
Recyclers/ ELV Operators	Limited upstream material visibility	Dismantle vehicles and recover material streams, Manage hazardous substances during ELV processing, Influence scrap quality and recycling outcomes	Central Pollution Control Board (CPCB), SPCBs, ELV regulations
Regulators, Policymakers, Auditors & Approval Agencies	Oversight, enforcement, and verification authority	Define compliance, ELV, and reporting requirements, Conduct audits, conformity assessment, and approvals, Enforce compliance and enable market access	MoRTH, CPCB, Type Approval Agencies, Certification bodies.
Industry Bodies & Ecosystems	Facilitators and capability enablers	Develop guidance, frameworks, and interpretations, Enable capability building and supplier readiness, Promote Interoperability and industry alignment	Society of Indian Automobile Manufacturers (SIAM), Global platforms

10.2 Digital compliance infrastructure and interoperability

India's execution gap is not awareness. It is the lack of system-level digital governance that can survive scale and tier-n variation. This does not require a national IT platform immediately. It requires building a compliance backbone aligned with global direction.

Recommended digital roadmap:

1) Strengthen OEM internal compliance data governance

Each OEM should maintain a controlled repository of material declarations and evidence packs, linked to part IDs, revision history, and supplier/manufacturing sources. This is the minimum requirement for audit defensibility, reproducibility, and controlled change.

2) Apply IMDS systematically where it delivers maximum value

IMDS remains the global backbone for structured material/substance declarations.? A practical approach is risk-based:

- Enforce IMDS discipline in export programs and high-risk categories like polymers, coatings, electronics & interiors
- Use simplified but structured templates for low-risk domestic categories during transition.

3) Design toward interoperability

Global practice is shifting from isolated tools to interoperable ecosystems. Catena-X reflects this trend: structured cross-value-chain data exchange while protecting data sovereignty.? Even if adoption is phased, India's datasets and governance should be designed to remain compatible with such principles, enabling future integration.

It is important to look at this step from a feasibility lens:

- OEM repositories are highly feasible: governance-led, process-driven.
- Interoperability is medium-term and investment-linked, best piloted first with export-critical suppliers and high-risk categories.

10.3 Supplier capability building

Supplier capability is the biggest success factor. A roadmap that ignores tier-2/3 realities will cause compliance disruption, supplier exits, and localization risk, hurting cost competitiveness and resilience.

A feasible capability-building program should include three components:

1) Tiered compliance maturity model

Avoid one compliance threshold. Use staged readiness:

- Level 0: basic MMCD compliance via templates
- Level 1: Structured declarations + evidence retention
- Level 2: IMDS competent, audit-ready, change-managed
- Level 3: interoperability-ready (data space aligned)

This avoids creating a "digital cliff" for MSMEs.

2) Standardized training and playbooks

Fast maturity gains come from structured enablement:

- Material tree construction and declaration discipline
- Common rejection causes and corrective routines
- Confidentiality handling (masked substances with governance)
- Standard change triggers requiring re-declaration and approval

Evidence from REACH compliance capability studies shows smaller firms often lack systems/tools to manage requirements.[1]? Upgrading must therefore be enabled not assumed.

3) Shared support mechanisms

To reduce burden:

- Pooled training hubs in supplier clusters
- Shared interpretation repositories and templates
- Low-cost tooling pathways for structured readiness

Supplier upliftment is feasible if staged and enablement led. It reduces compliance shock and strengthens the base ecosystem instead of concentrating supply among a few large suppliers.

10.4 Readiness for emerging requirements

India must prepare for two emerging pressure categories:

(i) Substance-class governance and anticipatory restriction management

PFAS shows how regulation is moving from substance-level bans to substance-class governance and use-case controls.[3] OEMs need horizon scanning and substitution planning built into engineering and procurement, so restrictions do not create platform-scale disruption.

(ii) Integration with product-level disclosures and PCF discipline

Material compliance is converging with product sustainability disclosure. Product Carbon Footprint (PCF) systems reinforce the same operational requirements: tier-to-tier evidence exchange and governance of calculation integrity.? Even if PCF is not mandatory immediately, the foundational readiness, data quality, traceability, and versioning is the same.

Short-term feasibility of this initiative is moderate with a need of building capability, but medium-term feasibility becomes high once MMCD discipline, IMDS governance, and change control are institutionalized.

10.5 Phased implementation plan

A staged rollout is essential to ensure feasibility and avoid supply disruption.

1. Phase 1 (0-6 months): Foundation (high feasibility)

- Define MMCD and standard templates
- Standardize evidence pack formats and documentation rules
- Strengthen OEM repositories (versioning and retention)
- Pilot supplier segmentation in limited-scope programs

2. Phase 2 (6-18 months): Scale (medium feasibility)

- Expand supplier uplift programs (training + shared support)
- Embed standard change triggers for re-declaration
- Mandate IMDS for export programs and high-risk categories[6]
- Institutionalize audit readiness routines in supplier management

3. Phase 3 (18-36 months): Advanced readiness (selective feasibility)

- Run interoperability pilots with export-critical suppliers[4]
- Harmonize datasets toward global exchange principles
- Implement restriction watchlists and substitution roadmaps[3]
- Align evidence discipline to PCF-ready reporting where required[5]

Conclusion: feasibility and competitiveness

India can strengthen material compliance without destabilizing suppliers if implementation is staged, risk-based, and enablement-driven. For OEMs, this roadmap reduces export risk, strengthens audit defensibility, and improves supply-chain discipline turning material compliance from a recurring disruption into a long-term competitive capability.

Endnotes

1. European Chemicals Agency (ECHA). Candidate List of Substances of Very High Concern (SVHC) for Authorization. (REACH Regulation (EC) No 1907/2006-Article 33 communication duties).
2. European Union. Regulation (EU) 2024/1781 establishing a framework for setting Ecodesign requirements for sustainable products (ESPR) and provisions for Digital Product Passports. Official Journal of the European Union.
3. European Chemicals Agency (ECHA) / European Commission. PFAS restriction proposal and related policy developments under REACH.
4. Catena-X Automotive Network. Catena-X ecosystem documentation: data space, interoperability principles, and data sovereignty approach.
5. Catena-X (PCF Rulebook / Governance). Product Carbon Footprint (PCF) methodology, data exchange governance and reporting requirements within Catena-X.
6. International Material Data System (IMDS). IMDS Information Pages / IMDS Recommendation & IMDS Guidelines for material and substance reporting in the automotive supply chain.
7. International Electrotechnical Commission (IEC). IEC 62474: Material declaration for products of and for the electrotechnical industry-Declarable substance list, database, and XML schema.
8. Automotive Industry Standards (AIS). AIS-129: End-of-Life Vehicles (ELV) requirements and restricted substances / heavy metal restrictions. (Type approval-linked compliance expectation).
9. Government of India (MoRTH). Central Motor Vehicles Rules (CMVR) and type approval regulatory framework; MoRTH notifications relevant to vehicle approval and standards compliance.
10. Academic / industry research on automotive change management. Studies on part change management complexity and governance requirements in automotive manufacturing and supply chains.
11. OEM / industry IMDS supplier guidance documents. Supplier rejection logic, submission quality requirements, and common error guidance for IMDS declarations.
12. IMDS / OEM structured data-entry rules. Guidelines defining acceptable declaration depth, material tree structure, and prevention of template/placeholder compliance.

13. Catena-X interoperability pilots / demonstrations. Cross-company data exchange demonstrations for compliance-related use cases (traceability / evidence exchange / PCF).

14. Academic literature on multi-tier transparency in automotive supply chains. Studies on supply chain mapping, sustainability transparency, and challenges of maintaining multi-tier visibility.

15. Academic literature on SME/firm size and chemical compliance capability under REACH. Evidence on capability constraints, tool gaps, and reliance on upstream information among smaller firms.

16. Industry/academic research on trust deficits in OEM-supplier transparency reporting. Work highlighting misaligned incentives, limited data confidence, and reporting disputes in multi-tier supply chains.

17. Lifecycle assessment literature on lightweighting trade-offs. Studies on lightweighting, material substitution, and lifecycle impacts relevant to compliance and governance needs.

18. Polymer/additives research. Studies showing how additive packages influence polymer performance and increase complexity in substance governance.

19. IMDS quality and validation guidance. IMDS recommendations on warnings, plausibility checks, validation logic, and disciplined acceptance/rejection practices

SIAM
Society of Indian Automobile Manufacturers

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Society of Indian Automobile Manufacturers (SIAM)
Core 4-B, 5th Floor, India Habitat Centre, Lodhi Road, New Delhi – 110003, India
Phone: +91-11-24647810-12, 47103010 | Fax: +91-11-24648222 | E-mail: siam@siam.in
Website: www.siam.in

Social Media Handles siamindia siam SIAMIndia1 siamindia siamindia9379