


Communication

# Asymmetric Trajectories in the Automotive Green Transition: A Hybrid FMEA–AHP Risk Assessment of Developed Versus Emerging Market Resilience

Maxime Giraud, Alexandru Silviu Goga \* and Mircea Boşcoianu

ITMI Faculty, Interdisciplinary Doctoral School, Transilvania University of Braşov, 500036 Braşov, Romania; maxime.giraud@utbm.fr (M.G.); mircea.boscoianu@unitbv.ro (M.B.)

\* Correspondence: alexandru.goga@unitbv.ro

## Abstract

This paper proposes and validates a hybrid FMEA-AHP framework designed to quantify the systemic asymmetries inherent in the automotive green transition. By moving beyond traditional component-level failure analysis, this model introduces the Market Maturity Coefficient ( $k_m$ ), a novel diagnostic tool that benchmarks transition readiness by comparing risk profiles across divergent geoeconomic landscapes. Utilizing France and Romania as proxies for developed and emerging markets, the research demonstrates a significant “RPN Divergence,” where infrastructure and grid risks in emerging contexts are effectively amplified by factors exceeding  $8.0\times$  compared to developed counterparts. The results indicate that while software and technological risks show convergence ( $k_m \approx 1.3$ ), systemic vulnerabilities regarding grid stability and digital maturity remain the primary barriers to a uniform European transition. This framework provides policymakers with a mathematically rigorous method to move beyond “one-size-fits-all” policies toward targeted resilience funding.

**Keywords:** ICE-EV transformation; hybrid FMEA (failure mode and effects analysis)-AHP (analytic hierarchy process); RPN (risk priority number) divergence

## 1. Introduction

### 1.1. The Global Imperative and Industrial Disruption

The decarbonization of the transport sector constitutes one of the most significant industrial challenges of the 21st century. Driven by the existential threat of climate change and codified in international treaties such as the Paris Agreement, the shift from fossil fuel-dependent Internal Combustion Engines (ICsw) to Battery Electric Vehicles (BEVs) is no longer a matter of corporate social responsibility but of regulatory survival. The European Union’s legislative package, “Fit for 55,” mandates a 100% reduction in CO<sub>2</sub> emissions for new cars and vans by 2035, effectively setting an expiration date on the technology that has underpinned the automotive industry for over a century [1] This mandate forces a reconfiguration of value chains, production methodologies, and consumption patterns at a speed and scale without historical precedent. Developed markets possess fiscal space, grid robustness, and digital maturity, framing electrification as an optimization challenge. Emerging markets face systemic risks such as energy poverty, aging electrical grids, and reliance on ICE-based manufacturing, making the transition a potential economic shock.

However, the “Green Transition” is not a uniform, monolithic wave washing over the global economy. Rather, it is a fragmented, asynchronous process defined by local



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constraints, industrial legacies, and economic capabilities. While the destination—Net Zero—is shared, the path is highly uneven. Developed markets, such as those in Western Europe (e.g., France, Germany), possess the fiscal space, grid robustness, and digital maturity to treat this transition as an optimization problem. Conversely, emerging markets, such as those in Central and Eastern Europe (e.g., Romania, Bulgaria), face the transition as a potential shock to their economic and infrastructural systems. These regions often grapple with “energy poverty,” aging electrical grids, and a reliance on low-cost labor for ICE component manufacturing, making them uniquely vulnerable to the systemic disruptions of electrification [2].

The urgency of this research is underpinned by the increasing bifurcation of the global automotive landscape. In 2024, data revealed a stark contrast in EV adoption resilience [3]. The risk of emerging markets becoming “islands of obsolescence” is a phenomenon documented in the study of Path Dependency and Technological Lock-in. When developed economies pivot toward new technological paradigms (such as electrification), regions with significant infrastructure deficits or reliance on legacy Internal Combustion Engine (ICE) manufacturing often face “stranded assets”—infrastructure and labor skills that lose value but cannot be easily repurposed. This creates a two-speed transition: one characterized by high-tech optimization and another by infrastructural stagnation. Without strategic intervention, these markets risk being decoupled from the global supply chain, relying on aging, carbon-intensive fleets that exacerbate local environmental degradation while being excluded from the economic benefits of the cyber-physical automotive era [4]. While Western markets continued to expand their charging infrastructure and EV fleets supported by stable (though tapering) incentives, emerging markets experienced significant volatility. In Romania, for instance, a reduction in the “Rabla Plus” subsidy program led to a sharp contraction in EV sales, highlighting the extreme price sensitivity and fragility of the market [5]. This divergence poses a critical risk to the cohesion of the European Single Market and the global automotive supply chain. If emerging markets cannot keep pace, they risk becoming “islands of obsolescence,” relying on aging ICE fleets while the rest of the continent moves forward, or worse, facing systemic failures in their energy and mobility networks.

The current state of the research field suggests that energy transitions are inherently geographic and prone to creating spatial inequalities. As noted by Sovacool and Hess (2017) [4], technological shifts often follow a “core-periphery” model where mature markets set the regulatory and technical standards, forcing emerging markets to either adapt at prohibitive costs or face systemic exclusion [3,6]. This theoretical framework aligns with our empirical findings in the France–Romania comparison, where the  $k_m$  coefficient serves to quantify this specific geographic risk.

### 1.2. The Inadequacy of Traditional Risk Frameworks

Navigating this volatile landscape requires robust risk management tools. Traditionally, the automotive industry has relied on Failure Mode and Effects Analysis (FMEA) as its gold standard for reliability engineering. Formalized by standards such as IEC 60812 and the AIAG & VDA Handbook, FMEA is designed to identify potential failure modes, assess their Severity ( $S$ ), Occurrence ( $O$ ), and Detection ( $D$ ), and calculate a Risk Priority Number ( $RPN = S \times O \times D$ ) [7,8].

However, traditional FMEA was designed for component-level analysis—predicting the fatigue life of a valve or the failure rate of a sensor. It was not designed to model systemic, socio-economic, or geopolitical risks. In the context of the green transition, the limitations of FMEA become glaring:

1. **Subjectivity and Bias:** The assignment of *S*, *O*, and *D* scores is often heavily influenced by the experience and bias of the expert team. A “Severity” of 8 might mean “Customer Dissatisfaction” to one engineer and “Regulatory Non-Compliance” to another [9].
2. **Ordinal Scale Limitation:** The RPN is an ordinal number, not a cardinal one. An RPN of 200 is not necessarily “twice as bad” as an RPN of 100, yet decision makers often treat it as such, leading to misallocation of resources.
3. **Lack of Strategic Weighting:** Traditional FMEA treats Severity, Occurrence, and Detection as equally important. In a strategic transition scenario, however, a “Severity 10” event (e.g., total grid collapse) is unacceptable regardless of how low the Occurrence is, whereas a “Detection 10” issue (e.g., a hard-to-diagnose software bug) might be tolerable if the Severity is low. The standard RPN formula masks these nuances [10].
4. **Static Assessment:** FMEA is typically a snapshot in time. It fails to capture dynamic risks, such as the rapid degradation of grid reliability due to the sudden influx of renewable energy sources or the swift obsolescence of suppliers unable to pivot to EV components [10].

### 1.3. Research Gap and Objectives

The existing body of literature on the ICE-EV transformation focuses heavily on three areas: technological feasibility (battery chemistry, range), economic modeling (TCO analysis), and policy impact (emissions targets). There is a significant scarcity of research that operationalizes these high-level risks into a granular, engineering-grade framework that allows for direct comparison between different geoeconomic regions. Specifically, there is a lack of tools that combine the technical rigor of reliability engineering with the strategic flexibility of multi-criteria decision-making.

This paper addresses this gap by proposing a Hybrid FMEA–AHP Model. By integrating the Analytic Hierarchy Process (AHP)—a method designed to organize and analyze complex decisions—with standard FMEA, we create a framework that utilizes the following:

- **Correction of Subjectivity:** Uses pairwise comparisons to derive mathematically consistent weights for risk factors, reducing individual bias [11].
- **Strategic Alignment:** Allows for the prioritization of corrective actions based on strategic criteria (e.g., “Sustainability Impact,” “Cost Efficiency,” “Time to Implementation”) rather than just raw risk scores.
- **Comparative Benchmarking:** Enables a direct, “apples-to-apples” comparison of risk profiles between developed and emerging markets by normalizing the assessment criteria.

The primary objective of this research is to utilize this hybrid model to benchmark the “Green Transition Risk” in France (representing developed markets) versus Romania (representing emerging markets). By quantifying the “RPN Divergence” between these two archetypes, we aim to provide actionable, data-driven insights for policymakers and industry leaders to manage the transition’s asymmetries effectively.

## 2. Theoretical Framework and Methodological Foundation

To build a robust risk assessment model, we must first establish the theoretical underpinnings of the transition. This involves defining the specific nature of “Green Risks,” understanding the evolution of the automotive supply chain, and rigorously defining the mathematical tools (FMEA and AHP) used in the analysis. The hybrid FMEA-AHP model explicitly maps transition risks to Environmental, Social, and Governance (ESG) pillars to ensure a holistic assessment. Environmental (E) risks focus on grid-mix carbon intensity

and battery EOL recycling; Social (S) risks address mobility exclusion and labor displacement; and Governance (G) risks evaluate policy volatility. Crucially, the “Digital Divide” is integrated as a cross-cutting risk multiplier. Because low digital maturity directly correlates with high Detection (D) scores, a lack of Industry 4.0 adoption in emerging markets acts as a multiplier that delays the response to disruptions, thereby increasing the effective severity of any given failure mode.

### 2.1. Sustainable Development in Automotive Engineering: The ESG Nexus

Sustainable development in the automotive sector is no longer limited to tailpipe emissions. It encompasses a holistic integration of **Environmental, Social, and Governance (ESG)** objectives into every stage of the vehicle lifecycle, from mineral extraction to end-of-life (EOL) recycling. In our hybrid FMEA framework, we explicitly map potential failure modes to these ESG pillars to ensure comprehensive risk coverage [11].

- **Environmental (E) Risks:** These are failures that compromise the ecological integrity of the transition.
  - Example: **Insufficient Battery Recycling Infrastructure.** If an emerging market lacks the facility to recycle Li-ion batteries, the “Green Transition” creates a toxic waste legacy. This represents a high-severity environmental failure mode [12].
  - Example: **Carbon-Intensive Grid Mix.** An EV charged on a coal-heavy grid (common in parts of Central/Eastern Europe) yields marginal or negative environmental benefits compared to efficient ICEs. This is a “Systemic Failure” of the decarbonization objective.
- **Social (S) Risks:** These involve the human and societal impacts of the transition.
  - Example: **Mobility Exclusion/Affordability.** The high upfront cost of EVs creates a risk of “mobility apartheid,” where lower-income demographics in emerging markets are priced out of personal transport. This social friction can lead to “Market Resistance,” a valid FMEA failure mode with high Severity regarding adoption rates [13].
  - Example: **Labor Displacement.** The shift to EVs reduces the need for mechanical assembly labor (fewer moving parts) but increases demand for software and chemical engineering skills. In markets dependent on traditional manufacturing jobs, this skill mismatch is a critical failure mode for the local economy [2].
- **Governance (G) Risks:** These relate to the stability and transparency of the regulatory and operational environment.
  - Example: **Policy Volatility.** Frequent changes in subsidy schemes (as seen in Romania’s 2024 cuts) create a chaotic planning environment for OEMs and consumers, leading to market stagnation [5].
  - Example: **Supply Chain Opacity.** The inability to trace raw materials (e.g., Cobalt, Lithium) exposes companies to compliance risks (e.g., EU Battery Regulation) and reputational damage.

### 2.2. The Continuum Redefinition: From Mechanical to Cyber-Physical

The ICE-to-EV transition represents a “continuum redefinition” of the vehicle. We are moving from a mechanical product defined by thermodynamics and tribology to a cyber-physical system defined by electrochemistry and software code. This shift fundamentally alters the nature of “failure.”

- **Mechanical vs. Systemic Failure:** In the ICE era, risks were often localized (e.g., a fuel pump failure). In the EV era, risks are systemic. A software bug in the Battery Management System (BMS) can brick the entire vehicle or cause a thermal runaway

event. Similarly, a failure in the charging infrastructure (external to the vehicle) renders the vehicle useless. Our FMEA model must therefore expand its scope to include external infrastructure failure modes as critical components of the “Vehicle System” [14].

- **The “Software-Defined Vehicle” (SDV):** Modern EVs are essentially computers on wheels. This introduces “Cybersecurity” and “OTA (Over-the-Air) Update Failure” as new, high-occurrence failure modes. Developed markets with high digital maturity are better equipped to manage these risks through “Digital Twins” and real-time monitoring, whereas emerging markets may lack the connectivity infrastructure to support reliable OTA updates, increasing the risk of software obsolescence [15].

### 2.3. The Evolution of Risk Assessment: FMEA and AHP

#### 2.3.1. Failure Mode and Effect Analysis (FMEA)

FMEA originated in the US Military (Mil-Std-1629A) and was adopted by the aerospace (NASA) and automotive industries (Ford) in the 1970s and 80s. It remains the backbone of quality assurance. The 2019 harmonization of AIAG (US) and VDA (German) standards [8] introduced significant changes, moving towards “Action Priority” (AP) tables to address the limitations of RPN. However, RPN remains a widely understood heuristic [9]. Traditional FMEA defines risk as:

- **Severity (S):** The measure of the effect of a failure on the end-user (1 = None, 10 = Hazardous).
- **Occurrence (O):** The likelihood of the cause of the failure occurring (1 = Remote, 10 = Very High).
- **Detection (D):** The probability that the control plan will detect the failure before it reaches the user (1 = Certain detection, 10 = Absolute uncertainty).

**Critique of Standalone FMEA:** In comparative analysis, FMEA fails because it is context-agnostic. A “Grid Failure” (Severity 8) has the same numerical impact on RPN whether it happens once a year ( $O = 2$ ) or once a week ( $O = 8$ ), but the strategic implication is vastly different. Furthermore, FMEA cannot weigh the cost of mitigation against the risk reduction, making it a poor tool for resource allocation budgeting [7].

#### 2.3.2. The Analytic Hierarchy Process (AHP)

To resolve the deficiencies of FMEA, we integrate the Analytic Hierarchy Process (AHP), developed by Thomas Saaty. AHP is a structured technique for organizing and analyzing complex decisions, based on mathematics and psychology. It decomposes a decision problem into a hierarchy of more easily comprehended sub-problems, each of which can be analyzed independently [16]. AHP uses a pairwise comparison matrix  $A$  as explained in Equation 1,

$$A = \begin{matrix} & 1 & a_{12} & \dots & a_{1n} \\ 1/a_{12} & 1 & & \dots & a_{2n} \\ \vdots & \vdots & \ddots & \ddots & \vdots \\ 1/a_{1n} & 1/a_{2n} & \dots & & 1 \end{matrix} \quad (1)$$

The principal eigenvector of this matrix provides the normalized weights ( $w$ ) of the criteria. A crucial feature of AHP is the Consistency Ratio (CR), which measures the logical consistency of the expert judgments. A  $CR < 0.1$  is generally considered acceptable [17].

**The Hybrid Benefit:** By feeding FMEA scores into an AHP framework, we can weight “Severity” higher than “Detection” (if safety is the goal) or weight “Cost” against “Risk Reduction” (if budget is the constraint). This allows us to tailor the risk assessment to the specific economic realities of Emerging vs. Developed markets.

#### 2.4. The Digital Divide: A Structural Risk Determinant

A critical theoretical addition to this research is the integration of the “Digital Divide” as a risk determinant. Supply chain resilience literature increasingly cites **Digitalization** (Industry 4.0, IoT, Blockchain) as the primary enabler of risk mitigation [18].

- **Theory of Visibility:** Digital tools provide visibility. In a digitally mature supply chain (France), a disruption is visible immediately (Low Detection Score). In a digitally immature chain (Romania), visibility is limited to tier-1 suppliers, and disruptions in tier-3 are hidden until they cause a stoppage (High Detection Score).
- **The Bullwhip Effect:** Information asymmetry, caused by the digital divide, exacerbates the bullwhip effect, leading to massive inventory inefficiencies and “Just-in-Case” hoarding, which is financially toxic for emerging market suppliers with limited working capital [19].

### 3. Methodology

This research employs a mixed-methods approach, combining quantitative data analysis (for parameterizing the model) with qualitative expert systems (for the AHP weighting). The methodology is designed to be auditable, repeatable, and scalable.

#### 3.1. Research Design and Process Flow

The study is structured into six distinct phases:

1. **Scope Definition & System Decomposition:**
  - The “Automotive Transition System” is decomposed into four interacting sub-systems: **Technology** (Vehicle, Battery, Software), **Policy** (Regulations, Incentives), **Infrastructure** (Charging Network, Grid), and **Market/Consumer** (Adoption, Purchasing Power).
  - **Rationale:** This prevents “siloes” risk analysis and ensures systemic risks (e.g., policy affecting infrastructure) are captured.
2. **Failure Mode Identification (FMI):**
  - A repository of failure modes is generated based on a literature review of recent (2023–2025) automotive trends and insolvency reports.
  - **Selection Criteria:** Failure modes must be specific to the transition (e.g., “Inverter Failure” is a standard risk, but “Charging Station Interoperability Failure” is a transition risk).
3. **Data-Driven FMEA Parameterization:**
  - Instead of relying solely on opinion, we use empirical proxies to assign baseline *S*, *O*, and *D* scores for France and Romania.
  - **Proxy for Occurrence (O):** System Average Interruption Duration Index/System Average Interruption Frequency Index data for grid risks; Charger density stats for infrastructure risks.
  - **Proxy for Detection (D):** Digital Economy and Society Index 2024 scores for digital risks.
  - **Proxy for Severity (S):** Insolvency impact and consumer survey data regarding reliance on vehicles.
4. **AHP Model Construction and Weighting:**
  - An AHP hierarchy is constructed with the goal “Prioritize Corrective Actions.”
  - **Criteria:** Severity Reduction ( $\Delta S$ ), Occurrence Reduction ( $\Delta O$ ), Detection Improvement ( $\Delta D$ ), Implementation Cost (*C*), and Time-to-Impact (*T*).
  - **Expert Panel Simulation:** Weights are derived simulating three expert groups (Technical, Strategic, Economic) to represent diverse stakeholder views. Group 1 emphasizes

safety ( $\Delta S$ ), Group 2 emphasizes feasibility ( $C, T$ ), and Group 3 emphasizes reliability ( $\Delta O, \Delta D$ ). The final weights are an aggregation.

5. Comparative Simulation (The RPN Divergence):

- The model is run for both France and Romania using their respective datasets.
- We calculate the **Market Maturity Coefficient** ( $k_m$ ), defined as the ratio of Emerging Market Risk to Developed Market Risk for identical failure modes.

6. Validation:

- Consistency Ratios (CR) are checked for all AHP matrices.
- Results are cross-referenced against real-world 2024 insolvency and sales data to verify predictive validity.

### Expert Selection & Normalization Methodology

To ensure the mathematical validity of the expert-weighted criteria, the Analytic Hierarchy Process (AHP) component incorporates a rigorous consistency check for all pairwise comparison matrices. A Consistency Ratio (CR) threshold of  $<0.1$  was strictly enforced, as this is the widely accepted standard to confirm that expert judgments are logically consistent and not the result of random selection. For cases where initial assessments exceeded this threshold, a re-evaluation process was simulated to align judgments with the transitivity rule (e.g., if criterion A is twice as important as B, and B is three times as important as C, then A should be six times as important as C). This adherence to CR standards mitigates the inherent subjectivity of traditional risk assessment methods and ensures that the resulting Market Maturity Coefficient ( $k_m$ ) is based on a stable and reliable mathematical foundation.

### 3.2. FMEA Scoring Standards (AIAG & VDA Alignment)

We adhere to the standard 1–10 ordinal scales, interpreted for the transition context:

- Severity ( $S$ ):
  - 10: Safety hazard without warning (e.g., Battery Thermal Runaway, Grid Blackout).
  - 9: Regulatory non-compliance (e.g., Missing CO<sub>2</sub> targets, Illegal dumping).
  - 8: Major function loss (e.g., Vehicle won't charge, Range  $< 50\%$  of nominal).
  - ...
  - 1: No discernible effect.
- Occurrence ( $O$ ):
  - 10: Failure is almost inevitable (Probability  $> 10\%$ ).
  - 8–9: Frequent failure (e.g., Daily charging queues, Weekly software bugs).
  - ...
  - 1: Failure is unlikely ( $<1$  in 100,000).
- Detection ( $D$ ):
  - 10: Absolute uncertainty (No monitoring, failure detected by user).
  - 9: Very remote chance of detection.
  - ...
  - 1: Almost certain detection (AI/Digital Twin predicts failure before occurrence).

### 3.3. The Logic of Corrective Actions

In this methodology, "Risk Management" is defined as the mathematical reduction in the RPN. A corrective action is valid only if it demonstrably lowers  $S$ ,  $O$ , or  $D$ .

- $\Delta S$ : Hard to achieve in engineering (a fire is always a fire), but achievable in systemic terms (e.g., redundancy reduces the severity of a single point of failure).

- $\Delta O$ : Achieved through improving process capability ( $C_{pk}$ ), infrastructure investment (grid hardening), or supplier diversification.
- $\Delta D$ : Achieved through digitalization (IoT sensors, real-time telemetry).

The AHP component then answers the question: Which delta is most valuable? Is it better to spend €1 M to reduce Detection from 8 to 2, or to reduce Occurrence from 4 to 3? The answer depends on the market context, which our model resolves.

#### 4. Empirical Diagnostics: Benchmarking the Divide

To populate our model with realistic data, we conduct a deep diagnostic of the two target markets using the latest available statistics (2023–2025) as seen in Table 1 below. This section provides the “ground truth” for our FMEA scoring.

##### 4.1. Infrastructure Density and Charging Availability

The “Range Anxiety” failure mode is essentially a function of charger availability ( $O$ ) and redundancy.

**France (Developed Market Archetype):** France has achieved critical mass in its charging infrastructure. As of early 2025, the country reports over 123,000 public AC charging points and nearly 28,000 DC fast-charging points [20]. The growth rate is aggressive, with a 51% year-on-year increase in fast-charging deployment. This expansion is driven by the Mobility Orientation Law (LOM), which mandates charger installation in non-residential parking lots, creating a pervasive network across retail and hospital-ity sectors [20]. The network density stands at approximately 249 charging points per 100,000 inhabitants, ensuring that “Charging Unavailability” is a low-occurrence event for most drivers [21].

##### **Romania (Emerging Market Archetype):**

Romania faces a significant infrastructure deficit. It ranks 27th out of 33 countries in the global EV Charging Index [22]. While the network expanded by 33% in 2024, the absolute number of public charging points remains low at approximately 4500 [5].

- **Crucial Insight:** A structural vulnerability exists in home charging. In France, 67% of EV drivers have home charging access. In Romania, **38–40% of EV drivers lack home charging**, forcing reliance on the sparse public network [5].
- **Risk Implication:** For a Romanian driver, a public charger failure is a “Severity 10” event (stranded vehicle), whereas for a French driver with home charging, it is a “Severity 5” inconvenience.

**Table 1. Comparative Infrastructure Metrics (2024/2025 Data)** (Sources: [5]).

Metric	France	Romania	Risk Implication
Total Public Charging Points	~169,000+	~4500	High O for Romania.
Chargers per 100 k Inhabitants	249	<30	Network saturation risk.
DC Fast Charging Share	~15–16% of total	42% of total	Romania prioritizes speed over density to cover highways, leaving urban gaps.

Table 1. Cont.

Metric	France	Romania	Risk Implication
Home Charging Access	~67%	~60%	Higher severity of public failure in Romania.
User Satisfaction	92% Satisfied	60% find infra “insufficient”	Validates the “Social” failure mode.

#### 4.2. The Digital Divide and Supply Chain Visibility

The “Detection” ( $D$ ) score is driven by digital maturity.

**France:** France performs well in the Digital Economy and Society Index (DESI), particularly in connectivity and human capital. While SME digitalization is an ongoing challenge, the automotive sector benefits from high adoption of Industry 4.0 technologies (Digital Twins, AI) [23].

**Romania:** Romania faces a severe digital gap. The 2024 DESI data reveals that 72% of the population lacks basic digital skills, and only 27% of SMEs have reached a basic level of digital intensity (vs. EU average of 58%) [24].

- **Risk Implication:** A Romanian Tier-2 supplier is statistically less likely to use digital tools for risk monitoring. This results in a very high “Detection” score ( $D = 7+$ ), as quality or supply issues are likely to be detected only upon physical failure or delivery delay, rather than predictively.

#### 4.3. Economic Resilience and Insolvency

Economic health dictates the “Occurrence” of Supplier Insolvency (FM-03).

**Insolvency Dynamics:** In 2024, Romania saw a 9.38% increase in insolvencies, with the “Wholesale and retail trade of motor vehicles” sector being the hardest hit (1927 cases) [25]. This signals extreme fragility in the local automotive ecosystem. France also saw record insolvencies (64,000 failures), but these were distributed differently, with stronger state protections for critical industrial players compared to the fragmented Romanian market.

## 5. Risk Simulation and Results

Using the empirical data from Section 4, we populated the Hybrid FMEA-AHP model for five representative failure modes as seen in Table 2 below.

#### 5.1. FMEA Scoring and RPN Calculation

We assigned scores based on the “Ground Truth” data:

- **Example Logic:** For FM-01 (Grid Overload), Romania gets  $O = 6$  (due to high SAIDI) and  $D = 5$  (lower smart grid automation). France gets  $O = 2$  and  $D = 2$ .
- **Example Logic:** For FM-02 (Charging Unavailability), Romania gets  $S = 10$  (User stranded due to lack of home charging/low density), whereas France gets  $S = 5$  (Alternative charger likely nearby).

Table 2. Comparative FMEA Simulation Results.

Failure Mode (FM)	Risk Description	Market	Severity (S)	Occurrence (O)	Detection (D)	RPN	Divergence Factor ( $k_m$ )
FM-01	Grid Overload (Peak Charging)	France	8	2	2	32	–

Table 2. Cont.

Failure Mode (FM)	Risk Description	Market	Severity (S)	Occurrence (O)	Detection (D)	RPN	Divergence Factor ( $k_m$ )
		Romania	9	6	5	270	8.4×
FM-02	Charging Unavailability	France	5	3	2	30	–
		Romania	10	7	4	280	9.3×
FM-03	Tier-2 Supplier Insolvency	France	7	4	3	84	–
		Romania	8	6	6	288	3.4×
FM-04	Battery EOL Non-Compliance	France	9	2	2	36	–
		Romania	8	5	7	280	7.7×
FM-05	Software/OTA Failure	France	9	5	3	135	–
		Romania	9	5	4	180	1.3×
Average		France			4	63.4	
Average		Romania				259.6	4.1×

**Analysis of Results:** The simulation results highlight a significant disparity between infrastructure-dependent risks and technology-inherent risks. While grid and charging failure modes show an RPN Divergence exceeding  $8.0\times$ , the Software/OTA Failure (FM-05) presents a low divergence factor of  $k_m = 1.3$ . This low value indicates a state of 389 Technological Convergence.

The residual risk gap in emerging markets is primarily attributed to a lack of digital monitoring infrastructure (reflected in higher Detection scores) rather than a failure of the software itself. Consequently, while developed markets can focus on high-level software optimization, emerging markets face the existential challenge of building the foundational infrastructure necessary to support these globalized technological standards.

## 5.2. AHP Weighting and Prioritization

To prioritize corrective actions, we applied AHP weights.

- **Scenario A (Emerging/Romania):** We assumed a strategy focused on Survival and Feasibility. Weights: Cost (30%), Occurrence Reduction (30%), Severity (20%).
- **Scenario B (Developed/France):** We assumed a strategy focused on Perfection and Safety. Weights: Severity Reduction (40%), Detection (20%), Time (20%).

AHP-Derived Strategic Priorities:

- For Romania (Emerging):
  1. **Grid Modernization (Addressing FM-01):** Despite high cost, the sheer magnitude of the RPN (270) and the high Occurrence score ( $O = 6$ ) make this the mathematical priority.
  2. **Infrastructure Subsidies (Addressing FM-02):** Prioritized to reduce the Occurrence of charging gaps.
- Observation: High-tech software fixes (FM-05) are deprioritized because they do not address the foundational instability of the system.
- **For France (Developed):**

1. **Software Reliability (Addressing FM-05):** With infrastructure risks managed (RPN~30), the highest residual risk is software failure (RPN 135). AHP prioritizes this as it threatens brand reputation and safety ( $S = 9$ ).
2. **Circular Economy/EOL (Addressing FM-04):** Prioritized due to regulatory pressure (Governance risk), even if technical RPN is low.

## 6. Discussion

### 6.1. The Market Maturity Coefficient ( $k_m$ )

This research proposes the Market Maturity Coefficient ( $k_m$ ) as a standard metric for benchmarking global automotive transitions as explained below in Equation (2).

This coefficient provides a quick “health check” for global strategy.

$$k = \frac{RPN_{\{Emerging\}}}{m RPN_{\{Developed\}}} \quad (2)$$

- $k_m \approx 1$ : The risk is technology-inherent (e.g., Battery Chemistry). Global standardization works here.
- $k_m \gg 1$ : The risk is context-dependent (e.g., Grid, Logistics). “One-size-fits-all” policies will fail. The finding that Infrastructure risks have a  $k_m > 8$  suggests that for every Euro spent on charger reliability in France, eight Euros might be needed in Romania to achieve parity in risk reduction.

### 6.2. The “Hype Cycle” Divergence

The divergence in risk profiles creates a split in the Gartner Hype Cycle for the green transition [11]:

1. **Trajectory A (The Recovery Path—Developed):** Markets like France have surmounted the “Peak of Inflated Expectations” and are navigating the “Slope of Enlightenment.” The risks are known and managed via digital tools. The growth is L-shaped (steady, maturing) [11].
2. **Trajectory B (The Stagnation Plateau—Emerging):** Markets like Romania risk getting stuck in the “Trough of Disillusionment.” The removal of subsidies (a Governance shock) combined with high infrastructure risk (a Systemic shock) has caused a market correction. Without intervention to lower the  $k_m$  of grid and charging risks, these markets may regress to ICE/Hybrid dependency as a survival mechanism [5].

### 6.3. The Digital Multiplier Effect

The analysis confirms that the Digital Divide is not just an IT issue; it is a Supply Chain Risk issue. The high Detection ( $D$ ) scores in Romania (driven by low DESI rankings) act as a multiplier for all other risks.

- **Mechanism:** A manual supply chain ( $D = 7$ ) delays the response to a disruption. By the time the disruption is identified, it has cascaded through the system (The Bullwhip Effect), increasing the effective Severity.
- **Implication:** Investments in digital skills and “Lightweight” digitalization (e.g., cloud-based inventory tools for SMEs) in emerging markets are effectively “Risk Management” investments, offering high ROI in terms of RPN reduction [18].

## 7. Conclusions and Policy Recommendations

### 7.1. Synthesis

The transition to sustainable mobility is an asymmetric shock. This research, through the application of a hybrid FMEA-AHP framework, has quantified that asymmetry. The dif-

ference between a developed and an emerging market in the automotive green transition is not merely a difference in degree (slightly fewer chargers) but of kind (existential grid risk vs. operational software risk).

The **RPN Divergence** (Average RPN 63.4 vs. 259.6) and the **Market Maturity Coefficient** ( $k_m > 4.0$ ) serve as empirical evidence that the strategies which work in Paris or Berlin—such as aggressive Low Emission Zones and rapid subsidy phase-outs—are mathematically likely to cause market failure if applied without adaptation in Bucharest or Sofia.

## 7.2. Actionable Recommendations

### For Industry (OEMs & Tier-1s):

- **Bifurcated Strategy:** Do not apply a uniform risk management strategy globally. Based on the high  $k_m$  values identified for grid and infrastructure risks, policy interventions must be bifurcated. For emerging markets, EU Cohesion funds should be strategically redirected from traditional road infrastructure toward “Grid Resilience” and “Digital Leapfrogging” for Tier-2 suppliers. Maintaining “Subsidy Stability” is mathematically more valuable than the subsidy’s absolute magnitude in high-RPN contexts, as it reduces the Governance (G) risk associated with market volatility and boom–bust cycles. In developed markets, focus FMEA efforts on **Software/Cybersecurity** (S & D reduction). In emerging markets, focus on **Supply Chain Continuity and Infrastructure Partnership** (O reduction).
- **Digital Leapfrogging:** Actively support the digitalization of Tier-2/3 suppliers in emerging markets. Providing digital tools is cheaper than insuring against the bankruptcy of a critical supplier.

### For Policymakers (EU & National):

- **Targeted Infrastructure Funds:** Recognize that  $k_m$  for infrastructure is  $>8$ . EU Cohesion funds must be aggressively targeted at **Grid Modernization** in Eastern Europe, not just road building.
- **Subsidy Stability:** In emerging markets, stability is more valuable than magnitude. A consistent, moderate subsidy (to reduce Governance risk) is superior to a high, volatile one that creates boom–bust cycles.

### For Future Research:

- **Dynamic FMEA:** The industry must move from static spreadsheets to AI-driven, dynamic risk models that ingest real-time data (e.g., live SAIDI feeds, supplier financial health APIs) to update RPNs continuously. Future iterations of this model should leverage real-time data ingestion. For instance, integrating supplier financial health APIs can provide early warning signals for FM-03 (Insolvency), while live smart grid feeds can dynamically adjust the ‘Occurrence’ rating for FM-01 (Grid Overload) based on seasonal or hourly peak demands.

By acknowledging and quantifying these divergences, stakeholders can navigate the green transition not as a blind march into uncertainty, but as a calculated, engineered evolution toward a resilient and sustainable future.

(Note on Citations: References refer to the specific research snippets utilized to substantiate the data and theories presented in this manuscript.)

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