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Integrating Economic Analysis and Reliability Assessment for Sustainable Management in the Italian Used Car Market

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Received: 02-13-2025 **Revised:** 04-03-2025 **Accepted:** 05-06-2025

Citation: Verna, E., Puttero, S., Saluto, P., Guelfi, S., & Galetto, M. (2025). Integrating economic analysis and reliability assessment for sustainable management in the Italian used car market. *Chall. Sustain.*, *13*(2), 193–206. https://doi.org/10.56578/cis130204.

Abstract: The used vehicle market has increasingly been recognised as a critical component in advancing sustainability objectives, particularly within the framework of a circular economy. In this study, a comprehensive assessment of the Italian used car sector has been conducted, with emphasis placed on its economic viability, environmental implications, and role in promoting resource efficiency through extended product life cycles. Economic indicators demonstrate that the reuse of vehicles not only reduces material waste and energy consumption associated with new car production, but also enhances accessibility and cost-effectiveness for consumers. To quantify the reliability of used vehicles and support informed decision-making among stakeholders, a predictive model was developed employing a dataset comprising over 100,000 pre-owned vehicles. Reliability was evaluated through the estimation of the Percentage of Residual Life (PRL), derived using a hybrid approach that integrates Weibull distribution-based survival analysis with multivariate regression techniques, calibrated against vehicle age and mileage. This modelling framework enables the estimation of remaining service life with high granularity, offering a standardised metric to assess vehicle longevity and performance risk. The integration of economic and reliability analyses provides a multidimensional understanding of the market, addressing both financial sustainability and operational dependability. Through this dual approach, a pathway has been proposed for enhancing the transparency, sustainability, and efficiency of used vehicle transactions in Italy. The findings are intended to inform policymakers, manufacturers, and consumers by highlighting the strategic potential of second-hand vehicles in reducing lifecycle emissions and promoting circularity in the automotive industry. Broader implications for sustainable transport policy, second-hand asset valuation, and market regulation are also discussed, situating the Italian used car market as a replicable model for sustainable vehicle ecosystem management in Europe and beyond.

Keywords: Circular economy; Used vehicle market; Reliability assessment; Percentage of Residual Life (PRL); Sustainable mobility; Life-cycle optimisation

1. Introduction

The transition towards a circular economy is reshaping industries globally, with the automotive sector at the forefront of this transformation. In the context of the used car market, circular economy principles promote the reuse, recycling, and life extension of vehicles, significantly reducing environmental impact (Gavazza et al., 2014). By reintroducing vehicles into the economy through second-hand transactions, the need for new resource extraction is mitigated, and the carbon footprint of the automotive industry is minimised (Du et al., 2025; Monburinon et al., 2018). This aligns with broader sustainability goals aimed at reducing waste and promoting resource efficiency.

The automotive industry has long been recognized as a major contributor to environmental degradation, primarily due to emissions during production and the resource intensity of vehicle manufacturing. The implementation of circular economy strategies, including remanufacturing, recycling, and component reuse, has proven essential for reducing the industry's overall environmental impact (Deore & Matai, 2024; Wurster, 2021). The application of closed-loop recycling systems and design-for-reuse frameworks has demonstrated potential in lowering both material waste and emissions (Ghisellini et al., 2016). By extending vehicle lifespans through these practices, the automotive sector can contribute significantly to the reduction of greenhouse gas emissions and resource consumption (Prochatzki et al., 2023; Su et al., 2013).

The used car market is particularly relevant to sustainability due to its ability to prolong the lifespan of vehicles, reducing waste and postponing the need for energy-intensive manufacturing processes. Vehicles that remain in use for longer periods lower the demand for energy-intensive production processes, a significant source of greenhouse gas emissions (Monburinon et al., 2018; Potting et al., 2017). While both aspects contribute to sustainability, the former emphasises reducing waste through reuse, while the latter focuses on minimising resource extraction and energy consumption. Despite these benefits, the market faces challenges, notably in terms of transparency regarding vehicle reliability. Buyers often struggle to assess the remaining lifespan of used vehicles, leading to uncertainty and potential dissatisfaction, which hinders trust in the market (Gegic et al., 2019).

To address these issues and promote sustainable management within the Italian used car market, this study first presents an economic analysis of the Italian used car market, focusing on how it supports sustainability by reducing waste and extending vehicle life cycles. This economic analysis assesses the market's contribution to resource optimisation and serves as a basic framework for integrating reliability assessment into sustainable management practices. By reducing waste and encouraging extended vehicle use, the analysis highlights how the market can support a circular economy.

The study then presents a reliability-based model for estimating the PRL of used vehicles. This model applies Weibull distribution techniques to failure data (R et al., 2022), providing an objective measure of a vehicle's remaining life based on key factors such as mileage and age. The integration of economic analysis with the PRL model provides a comprehensive approach to sustainable management where economic viability and technical reliability are addressed together to improve the overall sustainability of the market. By providing a quantitative assessment of vehicle reliability, the PRL model increases transparency and helps reduce the uncertainty that buyers often face in the used car market.

This study is a novel contribution to the Italian used car market from a technical point of view. It highlights the sector's role in sustainability by extending vehicle life, reducing waste and improving access to transport. The inclusion of over 100,000 vehicle data points in the PRL model ensures robustness and scalability, making it adaptable to different vehicle types and models. In addition, the combination of economic analysis and reliability assessment ensures that sustainable management practices are supported by both market performance assessment and technical reliability metrics. Beyond the used car market, the findings have broader implications, potentially informing sustainable management practices in other industrial sectors. In addition, future integration of machine learning and Internet of Things (IoT) technologies is expected to improve the predictive accuracy of PRL, enabling real-time vehicle health monitoring and further advancing the circular economy (Sarangi et al., 2021).

The Methodology section should be written concisely, yet provide enough details to allow others to replicate and build on published results. The well-established methods can be introduced briefly with proper citations. Do not describe these published methods in details. In contrast, detailed descriptions are required for new methods. If multiple methods are adopted in the work, this section may be divided into several subsections, each providing details on a specific method. Note that the publication of your manuscript means all materials, data, codes, and protocols associated with the publication must be made available to readers. Remember to disclose restrictions on the availability of materials or information at the submission stage. If your manuscript uses large datasets deposited in an opensource database, please specify where the data have been deposited. If your study requires ethical approval, do not forget to list the authority and code of the ethical approval.

2. Literature Review

The Italian used car market, while distinct in its structure and regulatory framework, shares many characteristics and challenges with global used car markets. As such, insights and practices from the Italian context often hold relevance on an international scale. This sector plays a critical role in providing accessible vehicle options, promoting sustainability goals, and aligning with global trends such as the adoption of circular economy principles.

With increasing environmental regulations and consumer demand for ethical practices, the market is forced to adopt innovative strategies and sustainability principles. The sector promotes Sustainable Development Goals (SDGs) such as promoting responsible consumption (SDG 12) and reducing emissions (SDG 13) by extending vehicle lifecycles, which is in line with circular economy principles. However, the market faces several challenges:

1. Information asymmetry: Consumers often lack reliable information on vehicle history and quality, leading to mistrust. This barrier can be mitigated by improving transparency through digital tools (Liang, 2023);
2. Environmental footprint: The adoption of sustainable vehicles, such as electric and hybrid cars, comes with complexities related to higher upfront costs and limited infrastructure for charging and maintenance (Miconi & Dimitri, 2023; Prochatzki et al., 2023).
3. Lack of standardised practices: There is a need for universally accepted methodologies for vehicle

evaluation and environmental impact assessment to create market uniformity and consumer confidence (Sharma & Pandey, 2020).

The absence of standardized practices in vehicle valuation and environmental impact assessments complicates the establishment of market uniformity and consumer trust. To address these challenges, the market is integrating practices that promote sustainability across the vehicle lifecycle. For example, circular economy models that emphasize resource recovery and reuse are becoming more prevalent, supported by tools like the Automotive Sustainability Assessment Model (A-SAM), which aids in quantifying sustainability impacts and balancing cost-efficiency with environmental goals. Furthermore, the adoption of artificial intelligence and machine learning is enhancing market analysis, pricing prediction, and overall transparency, facilitating informed purchasing decisions (Miconi & Dimitri, 2023).

Policy-driven initiatives are also taking hold, with non-financial and sustainability reporting mandates pushing companies to integrate sustainable practices, increasing transparency and building consumer trust (Sharma & Pandey, 2020). Effective end-of-life vehicle (ELV) management offers opportunities for significant sustainability improvements. Recycling materials such as aluminium and iron from ELVs minimises dependence on raw materials and reduces environmental impacts (Du et al., 2025). However, integrating the informal sector into formal recycling processes is essential to improve efficiency and scalability (Izzo et al., 2020). Collaborative models involving manufacturers, policy makers and recyclers can create more effective frameworks for the disposal and recycling of end-of-life vehicles.

Market dynamics are further influenced by the preferences of younger consumers, who prioritise corporate social responsibility and environmental stewardship (Dobrowolski et al., 2022; Gazzola et al., 2020). This trend urges companies to effectively market their sustainable practices (Pencarelli et al., 2019). To achieve sustainable management, several strategic approaches are recommended:

1. Regulatory support: Providing incentives for the adoption of green technologies and sustainable practices;
2. Stakeholder collaboration: Engaging industry players, policy makers and consumers to address systemic challenges such as information asymmetries and infrastructure gaps;
3. Awareness campaigns: Promoting the long-term economic and environmental benefits of sustainable car ownership to change consumer preferences and drive market transformation.

Accordingly, significant progress has been made in integrating sustainability principles into the Italian used car market, but several gaps remain. Existing tools and models, such as the A-SAM, provide valuable insights into environmental impacts, but often lack precision in estimating the life cycle of individual vehicles. In addition, current market practices and policy-driven initiatives tend to focus on broad systemic improvements, leaving a need for more granular, data-driven methodologies to improve transparency and decision-making for both buyers and sellers.

This study addresses these gaps by introducing the PRL model, a novel and reliable approach specifically tailored to the Italian used car market. Unlike previous models, the PRL model directly incorporates real-world data from over 100,000 vehicles and uses Weibull distribution techniques and regression analysis to estimate vehicle reliability. This data-driven framework provides a more accurate estimate of vehicle longevity and addresses information asymmetries by providing clear, quantifiable metrics for decision making. The PRL model complements existing frameworks such as A-SAM by providing individualised assessments that increase transparency and sustainability at the vehicle level.

By focusing on key factors such as mileage and age, the PRL model significantly increases transparency in the used car market, enabling buyers and sellers to make more informed decisions. Reliable PRL estimates encourage the continued use of vehicles in good condition, reducing the need for premature scrapping. From a sustainability perspective, the PRL model promotes the efficient use of resources and the reduction of waste. In addition, the economic factors driving Italian consumers towards older vehicles are in line with the principles of the circular economy, while the PRL model ensures that vehicles are used for their maximum reliable lifetime (Zirpoli & Cabigiosu, 2018).

3. Highlights of the Italian Automotive Market

This section aims to provide a comprehensive overview of the Italian automotive market, focusing in particular on the structural and economic factors that influence the dynamics of the used car market. By examining trends in vehicle production, sales, technological changes and market composition, this section lays the foundations for understanding how the Italian used car market contributes to broader sustainability objectives. It also highlights the increasing age of the circulating vehicle fleet and the importance of the used car market in promoting resource efficiency and extending vehicle life cycles. This contextual analysis is essential to establish a coherent link between the economic analysis and the reliability-based PRL model presented in the following sections.

The Italian automotive market is undergoing a profound transformation, driven by a series of systemic disruptions reshaping the production, sale, and lifecycle management of vehicles and their components. This transformation affects the production and sale of both new and used vehicles - including cars, trucks, buses, trailers and semi-trailers - and their components, such as engines, electrical and mechanical parts, rubber elements, sheet metal and glass. These components are also widely used in related industries, including the two-wheeler, rail, marine and agricultural sectors. The changes are inevitable, far-reaching and mutually reinforcing. Specifically, several systemic disruptions can be identified:

1. The product technology, from analog to digital and from thermal to electric/hydrogen and further towards autonomous and interconnected driving and the IoT;
2. The process technology, where automation, flexibility and the size of production plants and distribution and repair sites proceed at forced stages towards new goals;
3. The use of new materials, from aluminium alloys to carbon fibres to high-strength steels, to glass fibre-reinforced plastics, to titanium, to ceramics in the name of lightness, efficiency, safety and ecology;
4. Customer needs and values in terms of function of use, increasing mobility, ecological sensitivity, transition from ownership to possession of the vehicle;
5. Competitive context logics oriented towards the concentration of players, collaboration and competition at the same time, a more efficient and less risky reorganization of the supply chain;
6. New infrastructural needs, from charging stations for electric cars to the production of electricity, from the closure of historic centres to cars;
7. The geopolitics of car manufacturers increasingly favour the territory of Asian producers and, in particular, Chinese ones;
8. The criticality of many raw materials, in terms of availability, concentration (China holds 90 percent of the 17 fundamental chemical materials, the so-called rare earths from lithium downwards) and price volatility;
9. The ongoing deglobalization triggered by geopolitical tensions, by the crisis on microchips, the engine of artificial intelligence, and by the acquired awareness of the risks associated with the lack of a production structure and the related technical skills;
10. The increase in the selling prices of new cars and the record profits achieved in 2023 by car manufacturers;
11. The increasing age of the circulating fleet, reflecting a slowing renewal rate due to the rising cost of new cars and economic constraints. This trend has significant implications for sustainability, as older vehicles tend to be less efficient and more polluting. However, it also highlights the importance of the used car market as a viable way to promote circular economy principles by extending the life cycle of vehicles.

The increasing age of the circulating car fleet, highlighted by the average age rising from 10.5 years in 2014 to 12.4 years in 2023 (+19.4%), indicates an urgent need for sustainable management practices. By improving the reliability and lifetime of existing vehicles through the used car market, it is possible to reduce the negative environmental impact associated with the production of new cars (Du et al., 2025).

Before continuing into the detailed analysis of the used car sector, a brief mention of the Italian macroeconomic context is considered appropriate (Table 1) and of the Italian registrations and circulating fleet, for the period 2014-2023. In particular (ISTAT, 2024):

Table 1. The Italian macroeconomic scenario

Macroeconomic Drivers	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	Δ% p 23/14
GDP (% change)	0.1	0.6	1.4	1.7	0.8	0.6	-9.0	8.3	4.1	1.0	0.9
Unemployment (% level)	12.8	12.0	11.,7	11.3	10.6	9.9	9.3	9.5	8.1	7.6	-5.2
Inflation (%)	0.2	0.0	-0.1	1.2	1.1	0.6	-0.1	1.9	8.2	5.6	5.4

1. The gross domestic product shows a substantially flat start and finish interspersed with the significant negativity of -9.0% in 2020, due to the COVID-19 pandemic, and a relative rebound in the two-year period 2021-2022;
2. The inflation rate is substantially very close to zero until the two-year period 2022-2023 where it records an increase of +8.2% and +5.6%, respectively;
3. The unemployment rate progressively decreases by -5.2 percentage points, from 12.8% in 2014 to 7.6% in 2023.

In summary, in the period 2014-2023, an economic system with a very modest growth rate and an inflation rate much higher than the ECB's monetary policy equilibrium target of 2 % and a comforting reduction in the unemployment rate are evident.

On the other hand, in relation to the circulating fleet and car registrations on the Italian market, the analysis shows a constant increase in the former, +10.3% in the period 2014-2023, and a recovery in the latter compared to the minimum period of 2020, although still in decline, -18.28%, compared to the peak of 2019 (ISTAT, 2024). The 2024 ratio between the circulating fleet and registrations is equal to 26.1, which would imply, with the same annual registrations and constant circulating fleet, a renewal of the circulating fleet achievable in approximately 26.1 years.

In relation to the size of the used car market, the number of transfers of ownership in Italy of cars and off-road vehicles, net of mini transfers (the sale of a vehicle to a used vehicle dealer/reseller), highlights (ACI, 2024):

1. In 2023 a result equal to 2,865,332 units, i.e., an increase of +12.8% compared to 2014 and +7.4% compared to 2022;
2. The clear prevalence of the Fiat brand with 23.1% of transactions in 2023, 26.9% in 2014, followed by Volkswagen with 7.5%, 8.5% in 2014, and Ford with 5.0%, 6.8% in 2014;
3. A particularly significant increase and decline, respectively, for the Jeep brand, +399.4% from 2014 to 2023, and for the Smart and Lancia brands, -20.1% and -20.0% from 2014 to 2023;
4. Coverage by the top 15 brands of 82.2% in 2023, down from 93.6% in 2014 due to the entry of many new brands, especially Asian ones;
5. coverage by other brands increasing from 6.4% in 2014 to 17.8% in 2023;
6. the relationship between ownership transfers and registrations, equal to 1.83 in 2023 and substantially stable compared to 2014 with 1.87 (UNRAE, 2024).

Table 2 shows the volume of ownership transfers on a regional basis and the relationship with registrations, which is recalled being equal to 1.83 in Italy, highlights (ACI, 2024):

Table 2. Volume of ownership transfers on a regional basis

Region	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**	**2022**	**2023**	**Δ% 23/14**	**MS 2023**	**CMS 2023**	**MS 2014**
LOMBARDIA	405,997	429,002	439,872	463,469	485,903	468,846	399,490	442,649	409,271	444,006	9.4%	15.5%	15.5%	16.0%
Relationship with registations	1.7	1.6	1.4	1.4	1.5	1.4	1.7	1.9	2.0	1.8	7.3%			
LAZIO	281,536	297,700	296,316	310,409	316,130	316,561	269,461	301,066	272,039	283,971	0.9%	9.9%	25.4%	11.0%
Relationship with registations	2.6	2.4	2.0	2.0	2.1	2.0	2.4	2.5	2.2	1.8	-33.2%			
CAMPANIA	229,196	245,053	258,611	270,405	284,132	286,744	248,984	278,344	241,379	259,985	13.4%	9.1%	34.5%	9.0%
Relationship with registations	4.5	5.2	3.9	4.1	4.3	4.3	4.7	4.7	4.4	4.2	-7.4%			
SICILIA	200,814	216,120	227,204	240,347	249,395	258,086	233,917	263,218	236,284	240,730	19.9%	8.4%	42.9%	7.9%
Relationship with registations	4.3	3.8	3.4	3.5	3.6	3.8	4.4	4.5	4.7	4.3	0.4%			
VENETO	193,116	207,278	217,311	232,131	248,506	246,519	207,616	223,761	199,398	223,612	15.8%	7.8%	50.7%	7.6%
Relationship with registations	1.8	1.7	1.5	1.6	1.7	1.6	1.9	2.0	2.3	2.2	16.8%			
PIEMONTE	203,234	215,186	218,981	230,580	235,869	229,381	194,967	220,888	196,906	215,656	6.1%	7.5%	58.2%	8.0%
Relationship with registations	1.5	1.4	1.2	1.0	1.3	1.5	1.8	2.0	1.9	1.3	-9.3%			
EMILIA ROMAGNA	185,477	196,179	203,209	214,586	227,632	220,394	187,881	208,874	190,310	214,640	15.7%	7.5%	65.7%	7.3%
Relationship with registations	1.6	1.5	1.4	1.4	1.5	1.5	1.7	1.9	1.9	1.6	-1.9%			
PUGLIA	172,837	184,458	198,424	208,213	218,350	222,589	198,128	221,198	193,003	203,258	17.6%	7.1%	72.8%	6.8%
Relationship with registations	4.3	3.9	3.6	3.6	3.6	3.8	4.6	4.7	5.3	5.0	15.0%			
TOSCANA	148,804	155,397	162,320	170,076	176,312	176,123	147,538	170,730	154,794	170,339	14.5%	5.9%	78.7%	5.9%
Relationship with registations	1.1	1.0	0.9	1.0	1.0	1.0	1.1	1.1	1.1	1.0	-14.0%			
CALABRIA	75,0.13	79,687	84,550	88,642	92,541	93,556	82,941	96,539	85,852	91,463	21.9%	3.2%	81.9%	3.0%
Relationship with registations	3.7	3.3	2.9	2.9	3.0	3.3	3.7	3.7	4.2	4.0	6.6%			
SARDEGNA	74,379	78,481	82,340	85,875	91,952	94,475	83,000	95,497	86,212	90,150	21.2%	3.1%	85.1%	2.9%
Relationship with registations	3.5	3.1	2.8	2.7	2.8	2.9	3.8	4.0	4.6	4.4	26.7%			
TRENTINO ALTO ADIGE	52,139	56,192	58,768	63,772	77,350	85,550	64,826	70,705	79,338	76,760	47.2%	2.7%	87.8%	2.1%
Relationship with registations	0.3	0.3	0.2	0.2	0.3	0.3	0.3	0.3	0.4	0.4	21.3%			
MARCHE	61,027	63,436	67,427	71,808	75,362	74,433	63,199	70,760	61,807	68,332	11.6%	2.4%	90.1%	2.4%
Relationship with registations	1.9													
ABRUZZO	54,096	57,419	59,332	64,175	66,103	67,088	57,623	65,739	58,066	63,850	18.0%	2.2%	92.4%	2.1%
Relationship with registations	2.5	2.3	2.1	2.2	2.2	2.3	2.6	2.8	3.1	3.0	18.3%			
LIGURIA	62,533	63,036	65,284	67,681	69,340	68,813	59,410	66,952	58,868	62,909	0.6%	2.2%	94.6%	2.5%
Relationship with registations														
FRIULI VENEZIA GIULIA	52,410	55,073	57,286	60,476	63,861	64,920	54,914	60,500	53,606	58,901	12.4%	2.1%	94.6%	255%
Relationship with registations	2.0	1.8	1.7	1.6	1.8	1.9	2.2	2.4	2.6	2.6	26.8%			
UMBRIA	40,441	43,116	44,841	48,744	49,766	49,946	42,588	47,610	41,913	45,977	13.7%	1.6%	98.2%	1.6%
Relationship with	2.3	2.0	1.8	1.9	1.9	2.0	2.3	2.6	2.8	2.8	20.5%			

registations														
BASILICATA	24,546	27,165	27,848	28,624	29,097	28,536	25,071	29,037	25,204	26,900	9.6%	0.9%	99.2%	1.0%
Relationship with registations	4.2	3.3	3.2	3.3	3.2	3.3	3.7	3.8	3.8	3.8	-8.2%			
MOLISE	14,603	15,128	15,826	16,896	18,017	18,059	15,534	17,253	15,407	16,348	11.9%	0.6%	99.7%	0.6%
Relationship with registations	5.0	4.4	3.9	4.1	4.7	4.9	5.4	5.4	5.3	3.0	-41.1%			
VALLE D'AOSTA	6,688	6,845	6,932	7,478	13,681	7,972	6,319	7,235	6,561	7,188	7.5%	0.3%	100.0 %	0.3%
Relationship with registations	0.2	0.2	0.1	0.1	0.2	0.1	0.1	0.1	0.1	0.2	-3.4%			
ND	147	39	396	346	397	1084	145	330	696	357	142.9%	0.0%	100.0 %	0.0%
Total Market	2,539,210	2,693,992	2,793,078	2,944,763	3,089,696	3,079,675	2,643,552	2,958,885	2,666,914	2,865,332	12.8%	100.0 %		100.0 %

1. The leadership in absolute value of Lombardy with 15.5 % of ownership transfers of market share in 2023, slightly down from 16.0% in 2014; the first 5 regions, compared to the 20 total, recorded a market share of 50.7% in 2023, compared to 51.6% in 2014;
2. The highest ratio of ownership transfers to registrations by the regions of southern Italy: Puglia with a value of 5.0 compared to 4.3 in 2014, Sicily 4.3 in both 2023 and 2014, Campania 4.2 in 2023 and 4.5 in 2014, Calabria 4.0 in 2023 and 3.7 in 2014;
3. The extremely low ratios of Valle d'Aosta, 0.2 in 2023, and Trentino Alto Adige, 0.4 in 2023, are caused by the presence of long-term rental companies that register their vehicles in these regions.

One of the reasons underlying the limited number of car registrations in the period 2014-2023, and the consequent increasing age of the circulating car fleet and the significant sale of used cars is to be attributed to the significant increase in the price of new cars. Table 3 highlights (UNRAE, 2024):

Table 3. Weighted average price on car and off-road vehicle registrations by segment/body type

Segment-Body Type	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	Δ% 23/14
A	11,611	11,557	11,401	11,801	11,818	12,187	12,621	13,650	15,031	15,976	37.6%
B-SEDAN	13,145	13,184	13,327	13,680	14,145	14,491	15,754	16,602	17,907	19,307	46.9%
B-SUV	19,644	20,421	20,408	20,745	20,422	20,426	21,691	22,451	24,043	25,264	28.6%
C-SEDAN	23,085	23,022	22,155	22,126	22,751	24,308	26,082	28,619	30,983	32,882	42.4%
C-SUV	25,606	25,935	27,258	27,452	27,636	28,024	29,427	31,437	33,921	35,528	38.7%
D-SEDAN	34,655	36,019	36,054	38,093	36,878	41,162	44,682	48,451	51,389	46,859	35.2%
D-SUV	38,231	40,549	42,898	44,786	46,214	46,492	48,022	49,382	54,001	55,532	45.3%
E/F-SEDAN	58,604	61,349	60,431	63,569	65,649	65,769	69,077	76,201	82,415	95,508	63.0%
E/F-SUV	65,618	68,737	68,761	70,358	73,605	79,527	82,823	85,775	92,246	103,124	57.2%
SATION WAGON	25,583	26,063	27,182	26,303	26,369	28,486	30,782	32,315	35,067	35,325	38.1%
MPV	18,928	19,696	20,265	20,377	20,902	21,608	22,925	23,454	28,179	33,312	76.0%
SPORTS CARS	51,266	62,900	55,142	54,894	65,418	65,865	85,823	71,762	80,388	98,055	91.3%
Total Market	19,312	19,695	20,349	20,947	21,589	22,135	23,591	24,892	27,655	29,872	54.7%
Δ% year on year		2.0%	3.3%	2.9%	1.8%	4.1%	10.8%	-9.3%	-0.8%	0.7%	

1. An increase in the average price of new cars between 2014 and 2023 equal to +54.7%, from €19,312 to €29,872 with particular intensity in the two-year period 2022/2023 with high inflation certainly as a contributing factor;
2. The segments with the greatest increases in the sales price in the period 2023-2014 were sports cars, +91.3%, Multi-Purpose Vehicles, +76.0%, and E/F Sedans, +63.0%;
3. The segments with the smallest increases in the sales price were the B-SUV, +28.6%, D-Sedan, +35.2%, and A, +37.6%.

The aforementioned increase in the selling price of new cars, on the one hand, slows down the requalification of the vehicle fleet, with very significant costs in terms of road safety and environmental impact, and, on the other hand, increases the value of used cars and favours the development of aftermarket components.

The analysis of transfers of ownership of cars and off-road vehicles, net of mini transfers, in relation to the type of contractor, shows the clear prevalence of transactions from private company to private company, equal to 56.7% of market share and decreasing from 59.1% in 2015, and from operator to private company, 39.1%, increasing compared to 37.0% in 2015 (UNRAE, 2024).

A further relevant question to answer is whether current registrations, for example, in the period 2014-2023, will be able to improve, with the introduction of new technologies and hybrid and electric engines, the level of CO_2 emissions of used cars in the coming years (Table 4) (UNRAE, 2024):

Table 4. Weighted average of CO_2 emissions on car registrations and off-road vehicles by segment

Segment-Body Type	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	Δ% 23/14
A-SEDAN	107.8	107.4	107.5	108.0	109.3	111.6	120.8	106.4	104.3	104.7	-2.9%
A-SUV	162.4	162.4	156.9	118.0	113.6	120.8	127.0	84.2	98.7	103.9	-36%
B-SEDAN	109.1	109.1	105.4	104.2	103.6	109.0	116.6	111.0	111.0	111.2	1.9%
B-SUV	121.0	121.0	116.0	115.8	116.5	121.3	131.1	121.8	120.6	124.2	2.6%
C-SEDAN	108.4	108.4	106.2	106.7	108.5	112.3	123.7	111.3	112.0	113.8	5.0%
C-SUV	132.8	132.8	121.2	118.4	121.5	125.1	138.9	120.6	119.0	122.3	-7.9%
D-SEDAN	121.2	121.2	113.9	114.6	116.6	109.7	100.9	75.4	107.4	60.6	-50.0%
D-SUV	160.4	160.4	143.3	139.8	145.1	151.2	162.4	138.1	121.2	117.7	-30.4%
E/F-SEDAN	147.7	147.7	129.4	125.8	134.4	136.0	148.1	154.1	142.3	108.4	-26.6%
E/F-SUV	185.8	185.8	168.3	166.2	172.0	173.2	184.3	160.7	148.1	151.8	-18.3%
SATION WAGON	119.1	111.9	108.7	108.4	110.8	115.7	128.8	121.2	121.2	122.0	2.4%
MPV	121.2	119.0	116.6	116.4	119.2	127.3	137.0	137.1	126.6	121.8	0.5%
SPORTS CARS	146.8	153.3	144.4	143.6	150.2	155.0	156.6	131.8	130.0	143.7	-2.1%
Total	117.5	114.8	112.7	112.4	114.4	119.1	132	119.7	118.7	119.5	1.7%
Δ% year on year		-2.3%	-1.8%	-0.3%	1.8%	4.1%	10.8%	-9.3%	-0.8%	0.7%	

1. CO_2 emissions from registered cars increased from 2014 to 2023 by 1.7%, from 117.5 to 119.5, with the interruption of the reduction trend starting from 2020 (to limit global temperature rise to around 1.5°C, the safest threshold recommended by science and the 2015 Paris Agreement to avoid the worst effects of climate change, net greenhouse gas emissions would need to fall by 43% by 2030, compared to 2010 levels);
2. The segments with the largest reductions in CO_2 emissions in the period 2023-2014 were D-Sedan, -50.0%, A-SUV, -36.0%, D.SUV, -30.4%, and E-Sedan, -26.6%;
3. The segments that worsened CO_2 emissions the most were C-Sedan, +5.0%, B-SUV, +2.6%, Station Wagon, +2.4%, and B-Sedan, +1.9%, unfortunately those with the highest sales volumes.

The aforementioned increase in CO_2 emissions with reference to registrations is confirmed by the persistence of thermal, petrol and diesel engines, which represent, respectively, 39.0% and 47.6% of ownership transfers in 2023, while the hybrid electric world represents 6.5% (5.4% of phev+rex and 1.1% of bev) (UNRAE, 2024).

A final analysis relating to ownership transfers concerns, from a safety perspective, the dynamics of the number of road accidents involving cars. In this case, the result is comforting (ISTAT, 2024):

1. The number of road accidents involving private and public cars decreased, in the period 2023-2014 by -8.3%, both the isolated road accidents by -7.3%, and the road accidents involving vehicles by -8.7%;
2. The incidence of road accidents involving private and public cars compared to the total number of road accidents decreased from 73.72% in 2014 to 71.84% in 2023;
3. The incidence of road accidents involving private and public cars compared to the total number of road accidents in circulation decreased from 0.35% in 2014 to 0.29% in 2023.

In summary, the used car market in Italy (net of mini transfers) records a number of transactions almost double compared to the number of new cars sold, in particular in the southern regions, consisting of 99.9% cars with internal combustion engines and with substantially constant CO_2 emissions. With the aim of improving the level of safety of cars, reducing the environmental impact, promoting sustainable practices through reuse and resource optimization, incentivizing the circular economy and enhancing the aftermarket components supply chain, the authors believe that a renewal of the circulating fleet is absolutely necessary and this direction can be encouraged by favouring, also using the tax leverage and reducing the costs of transfers, the commercial transactions of used cars and, in particular, those of more recent construction (Mura et al., 2020).

4. Reliability-Based Model for Estimating the PRL in Used Vehicles

The used car market represents an important segment of the automotive industry at the intersection of sustainability and economic efficiency. This market plays an important role in the circular economy by extending the life cycle of vehicles (Aguilar Esteva et al., 2021). However, the reliability of used vehicles remains a critical concern for buyers and sellers, as it significantly impacts purchase decisions and market dynamics. To address this issue, this study proposes a reliability-based model for estimating the PRL of used vehicles. The proposed model integrates statistical methods and failure data to quantify the remaining life of a vehicle, thereby promoting informed decision-making and increasing transparency and confidence in the used car market.

The PRL model is rooted in reliability theory and conceptualises a vehicle as a complex system comprising multiple subsystems and components, each contributing to the overall reliability. It uses the concept of system reliability, where the failure of a critical component can significantly affect the overall reliability of the vehicle. This approach is particularly relevant for used vehicles, where component wear and maintenance history are key determinants of remaining life. Similar methodologies have been successfully applied in other domains, such as aviation and industrial machinery, to predict system performance and optimise preventive maintenance schedules (Ghasemi et al., 2010; Wang et al., 2015). These precedents demonstrate the robustness and versatility of reliability-based models for complex systems, including used vehicles.

The Weibull distribution is particularly suitable for modelling component reliability in the context of used vehicles due to its flexibility in capturing different failure behaviours. Unlike other distributions, the Weibull distribution can model increasing, decreasing or constant failure rates depending on the value of its shape parameter (k) (Montgomery et al., 2010). Specifically:

- When $k < 1$, the failure rate decreases over time, which is typical for components that fail early in life (infant mortality).
- When $k = 1$, the failure rate is constant, representing random failures independent of age or mileage.
- When $k > 1$, the failure rate increases over time, which is common for components that deteriorate due to wear and age.

This flexibility makes the Weibull distribution highly suitable for modelling a wide range of components within used vehicles, which may exhibit different failure patterns due to different usage histories and maintenance conditions (Devore, 2011). In addition, regional and market-specific analyses reveal significant variability in vehicle lifetime and survival rates, highlighting the need for accurate lifetime modelling to better understand market dynamics (Held et al., 2021).

The PRL model is grounded in reliability theory, treating a vehicle as a complex system composed of various subsystems and components, each contributing to the overall reliability. The model employs the concept of system reliability, where the failure of any critical component can significantly impact the vehicle's overall reliability. This approach is particularly relevant in the context of used vehicles, where component wear and historical maintenance play crucial roles in determining the remaining lifespan.

The reliability $R_{C_i}(T)$ of a generic component C_i is defined as the probability that the component will perform its intended function without failure for $t > T$. Mathematically, it is expressed as:

$$R_{C_i}(T) = P(t > T) = \int_T^{+\infty} f(t)dt \tag{1}$$

where, *f(t)* is the probability density function and *T* is the considered time point. For a system *S* composed of *N* independent components ($S = \{C_1, C_2, \dots, C_N\}$), the system reliability $R_{C_i}(T)$ is the product of the reliabilities of its components:

$$R_S(T) = R_{C_1}(T) \cdot R_{C_2}(T) \cdot \ldots \cdot R_{C_N}(T) \tag{2}$$

The PRL is thus a function of the reliabilities of all critical components, adjusted for the vehicle's age and mileage.

To estimate the reliability of each component, the model employs the Weibull distribution, which is widely used in reliability analysis due to its flexibility in modelling various types of failure rates. The probability density function of the Weibull distribution is given by (Bertsche, 2008):

$$f(t) = \frac{k}{\lambda^k} t^{k-1} e^{-\left(\frac{t}{\lambda}\right)^k} \tag{3}$$

where, λ is the scale parameter and k is the shape parameter. The parameters λ and k were estimated using Maximum Likelihood Estimation (MLE) techniques (Montgomery et al., 2010), applied to the historical failure data for each component. The goodness-of-fit for the Weibull distribution was verified using appropriate "goodness-of-fit" tests (Devore, 2011; Montgomery et al., 2010). The data, subjected to fitting concerning the variables "mileage" and "age," were treated as censored, given that the warranty coverage (and thus the information reported in the analysed database) typically relates to a limited time period of 12/24 months. As an example, Figure 1 shows a Quantile-Quantile (QQ) plot for the distribution of alternator failures concerning the mileage at failure.

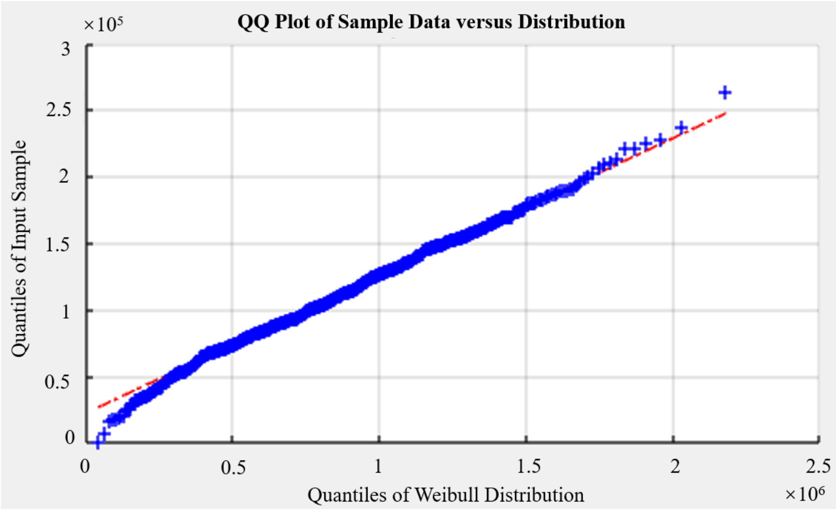


Figure 1. Quantile vs Quantile (QQ) plot

The observed values for these failure data align along the dotted line, supporting the hypothesis that the data distribution follows a Weibull distribution.

Thus, the two parameters λ (scale parameter) and k (shape parameter) of the Weibull distribution for each component were calculated, along with their respective confidence intervals at a significance level of α = 10%.

For each component reliability $R_{C_i}(T)$, where T represents the mileage or age, the confidence interval with a 10% significance level (α=10%) was calculated. This interval provides a range within which the true reliability is expected to fall with a high degree of confidence:

$$f\left[R^{10\%}{}_{C_i}(T);\ R^{90\%}{}_{C_i}(T)\right] \tag{4}$$

This approach allows the uncertainty inherent in reliability estimates to be captured, especially for components with limited failure data.

For components where the database lacked sufficient failure data to perform a reliable fitting (e.g., vehicles under warranty with incomplete failure histories), reliability was estimated by interpolating the values from other components with similar characteristics. This interpolation ensures that all critical components are accounted for in the PRL calculation.

Accordingly, to account for uncertainties in the input data and improve the robustness of the PRL estimates, the model incorporates confidence intervals for the reliability calculation of each component. Specifically, the 10% significance level (α = 10%) is used to construct a confidence interval, which provides a range within which the true reliability is expected to fall with a high degree of confidence. By using the lower bound of this interval in PRL calculations, the model takes a conservative approach that accounts for data limitations and measurement error, thereby increasing the reliability of the estimated PRL for each component:

$$PRL = \prod_{i=1}^{N} R^{10\%}{}_{C_i}(T) \tag{5}$$

This conservative approach minimizes the risk of overestimating the remaining life of the vehicle, providing a more cautious estimate that enhances buyer confidence and aligns with the goal of sustainability by potentially extending the useful life of vehicles.

The PRL model was implemented in a software tool developed in Matlab®, designed to process the input data (vehicle brand, model, mileage, age) and output the PRL value along with a detailed reliability report. The tool operates in two phases:

1. Fitting phase: This phase updates the parameters of the Weibull distributions based on the latest available data. The process is computationally intensive and is performed periodically to incorporate new failure data. A flowchart of this phase is represented in subgraph (a) of Figure 2;
2. Evaluation phase: This phase calculates the PRL for a specific vehicle, using the precomputed distribution parameters. The process is optimized for rapid execution, allowing the tool to be used in real-time assessments by car dealers and consumers. A flowchart of this phase is represented in subgraph (b) of Figure 2.

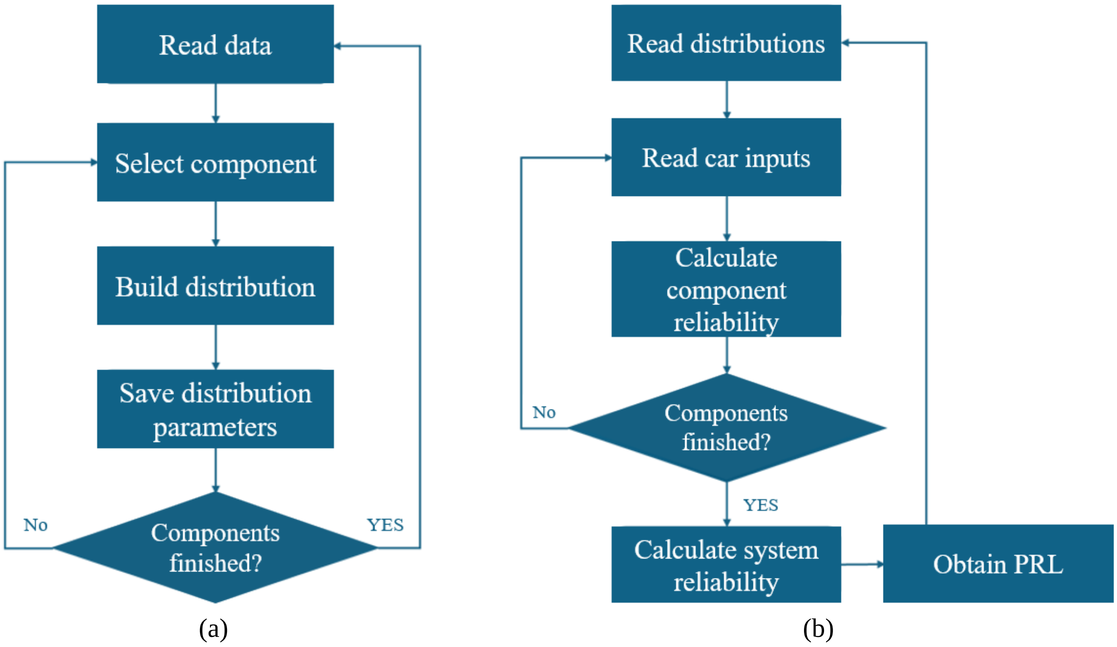


Figure 2. Flowchart of the (a) fitting phase and (b) evaluation phase

5. Results and Discussion

The PRL model was developed using an extensive and anonymized dataset comprising records from over 100,000 used vehicles. This dataset included detailed information on vehicle maintenance, repair history, mileage, and age, sourced from multiple data repositories. To protect the confidentiality of the data provider, the specific Italian company supplying the data is not disclosed. This large and diverse dataset provided valuable insights into the performance and failure rates of vehicle components, which were essential for fitting the distributions and building the reliability model.

Figure 3 illustrates the application of the Weibull distribution to key vehicle components, including transmission kinematics, the turbo compressor, and the EGR valve, and their failure data, enabling to model reliability as a function of mileage and vehicle age. These key components were chosen as representative due to their critical role in vehicle functionality and their prevalence in the failure data. The fitting was performed on datasets where the number of failure events was greater than 30, ensuring robust reliability estimates. The graphs show a strong correlation between the empirical data and the fitted Weibull distribution, indicating a good fit for all components. In each case, the probability of failure increases with distance travelled, following a typical S-shaped cumulative failure curve. In particular, reliability decreases sharply beyond certain mileage thresholds: around 150,000 km for the transmission kinematics and EGR valve, and around 200,000 km for the turbocharger. This pattern confirms the relevance of mileage as a primary factor influencing component degradation.

As illustrated, the reliability (the complement of failure probability) decreases sharply with increasing mileage, reflecting the wear and tear experienced by these components over time. A similar trend is observed when vehicle age is considered as the independent variable. This result aligns with expectations, as components are more likely to fail after prolonged usage or aging.

The PRL value was computed for several vehicle models, taking both mileage and age into account as key factors in assessing the remaining lifespan of each vehicle. The model employs a weighted average approach to combine the information from these two variables, with mileage weighted at 65% and age at 35%. These weights were determined through regression analysis performed on the dataset, which showed that mileage had a stronger correlation with failure rates and reliability estimates than age. This result is in line with previous studies which indicate that accumulated mileage is generally a more direct indicator of component wear and degradation (Ghasemi et al., 2010; Wang et al., 2015). However, the age of the vehicle also has a substantial influence on component degradation, independent of mileage.

To ensure an accurate representation of the vehicle's overall condition, the model also incorporates a corrective coefficient. This coefficient is applied when there is a significant discrepancy between the PRL calculated from age and the PRL calculated from mileage. Specifically, the corrective factor ensures that when one measure (e.g., PRL based on age) is notably lower than the other (e.g., PRL based on mileage), the lower value is given more weight in the final PRL calculation. This conservative approach is designed to provide a cautious and reliable estimate of the vehicle's remaining life, prioritizing the worst-case scenario to avoid overestimating reliability.

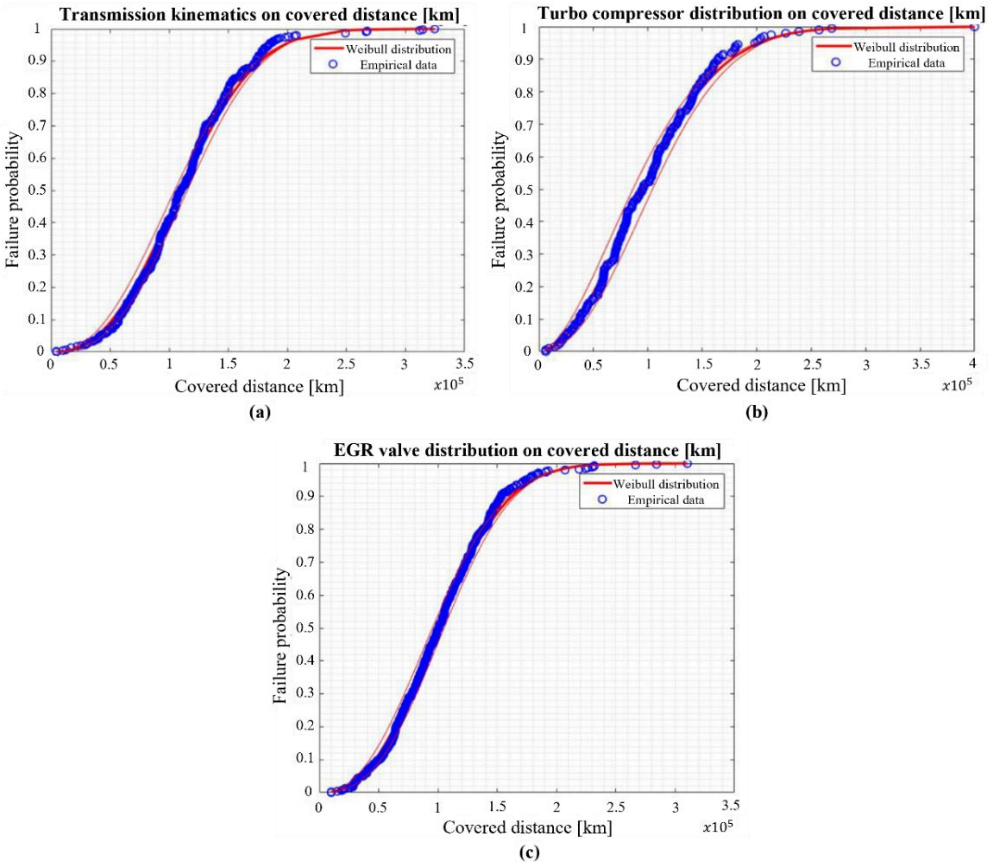


Figure 3. Weibull distribution on covered distance for (a) transmission kinematics, (b) turbo compressor, and (c) EGR valve

The corrective coefficient r is defined as the ratio of PRL based on age to PRL based on mileage ($r = \frac{PRL_{age}}{PRL_{km}}$). If $r \leq 1$, it means that the PRL based on age is lower than or equal to the PRL based on mileage, the model applies a factor that adjusts the final PRL downward. Conversely, if $r > 1$, indicating that the PRL based on mileage is lower, a different corrective formula is used to avoid overcompensating in the other direction.

In practical terms, this approach provides a balanced and cautious assessment of vehicle reliability. By incorporating this corrective mechanism, the model avoids potential bias that could result from relying too heavily on either mileage or age alone, thus offering a more holistic and trustworthy estimate of a vehicle's residual life.

A more detailed analysis of the PRL results shows that different vehicle models show different patterns in their PRL values (Table 5). This variability reflects differences in build quality, maintenance history, usage patterns and inherent reliability of the models. For example, the Fiat Panda, which has a relatively low mileage of 66,299 km and was registered in 2016, has a high PRL of 83.8%. This suggests that the vehicle is still in good condition and has a significant amount of life remaining, making it an attractive option for consumers looking for reliable and affordable transport. On the other hand, the Audi Q5 with 200,000 km registered in 2013 has a significantly lower PRL of 30.8%, indicating a more limited remaining useful life despite being a premium car.

Table 5. Example of PRL values for various vehicle models

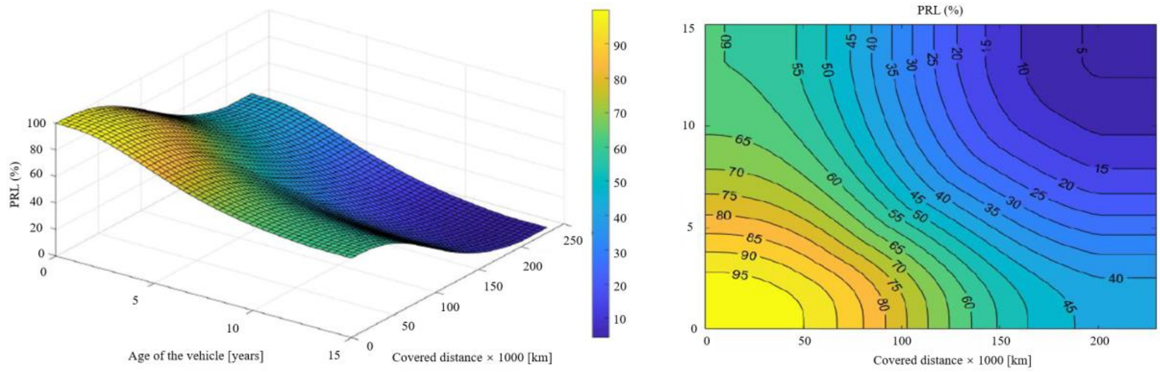
Vehicle Model	Mileage (km)	Registration Date	PRL (%)
Fiat Panda	66,299	27/08/2016	83.8
Fiat Stilo	76,000	31/05/2006	51.6
Audi Q5	173,200	22/03/2016	45.3
Alfa Giulietta	151,000	10/06/2012	37.0
Audi Q5	200,000	11/11/2013	30.8

These results suggest that the PRL model can effectively differentiate between vehicles based on their usage history and condition. Such information is particularly valuable to consumers who need to make purchase decisions based on reliability and expected longevity. It also highlights the potential of the PRL model to support sustainable practices by encouraging the sale and use of vehicles with significant remaining useful life, thereby reducing the demand for new vehicles and contributing to resource conservation.

In addition, the PRL model can be used by used car dealers to more accurately assess the quality of their stock. Vehicles with high PRL values can be promoted as reliable options, potentially commanding higher resale prices. Conversely, vehicles with low PRL scores can be targeted for refurbishment or repair, improving their reliability and extending their life.

Subgraph (a) of Figure 4 presents a 3D surface of the PRL index based on vehicle age and mileage. The contour lines represented in subgraph (b) of Figure 4 help visualize how PRL values evolve with increasing mileage and age. The model demonstrates saturation effects at higher distances and vehicle ages, where the PRL value flattens, indicating that further use or aging results in only marginal decreases in reliability.

The implications for consumer decision-making are clear: by providing an objective and quantifiable measure of vehicle reliability, the PRL model enables buyers to make more informed purchasing decisions. This transparency promotes confidence in the used car market and is consistent with sustainability goals by encouraging the purchase of vehicles with significant residual value. In addition, the model could support the development of extended warranties or maintenance plans tailored to vehicles with lower PRL values, thereby increasing their usability and lifetime.



(a) (b)

Figure 4. (a) 3D map and (b) contour lines of PRL as a function of vehicle age and mileage

6. Conclusions

This study successfully developed a reliability-based model (PRL model) to provide accurate estimates of the remaining life of used vehicles based on key factors such as mileage and age. The model demonstrated robustness in differentiating between vehicles with different usage histories, providing objective measures that can improve decision making and promote transparency in the Italian used car market. The analysis also highlighted the sector's contribution to sustainability by promoting resource efficiency and extending the life of vehicles.

The global automotive industry is undergoing significant changes, driven by the shift towards more sustainable practices and the increasing emphasis on the circular economy. In this context, the Italian used car market plays a key role in reducing resource consumption and extending vehicle lifespans. By facilitating the reuse and re-sale of vehicles, the Italian market helps decrease the demand for new car production, which is often associated with high energy consumption and environmental impacts. The rising importance of older vehicles in ownership transfers highlights the growing relevance of sustainability in this market. As more consumers in Italy turn to used cars, assessing their reliability and residual lifespan accurately becomes essential to promote consumer trust and efficient resource use.

This study examines the Italian used car market from a technical perspective. The analysis highlights the sector's contribution to sustainability by extending the life of vehicles, minimising waste and improving access to transport. With a growing share of vehicles over 10 years old in Italy, the market shows its potential to support sustainability efforts through the resale and prolonged use of durable vehicles.

On the technical side, the PRL model introduces a reliable and data-driven method for estimating a vehicle's remaining lifespan. By focusing on key factors such as mileage and vehicle age, the model enhances transparency in the used car market, helping buyers and sellers make more informed decisions. This contributes not only to economic efficiency but also to resource conservation, as reliable PRL estimates encourage the continued use of vehicles that are still in good condition, reducing the need for premature scrapping.

From an economic and social perspective, the PRL model has the potential to positively influence market dynamics. By providing reliable and accessible information on the expected lifetime of a vehicle, it promotes fairer pricing mechanisms and consumer confidence in the used car market. In addition, widespread adoption of the PRL model could encourage longer vehicle use, contributing to social equity by making affordable and reliable vehicles more accessible to low-income consumers. This is in line with the principles of the circular economy, as extending the lifetime of existing vehicles helps to reduce the environmental impact associated with the production of new vehicles.

Nevertheless, despite this progress, there are several areas that need to be further developed. This analysis is limited to the Italian used car market; future research should extend to a global market analysis for a more comprehensive understanding of the sector. In addition, the model's focus on mileage and age as the primary variables is a limitation that may affect the accuracy of PRL estimates. Factors such as maintenance history, driving conditions and environmental influences are not currently included in the model, which could lead to under- or overestimates of vehicle reliability, particularly for vehicles with atypical usage patterns or poor maintenance records. Addressing these limitations by including additional variables would improve the robustness and reliability of the model.

Future research should also explore the integration of advanced technologies, such as machine learning and IoT systems, to improve the predictive accuracy of the PRL model. Machine learning algorithms, particularly deep learning models, can be trained on large datasets to identify complex patterns and relationships between variables that may not be captured by traditional statistical methods. In addition, the application of IoT technologies could enable real-time monitoring of vehicle health, providing continuous updates on key metrics such as temperature, vibration, pressure and engine performance. This real-time data could be integrated into the PRL model to provide dynamic, continuously updated predictions of a vehicle's condition. By leveraging these technologies, the PRL model could be transformed from a static tool to a more responsive and adaptive framework capable of providing accurate, real-time insights into vehicle reliability.

In conclusion, the PRL model complements existing sustainability frameworks, such as the A-SAM, by providing accurate life cycle assessments at the individual vehicle level. Future research can extend the PRL model to perform broader life cycle analyses, integrating emerging technologies such as artificial intelligence and machine learning to refine predictions and incorporate dynamic variables. In particular, real-time monitoring of vehicle health through IoT technologies could provide continuous updates on a vehicle’s condition, while machine learning models could enhance the model’s capacity to process large datasets and integrate a broader range of variables. These advancements would allow the PRL model to offer more personalized and accurate predictions, further strengthening the transparency and sustainability of the Italian used car market. Furthermore, its alignment with circular economy principles establishes the model as a valuable tool for assessing resource efficiency and waste reduction strategies, with potential applications in other sectors that emphasise sustainable life cycle management.

Author Contributions

All authors contributed equally to the conceptualization, investigation, methodology, formal analysis, and writing of the study. All authors have read and agreed to the published version of the manuscript.

Data Availability

The data presented in this study are available on request from the corresponding author due to privacy reasons.

Conflicts of Interest

The authors declare no conflicts of interest.

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