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Causes of automotive recalls and classification of product and process failures: evidence from Brazil, the European Union and the United States

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Abstract

There is growing international concern regarding product quality failures that compromise public safety, as evidenced by the increasing number of automotive recalls and the scale of affected vehicles. This study examines the phenomenon, evaluates potential responses and analyses regulatory frameworks in Brazil (BR), the European Union (EU) and the United States of America (USA). Where data were not readily available, they were obtained from official databases and via web-scraping, enabling the analysis and classification of 12,466 automotive recalls for the period 2011 to 2019. The results indicate that recall effectiveness is shaped by region-specific policy priorities and systemic factors. For Brazil, it is recommended that regulatory agencies be strengthened, nationwide periodic inspections be implemented, and advanced safety technologies be incentivised. For the United States of America, it is recommended that litigation-driven incentives be balanced, predictive analytics be expanded, and supply-chain oversight be reinforced. For the European Union, it is recommended that data reporting be harmonised, certification protocols for embedded software be developed, and cross-border enforcement mechanisms be strengthened. Across jurisdictions, the exchange of best practices is likely to improve product quality, reduce warranty costs, and mitigate risks to public safety. The findings indicate the absence of global standardisation in recall data, the greater severity of product recalls relative to process recalls, and the urgent need for coordinated strategies to reduce systemic failures. This research represents a comprehensive effort to classify and compare recall data from over 428,754,988 vehicles by cause, distinguishing between product and process recalls. Finally, the validation of web-scraping as a methodological tool demonstrates its potential applicability for future studies across diverse fields.

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1. Introduction

There is growing international concern about quality failures in products and services, particularly those that pose significant risks to public safety. Academic interest in this topic has increased accordingly, as evidenced by a sustained rise in studies of recalls.

This study examines automotive recalls in Brazil (BR), the European Union (EU), and the United States of America (USA) for the period 2011–2019.The analysis covers a range of vehicle types, including automobiles, pickups, motorcycles, mopeds, tricycles, quads, ATVs, motorhomes, trailers, lorries, buses, tractors, and special vehicles (NHTSA, 2014; European Commission, 2018c).

A figure illustrating the total number of vehicle recalls and the number of affected vehicles across the studied regions is provided (see Figure 1).

Because the EU recall database excludes pharmaceuticals, medical devices and foodstuffs, comparable entries from Brazil and the USA for these categories were omitted from the regional totals to ensure comparability.

The analysis identifies an upward trend in recall numbers until 2016; this increase may reflect strengthened regulatory

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oversight and the imposition of more stringent legal penalties on manufacturers for delayed reporting of safety defects.

The substantial number of recalls recorded in BR, the EU and the USA between 2011 and 2019 underlines the need for further investigation into the regulatory, industrial and reporting factors that influence recall incidence and effectiveness.

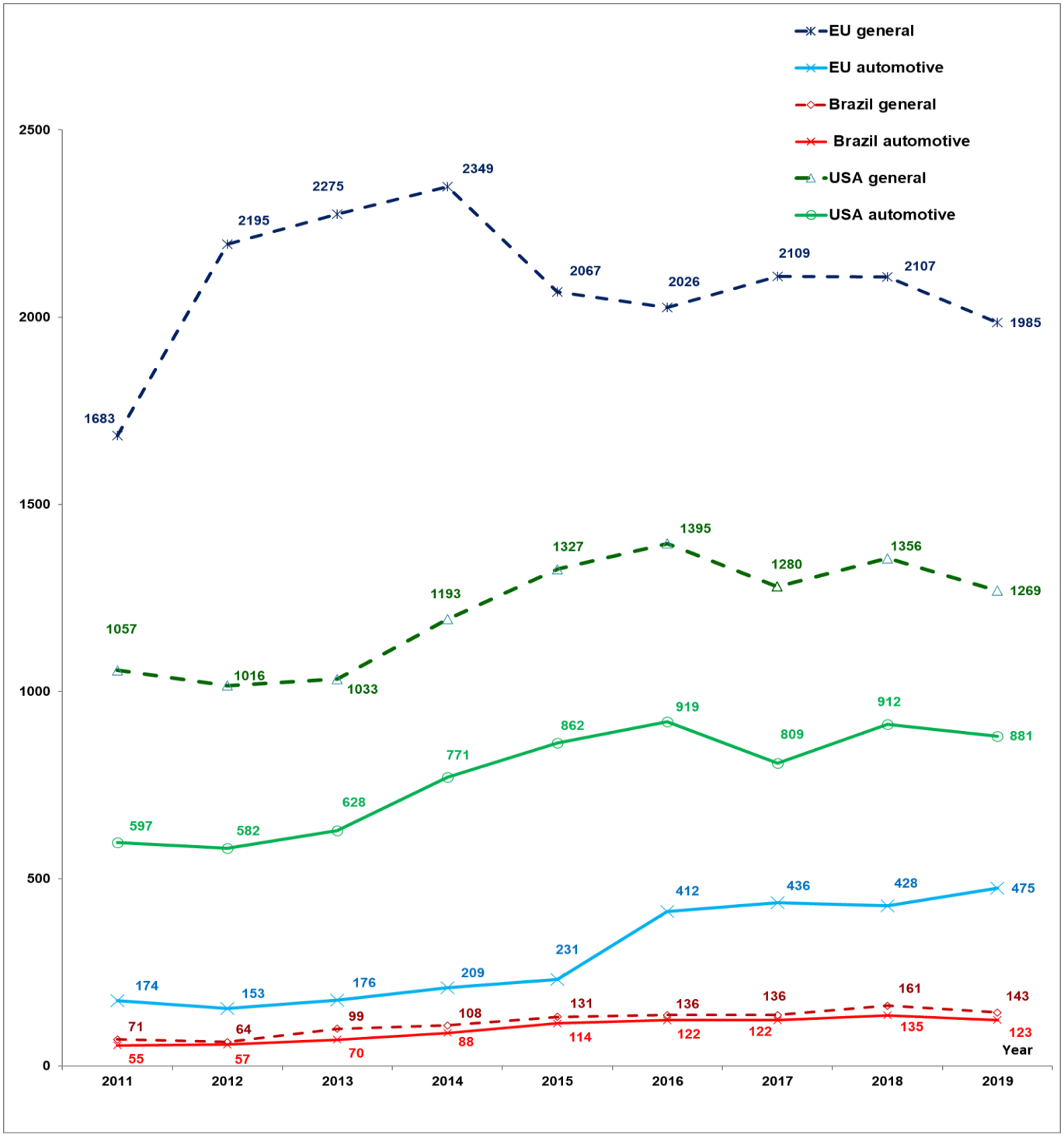


Fig. 1. Presents the number of recalls from BR, the EU and USA

Source: Own elaboration, data sources include: (Ministério da Justiça, 2017; 2020; 2020a; Secretaria Nacional do Consumidor, 2018; Brasil, 2018; Broughel and Ellig, 2018; CPSC, 2020; EPA, 2018a, 2018b; 2018c; European Commission, 2018b; 2020; FDA, 2020; NHTSA, 2020; USGC, 2020).

2. Literature review

Maruchecka et al. (2011) note that the increase in recall events has heightened public awareness of safety and protection. While product safety longstanding, its impact on the global supply chain and the creation or exacerbation of risks and security vulnerabilities is critically important. To safeguard against product liability issues, designers must anticipate even unlikely conditions of use (Babcock and Morse, 2002).

There is an increasing globalization of products manufactured by Original Equipment Manufacturers (OEMs), as well as of components provided by Tier 1 suppliers, which are distributed across multiple production facilities operated by automakers worldwide (Schniederjans & Khalajhedayati, 2021).

The use of identical components across various products from the same original equipment manufacturer (OEM) and from different OEMs significantly increases the risk of vehicle recalls.

A notable example is the Takata Corporation, whose airbags resulted in recalls affecting 19 manufacturers and over 41 million vehicles in the USA due to approximately 56 million defective Takata airbags (NHTSA, 2021).

Kalaignanam et al. (2013) conducted a study in the U.S. automobile industry utilizing 459 samples from 27 car manufacturers spanning the years 1985 to 2011. This research aimed to assess the direct impact of recalls on future accidents, as well as the influence of recalls on future product reliability.

Companies' motivation to enhance product reliability post-recall is influenced by their existing quality levels. Following a recall, lower-quality brands achieved a product reliability improvement index of 0.773, while higher-quality brands realized only an index of 0.322 (Kalaignanam et al., 2013).

The costs associated with a recall far exceed those of merely correcting a product nonconformity (Souiden and Pons, 2009; Slack et al., 2010; Kumar and Schmitz, 2011; Kim, Koenigsberg, Ofek, 2022). Additional factors to consider include the brand's association with quality issues, customer dissatisfaction with defective products, the inconvenience of product repairs, potential risks to safety, market share loss, legal penalties, and civil liability, among others (Souiden and Pons, 2009; Baraldi and Kaminski, 2018).

2.1. Safety

A safe product is defined as one that, when used under normal or reasonably foreseeable conditions, does not pose any risk of injury or damage to the health of users or property (Official Journal of the European Communities, 2002; Zhu et al., 2018).

Kalaignanam et al. (2013), examined the direct impact of recalls on future accidents and the indirect effects on product reliability within the U.S. automotive industry for 1985–2011. Building on this research, Eilert et al. (2017) assessed the severity of recall-related issues in the U.S. and the time-related implications between 2000 and 2017.

Numerous automotive manufacturers have experienced significant quality issues, resulting in loss of life (Maiorescu, 2016; Committee for Commerce, Science and Transport, 2019; Schniederjans and Khalajhedayati, 2021). Furthermore, it is essential to acknowledge the broader social consequences of recalls, such as substantial financial losses, industry closures, and employee layoffs (Janssen et al., 2015; Conner and Wanasika, 2018; Nassar et al., 2020).

A study on safety recalls in motor vehicles conducted in the United Kingdom revealed that out of 23.1 million vehicles registered between 1992 and 2002, 10.8 million were recalled, accounting for 47% of all registered vehicles during that period (Bates et al., 2007).

The Consumer Product Safety Commission (CPSC) estimates that consumer product incidents cost the U.S. economy over US$1 trillion annually (CPSC, 2018a).

Companies are vulnerable to variations in product quality, and despite their best efforts, some product failures can breach internal quality assurance measures. Quality is a critical and strategic focus for companies (Mallik, 2023). According to Zhu et al. (2018), hundreds of millions of products are recalled each year for safety reasons

Zhu et al. (2018) also note that product safety is often addressed and improved primarily through information gathered from external sources, such as customer feedback, organized consumer interventions, lawsuits, and political lobbying. They argue that there are "too many recalls, too little research".

A notable example is the General Motors Corporation (GMC) ignition switch recall, which unfolded over nearly a decade, resulting in over 30 million vehicles recalled, multiple fraud investigations, US$900 million in damages, and links to the deaths of over 100 individuals (Eifler and Howard, 2018; Conner and Wanasika, 2018) (see Figure 2).

An abnormal increase in recalled vehicles in the USA was observed between 2014 and 2016 when compared to the number of newly licensed motor vehicles. This surge can be attributed to specific recalls involving large volumes of vehicles during this period.

Two significant recalls alone accounted for 30 million vehicles in the GMC ignition switch recall and 41.6 million vehicles in the Takata Corporation airbag recall, totalling 71.6 million vehicles.

Another serious issue associated with the high volume of motor vehicle recalls is that many consumers do not have their vehicles repaired, even after being notified of the risks.

Schoettle and Sivak (2020) conducted a national survey in the USA to explore the reasons behind consumer non-compliance with safety recalls and identify measures to increase compliance.

The survey revealed that 20% of vehicle owners do not respond to recall notices. The primary reasons cited for this non-compliance include:

- 37% said that it is difficult to be without a vehicle;
- 38% said they are concerned about the dealership trying to sell more repairs during their visit;
- 36% said the wait for repairs was too long.

Industries typically prioritise cost reductions, often offering economic incentives, but rarely do the same for improvements in product reliability (Levin, 2000).

A pressing question is why industries do not enhance product quality before issues emerge but only respond after problems are identified?

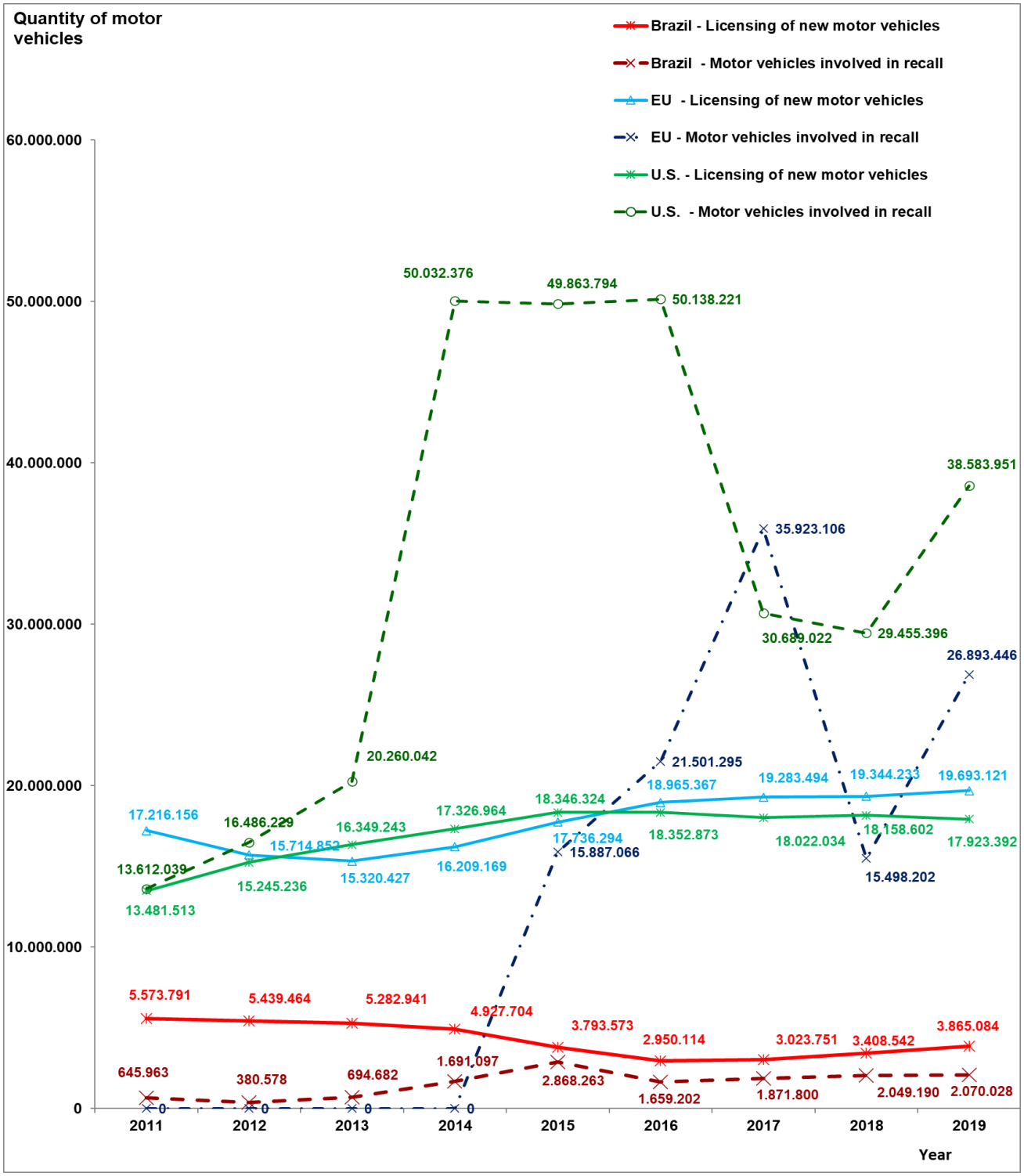


Fig. 2. illustrates the number of licensed motor vehicles in comparison to those recalled from 2011 to 2019.

Source: Adapted from Maione, Kaminski, and Baraldi (2021). Figure 2 used data from: (ABRACICLO, 2020; ANFAVEA, 2020; ACEM, 2019; ACEM, 2020; Brasil, 2018; Broughel and Ellig, 2018; CPSC, 2020; Eifler and Howard, 2018; EPA, 2018b; 2018c; European Commission, 2020; 2021; FDA, 2020; MIC, 2020; Ministério da Justiça, 2017; 2020; 2020a; Motorcycles Data, 2020; NHTSA, 2020; 2020a; OICA, 2020; Secretaria Nacional do Consumidor, 2018; USGC, 2020).

2.2. Causes for a recall

Recalls can be categorised into two main causes: defects resulting from failures in the Product Development Process (PDP) and/or failures in the Manufacturing Process Development (MPD), (Hora et al., 2011; Mackelprang et al., 2015) Baraldi and Kaminski, 2016; Eilert et al., 2017).

Failures in PDP may arise from errors in development, product specifications, validation, or testing. Similarly, failures in MDP can result from errors during the development of manufacturing processes, inadequate process control planning, defects in manufacturing methods, poor storage practices, damage during distribution, or the use of defective raw materials (Baraldi and Kaminski, 2016).

Global motor vehicle manufacturers face increasing pressure to manage a growing diversity of parts and complex manufacturing processes, in addition to engaging with both internal and external stakeholders in a global production network (Haefele and Westkämper, 2014; Shi et al. 2020).

Deliberate innovation begins with analysing opportunities that must be systematically evaluated (Drucker, 2017). This encompasses New Product Development (NPD) and manufacturing processes, which should be meticulously planned to ensure products meet predetermined quality and variation standards.

Ibusuki and Kaminski (2007) emphasise this notion in their research, demonstrating the significance of aligning product development with quality, cost, and functionality in accordance with consumer values.

Furthermore, automotive companies are increasingly focusing on ergonomic aspects. Ergonomics has been shown to yield benefits for both companies and employees, including disease prevention, reduced absenteeism, enhanced productivity, improved product quality and quality of life for workers (Baraldi and Kaminski, 2011).

2.3. Legislation

Product safety is central to industry regulations focused on internal processes, such as Good Manufacturing Practice (GMP) and Good Laboratory Practice (GLP) in the pharmaceutical sector (Zhu *et al.*, 2018). Similar standards should apply to motor vehicle manufacturers.

2.3.1. Recall in BR

The mission of the Brazilian Ministry of Justice is to guarantee and promote citizenship, justice, and public safety through collaborative actions between the state and society (Brasil, 2018a).

The Ministry of Justice Ordinance No. 487, dated 15 March 2012, regulates the procedure for notifying consumers or recalling products and services deemed harmful or dangerous after their entry into the consumer market (Brasil, 2012).

2.3.2. Recall in the EU

The European Commission establishes general EU product safety rules through Directive 2001/95/EC of the European Parliament and the Council dated 3 December 2001 (European Commission, 2018a).

National authorities within the EU are responsible for imposing sanctions on products as necessary and for notifying the Rapid Alert System (RAPEX) about dangerous non-food products (European Commission, 2018a).

2.3.3. Recall in the USA

To enhance motor vehicle safety, the US Congress enacted the National Traffic and Motor Vehicle Safety Act of 1966 (15 U.S.C. 1381) on 9 September 1966 (Rupp and Taylor, 2002).

This act required the Department of Transportation to establish safety standards for motor vehicles and equipment to mitigate traffic accidents, injuries, and fatalities (Rupp and Taylor, 2002).

Subsequently, the National Highway Traffic Safety Administration (NHTSA) was established, with responsibilities including setting federal safety performance standards for vehicles and equipment, ensuring compliance with these standards, investigating potential safety violations, and overseeing recall campaigns in cases of non-compliance (Rupp and Taylor, 2002).

The USA utilizes various federal agencies to alert the public about dangerous or defective products. Six federal agencies with distinct jurisdictions collaborated to create the website <www.recalls.gov>, facilitating public access to relevant information (Recalls, 2018).

2.3.4. Main laws and regulations of regions

The evolution of relevant recall legislation has varied across the regions studied. Table 1 summarises the primary laws and regulations on this subject.

Table 1. Main recall laws and regulations in the three regions

Year	BR	EU	USA	Law	Description
1966			x	National Traffic and Motor Vehicle Safety Act (9 September 1966)	Gives NHTSA the automotive vehicle safety authority, including recalls disclosure and making them mandatory in case of health risks
1978			x	U.S. Code: Title 49 -Transportation (17 October 1978)	Dissertation on permanent US laws related to transportation, including recall procedures

1985	x		Protection Council – Decree No 91469 (24 July 1985)	Disciplines the public civil action for liability for damages caused to the environment, to the consumer, to goods and rights of artistic, aesthetic, historical, touristic and landscape value and takes other measures
1990	x		Consumer Protection Code - Law 8078/1990 (11 September 1990)	Provides for consumer protection and other measures, including mandatory recall and its rules
1993	x		Law 8656/1993 (21 May 1993)	Changes the provision of fines and penalties, in case of violation, of Law 8078/1990
1997	x		National Consumer Protection System - Law 2181/1997 (20 March 1997)	Provides for the organization of the National Consumer Protection System - SNDC and establishes the general rules for the application of administrative sanctions provided for in Law No. 8078
2001		x	Directive 2001/95/EC - General Product Safety Regulations or GPS Regulations (3 December 2001)	Establishes safety rules and standards for non-food products in the EU, including mandatory recalls
2019	x		Joint Ordinance No 3 - 2019 (1 July 2019)	Disciplines the procedure of calling consumers - recall, for replacement or repair of vehicles that are considered harmful or dangerous after their introduction into the consumer market.
2019	x		Joint Ordinance No 618 - 2019 (1 July 2019)	Disciplines the communication procedure of the harmfulness or dangerousness of products and services after being placed on the consumer market

Source: Adapted from Maione *et al.* (2023), data sources include: (Brasil, 1985, 1990, 1993,1997, 2019; 2019a; European Union, 2001; NHTSA, 2020b; U.S. A., 2023).

3. Methodology and databases

This research is classified as exploratory, aiming to enhance understanding of the problem, clarify its nuances, and develop relevant hypotheses (GIL, 2002). Blessing and Chakrabarti (2009) describe this approach as a comprehensive study of an existing situation to facilitate model development. Such research is particularly beneficial for establishing theoretical underpinnings when the existing understanding is limited. It encompasses both a literature review and an empirical study, generating and/or evaluating contributions while yielding results (Blessing and Chakrabarti, 2009).

The pilot study initially focused on Brazil, establishing the foundation for the research design. Subsequently, the scope was expanded to include additional regions to enhance the comparative aspect of the study. Selection criteria emphasised regions with global representativeness, publicly accessible governmental databases, and data availability within comparable temporal windows. Regulatory and market diversity were also considered to ensure methodological rigour and broaden the applicability of the findings.

Nonetheless, the study is limited by incomplete global representativeness. Despite efforts to include diverse regions, some areas remain underrepresented due to data constraints, which may affect the generalisability of the results.

The rapid evolution of vehicle technologies, encompassing advanced electrical architectures, sophisticated safety systems, and increasingly stringent regulatory landscapes, has heightened the need for systematic approaches to classifying and analysing vehicle system failures. Accurate categorisation of failure notifications is essential for diagnostics, safety assurance, regulatory compliance, and the development of predictive maintenance strategies (Jun et al., 2025).

3.1. Automotive recall database

The importance of utilizing data for generating reports and conducting analyses is increasingly critical. Contemporary engineering faces a significant challenge regarding technological advancement and machine learning: the reliability of databases (Maione et al., 2023; 2023a).

The necessity for solid, complete, and clean data is paramount. Thorough research allows for innovative developments, enabling new functionalities within the realms of statistics and machine learning since their inception (Imielinski and Mannila, 1996).

In studying automotive recalls, the situation is no different. The datasets utilized to collect references and develop models must be meticulously curated to facilitate the construction of entities that are accurately aligned with the real-world scenarios under investigation.

Moreover, for a comprehensive analysis, the datasets employed should be as extensive as possible, containing the maximum number of relevant fields within the constraints of source availability and study scope.

In technical terms, the volume of data related to recalls is relatively limited in terms of entries. Thus, for this study, data were stored in Microsoft Access databases and presented in an

intuitive format using Microsoft Excel for analysis (Maione et al., 2023a).

Each geographical area presents unique characteristics and various levels of restrictions on data sources. Therefore, it is essential to discuss the acquisition of the datasets upon which the models were built, enhancing information clarity and ensuring greater replicability, while also facilitating ongoing improvements in the research (Maione et al., 2023).

3.1.1. Brazil

In the Federative Republic of Brazil, relying solely on databases provided by the National Consumer Secretariat (SENACON, 2020a) was insufficient.

To augment the data, a web-scraping technique was employed to extract additional information from the national agency. This technique functions as a data mining method that allows for the extraction of information from websites, converting it into a structured format suitable for analysis through a Python script on the Brazilian entity Information Portal. This portal enables users to access sequential records (SENACON, 2020b).

The programme automates the process of reading all records on the platform and transcribing them to a local database, effectively conserving time and reducing the risk of human error (Maione et al., 2023a).

The final dataset includes fields such as recall title, protocol number, start date, description, corrective measures, accident report, components, verification date, defect type, risk details, risk implications, sector, product type, manufacturer, country of origin, export country, model, year of manufacture, affected quantity, and a link to the call on the portal (Maione et al., 2023).

3.1.2. European Union

Data acquisition from the European Union utilised the alert search tool on the RAPEX platform, the Rapid Alert System for dangerous non-food products, provided by the European Institute. This facilitated the extraction of data for constructing the models (European Commission, 2020).

Unlike the Brazilian case, the EU does not disclose the number of affected products, complicating the construction of more detailed models. Attempts to create a Python script to pull this information, as done for the Brazilian database, proved ineffective, since this information is not available on the platform.

When juxtaposed with the Brazilian and North-American experiences, varying data distribution methods may highlight significant causal variables worthy of study, particularly concerning regional legislative differences in data openness (Maione et al., 2021).

The dataset provided includes fields such as year of the recall, week of the recall, type of alert, product user, alert ID, country where the alert was issued, category, product type, brand, product name, model number, barcode, OECD portal category, description, country of origin, counterfeit presence, risk type, technical defect description, risk, measures taken by the notifying country, locations where the products were found, whether further actions were taken, company registration page, case link, company code, production dates, and package description (Maione et al., 2023). Note that the EU database contains information beyond solely motor vehicles; and thus additional filtering is required when conducting analysing data (Maione et al., 2023).

3.1.3. United States of America

In contrast to the other regions, the United States, through the Office of Defects Investigation (ODI) of the NHTSA, provides an official database for model-building covering the period from 1966 to 2020 (NHTSA, 2021).

This database includes fields such as campaign ID for NHTSA, campaign ID for the manufacturer, vehicle manufacturer, vehicle model, model year, recall type, affected component, start date, end date, estimate number of affected units, recall initiative classification, manufacturer associated with the recall, notification date, defect description, summary of the recall, and remedial approach to the problem the latter three being generated by the developed script (Maione et al., 2023).

3.1.4. Synthesis of databases

To enhance the visualisation of the data obtained through the aforementioned techniques for each region, Table 2 presents the aligned fields. This table aligns the fields of each database with the target, indicating which fields are present or absent across the three datasets of interest (Maione et al., 2023) (see Figure 3).

Table 2. – Comparison of databases by region

Field	BR	EU	USA
Recall Title	Present	Present	Present
Identification	Present	Present	Present
Risk Description	Present	Present	Present
Type of Product	Present	Present	Present
Manufacturer	Present	Present	Present
Country of Origin	Present	Present	Absent
Model	Present	Present	Present
Year of Manufacturer	Present	Present	Present
Number of Affected	Present	Absent	Present
Link to Source	Present	Present	Absent
Date of Recall	Present	Present	Present
Type of Alert	Absent	Present	Present
Measures Taken	Absent	Present	Present
Affected Component	Present	Present	Present

Source: Adapted from Maione et al. (2023).

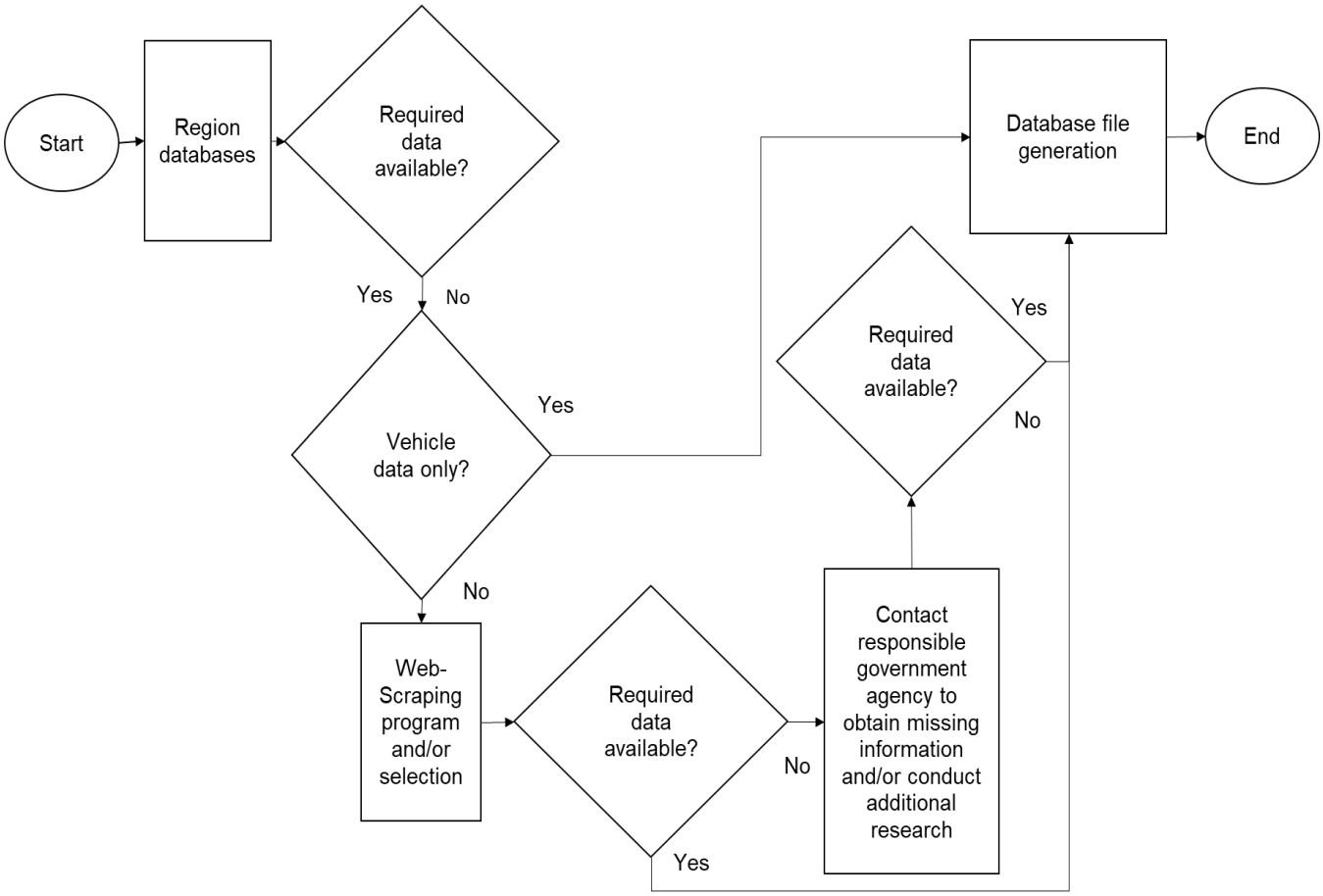


Fig. 3. Flowchart for obtaining data

3.2. Classification and validation procedures

Recalls were classified using a predefined codebook (Appendices A–B). To ensure full traceability, the taxonomy in Section 3.2 and the codebook in Appendices A–B have been reconciled so that every category name, definition, inclusion/exclusion criterion and illustrative example in the appendices corresponds exactly to the terms and rules used in the methodological description below. For clarity, each category in the codebook is assigned a unique alphanumeric identifier (for example, P 01 for product categories and R 01 for process categories) and these identifiers are referenced throughout the coding logs and validation records.

Product recalls. Keywords and synonyms were used to identify underlying defects and failure modes, including (a) regulatory non-compliance and indicator/instrumentation failures; (b) calibration and system calculation errors; (c) lighting and signalling faults; (d) structural and fastening defects; (e) restraint system (airbag) deployment anomalies and related component degradation; (f) control module and warning system vulnerabilities; and (g) electrical system failures such as cable and harness abrasion, component overheating, inadequate circuit protection, sensor and circuitry malfunctions, ignition and power supply anomalies, programming and connector faults, and related design errors. Each of these failure modes maps to one or more discrete product categories in Appendix A; cross references to the category identifiers are provided.

Process recalls. Keyword sets captured manufacturing and assembly origins, including process design flaws, dimensional non-conformities, installation and torque errors, deficiencies in heat or surface treatment, bonding and welding defects, quality control failures, missing or incorrect components, inadequate wiring and routing, and other specification or material treatment deficiencies. Each process failure mode maps to a discrete process category in Appendix B and is assigned a unique identifier for auditability.

Reproducibility and audit trail. An operational protocol specifies explicit decision rules for mapping notification text to categories, requires manual application of the codebook, and mandates that every label assignment be recorded in a coding log which includes: the recall identifier, assigned category identifier(s), primary/secondary designation, coder identifier, timestamp, and the supporting excerpt(s) from the notice used to justify the assignment. Two independent coders validated a random control sample comprising at least 20% of the dataset; disagreements were resolved by consensus and documented in the adjudication log. Inter-rater reliability for the validated sample was Cohen's $\kappa = 0.762$. Following recommendations from Krippendorff (2013), the complete reconciled codebook, the decision rules, the keyword dictionaries,

and the coding and adjudication logs are provided to facilitate transparency and replication.

3.2.1. Decision Rules for Classification

3.2.1.1. Primary assignment rule

Product recall: Assign when the notice identifies a defective component, system behaviour, or safety function that is attributable primarily to design, material selection, or component failure. (Use product category identifiers P xx.).

Process recall: Assign when the notice attributes the defect primarily to manufacturing, assembly, material treatment, or process control deficiencies. (Use process category identifiers R xx.).

If the notice explicitly states a root cause, the root cause stated in the notice determines the primary assignment.

3.2.1.2. Keyword and functional cues

Product indicators

Keywords: airbag; inflator; ignition switch; ECU (Electronic Control Unit); battery; warning lamp; deployment; stall; FMVSS (Federal Motor Vehicle Safety Standards citation).

Interpretation: Terms that directly reference vehicle components, system behaviours, safety functions, or regulatory citations; these cues indicate defects attributable to component design, materials, or in-service system performance. (Map to product categories P 01 … P nn as specified in Appendix A.).

Process indicators

Keywords: assembly; torque; welding; stamping; heat treatment; out-of-spec; manufacturing defect; crimp; adhesive application.

Interpretation: Terms that denote manufacturing, assembly, or material-treatment activities and deviations; these cues indicate defects originating from production or process control. (Map to process categories R 01 … R nn as specified in Appendix B.).

Keyword matching is supplemented by syntactic and semantic parsing rules to reduce false positives (for example, distinguishing "airbag sensor replaced during service" from "airbag sensor failed in service"). All automated matches require manual confirmation by a coder.

3.2.1.3. Hierarchy and override rules

Regulatory override: Any explicit indication of regulatory non-compliance (for example, citation of FMVSS) shall be classified under Regulatory and Compliance Failures (P REG) within the product recall taxonomy, even when a manufacturing or process cause is also described. The regulatory override is recorded as a primary label only when the notice emphasises statutory non-compliance as the principal issue.

Root cause precedence: When a notice attributes a defect to both product and process factors, classification shall follow the root cause as stated in the notice (for example, "weld failure caused fuel leak" → assign Process: Bonding and Welding Problems (R BOND)). If the notice is ambiguous about root cause, apply the Default rule for vague text (see below).

Safety critical override: Notifications that describe occupant protection outcomes (for example, airbag non-deployment or misclassification) shall be classified as Restraint System Malfunctions (P REST) irrespective of any upstream process attribution only when the safety outcome is the primary focus of the notice.

Default rule for vague text: If a notice is non-specific (for example, "system malfunction") and no system is identified, default assignments shall be Electrical System Vulnerabilities (P ELEC) for product recalls and Manufacturing Process Failures (R MFG) for process recalls, pending further review or adjudication. All default assignments must be flagged in the coding log for subsequent expert review.

3.2.1.4. Multi-labeling

When a single recall notice legitimately implicates multiple independent failure modes, assign all applicable category labels and record them with their identifiers. Designate one label as the primary classification according to the relative safety impact, and document the primary designation and its justification, including supporting text excerpts or evidence, in the coding log. Secondary labels must be ordered by descending relevance and similarly justified.

3.2.1.5. Coding Method

Manual coding was employed. Trained human coders applied the reconciled codebook to an initial batch of recall notifications to establish reference labels and to iteratively refine the keyword dictionaries and decision rules. Coding was conducted using an Excel-based platform configured to record assigned labels, coder identifiers.

4. Results

The majority of recalls do not pertain to vehicles produced in the same year they are disclosed, rendering comparisons between the number of recalled vehicles and the number of newly licensed vehicles ineffective.

To enhance comparability, was developed a factor was developed representing the number of vehicles involved in recalls divided by the fleet of vehicles used in the preceding year, as shown in Equation 1 and Figure 4.

Equation 1 – was used to calculate this recall factor:

$$Year_{current}\ region = \frac{Number\ of\ vehicles\ involved\ in\ recalls\ in\ the\ region}{Vehicle\ fleet\ in\ the\ previous\ year\ in\ the\ region} =$$

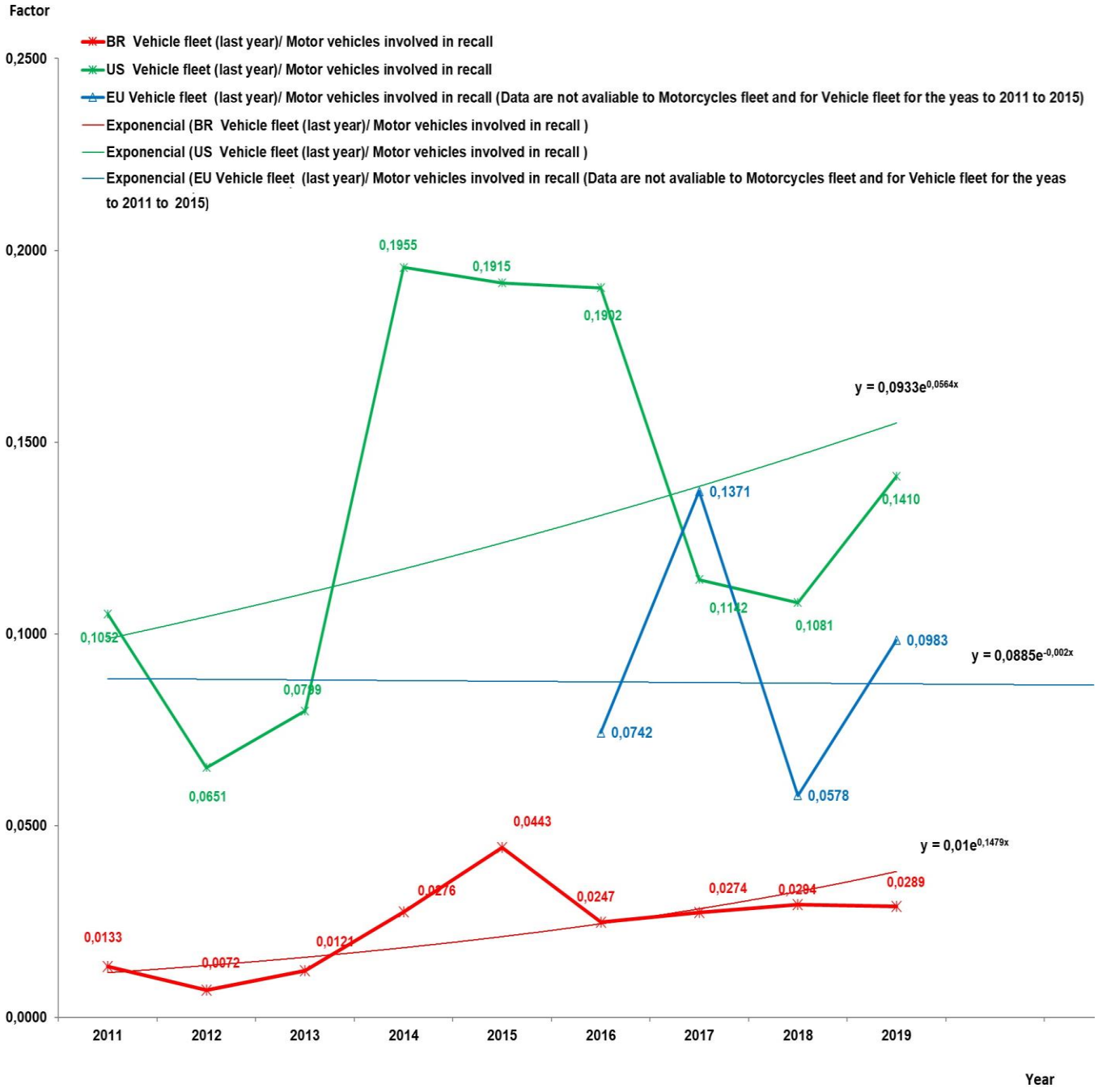


Fig. 4. Recall factor - number of vehicles involved in recalls by region from 2011 to 2019

From 2011 to 2019, both Brazil (BR) and the USA exhibited an exponential upward trend in the number of vehicles involved in recalls. In contrast, the EU demonstrated stability in the number of vehicles affected, with a slight downward trend likely due to the limited period analysed.

The arithmetic means of the recall factor (number of vehicles involved in recalls divided by the fleet of vehicles in use the previous year) during the study period were 0.029 for BR, 0.1325 for the USA, and 0.0919 for the EU.

Next, an examination of each of the 12,466 recalls was conducted, classifying them by cause.

4.1. Brazil

Figures 5 and 6 present the graphs for BR and the USA.

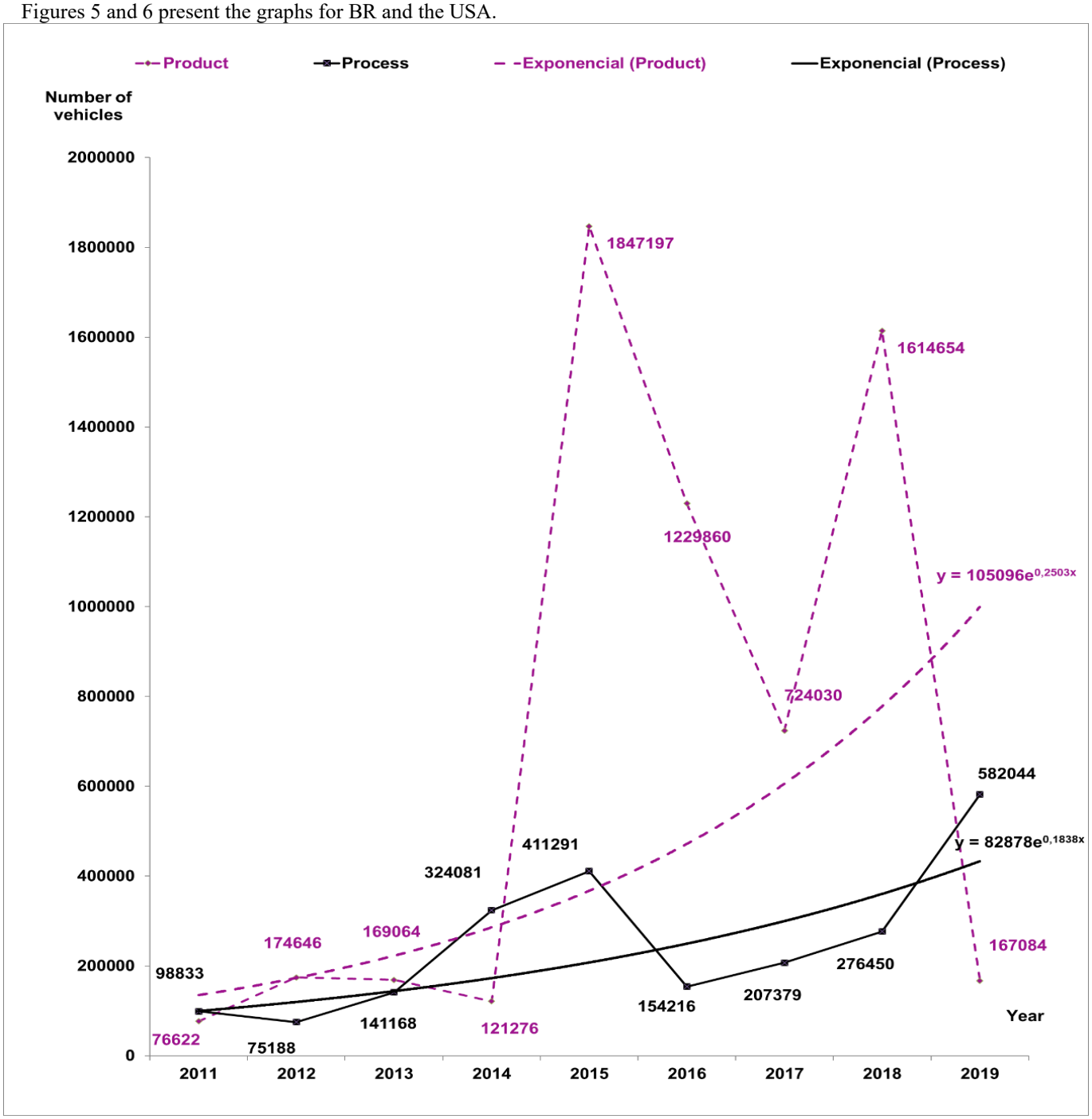


Fig. 5. Motor vehicle recall causes from 2011 to 2019 in BR

In the studied period, 8,395,083 vehicles were subject to recalls in Brazil, with 6,124,433 units (72.95% of the total) related to product recalls, and 2,270,650 units (27.05%) related to process recalls.

4.2. United States of America

During the same period, 299,225,438 vehicles in the USA were recalled, with 254,366,106 units (85.01%) associated with product recalls, and 44,859,332 units (14.99%) related to process recalls.

Due to the EU's lack of data on the number of vehicles involved in each recall, creating a regional graph was not feasible.

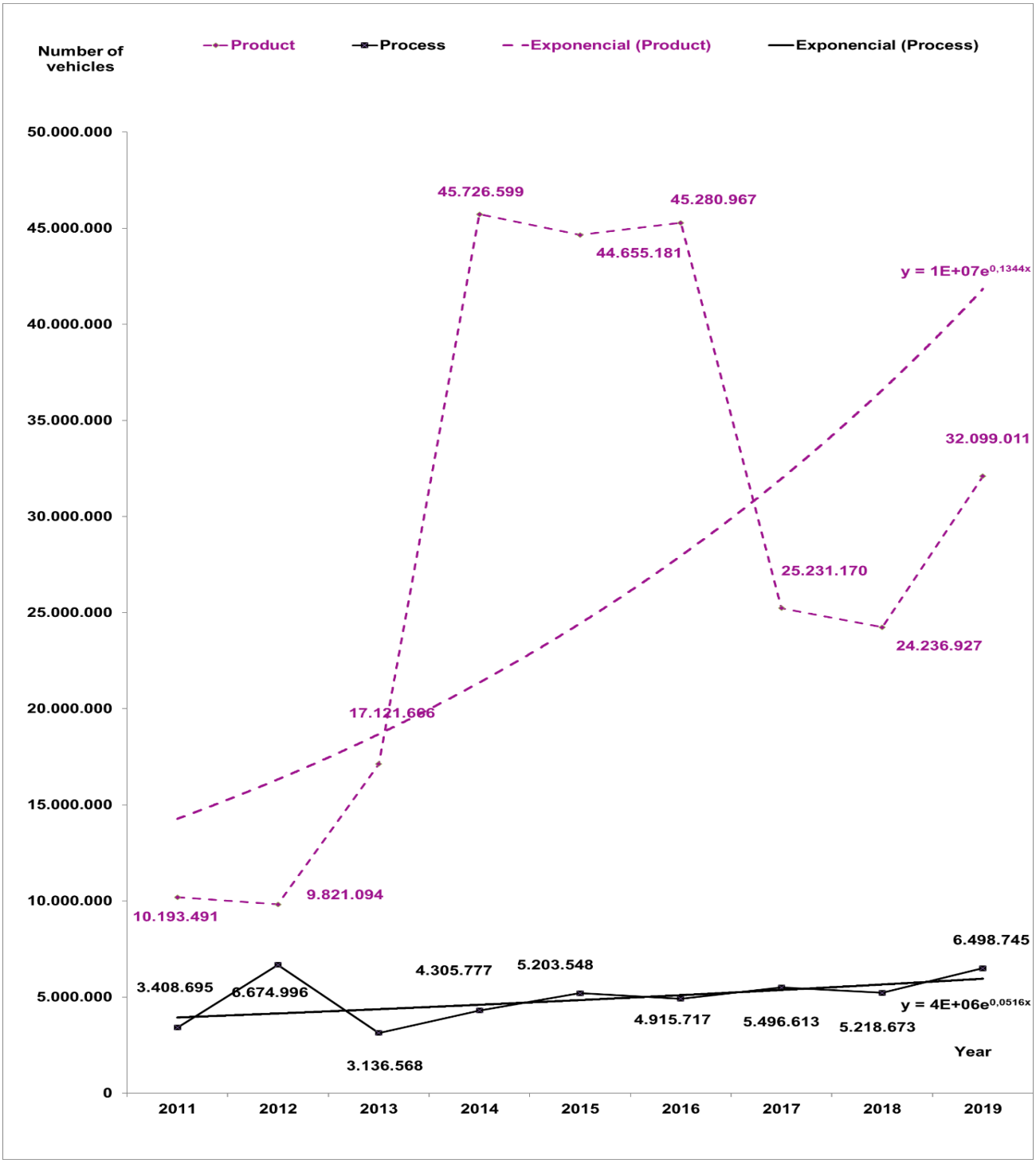


Fig. 6. Motor vehicle recall causes from 2011 to 2019 in the USA

5. Hypotheses and Determinants of Automotive Recall Factors

This section introduces the hypotheses, together with their analyses and comparative data, concerning the determinants of the automotive recall factor in the regions under study. It highlights the structural differences that plausibly account for the disparities in the automotive recall factor across the three regions analysed. Table 3 provides a summary of the principal factors discussed.

Table 3. Comparative Factors: Brazil, United States, and European Union

Factor	Brazil	United States	European Union
Regulatory rigour	Medium	High	High
Litigation culture	Low	Very high	Medium
Industrial structure	Subsidiaries	Local headquarters	Local headquarters
Transparency and oversight	Medium/low	High	High
Approval standards	Flexible	Strict	Strict
Compliance cost	High	High	High
Agency capacity	Limited	Elevated	Elevated
Adoption of advanced technologies	Slow	Rapid	Rapid
Recall communication	Limited	Comprehensive	Comprehensive
Model life cycle	Long	Short	Short
Supply chain	Fragmented	Integrated	Integrated
Periodic vehicle inspection	Not mandatory	Partial	Mandatory
Incentive to report defects	Low	High	High
Fleet composition	Basic	Diverse	Diverse
Industrial policies	Protectionist	Variable	Harmonised
Recall practices	Restricted	Comprehensive	Comprehensive
Media/NGO pressure	Low	High	Medium/high
Calculation methodology	Variable	Standardized	Variable

Before presenting the hypotheses, it is important to emphasize that a lower recall rate should not be interpreted as evidence of superior recall effectiveness without additional assumptions; such a pattern may instead reflect underreporting, limited detection capacity, heterogeneity in disclosure practices, or variation in regulatory enforcement. Accordingly, the determinants discussed below are framed as testable hypotheses that require rigourous empirical evaluation.

In the United States, the NHTSA enforces recalls under long standing legislation and has authority to mandate corrective actions and require detailed reporting, which is consistent with greater public traceability of recall events (NHTSA, 2026). Hypothesis 1: differences in recorded recall incidence are associated with variation in the rigour and scope of vehicle safety regulations across regions; this relationship is conditional on reporting rules and enforcement intensity.

EU vehicle regulation is coordinated through harmonised type approval rules and the General Safety Regulation, which mandates certain advanced driver assistance systems (ADAS) (European Commission, 2019). Hypothesis 2: incorporation of ADAS increases system complexity and is associated with a higher incidence of software related recalls, conditional on detection and reporting practices.

Brazil's Consumer Protection Code establishes mandatory recalls and supplier liability; oversight is more decentralised and some enforcement capacities are reported to be more limited relative to other jurisdictions (Brasil, 1990). Airbags and ABS were mandated in Brazil in 2014; the EU's regulatory timeline includes earlier and more prescriptive requirements for certain advanced safety systems.

Stricter regulatory frameworks and higher technical standards may be associated with greater defect detection and higher recorded recall frequency; alternative explanations (e.g., reporting practices, market composition) should be evaluated (Maione et al., 2023). Hypothesis 3: consumer culture and litigation propensity influence manufacturers' incentives to detect, disclose and remedy defects and recall practices.

The US legal environment possesses a strong litigation culture, reinforced by class action lawsuits (Abdul, Majid & Bapuji, 2024). Hypothesis 4: higher litigation risk and collective redress mechanisms incentivise manufacturers to disclose and remediate defects more proactively.

Hypothesis 5: in the EU, non-litigation pressures (NGOs, media, consumer agencies) and administrative sanctioning mechanisms increase corporate transparency and precautionary responses; the magnitude of these effects likely varies by country and sector.

In Brazil, litigation culture is less developed and access to justice is constrained by economic, bureaucratic and cultural barriers; lawsuits are typically individualised. Limited collective litigation pressure may reduce incentives for large scale preventive recalls, which could contribute to lower recorded recall incidence, subject to alternative explanations.

The USA and EU markets include major locally headquartered manufacturers with integrated R&D and production. (Maione et al., 2023). Industry structure (e.g., presence of integrated domestic manufacturers versus subsidiaries) affects recall detection, traceability, and response capacity.

Brazil's market has a high share of multinational subsidiaries and fewer large independent domestic manufacturers. Hypothesis 6: markets dominated by subsidiaries face coordination or investment constraints that reduce priority for local technological updates and rapid recall responses; this should be empirically tested.

Transparency in recall disclosure and the enforcement capacity of regulatory agencies differ markedly across regions. In the United States, the NHTSA provides comprehensive public databases and real-time monitoring through the Office of Defects Investigation, enabling early detection of systemic failures (NHTSA, 2026).

In the European Union, RAPEX centralises recall alerts, though the absence of unit-level data limits comparability with

the US; nonetheless, detailed reporting requirements and coordinated oversight ensure the transparency and traceability (European Commission, 2019).

In Brazil, recall information is available through National Consumer Secretariat (Senacon), but data are less granular and less timely, with oversight constrained by technical, budgetary, and staffing limitations, as well as fragmented database integration across government levels.

Certification and homologation standards for vehicle components differ across regions, and may shape recall incidence. In the European Union, type approval is centralised under harmonised regulations, requiring extensive laboratory and field testing across emissions, safety, and electromagnetic compatibility (European Commission, 2019).

In the United States, the Federal Motor Vehicle Safety Standards (FMVSS) establish globally recognized requirements for each vehicle system; although homologation is decentralised, enforcement is strict, and the NHTSA can mandate compulsory recalls for non-compliance (NHTSA, 2026).

In Brazil, homologation is overseen by National Traffic Department (Senatran) and National Institute of Metrology, Quality and Technology (Inmetro), based on national standards and occasionally aligned with U.S. or EU norms. Greater flexibility in accepting foreign standards and less frequent conformity inspections particularly for imported or small-series vehicles may result in weaker enforcement and lower regulatory rigour (TÜV Rheinland, 2025).

In the United States and the European Union, the high cost of non-compliance stemming from fines, litigation, reputational damage, and market loss encourages recalls as preventive measures despite their expense (Bowdle & Kamal, 2025).

Economic incentives and expected compliance costs influence manufacturers' decisions about whether and when to initiate recalls. The effectiveness of recall campaigns is associated with regulatory agencies' technical capacity, institutional autonomy, and sanctioning authority; this relationship should be tested controlling for market size and reporting rules (Raithel, Hock & Mafael, 2024).

NHTSA has dedicated funding, specialised staff, and statutory powers to impose fines and mandate recalls; these institutional features are documented in US legislation and agency reports.(U.S.A.; 2023).

EU governance combines Commission-level rules and national agency cooperation, including mechanisms that can restrict commercialisation of non-compliant vehicles.(European Union, 2019).

In Brazil, Senacon and Inmetro have statutory roles in consumer protection and conformity assessment (Brasil, 2019a). Hypothesis 7: budgetary, technical and institutional coordination constraints reduce their operational effectiveness; this should be empirically evaluated.

In the European Union, mandatory systems such as automatic emergency braking, lane keeping assistance and driver fatigue detection increase vehicle complexity and the likelihood of software and sensor related recalls (European Commission, 2019; Gruber et al., 2021). Hypothesis 8: adoption of advanced safety technologies affects recall incidence, with effects depending on detection, reporting and software update practices. In the US, high electronic integration and connectivity may increase exposure to certain failures; connected vehicle telemetry could improve early detection in some cases, but the extent of this effect requires empirical validation (Bansal & Kockelman, 2017).

Hypothesis 9: slower ADAS adoption in Brazil lowers the incidence of technology related recalls while potentially obscuring detection of other safety problems in less instrumented vehicles; this trade off should be tested with fleet level data (ANFAVEA, 2024).

Recall effectiveness is expected to depend on the reach and accuracy of owner notification and follow up mechanisms. In the United States, automakers must notify owners individually by letter, with the NHTSA providing VIN based online systems and monitoring completion rates subject to sanctions (NHTSA, 2020).

In the European Union, notifications are disseminated through multiple channels including letters, emails, online systems, and mobile applications supported by legislation mandating broad public communication and monitoring (European Commission, 2018a).

In Brazil, notifications rely on traditional media and the Digital Traffic Wallet (CDT) app for notifications; vehicle registration data quality issues have been reported. Data limitations may reduce notification reach and campaign effectiveness; this should be quantified.

In the US and EU markets, rapid platform turnover and innovation pressures may raise early production defect risk; competitive dynamics (including new entrants) could influence development speed and risk exposure, a relationship that requires empirical testing (Maione et al., 2023). Hypothesis 10: Shorter model life cycles and frequent platform updates are hypothesised to increase early production defect risk and recorded recall incidence.

Longer model life cycles in Brazil may lower exposure to novel design defects but could sustain legacy issues when technological updates are infrequent; empirical analysis should compare defect types across platform vintages. Global supply-chain integration can propagate component defects across markets; the Takata airbag case is a documented example (NHTSA, 2020a).

Global integration may both accelerate defect dissemination and enable coordinated recall responses from centralised manufacturer headquarters; the net effect depends on corporate governance and logistics. Import dependence combined with tariffs, logistics and currency volatility may delay defect identification and recall execution in Brazil; this mechanism should be tested with case level timelines. Hypothesis 11: Supply chain fragmentation is hypothesised to reduce batch traceability and complicate campaign coordination, especially for small series production; traceability metrics can be used to evaluate this claim.

In the EU, mandatory inspections are carried out annually or biennially with the aim of increasing vehicle safety and facilitating the identification of defects that may lead to recalls (European Commission, 2014). Hypothesis 12: Mandatory periodic inspections and robust post sale oversight are

expected to enhance defect detection and support recall execution.

Hypothesis 13: US inspection regimes vary by state; preventive maintenance and other oversight mechanisms contribute to defect detection in some jurisdictions (US GAO, 2012).

Brazil lacks a uniformly implemented periodic inspection system; recent legislative changes have altered inspection requirements. Reduced inspection coverage may lower observed defect detection and reduce external pressure for recalls, potentially affecting recorded recall rates; alternative explanations should be considered.

In the US and the EU, strict legislation imposes severe sanctions for concealment, while anonymous reporting systems and whistleblower protections enhance the detection of hidden defects (Raithel, Homburg & Bornemann, 2024). Hypothesis 14: Regulatory stringency and enforcement mechanisms are hypothesised to influence firms' incentives to disclose versus conceal defects.

Brazilian law includes recall provisions, but some observers report weaker enforcement and different compliance norms, allowing practices such as "silent recalls" during routine maintenance. Hypothesis 15: If informal or maintenance based remedies are common, they may reduce public visibility of recalls; this hypothesis requires empirical verification.

Growth in SUVs, pick-ups, and electrified vehicles may increase system complexity and change the profile of systemic failures; empirical analysis should disaggregate by vehicle class and technology. Hypothesis 16: Fleet composition (vehicle types and technology penetration) is expected to influence the frequency and nature of recalls.

Brazil's fleet has historically had a higher share of passenger cars and light commercial vehicles and lower electrified vehicle penetration (ANFAVEA, 2024). Lower technological content may reduce software-related recalls while potentially masking mechanical safety risks; this should be tested with defect-type data.

Industrial policy and trade agreements are hypothesised to influence industry structure and the pace of alignment with international safety standards. The Mercosur European Union agreement introduces a gradual reduction of vehicle import tariffs while safeguarding Brazil's automotive sector against sudden surges in European imports. Hypothesis 17: Recent US trade measures, including tariffs and import restrictions affecting certain components, may raise compliance costs and alter innovation incentives, with potential downstream effects on product development and recall risk (Bowdle & Kamal, 2025).

Brazilian policy has included incentives for local content and protection measures; the market faces tax and logistical challenges. Hypothesis 18: These factors may slow alignment with international safety norms and affect manufacturers' investment in safety related upgrades.

Observed recall practices vary by jurisdiction in scope and coverage. Differences in scope may reflect regulatory rules, corporate strategy, and public pressure.

In the US, preventive recalls are common and often encompass large batches across multiple years and models, with the NHTSA able to expand scope when shared component failures are identified (NHTSA; 2020b).

In the EU, NGOs such as the European Transport Safety Council (ETSC) play a key role in advocating for high safety standards and scrutinising regulatory harmonisation with the EU (European Commission 2018a). Hypothesis 19: It is hipothesised that the Brazilian market exhibits narrower recall campaigns and lower visibility, driven by a combination of diminished media coverage, limited NGO involvement and weak public pressure.

Differences in methodologies for calculating the recall factor and in data availability complicate cross-regional comparability. In the United States, calculations rely on detailed NHTSA data covering affected vehicles, fleet size, and recall completion rates (NHTSA, 2020). In the European Union, the absence of unit-level data in some countries and methodological variation across sources hinder direct comparison (European Commission, 2018a). In Brazil, estimates are based on Senacon and Anfavea data, but limited updates and accuracy particularly regarding the active fleet and completion rates reduce reliability (ANFAVEA, 2024). Additionally, the inconsistent inclusion of vehicle types and campaigns for parts and accessories may distort aggregated figures, further challenging comparability among regions.

Differences in recall factors across Brazil, the US, and the EU likely reflect interacting regulatory, cultural, industrial, economic, and technological influences; empirical models should account for these multiple channels.

Higher recorded recall factors in the U.S. and EU may be associated with stronger regulatory rigour, litigation pressure, integrated industry structures, greater reporting transparency, and public scrutiny; alternative explanations (e.g., market composition, reporting incentives) must be evaluated.

Brazilian policymakers should prioritise empirical diagnostics of reporting and enforcement gaps, consider targeted capacity-building for agencies, and evaluate reforms to notification, inspection, and traceability systems to strengthen vehicle safety culture and alignment with international norms.

6. Conclusion

The policy recommendations for enhancing the effectiveness of the recall process are first outlined by region, followed by a set of general recommendations applicable across the jurisdictions examined.

In Brazil, priorities include strengthening the technical capacity, budget, and autonomy of regulatory agencies (Senacon, Inmetro, Senatran), implementing nationwide periodic vehicle inspections, enhancing communication systems through integrated databases, incentivising the adoption of advanced safety technologies, and aligning industrial policy with international standards to facilitate compliance and technology transfer.

In the United States, measures focus on balancing litigation-driven incentives by establishing clearer thresholds for recalls, expanding predictive analytics through connected vehicle data and AI, fostering collaborative industry standards for emerging technologies, enforcing lifecycle risk management across shorter model cycles, and strengthening supply chain oversight to prevent systemic failures.

In the European Union, recommendations emphasize harmonizing recall data reporting across member states, expanding RAPEX to include quantitative monitoring indicators, developing certification protocols for embedded software and cybersecurity, institutionalizing NGO and media engagement to sustain public pressure, and reinforcing cross-border enforcement mechanisms to ensure uniform recall execution within the single market.

By sharing advancements in best practices across regions, even among different automakers where knowledge is not proprietary, the industry can enhance product quality, reduce warranty repair costs, and mitigate risks to public safety.

This study highlights the lack of global standardisation in recall data availability, which hinders effective comparisons between countries and regions. The Oslo Manual provides an example of existing standardisation and offers guidelines for collecting and interpreting innovation-related data (OECD/Eurostat, 2005).

Given the significant number of vehicles involved in recalls, could be crucial to implement strategies that ensure product safety during the Product Development Process (PDP) and the Development of Production Processes (DPPr), ultimately providing society with safer products.

Employing a reference model for implementing new assembly processes in the automotive sector may help reduce recalls related to DPPr (Baraldi and Kaminski, 2018).

The automotive industry must demonstrate a stronger commitment to product safety. New tools should be utilized to mitigate recalls, and existing methodologies such as Good Manufacturing Practices (GMP), Fault Tree Analysis (FTA), Six Sigma, and Failure Mode Effect Analysis (FMEA) should be systematically applied to enhance effectiveness (Gazcón-Rivera et al., 2021).

It was observed that product recalls tend to be more severe than process recalls, despite the latter occurring less frequently. Product recalls typically encompass large volumes of vehicles, as defects often arise from shared platforms and components across multiple models. In contrast, process recalls are generally confined to specific regions or manufacturing plants and therefore affect a comparatively smaller number of vehicles.

To incentivise automotive industries, government agencies could enhance control mechanisms by comparing recall data across manufacturers, establishing stricter standards, and compelling them to adopt policies to reduce defects and address quality concerns.

Recurring, systematic problems related to automotive recalls should be viewed as opportunities to decrease costs and enhance customer service. There is no justification for the continual sale of products that may endanger public safety.

Effective initiatives are needed to reduce the global incidence of recalls. The rising trend in the number and scale of affected vehicles annually is unsustainable and warrants coordinated policy responses.

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Appendix A - Product Recall Codebook (reconciled)

Category ID	Category	Definition	Illustrative example phrase
P-ELEC	**Electrical System Vulnerabilities**	Failures caused by deficiencies in electrical design, protection, or environmental resilience that create shorts, overheating, or loss of electrical isolation.	"Battery cable abrasion caused shorts and overheating."
P-REST	**Restraint System Malfunctions**	Failures of occupant-protection systems (airbags, seat sensors, control modules) that impair deployment or classification.	"OCS misclassified adult as child, deactivating frontal airbag."
P-IGN	**Ignition and Engine Control Defects**	Failures in ignition switches, ECUs, or engine-control software that cause stalling, unintended shutdowns, or accessory interference.	"Ignition switch moved out of run position, shutting off engine."
P-REG	**Regulatory and Compliance Failures**	Defects or configurations that violate statutory safety standards or regulatory requirements (for example, FMVSS).	"ABS telltale failed to illuminate, violating FMVSS requirements."
P-SENS	**Sensor and Instrumentation Failures**	Sensor, gauge, or instrumentation faults that produce incorrect readings or loss of function leading to unsafe behaviour.	"Fuel-level sensor reported empty when tank was full."
P-LIGHT	**Lighting and Signalling Faults**	Failures in external or internal lighting and signalling that reduce conspicuity or driver information.	"Brake lamp circuit intermittent, causing non-illumination."
P-STRUCT	**Structural and Fastening Defects**	Defects in structural components or fastenings that compromise integrity or attachment.	"Seatbelt anchor bolt fractured under load."
P-CTRL	**Control-Module and Warning-System Vulnerabilities**	Software or hardware vulnerabilities in control modules or warning systems that impair function or produce false indications.	"ECU software error disabled traction control."
P-DES	**Design and Component Durability Issues**	Design choices or material selections that lead to premature wear, fatigue, or failure in service.	"Component vibrated excessively under normal load."

Appendix B - Process Recall Codebook (reconciled)

Category ID	Category	Definition	Illustrative example phrase
R-ASM	**Assembly and Torque Problems**	Incorrect fastening or fixation (under/over-torque, mislocated fasteners) affecting safety-critical components.	"Insufficient torque on seatbelt bolts caused loosening."
R-MFG	**Manufacturing Process Failures**	Dimensional non-conformities or defects from stamping, molding, or machining that compromise fit or strength.	"Transmission shaft out-of-spec led to premature cracking."
R-MAT	**Material Treatment Deficiencies**	Inadequate heat treatment, wrong alloy selection, or inconsistent thickness causing fatigue or microcracks.	"Absence of heat treatment produced early fatigue."
R-ELECPROC	**Electrical/Electronic Process Defects**	Process-related terminal contact failures, poor sealing, or assembly errors that cause corrosion or shorts.	"Poor terminal crimping caused intermittent short circuit."
R-BOND	**Bonding and Welding Problems**	Deficient adhesive application or poor welds producing misalignment, cracks, or structural rupture.	"Incomplete weld seam resulted in structural crack."
R-DESPROC	**Design and Durability Process Issues**	Process or design choices during production that produce components outside specification or with insufficient load resistance.	"Incorrect machining tolerance produced excessive vibration."
R-QC	**Quality Control Failures**	Failures in inspection, testing, or release procedures that allow defective parts to proceed to assembly or shipment.	"Final inspection missed cracked housings."