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Formaldehyde Emission from Passenger Vehicle Interior Materials: Sources, Release Dynamics, and Formaldehyde-Free Alternatives

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Abstract. Passenger-vehicle cabins contain a large exposed material area within a small air volume, so emissions from seats, carpets, headliners, dashboards, door trim, seals and adhesives can accumulate when ventilation is limited. This paper examines how interior-material composition and manufacture determine formaldehyde formation, migration and release, and whether nominally formaldehyde-free alternatives can be regarded as low-emitting throughout service life. A structured secondary-data synthesis was developed around source chemistry, the initial emittable concentration (C_0), material-phase diffusion coefficient (D_m), material-air partition coefficient (K), environmental conditions and ageing. Published chamber and vehicle studies show that temperature strongly changes emission parameters and cabin concentration, while multilayer construction and concealed adhesive layers complicate source attribution. Field evidence further shows that formaldehyde concentration is not described adequately by a single universal release period: early depletion can be followed by slower diffusion, humidity-sensitive hydrolysis, thermal reactivation or secondary formation. Formaldehyde-free preparation routes include isocyanate, polyurethane, epoxy, polyvinyl acetate, hot-melt and bio-based adhesive systems, but replacing formaldehyde as a feedstock does not establish zero lifetime emission. The most defensible evaluation therefore distinguishes formaldehyde-based, low-formaldehyde, no-added-formaldehyde and below-detection claims, and combines formulation disclosure, standardised emission testing and heat/humidity ageing. The evidence supports a condition-specific, mechanism-based description of vehicle formaldehyde emissions rather than a fixed release cycle.

Keywords: formaldehyde, passenger vehicle, interior materials, VOC emissions, diffusion

1. Introduction

Passenger-vehicle cabins are compact microenvironments with a high ratio of exposed material area to air volume. When a vehicle is parked with the windows closed, low air exchange and solar heating can increase the concentration of volatile organic compounds (VOCs) released from seats, carpets, headliners, dashboards, door panels, sealants and adhesives. Formaldehyde deserves particular attention because it may be present as a residual manufacturing chemical, regenerated by

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hydrolysis, produced by thermo-oxidative degradation, or formed secondarily from other emitted VOCs. At the same time, the characteristic odour of a new vehicle is not direct evidence of formaldehyde because aromatic hydrocarbons, alkanes, esters and other aldehydes may coexist in cabin air [1-3].

Interior components are chemically and structurally heterogeneous. A seat may combine polyurethane foam, textile or leather, coatings and lamination adhesives; a headliner or carpet may include fibres, polymer backing and bonding layers; dashboard and door-trim assemblies may contain polypropylene, acrylonitrile-butadiene-styrene, polyvinyl chloride, thermoplastic polyurethane or fibre-reinforced composites. Consequently, formaldehyde detected above a visible component cannot automatically be attributed to that surface material. It may originate from a concealed adhesive, a coating, a preservative, a curing residue or a reaction product generated during ageing.

A mechanistic description of emission is more informative than a single concentration measurement. Chamber studies commonly represent material emission through the initial emittable concentration (C_0), the material-phase diffusion coefficient (D_m), and the material-air partition coefficient (K). C_0 describes the amount initially available for release, D_m governs transport through the material, and K represents equilibrium partitioning between the material and air. These parameters can be estimated through chamber-based methods and used to predict multi-source cabin behaviour [4, 5]. Temperature can alter all three parameters, while ventilation mainly lowers the air concentration and does not necessarily remove the remaining reservoir inside the material.

Formaldehyde-specific parameter studies extend this approach by estimating C_0, D_m and K for multiple building and vehicle-cabin materials over different temperatures [6]. Such work is important because an apparent decrease in cabin concentration may reflect dilution or temporary cooling rather than source depletion. Likewise, a later increase after heating or high humidity may indicate accelerated diffusion or chemical regeneration rather than a new 'initial' emission stage.

The phrase 'formaldehyde-free' therefore requires careful definition. It can mean that formaldehyde was not deliberately used as a feedstock, that a conventional formaldehyde-based resin was replaced, or simply that a measured value fell below a stated analytical threshold. These meanings are not chemically equivalent. A no-added-formaldehyde material may still contain trace background formaldehyde or generate carbonyl compounds during ageing, whereas a formaldehyde-based resin modified with a scavenger can show low short-term emissions without being chemically formaldehyde-free.

This paper addresses five linked questions: which vehicle-interior materials are plausible direct or indirect formaldehyde sources; how environmental and material parameters alter emission intensity and duration; whether the evidence supports a universal release cycle; how no-added-formaldehyde alternatives are prepared; and what evidence is needed to support a scientifically defensible formaldehyde-free claim. The paper combines material chemistry, mass-transfer theory and published chamber and field data, with particular attention to the distinction between short-term concentration control and lifetime source reduction.

2. Material systems and potential formaldehyde sources

A useful source analysis treats a vehicle component as a multilayer assembly rather than a single visible material. The visible surface can emit formaldehyde directly, but it can also act as a diffusion barrier that delays emission from backing, foam or adhesive layers. Recent multi-source modelling of vehicle materials indicates that concealed adhesives can make a substantial contribution to cabin formaldehyde and can extend the effective emission period when their emission parameters favour

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long-term release [7]. Table 1 summarises the principal vehicle-interior material systems, their typical uses, plausible formaldehyde pathways and expected temporal behaviour.

Table 1. Principal vehicle-interior material systems and plausible formaldehyde pathways

Material/component	Typical use	Potential source or formation route	Expected temporal behaviour
Polyurethane foam	Seat cushions, headrests, acoustic layers	Impurities or process residues in polyol/catalyst systems; oxidation of organic constituents	Early release followed by diffusion-controlled and heat-activated emission
Textiles and carpets	Seat coverings, headliner, flooring	Finishing resins, dyes, preservatives, backing layers and adhesives	Surface release followed by slower backing or adhesive diffusion
Synthetic leather	Seats, dashboards, door trim	Coatings, stabilisers, lamination adhesives and oxidation of polymer/additive systems	Multilayer behaviour governed partly by coating permeability
Natural leather	Seats and premium trim	Tanning/finishing agents, preservatives, coatings and adhesives	Highly formulation-dependent; surface and sub-layer contributions
Thermoplastics	Dashboard, console, pillars, door parts	Residual additives, coatings and thermo-oxidative degradation	Often lower direct release but possible ageing-related formation
Rubber/sealing strips	Door, window and body seals	Process additives, curing residues and oxidation products	Low-to-moderate sustained emission under heating
Wood-based composites	Decorative inserts and fibreboard elements	UF, MF or PF resin residues and later bond hydrolysis	Residual release followed by humidity-sensitive regeneration
Adhesives/sealants	Lamination and component assembly	Formaldehyde-containing resin, preservatives, residual monomers or degradation products	Potentially prolonged because sources are enclosed beneath other layers

2.1. Polyurethane foams, textiles and leather systems

Polyurethane foam is widely used in seat cushions, headrests and acoustic layers. The polyurethane backbone is not inherently a formaldehyde resin, but commercial foam is a formulated material containing polyols, isocyanates, catalysts, surfactants, flame retardants and other additives. Residual low-molecular-weight compounds can be released soon after manufacture, while heat and oxygen may later generate smaller carbonyl products from organic constituents. A seat therefore cannot be classified by the foam alone; its covering, coating and adhesive system must be considered simultaneously.

Textiles and carpets add further uncertainty because formaldehyde can be associated with finishing resins, preservatives, backing materials or adhesives rather than the fibre itself. A rapid initial decrease is plausible when surface-accessible compounds desorb, but emissions from backing layers may persist because diffusion distance is longer. Synthetic and natural leathers are similarly multilayered. Their observed emission depends on surface coatings, stabilisers and lamination systems, while permeability of the outer layer can delay release from underlying materials.

2.2. Thermoplastics, seals and wood-based components

Thermoplastic components such as polypropylene or acrylonitrile-butadiene-styrene are typically not major formaldehyde reservoirs in the same way as amino-resin bonded wood products.

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However, residual additives, coatings and thermo-oxidative degradation can create carbonyl emissions during service. Rubber seals can also release process residues or oxidation products, particularly under elevated cabin temperatures.

Wood-based decorative components require separate attention because urea-formaldehyde (UF), melamine-formaldehyde (MF) and phenol-formaldehyde (PF) resins can contain residual formaldehyde and susceptible chemical bonds. Initial emissions may decline as accessible residual formaldehyde is removed, yet humidity and heat can promote hydrolysis or other degradation reactions. This produces a source profile that cannot be described adequately by a single depletion constant.

2.3. Adhesives as concealed sources

Adhesives and sealants are analytically important because they often occupy less visible area but may be positioned beneath relatively impermeable surface layers. Their contribution is therefore controlled not only by source strength but also by the partition and diffusion properties of the complete assembly. Evidence from a five-source vehicle-material model, including carpet, a car-door component, a sealing strip and two adhesives, identified the adhesives as important contributors and associated higher C_0/K behaviour with longer emission persistence [7]. This finding supports source control at the assembly level rather than selection of visible trim alone.

3. Formaldehyde formation and release mechanisms

Residual formaldehyde can remain after incomplete curing of formaldehyde-based resins or after use of formaldehyde-releasing agents in finishing and preservation. Resin molar ratio, catalyst concentration, curing temperature, curing duration and post-curing ventilation all affect the mobile fraction. General indoor-material literature also shows why formaldehyde should be treated as both a formulation-dependent residual and a possible reaction product rather than as a single fixed contaminant [1].

Once formaldehyde is present in a material, its release to cabin air is constrained by internal transport and surface partitioning. The C-history framework and related chamber approaches estimate C_0, D_m and K from concentration-time data [4, 5]. A high D_m permits more rapid movement to the surface, whereas a high K favours retention in the material relative to air. Because these parameters are temperature-sensitive, the same component can display very different apparent 'release periods' under cool storage and summer solar heating.

Hydrolysis is particularly relevant to amino-resin networks and other susceptible bonds. Water increases the availability of reactant at the polymer network, and higher temperature can accelerate both the chemical reaction and subsequent mass transfer. This mechanism explains why a material that performs well in a short dry chamber test may show a later increase under warm, humid service conditions. The distinction between residual formaldehyde and regenerated formaldehyde is therefore central to lifetime evaluation.

Heat and oxygen can transform polymers, plasticisers, antioxidants, coatings and other organic additives into smaller carbonyl compounds. A useful ageing experiment should therefore compare unaged and thermally aged specimens and measure formaldehyde alongside acetaldehyde and relevant VOC precursors. If formaldehyde increases after ageing, the result is inconsistent with a simple depletion-only model.

Formaldehyde may also form in cabin air through oxidation of other VOCs. Whole-cabin concentration is therefore a combined result of direct source emission, secondary chemistry, sorption

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to other surfaces and ventilation. Unless individual components have been isolated in chamber testing, source attribution should be expressed cautiously because a field concentration does not identify which layer or reaction pathway produced the measured formaldehyde.

For secondary-data synthesis, the emission history can be divided into operational phases: approximately 0-3 days for curing and assembly residues, 3-14 days for early desorption and accessible-pore depletion, 14-90 days for more strongly diffusion-controlled release, and 90-180 days or longer for slow diffusion, hydrolysis or degradation. Thermal reactivation can occur at any service stage. These windows are analytical coding intervals rather than empirical constants. The original sampling day and its time origin should be retained whenever available.

A simple monotonic dataset can be described initially by an exponential model, $C(t) = C_0 \exp(-kt)$, where k is an apparent depletion constant. However, a two-phase model is preferable when a fast and a slow component are distinguishable, and a generation term is required when a plateau or later increase occurs. A half-life should therefore be reported only when monotonic decay is actually supported by the observed time series.

4. Preparation and evaluation of nominally formaldehyde-free materials

Replacement systems can avoid formaldehyde-based condensation chemistry by using polymeric methylene diphenyl diisocyanate (pMDI), polyurethane, epoxy, polyvinyl acetate or hot-melt adhesive technologies. These systems use different curing mechanisms, including isocyanate reactions, epoxide ring opening, emulsion polymerisation, or thermoplastic melting and solidification. Reviews of formaldehyde-free adhesive technologies emphasise that evaluation must extend beyond initial formaldehyde emission to curing conditions, moisture resistance, process safety, recyclability and engineering performance [8-10].

Soy protein, tannin, lignin, starch, cellulose derivatives, chitosan and citric acid have been investigated as renewable adhesive feedstocks [9, 10]. Their preparation may involve denaturation, oxidation, esterification, grafting or crosslinking to achieve adequate wet strength and durability. The identity of the crosslinker is critical: a bio-based principal feedstock does not automatically make the complete formulation aldehyde-free. A chemically meaningful assessment should therefore report feedstock, crosslinker, catalyst, curing temperature and any scavenger or barrier coating.

Urea, amines, tannins and other nucleophilic compounds can lower free formaldehyde by chemical capture. This approach can reduce the mobile fraction and improve a short-term emission test, but it does not remove formaldehyde from the original manufacturing chemistry. Similarly, a low-permeability barrier film can reduce mass transfer without eliminating the source. Heat and humidity ageing are required to determine whether captured formaldehyde remains stable and whether the barrier retains its effectiveness.

Four terms should be distinguished. 'Formaldehyde-based' means that formaldehyde is intentionally used in resin synthesis. 'Low-formaldehyde' means that formaldehyde may still be used but measured emission is reduced under a specified method. 'No-added-formaldehyde' means that formaldehyde is not deliberately introduced as a feedstock, although trace background or later chemical formation remains possible. 'Below detection' refers only to a stated test and detection limit. The stronger expression 'zero emission' is generally not defensible without testing across relevant environmental conditions and service stages. Table 2 compares the chemistry, advantages, limitations and minimum supporting evidence for the principal formaldehyde-control approaches.

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Table 2. Comparison of formaldehyde-control approaches

Approach	Main chemistry	Potential advantage	Key limitation	Minimum evidence for claim
Conventional formaldehyde-based resin	UF/MF/PF condensation chemistry	Established curing and performance	Residual formaldehyde and possible hydrolytic regeneration	Formulation disclosure + standard emission test + ageing
Scavenger-modified resin	Formaldehyde-based resin plus nucleophilic scavenger	Lower mobile formaldehyde	Source chemistry remains; stability may vary	Initial and aged emission with stated detection limit
No-added-formaldehyde synthetic adhesive	pMDI, polyurethane, epoxy, PVAc, hot-melt	Removes formaldehyde as intentional feedstock	Other emissions, process hazards or ageing products may remain	Supply-chain declaration + targeted analysis + durability data
Bio-based adhesive	Soy/ tannin/ lignin/ starch/ cellulose/ chitosan/ citric-acid systems	Renewable feedstock and potential low formaldehyde	Crosslinker may reintroduce aldehyde chemistry; moisture resistance varies	Complete formulation + curing route + emission and mechanical performance
Barrier coating/film	Physical mass-transfer suppression	Can reduce short-term flux	Does not prove source removal; damage/ageing can change permeability	Permeability and emission before and after ageing

5. Secondary-data method

5.1. Eligibility and data extraction

The synthesis prioritised peer-reviewed chamber studies, component tests and whole-vehicle field studies that report formaldehyde concentration, emission factor or at least one mechanistic parameter together with sufficient contextual information to interpret the measurement. ISO 12219-4 provides a standard small-chamber framework for vehicle-interior parts and materials, while GB/T 27630 provides the principal Chinese passenger-car air-quality guideline context [11, 12]. Building-material studies were used only to support emission mechanisms or measurement methods and were not pooled directly with vehicle concentrations [13].

For each eligible record, the preferred extraction fields are study identity, country, design, vehicle or material age, component description, substrate and adhesive information, thickness or exposed area where available, temperature, relative humidity, air exchange rate, chamber volume, loading factor, sampling time, analytical method and detection limit. Outcome types are kept separate: cabin concentration, material emission factor, C_0, D_m and K are related but not interchangeable quantities.

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Time origin is recorded exactly as defined in each study - for example, days since production, assembly, unpacking or test start. This prevents a 10-day measurement after delivery from being treated as equivalent to a 10-day measurement after manufacturing. Likewise, chamber, bag and whole-cabin data are first displayed separately because different test volumes, loading factors and air exchange rates can produce different absolute concentrations even for similar materials.

5.2. Quantitative comparison strategy

Descriptive comparison uses medians, ranges and study-level distributions rather than a pooled mean when test conditions are heterogeneous. When a study reports a clear reference condition, a dimensionless response ratio can be calculated as $RR = C_{condition} / C_{reference}$. Log response ratios are useful for comparing relative temperature or humidity effects across different chambers, whereas percentage changes in C_0, D_m and K remain separate because they represent different physical processes.

Repeated concentration measurements can be fitted first with the exponential model introduced at the end of Section 3. If residuals indicate a fast early decline followed by a slower tail, a two-component model is considered. A later rise or sustained plateau is interpreted as evidence that a generation process, environmental reactivation or changing ventilation must be considered. Where sufficient independent studies are available, material category, surface temperature, relative humidity, air exchange rate, method and vehicle age can be explored as moderators; otherwise, the synthesis remains stratified and descriptive.

5.3. Evidence-quality controls

Evidence quality is judged from material description, environmental control, analytical specificity, time resolution, replication and reporting completeness. Particular caution is required when a study reports only one environmental condition or does not provide temperature or sampling duration. Manufacturer claims can identify a declared preparation route but are not treated as independent proof of emission performance. A claim of 'not detected' is also retained as a censored analytical result rather than converted into a numerical zero.

6. Results of the secondary-data synthesis

6.1. Temperature changes emission parameters rather than concentration alone

In a small-chamber study used to predict a simulated 3 m^3 vehicle cabin, Wang et al. measured multiple VOC-material combinations across 25-65 °C. Across the reported combinations, C_0 increased by approximately 40-640% and D_m by 40-170%, while K decreased by 38-71%; multi-source cabin validation produced R^2 values of 0.82-0.99 [4]. These percentage ranges should not be interpreted as formaldehyde-only averages, because they cover several VOCs and materials. Nevertheless, the pattern demonstrates why temperature cannot be treated merely as an external concentration multiplier: it changes the physical parameters controlling the source itself.

A later formaldehyde-specific parameter study measured multiple building and vehicle-cabin materials over different temperatures and showed that the same C_0-D_m-K framework can be applied directly to formaldehyde [6]. Together, these studies support temperature-stratified comparison and caution against transferring an emission period measured at one temperature to a different cabin environment.

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6.2. Field measurements show substantial short-term variability

A 12-day new-car field study measuring 20 VOCs reported that formaldehyde exceeded the study benchmark in 34.9% of observations [14]. Because the work involved one vehicle over a short period, it does not establish a general exceedance rate for all passenger cars. Its value for the present synthesis is instead that it confirms the coexistence of field variability, environmental response and multi-compound exposure in a real cabin.

A separate seven-summer-workday investigation collected 40 points in a new, unoccupied, engine-off car with the cabin closed. Formaldehyde concentrations were mainly 30-130 μg/m^3; some values exceeded 200 μg/m^3, and 15 of 40 measurements (37.5%) exceeded 100 μg/m^3. Material surface temperature ranged from 24.1 to 64.2 °C and the reported air exchange rate was 0.184-0.218 h^{-1} [15]. The study therefore offers a useful temperature-rich dataset, but its closed, unoccupied design should not be treated as representative of all driving scenarios.

6.3. Adhesive properties can extend source importance

The multi-source study by Wang et al. compared carpet, a car-door component, a sealing strip and two adhesives, and identified the adhesives as important sources in the modelled cabin environment [7]. The reported association between higher C_0/K behaviour and longer release persistence is consistent with a concealed source that retains a substantial material reservoir while releasing gradually through adjacent layers. This result helps explain why source ranking by exposed surface area alone can be misleading. Table 3 summarises the five vehicle-related studies used directly in the secondary-data synthesis and identifies the contribution and main limitation of each study.

Table 3. Secondary studies used for direct vehicle-related synthesis

Study/design	Key secondary data	Use in this paper	Main limitation
Wang et al. 2020 [4] 30 L chamber + simulated 3 m^3 cabin	Roof upholstery, carpet and seat; six VOCs; 25-65 °C. Across material-VOC pairs: C_0 +40-640%, D_m +40-170%, K -38-71%; validation R^2 0.82-0.99.	Temperature sensitivity; mechanistic parameter interpretation; multi-source modelling.	Reported percentage ranges cover several VOC-material pairs, not a formaldehyde-only mean.
Wang et al. 2022 [6] Parameter method	Formaldehyde parameters for six building materials and five vehicle-cabin materials at multiple temperatures.	Formaldehyde-specific C_0, D_m and K framework; exposure prediction.	Full comparison depends on consistent units and access to complete parameter tables.
Wang et al. 2023 [14] 12-day field study	Twenty VOCs; formaldehyde showed a 34.9% exceedance rate relative to the study benchmark.	Field variability and temperature-response context.	Single vehicle; short observation period.
Zhang et al. 2024 [15] 7 summer workdays	40 points; formaldehyde mainly 30-130 μg/m^3, some >200; 15/40 >100; surface temperature 24.1-64.2 °C; AER 0.184-0.218 h^{-1}.	Concentration distribution and environmental covariates.	Closed, unoccupied, engine-off cabin does not represent all driving conditions.
Wang et al. 2025 [7] Five material sources	Carpet, car door, sealing strip and two adhesives; adhesives identified as important sources; higher C_0/K associated with longer persistence.	Material-source comparison and release-duration interpretation.	Limited product set; formulations may not generalise.

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6.4. The evidence does not support a universal release cycle

Taken together, the available evidence supports distinct mechanisms rather than one fixed emission duration. An early decline can reflect depletion of readily accessible formaldehyde; a slower tail can reflect diffusion from the material interior or concealed adhesive layers; and a later increase can occur when temperature or humidity accelerates transport or chemical generation. Seasonal heating can therefore create non-monotonic concentration histories even when the total material reservoir is declining over longer timescales.

For this reason, statements such as 'formaldehyde is released for X months' are scientifically weak unless the material system, temperature, humidity, ventilation and time origin are specified. A more defensible description reports an initial source strength, the environmental conditions under which it was measured, the subsequent rate of decline, and whether ageing can regenerate or create formaldehyde.

7. Discussion

The central implication of the synthesis is that formaldehyde exposure in a vehicle cannot be predicted from material identity alone. A chemically similar material can produce different cabin concentrations when its thickness, exposed area, coating permeability, temperature and ventilation differ. Conversely, a low measured cabin concentration does not necessarily indicate that the material reservoir has been exhausted; dilution can lower air concentration while C_0 remains substantial.

This distinction matters for vehicle design and testing. Selection of a low-emitting visible trim is insufficient if the assembly contains a stronger concealed adhesive source. Component-level chamber tests are therefore most informative when they preserve the actual layer structure or when individual layers are also tested to identify the dominant contributor. Whole-cabin measurements remain necessary because multi-source interaction, air exchange and secondary chemistry determine the exposure actually experienced in the vehicle.

The evidence also separates three different control strategies: source replacement, chemical scavenging and mass-transfer suppression. Source replacement changes the formulation so that formaldehyde is not intentionally used. Scavenging retains the original source chemistry but captures free formaldehyde. Barrier strategies reduce the rate at which formaldehyde reaches cabin air. All three can lower a short-term measurement, but only source replacement directly removes formaldehyde as a deliberate feedstock.

Reviews of alternative adhesive systems show that no-added-formaldehyde technologies involve trade-offs in curing, water resistance, cost, processing and durability [8-10]. The appropriate comparison is therefore not 'emission versus no emission' but a process-performance matrix that includes initial emission, ageing response, curing requirement, bond strength, moisture resistance and other relevant emissions.

For scientific communication, 'no-added-formaldehyde' is usually more defensible than 'zero-formaldehyde' when a formulation deliberately avoids formaldehyde feedstock. The claim should be paired with the analytical method, test temperature, relative humidity, loading factor, sampling duration and detection limit. If the product is intended for a hot vehicle cabin, accelerated heat and humidity ageing is necessary because it tests whether low initial emission persists after transport, service exposure and chemical degradation.

Standardised chamber methods such as ISO 12219-4 improve comparability between vehicle components, while national cabin-air guidelines provide a benchmark context for whole-vehicle

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evaluation [11, 12]. Neither type of standard, however, converts a single passing test into proof of zero lifetime emission. The result remains conditional on the tested formulation and environmental conditions.

8. Conclusion

Formaldehyde emission from passenger-vehicle interiors is controlled by the interaction of material chemistry, layered construction, mass transfer and environmental exposure. Seats, carpets, headliners, thermoplastics, seals, wood-based composites and adhesives can contribute through different pathways, and concealed adhesives may remain important even when their visible area is small. Temperature alters source parameters as well as cabin concentration, while humidity, oxidation and secondary chemistry can produce non-monotonic behaviour.

The available chamber and field evidence does not support a single formaldehyde release cycle that can be applied to all vehicles or components. Instead, emission should be described through condition-specific phases: early desorption and residual release, slower diffusion-controlled transport, and possible later regeneration or thermal reactivation. Accordingly, a reported duration is meaningful only when the material system, environmental conditions and time origin are specified.

The same principle applies to formaldehyde-free materials. Replacing formaldehyde-based condensation resins can remove formaldehyde as an intentional feedstock, but it does not prove zero lifetime formaldehyde or zero carbonyl emission. A robust claim should distinguish source replacement from scavenging or barrier suppression and should be supported by formulation disclosure, standardised emission testing, stated detection limits and heat/humidity ageing. For many vehicle-interior applications, 'no-added-formaldehyde' is therefore a more scientifically defensible formulation claim than 'zero-formaldehyde'.

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