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Aging Passenger Car Fleet Structure, Dynamics, and Environmental Performance Evaluation at the Regional Level by Life Cycle Assessment

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Abstract: The need to limit climate change and to improve air quality clearly is a driver for technology and policy changes in the transport sector. This study investigates how this technology shift at the European level ages personal car fleets at the regional level in Romania through second-hand imports. It also asks what how the situation will evolve in terms of environmental impacts. The study presents an in-depth assessment of the environmental performance and evolution of the passenger car fleet in Iasi County (Romania). The analysis is based on the car fleet structure and dynamic statistics, and uses the Copert 5.5 model to estimate the specific use-phase emissions, which subsequently are used as input data into an LCA analysis. The study considers three scenarios regarding fleet evolution and environmental performance, and focuses solely on the use phase of passenger cars. It models exhaust emissions in various driving situations (rural, urban, hot-cold operation, and peak-offpeak traffic values) and considers the current environmental performance classes and age of vehicles in the fleet. The results show that by considering these vehicle performance aspects, impacts are better represented. The no-change scenario would lead to a 2.5 times increase of global warming impacts by 2035 as compared to 2020, while by limiting the import of used cars and increasing the share of electric and hybrid vehicles would lead to mitigating these impacts.

Keywords: life cycle assessment; automotive industry; used passenger cars; environmental performance

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1. Introduction

The recent changes in European policy regarding the necessary reduction of greenhouse gases (GHG) emissions, together with the important technological progress brought about by the new generation of electric vehicles (EV) have led to a change in the consumers' behavior in Western Europe: a major increase of the new registration of electric vehicles (from 3.5% to 11% in 2020) [1]. Consequently, most of the replaced vehicles became used passenger cars (or second-hand vehicles) in Eastern European countries, where they make up most of the newly registered vehicles each year. For example, the national car fleet of Romania has increased by almost 9.5% in just one year (2017) to more than 7.6 million vehicles of which approximately six million were passenger cars [2]. This increase was largely due to imported used passenger cars, which contribute to an already aging national fleet. According to official data from the National Registration Department, in 2020, approximately 1.76 million passenger cars (24%) were older than 20 years, 4.045 million units were 10–20 years old (56%), 1184 million units were 3–10 years old (16%), and only 0.277 million (4%) were new cars [2].

Expanding the duration of the use-phase in a product's life cycle represents a well-known strategy to improve its environmental performance, because it avoids consuming fresh resources for a new product [3]. However, this is not true if the replaced product has better environmental performance, as is the case with the new electric cars, or if the old product's usage generates higher levels of pollution and environmental impacts (as compared to the new version) [4].

Environmental performance investigation and assessment is common practice for production processes, but only relatively recently did the environmental impacts of products and their supply chains come to the attention of the research community, environmental politics, and policymakers. Product sustainability and performance along supply chains is commonly investigated by means of a life cycle assessment methodology. The common life cycle assessment (LCA) approach (from ISO 14040 and 14044) distinguishes between four essential steps needed in all types of studies: goal and scope, life cycle inventory, life cycle impact assessment, and interpretation of results [5].

In the automotive industry, the LCA methodology was historically applied with a focus on the production processes, on materials, or to compare the environmental performance of different car components or car technologies. Most of these studies focused on comparing different materials or technological options from an eco-design perspective in order to improve the environmental performance of the vehicle [6]. In this respect, most of the LCA research compares the environmental performance of different powertrain systems (mostly petrol and diesel vehicles, the so-called internal combustion engine vehicles (ICEVs)) to different types and configurations of electric-powered ones: battery electric vehicles (BEVs) [7], plug-in hybrid electric vehicles (PHEVs) [8,9], and fuel cell electric vehicles (FCEVs) [10,11]. These studies usually focus on discussing GHG emissions [12] or the climate change effects of ICEVs [13] versus those caused by the production, use, and post-use impacts of electric vehicles and batteries [14] and the corresponding emission transfer caused by the market uptake of these new products [15,16]. More recently, economic impacts [17,18] or the consumer acceptability issues [19,20] of these changes and their effects have been addressed. It is generally accepted that environmental impacts of a vehicle in the use phase are largely caused by fuel-dependent emissions and in this respect, various well-to-wheel or tank-to-wheel scenarios are often compared [21,22]. In this direction, there is research that thoroughly investigates how different types of fuels (mainly for ICEVs) would change the environmental profiles of using passenger cars [23,24]. With respect to the post-use phase of vehicles, life cycle assessment studies are usually performed to evaluate the environmental impacts, or the economic viability of different management practices of end-of-life vehicles (ELV) [25,26].

Furthermore, key improvement strategies that were investigated by LCA include increasing powertrain efficiency [27], vehicle electrification and development of electric mobility, and light weighting of vehicles by reducing their mass or by changing materials [28]. On the other hand, the changes brought by these technologies (decline of ICEV versus the uptake of EVs) are certainly driven by high-level policy changes (e.g., the European Green deal) and some studies have investigated how this technology shift is embraced by the public, by the automotive industry and the national regulators and which are the instruments needed to effectively implement this shift. For example, Danielis et al. [29] showed that decarbonization of passenger transport in European countries rely on the increased use of biofuels and the accelerated uptake of electric vehicles which can lead to a GHG reduction of up to −3.6% CO_2eq for biofuels and −8.3% for the electrification. On a more consumer-oriented level, Lam and Mercure [30] investigated which policy mixes are best for decarbonizing passenger cars and find out that by combining electric vehicle mandates with taxes and regulations on combustion vehicles can lead to rapid changes in the market because it simultaneously improves low-carbon options availability to the consumers while simultaneously penalizing high-carbon options.

The data presented in Table 1 summarizes the main research topics that deal with the use of LCA in the automotive field.

Table 1. LCA in the automotive industry.

Article Topic	Study Objectives	Main Findings	Reference
Environmental comparison of conventional and electric cars	Comparative case study of ICEV and electric cars	BEVs have fewer climate change impacts. BEV manufacturing has greater impacts as compared to ICEV. Other environmental impacts (acidification, human toxicity, particulate matter, photochemical ozone formation and resource depletion) have higher results for the BEV than the ICEV, primarily due to the major environmental loads of powertrain construction and manufacturing.	[7,31]
	Compare life cycle (LC) Energy and GHG Emission of BEVs and PHEVs	BEVs are less emission-intensive than PHEVs, but efficiency depends greatly on the electricity mix generation	[32,33]
Light weighting	Lightweight design vs. Electrification	Lightweight materials such as aluminum have the lowest energy consumption and the lowest CO_2 emissions compared to steel and magnesium-based designs. Hybrid vehicles perform better but this again depends on the electricity mix.	[34]
	Reducing vehicle mass to improve performance	Material substitution may reduce vehicle weight, but it may also lead to increased vehicle-cycle GHGs (e.g., by replacing steel with wrought aluminum, carbon fiber reinforced plastic (CRFP), or magnesium). However, lifetime fuel economy benefits often outweigh the vehicle-cycle, resulting in a net total life cycle GHG benefit.	[35,36]
Fuels and well-to-wheel systems impacts	Assess GHG emission impacts of diverse biofuels	Biofuels (liquid or gas) impacts depend strongly on the incorporation rate. A low incorporation rate (E10 and B7) leads to small benefits, but for the E85 and B100 fuels, the CO_2 emissions reduction would be great. Simulated results for E85 biofuel are close to extended range BEVs in 2019: 103 vs. 85 g CO_2 eq/km, respectively.	[23]
Economic impacts, consumer behavior	Effect of large-scale adoption of BEVs on environmental impacts economic variables and consumer acceptability	Fuel price changes, incentives by manufacturers, but mainly state subsidies are the main drivers for BEV adoption. Availability of charging stations is also important. Increased BEV productivity and uptake may lead to growth in non-tailpipe emissions which can cancel out some of the tailpipe benefices, so BEV adoption stimulation policies (subsidies) should be complemented by green manufacturing and green power generation initiatives.	[17,18,20]
		Large-scale adoption of BEVs leads to changes in national or regional electricity impact profiles.	[15]
	Investigation of 63 scenarios of using combinations of regulatory, procurement and fiscal policies	Combining electric vehicle mandates with taxes and regulations on combustion vehicles is highly effective in changing consumer behavior.	[30]

As previously shown, much of the LCA-based sustainability assessments have been carried out to investigate various technology-related aspects (ICEV vs. EVs, fuel-types, EoL impacts) and less attention has been given to the corresponding consumer behavior changes and the implications of these changes at regional levels. Concretely, most studies investigated how the increasing market uptake of electric vehicles led to environmental improvements, but to our current knowledge there is no study which investigates the environmental impacts of prolonging the use of used passenger cars (in different locations) instead of retreating them from use.

The objective of this study is to evaluate with the support of LCA and several scenarios, the potential environmental impacts of a growing fleet of used vehicles, their contribution to the total fleet impacts and to investigate how different policy decisions may lead to changes in the overall environmental profile of the car fleet. Our investigation is focused on Iasi County, a region in the North-Eastern part of Romania which is considered representative for the passenger car fleet characteristics and user behavior at national level. The environmental performance of personal cars is governed at European level by a series of Directives which bring amendments to the Directive 70/220/EEC. The latest of these European Emissions standards is the EURO 6 standard which came into force in 2014, but the majority of the used passenger cars imported in Romania fall in older emission categories (mostly EURO4 and older). One of the research questions we investigate refers to understanding how the car fleet dynamics would impact the environmental profiles. Thus, prior to conducting an environmental modeling and analysis, we thoroughly investigate from a statistic point of view the characteristics of the car fleet in this region and show that there are significant differences compared to the structure and trends at European level in this field.

The investigation is aimed to understand how the growing number of used cars contributes to increasing environmental impacts (in multiple categories). This is performed by employing a modeling tool which allows taking into consideration emission-related parameters that are specific to an aging passenger car fleet (decreasing performance due to high mileage, pollution class structure, etc.), to calculate updated emissions in specific conditions for various driving scenarios (highway, rural and urban peak and off-peak). These updated emissions are subsequently used to model three future scenarios that consider different policy-induced changes in the passenger car fleet structure.

2. Materials and Methods

2.1. Research Methodology

The research methodology is presented in Figure 1. Our investigation started with a statistical analysis concerning the age, structure, and evolution of a passenger car fleet in Iasi County between 2006 and 2021, in order to identify and classify vehicles according to their age and European pollution classes. This data were further used as input to define a series of future fleet dynamics scenarios which subsequently were investigated in the life cycle assessment.

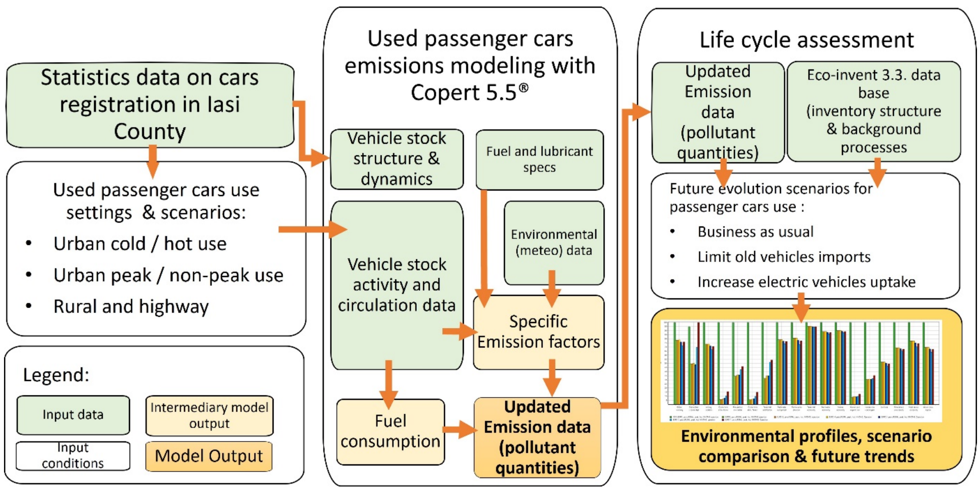

Figure 1. Used passenger cars environmental impacts research approach.

The next step in the research was to use the Copert 5.5 software package to model the passenger cars emissions in various driving contexts and to account for the vehicle's age and degradation in the emissions budget. The emission data were then used as input in the life cycle assessment study which considered the distribution of the passenger cars park based on the European pollution standard, the specific updated emissions as well as several scenarios for different driving conditions. Life cycle assessment was considered for the identification and analysis of specific environmental and human health impacts related to the extended use phase of passenger cars which otherwise could not be interpreted only by analyzing the emissions values (such as specific emissions of petrol engines uch as hydrocarbons).

2.2. Data Sources

The primary data concerning the distribution and dynamics of the passenger car fleet in Iasi County (Romania) was sourced directly from the national governmental database regarding the passenger cars registrations [2,37]. The data were then categorized considering criteria, such as the powertrain type, European pollution class, and age. The results of this analysis are presented in Section 3.1 and in detail in the Supplementary Materials.

2.3. Passenger Cars Emissions Modeling

Estimation of passenger cars emission was performed with the help of Copert 5.5, which is a software package developed by the European Environment Agency with the aim of calculating the air emissions of road transport [38]. Copert software offers the possibility to calculate specific emission factors and total emissions for different types of road vehicles (e.g., passenger cars, light commercial vehicles, trucks and buses, specialty vehicles) in all emission control categories (EURO standards). Beside these features, this model is useful because it enables the user to configure and consider various relevant road transport modes (e.g., thermal stabilized engine operation, the so-called "hot" emissions, the warming-up phase, 'cold start' emissions, and non-exhaust emissions such as fuel evaporation, tires, and brake wear emissions during operation), and it allows taking into consideration the vehicle age and associated damage to calculate updated vehicle emissions. This last feature is very important for the research reported in this study because it was used to estimate the used passenger cars' emission considering their age and mileage wear. In Table 2, a summary of the methodological aspects of emission calculation is provided. Emission estimation is based on specific technical data (Tier 3 method) and vehicle activity data, as presented in Figure 1, and it is calculated as the sum of hot emissions (with engines at normal operation temperature) and cold start emissions (during the transient phase of engine warm-up). This distinction is necessary between the two operation conditions, because there is a substantial difference in the vehicle emissions during these phases and concentrations of some specific pollutants during the warm-up period are many times higher than during the normal (hot) operation situations. Furthermore, the emission calculation model makes a clear distinction between the urban (<19 km/h), rural (19–63 km/h), and highway (>63 km/h) operation modes of passenger cars, by considering average speed in the calculation of hot emissions.

Table 2. Air emission calculation methodology.

Emission Group	Pollutants (Major Types)	Emission Calculation Methodology	Specific Conditions and Parameters
Group 1	CO, NOx, NMVOC, PM, N_2O, NH_3	Specific emission factors considering various models	
Group 2	CO_2, SO_2, heavy metals	Estimated based on fuel consumption (fuel quantity dependent)	Default values were used: Petrol calorific value: 43.774 MJ/kg Diesel calorific value: 42.695 MJ/kg E10 petrol mix (90% petrol, 10% bioethanol), B7 diesel mix (93% diesel, 7% biodiesel)
Group 3	Polycyclic aromatic hydrocarbons (PAHs) and persistent organic pollutants (POPs)	Simplified methodology considering bulk emission factors (instead of specific)	
Group 4	Alkanes, Alkenes, Alkynes, Aldehydes, Ketones, cycloalkanes, Aromatics	Estimation based on fraction of total NMVOCs	

2.4. Life Cycle Assessment Methodology

A life cycle assessment was performed according to the specifications of the ISO 14040:2006 standard [39] by considering the elements which are summarized below.

The goal of the study was to investigate the environmental impacts of the passenger cars in Iasi County Romania, for a period of 1 year (2020) considering various use scenarios. The scope of the evaluation only included the operational (use) phase of the vehicles which was modeled considering the structure of the car fleet distribution according to the European pollution class and other parameters such as: driving mode (urban peak, urban off-peak, rural and highway). The analysis was focused on the use phase of the used passenger cars and it has considered processes such as fuel consumption, maintenance, and direct operation. The functional unit of the study was chosen as 1 km of travel.

The life cycle inventory was modeled in SimaPro by partially sourcing data from the EcoInvent 3.3 database for some of the input/output entries in the inventory (well-to-wheel fuels inventories and maintenance processes inputs), while the direct operation processes inventory entries were modeled using the actual quantitative pollutant values as calculated using the Copert 5.5 model (updated emission data in Figure 1). The reason for this is that in the Ecoinvent database, the existing default inventories for different pollution class passenger cars operation consider average operation values based on the European car fleet structure and could not be used as such in this investigation where specific driving conditions and vehicle specifications were needed (especially to account for the higher emissions due to aging car fleet). Data in Table 3 show the inventory values for driving 1 km in urban conditions (hot emission) for EURO4 petrol and diesel engines (and Table S1 for all the engine types considered), as well as the eco-invent processes used in the model and the quantitative data source. For reasons of space, NMVOC emissions are given as a total, but these were considered to be individual pollutants in the LCA modeling (alkanes, alkenes, alkines, cycloalkanes, aldehydes, ketones, aromatics, PAH, POPs, dioxins, and furans).

Table 3. LCA inventory for passenger car use in an urban setting, hot emissions, off-peak operation.

Pollution Class	Units	EURO4 Petrol	EURO4 Diesel	Hybrid EURO5	EV	Ecoinvent Process/ Ecoinvent Flow	Data Source/ Comments
INVENTORY INPUTS:							
Fuel consumption	kg/km	0.0755	0.0756	0.0302	-	E10 Petrol: 10% ethanol by volume from biomass {RO} | production | Alloc Def, U + 90% Petrol, low sulfur {ROW} | market for | Alloc Def, U And Diesel B7: 7% Vegetable oil methyl ester {RoW} | esterification of rape oil | Alloc Def, U + 93% Diesel {RO} | market for | Alloc Def, U	Values (quantities) calculated in Copert 5.5
Electricity	kWh/km	-	-	0.158	0.119	2020 Electricity, low voltage {RO} | market for | Alloc Def, U	Modeled according to existing PHEV and EV data manuals
INVENTORY OUTPUTS:							
DIRECT OPERATION EMISSIONS (EXHAUST EMISSIONS)							

Table 3. *Cont.*

Pollution Class	Units	EURO4 Petrol	EURO4 Diesel	Hybrid EURO5	EV	Ecoinvent Process/ Ecoinvent Flow	Data Source/ Comments
Carbon monoxide	g/km	0.1591	0.1900	0.09984	-	Carbon monoxide	Values (quantities) calculated in Copert 5.5 considering specific driving conditions, passenger car age
Carbon Dioxide	g/km	232.99	206.48	93.196	-	Carbon Dioxide	
Methane	g/km	0.0020	0.0008	0.0008	-	Methane	
Sulfur Dioxide	g/km	0.0014	0.0012	0.0005	-	Sulfur Dioxide	
NOx, of which:	g/km	0.0789	0.7785	0.0160	-	NOx	
NO_2	g/km	0.0024	0.4282	0.0005	-	NO_2	
NO	g/km	0.0765	0.3503	0.0155	-	NO	
Dinitrous Oxide	g/km	0.0015	0.0064	0.0007	-	Dinitrous Oxide	
Particulates, PM 2.5	g/km	0.0004	0.0360	0.00026	-	Particulates, PM 2.5	
Lead	mg/km	1.20×10^{-4}	3.28×10^{-5}	4.80×10^{-5}	-	Lead	Values (quantities) calculated in Copert 5.5. considering specific driving conditions, passenger car age
Nickel	mg/km	1.73×10^{-4}	1.31×10^{-5}	6.90×10^{-5}	-	Nickel	
Zinc	mg/km	2.48×10^{-3}	1.18×10^{-3}	9.90×10^{-4}	-	Zinc	
Selenium	mg/km	1.50×10^{-5}	6.57×10^{-6}	6.01×10^{-6}	-	Selenium	
Mercury	mg/km	6.53×10^{-4}	3.48×10^{-4}	2.61×10^{-4}	-	Mercury	
Chromium	mg/km	4.73×10^{-4}	5.58×10^{-4}	1.89×10^{-4}	-	Chromium	
Arsenic	mg/km	2.25×10^{-5}	6.57×10^{-6}	9.01×10^{-6}	-	Arsenic	
Cadmium	mg/km	1.50×10^{-5}	3.28×10^{-6}	6.01×10^{-6}	-	Cadmium	
Volatile organic compounds	g/km	0.0115	0.0250	0.00317	-	VOCs	Values (quantities) calculated in Copert 5.5 considering specific driving conditions, passenger car age
Non-methane Volatile organic compounds	g/km	0.0094	0.0242	0.00051	-	NMVOCs	
NON-EXHAUST EMISSIONS:							
Specific brake pads wear emissions	kg/km	1.15×10^{-6}	1.15×10^{-6}	1.15×10^{-6}	1.15×10^{-6}	Break wear emissions, passenger car {GLO} | market for | Alloc Def, U	Default values from Ecoinvent database
Specific tire emissions	kg/km	7.42×10^{-5}	7.42×10^{-5}	7.42×10^{-5}	7.42×10^{-5}	Tire wear emissions, passenger car {GLO} | market for | Alloc Def, U	Default values from Ecoinvent database
Specific road abrasion emissions	kg/km	1.27×10^{-5}	1.27×10^{-5}	1.279×10^{-5}	1.27×10^{-5}	Road wear emissions, passenger car {GLO} | market for | Alloc Def, U	Default values from Ecoinvent database

Our analysis considers an extended lifetime of 10 years of use for each passenger car (more than its initial age) and an average yearly mileage of 15,000 km, which yields a total of 150,000 km. These values were chosen in accordance to the average European driving conditions (12,800 km/year; 11.8 years average car age) [1].

Life cycle impact assessment (LCIA) has included the classification and characterization steps according to ISO 14040:2006 recommendations using the ReCiPe 2016 method at the midpoint for the characterization of environmental impacts and by considering all its 18 impact categories (presented in the Abbreviations list [40]. SimaPro 9.035 software was used to compile the inventory and to perform the life cycle impact assessment. Previous life cycle assessment studies were targeted mainly t calculating the climate change related impacts, but our investigation seeks to evaluate impacts on human health and ecosystems, so all ground-level air emissions and categories are taken into consideration.

3. Results and Discussion

3.1. Passenger Car Fleet Dynamics

Data for the passenger car fleet statistical analysis was sourced from the national registry of car registrations and it was compiled from monthly data series which are publicly available. As presented in Figure 2 (and Table S2), one may observe that since Romania joined the European Union (EU) in 2007, the number of passenger cars in Iasi County has almost tripled, from 88 cars/1000 people to 260/1000 people, which is still less than the national numbers (150 to 376/1000 people). However, as compared to the European average (423–507 cars/1000 people), for the same period, the number of passenger cars remains small, albeit with a higher growth rate. The annual growth rate of the car fleet presented in Table 4 for Romania and Iasi county corresponds accurately to the changes in the national rules and legislation related to the import of used passenger cars and it can be a very good indication of the consumer behavior in this field. In 2007, Romania joined the EU and in the field of vehicle imports it meant that any import taxes from the common market were dismissed and this explains the high growth rate in 2007 and 2008.

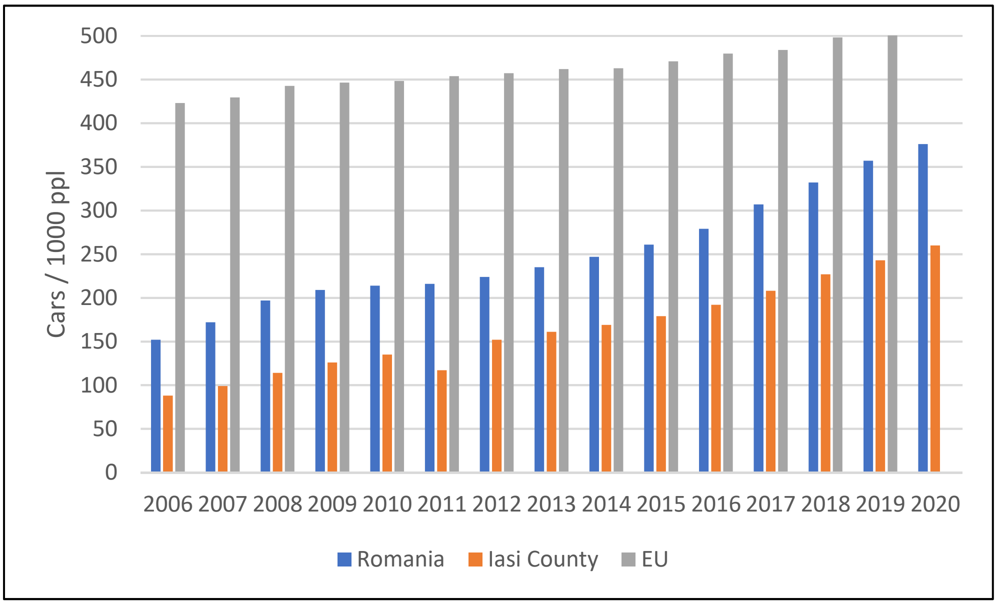

Figure 2. Passenger car fleets evolution 2006–2020.

Table 4. 2020 Iasi County passenger car distribution by pollution classes.

	Total	Non-EURO	EURO 1	EURO 2	EURO 3	EURO 4	EURO 5	EURO 6
2020 stock	193,187	22,744	607	21,543	35,088	68,099	24,322	20,784
2020 registrations	14,415	28	28	254	2237	4847	2416	4605
2020 outputs	−2048	−68	−244	−346	−817	−460	−73	−40
total	205,554	22,704	391	21,451	36,508	72,486	26,665	25,349
% of total	100	11.0%	0.2%	10.4%	17.8%	35.3%	13.0%	12.3%

In trying to limit the imports of old polluting cars, in 2009, the national government introduced a pollution tax which led to a decrease in car imports together with the decreasing purchasing power due to the economic crisis in that period. These regulations were subsequently modified and finally abandoned in 2017, which has led again to high growth rates in the passenger (used) car fleet. Although the total number of passenger cars is at Iasi County level is not a problem, their age and pollution standards compliance are performance aspects that impact the environmental status in this region. More exactly, in

Figure 3 (and Table S3), one may observe that the passenger car fleet in Iasi County is old, more than 80% of the vehicles are older than 10 years old (in all of the last 5 years) and only 6 to 8% are less than five years old (which for 2020 equate approximately with the last issue of European pollution norms (EURO 6)).

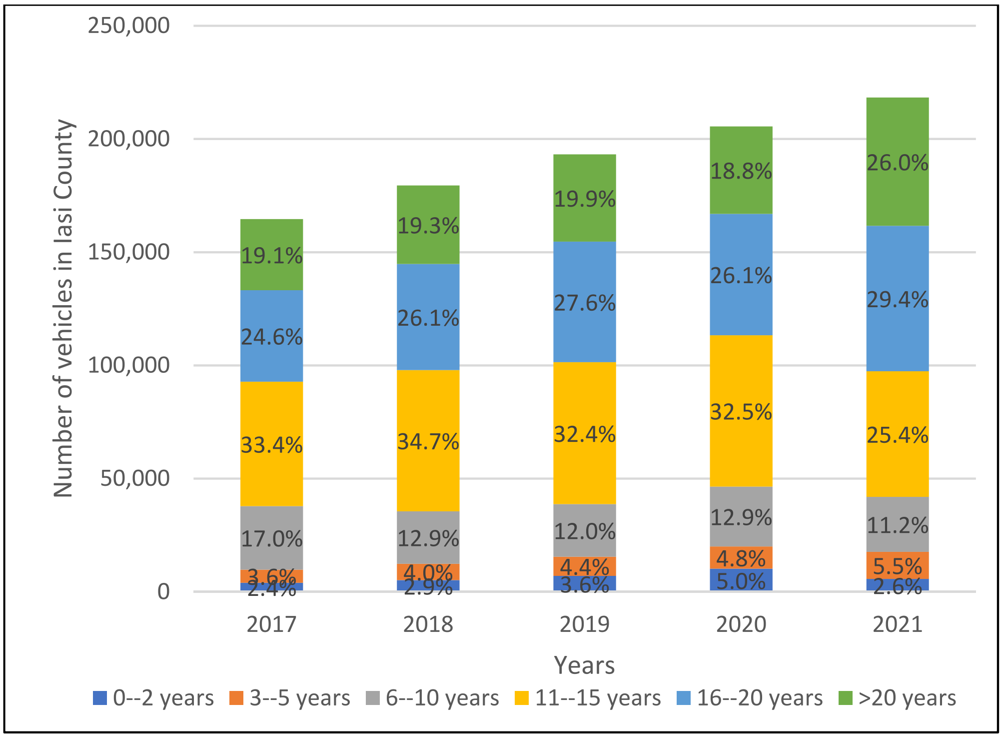

Figure 3. 2017–2021 Iasi county car fleet age dynamics.

When it comes to the distribution of engine types (which largely dictates the environmental performance of the vehicles in the use phase), in Figure 4 (and fully in Table S4) one may notice that since 2015 (when this type of data was available), the share of petrol engines cars decreased constantly, while the diesel engine one has recorded an inverse trend, which marks a shift in the public preference related to this aspect. Additionally, in Figure 4, one may notice that the number of hybrid and full electric cars increased exponentially for the recorded period, albeit the car numbers war very small compared to the number of cars with conventional engines. These data were used to model and estimate some scenarios related the dynamics and evolution of the car fleet in Iasi County until 2035.

The contributions to the growth rates in the Iasi County car fleet mainly come from imports of used passenger cars from across Europe, while the new cars registrations have a minor contribution. In Table 4, the car fleet dynamics regarding the pollution classes is shown for 2020. It may be noticed that in conformity with data presented in Table 4, 74.7% of vehicles conform to older pollution classes (non-EURO to EURO 4) and that the registrations in 2020 also have had the same structure. Only a small number of cars have been taken out (2048, 0.99% of the total 2020 car fleet) which represents a very small renewal rate of the car fleet [41]. Twenty percent of registrations in 2020 represent new vehicles which were purchased as part of a national program destined to support the renewal of the national car park by issuing a fixed-value voucher when decommissioning an old vehicle.

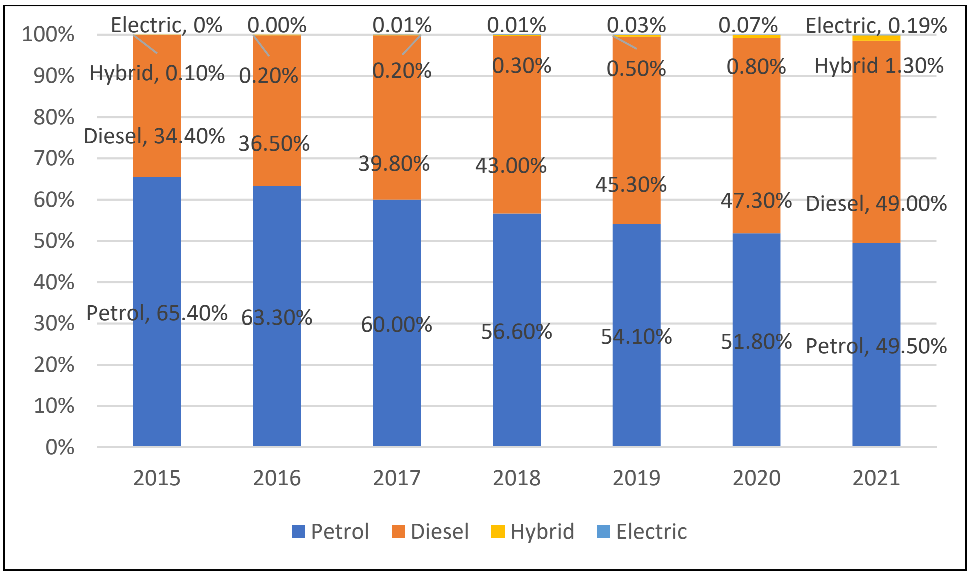

Figure 4. Iasi County passenger cars distribution by type of fuel.

3.2. Car Fleet Dynamics Scenarios

As stated before, the statistics presented in the previous section were used to model and estimate the future evolution of the Iasi County passenger car fleet in order to develop some scenarios regarding the structure of this fleet, and further to evaluate its prospective environmental performance.

The year 2020 was chosen as the reference year and a time horizon of 15 years to 2035 is envisaged, because 2035 represents the EU's target to ban the registration of internal combustion engines in all passenger vehicles [42]. These scenarios were defined considering the assumptions and characteristics presented in Table 5 and consist of estimating the evolution of the Iasi County car fleet numbers and structure based on these assumptions. This modeling was performed by fitting linear or non-linear time functions on the known data series (2015–2021), and then using these functions to estimate the car numbers for the future period (2022–2035). After the total number of cars in each scenario was estimated (Figure 5), a non-linear multi-function fitting algorithm was used to estimate the structure of the future fleet (age distribution, energy source and pollution class).

Table 5. Iasi County car fleet dynamics scenarios.

Scenario	Description
Scenario 1—no change	Used vehicles are being imported at the same rates since the last limits were dropped-out (2015–2021). Engine type and pollution class distribution follow historic trends.
Scenario 2—2023 ban on importing used passenger cars older than 15 years	Used vehicles are imported at the same rates as in the regulated period (2008–2014). Engine type and pollution class distribution are modeled considering S-type or bell-type growth curves. Hybrid and electric cars growth rates are modeled considering the initial exponential trend and then they reach a plateau based on the future development in this market sector such as: increased support in the car renewal program, increased production numbers of national electric cars, increasing the number of publicly available charging stations.
Scenario 3—2023 ban on used passenger cars imports and an accelerated intake rate for hybrid and electric cars	Growth rates consider that used cars are imported at the same rates as in the regulated period (2008–2014), and the current new cars registration rates. Hybrid and electric car uptake at a double rate as compared to Scenario 2.

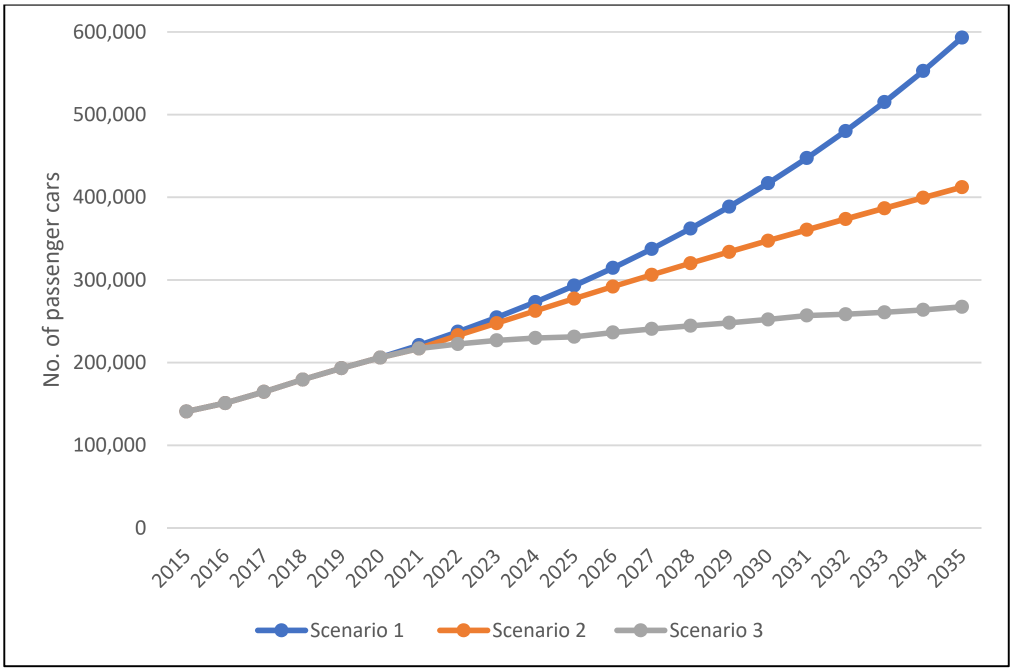

Figure 5. 2022–2035 Iasi County car fleet evolution scenarios.

3.3. Default Environmental Profiles

The environmental analysis of the Iasi County car fleet dynamics is based on the environmental profiles of each car type in different driving scenarios. These comparative profiles are presented in the Supplementary Materials for the EURO 4 petrol car (Figure S1) and diesel (Figure S2) cars in an urban setting (hot engine), as well as the profiles for hybrid PHEV EURO 5 petrol car (Figure S3) and all electric vehicles (BEV) (Figure S4).

These environmental profiles present the main contributors in each impact category: specific direct exhaust emissions (internal combustion engines), fuel (or electricity) production and processing, vehicle maintenance, and non-exhaust emissions caused by brakes, tires, and road wear. As expected, the direct exhaust emissions mainly contribute to air-related impact categories such as global warming (GWP), ozone depletion (O3 dep), particulate matter formation (PM), stratospheric ozone formation (O3 HH and O3 ECO). Fuel production (petrol and diesel alike) represent the most important contributor in most categories, while maintenance only makes a minor contribution. Non-exhaust emissions contribute to the terrestrial toxicity and particulate matter categories.

With respect to the current impact values, in the global warming category, values indicate a total of 310 g/km for the diesel engine, 366 g/km for the petrol engine, 237 g/km for the hybrid, and 90 g/km for the electric vehicle. These values are larger than the ones reported in the literature [31] because here we describe a particular driving situation (e.g., an urban setting, a driving speed of 33 km/h which implies a higher fuel consumption, larger evaporative emissions as compared to the average values that are usually reported). In the ozone formation categories (O3 HH and O3ECO), the nitrogen oxides have the highest contribution: 1.1 g NOx eq/km for the diesel engines and 3.4 g NOx eq/km for the petrol ones, and the well-to-pump fuel has a higher share as compared to the diesel system. The particulate matter formation reveals 0.3 g PM2.5 /km for the diesel power plant and 0.22 g PM2.5/km for the petrol driven cars, while the BEV is just 0.16 g PM/kg (with the mention that the airborne emissions of the BEV do not contribute to traffic emissions). The toxicity-related impacts are generated by direct non-exhaust emissions due to brake and tire wear which leads to considerable effects in the terrestrial toxicity category, while maintenance (which includes spare parts and oil changes) lead to impacts in the other toxicity-related categories.

The PHEV impact profile (Figure S3) shows that beside the ICEV system contribution are the impacts due to electricity consumption, which are modeled according to the 2020 Romanian electricity mix (17.81% fossil fuels, 17.13% natural gas, oil 1.07%, 20.50% nuclear, 28.16% hydro, 2.8% solar, 11.90% wind, biofuels 1.70%) and have the same structure as the electric car.

In Figure 6, a comparison of relative environmental impacts of several driving conditions for the same vehicle (diesel, EURO4) is shown and it shows that all of them generate considerable higher impacts than the default Ecoinvent scenario. This difference is due to the higher fuel consumption in the urban environment, but also due to the mileage damage that was taken into account when modeling the used passenger car operation, and it clearly shows the greater impact of used vehicles in all usage settings. In all cases, the cold engine operation had the highest impacts, followed by the urban driving in peak traffic conditions, which had approximately 2–10% higher impacts than the off-peak driving conditions. It must be noted that all the other vehicles (non-EURO to EURO6) generated similar profiles when compared across the same driving situations.

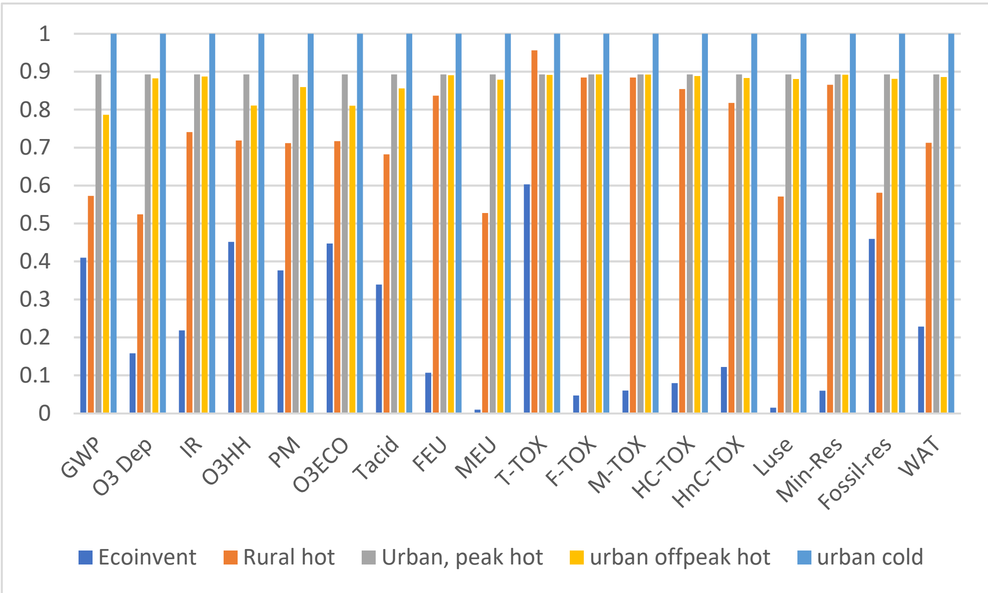

Figure 6. Environmental impacts of a diesel EURO4 passenger car in different driving situations.

3.4. Car Fleet Evolution Scenarios

In Figures 7–9, the evolution of environmental impacts according to the three proposed scenarios (Figure 5) are presented. All these scenarios were modeled considering the urban, off-peak, and hot engine driving settings, because these represent the most common driving conditions in Iasi County. All scenarios were modeled considering 15,000 km driving distance per year for every type of polluting-class vehicle. The worst-case scenario (according to Figure 6) would have been the urban, cold, peak driving, but this is a transient driving mode, it induces a lot of uncertainty, and for these reasons, the other driving setting was preferred.

Data in Figures 7–9 present the total impact values in each category as a sum of individual values obtained for every class of polluting vehicles and considering their share presented in the snippet of every scenario. Values for 2015 and 2020 are computed based on the actual number of cars in each category, and the values for 2025 and 2035 are estimated considering the scenario definitions (Table 5).

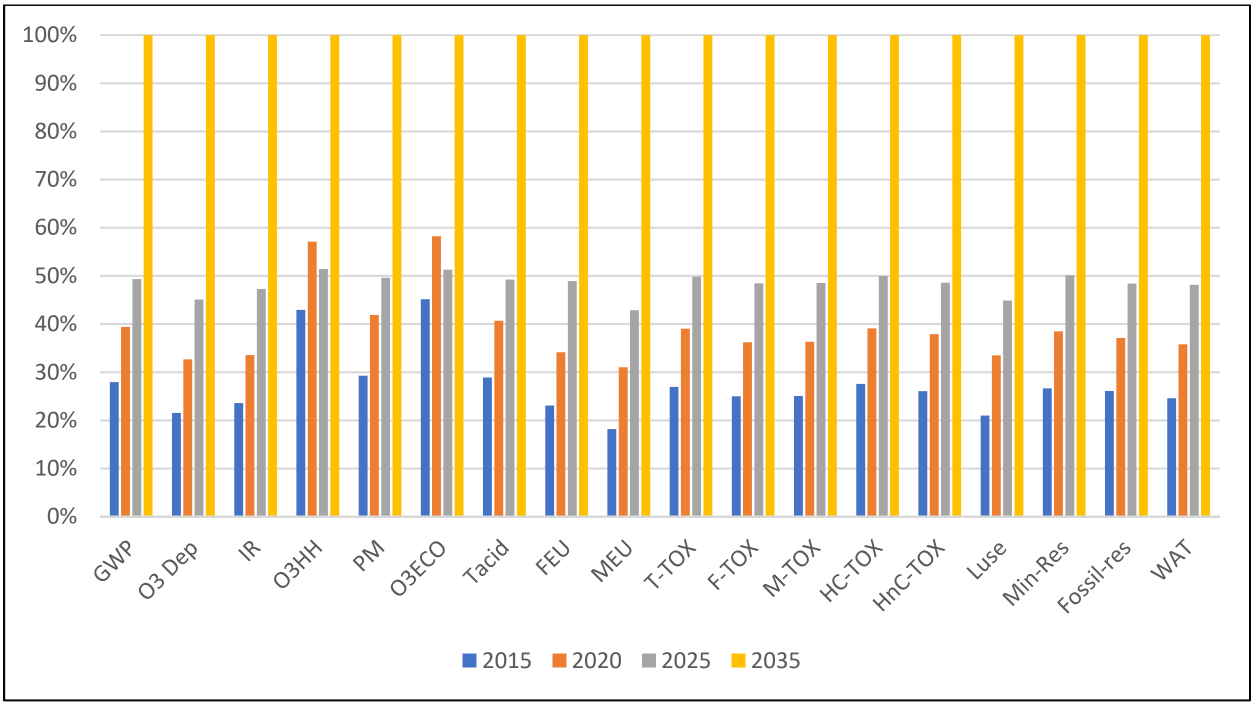

Figure 7. Evolution of the environmental impacts according to Scenario 1.

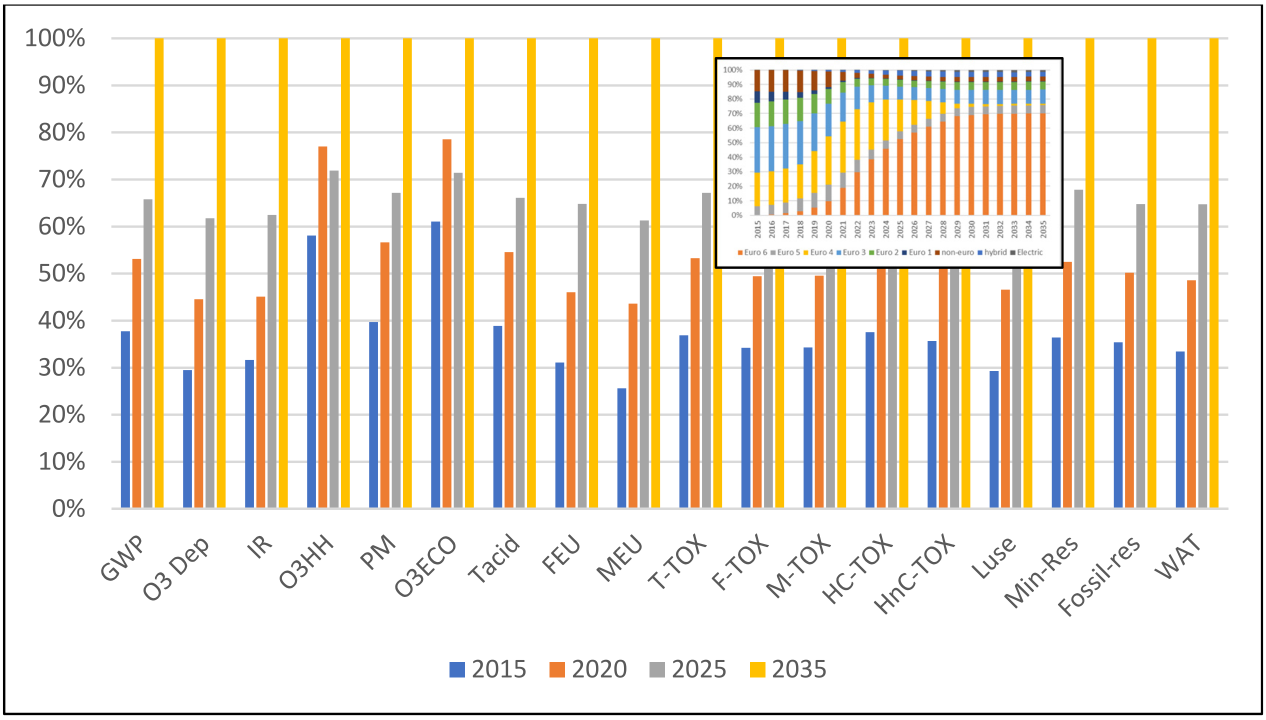

Figure 8. Evolution of the environmental impacts according to Scenario 2.

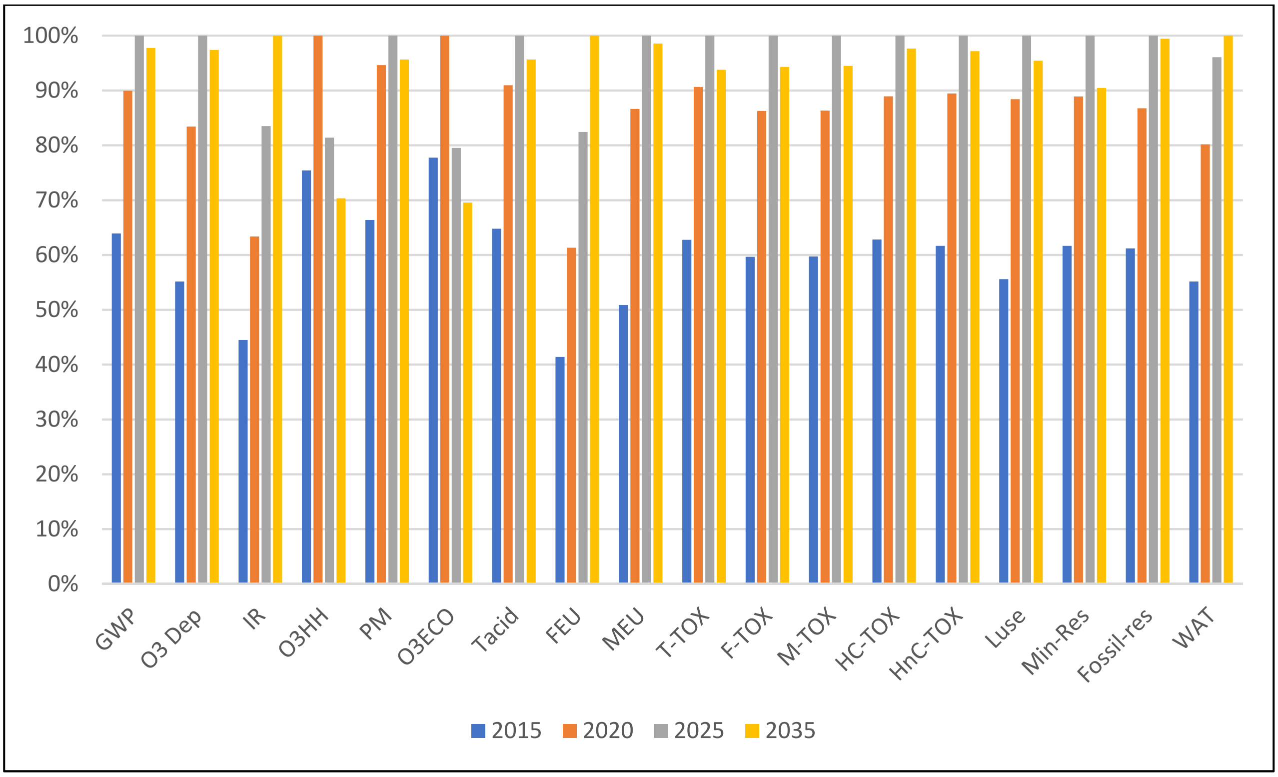

Figure 9. Evolution of the environmental impacts according to Scenario 3.

The evolution presented in Figure 7 shows that for this scenario, according to which no changes occur in the car fleet evolution and structure, the 2035 impact values are multiple times higher than the 2020 reference year in every impact category. The smallest impact increase occurs in the O3ECO category (169%), followed by the O3HH (173%) due to changes in the structure of the fleet, as in 2035 most of the vehicles will be in the EURO 6 class which has the much lower nitrogen oxides emissions that EURO4 class (which form the majority in 2020). In the global warming category, an increase of 249% is calculated for 2035 as compared to 2020 and this high increase is due to the fact that the global warming emissions do not depend on the vehicle performance, but are proportional to the fuel consumption which in our analysis is tied to the number of vehicles. The same type of trend is recorded for all the other impact categories (with a maximum increase of 316% in MEU). In the case of Scenario 2 (Figure 5), which considers a ban on imported used vehicles and much lower subsequent growth rates in car fleet, the same trend is recorded as for Scenario 1, but the differences are not so high. With respect to Scenario 3 (Figure 9), which besides the limited growth rates of car numbers considers an accelerated uptake of hybrid and electric cars, environmental impacts growth is limited and even reversed for most impact categories. Impacts are still higher as compared to 2020 in the IR (138%), FEU (140%) categories, which are connected to the electricity used by the increasing number of hybrid and electric vehicles. Even when the share of electric and hybrid cars increases (4.48% electrics and 10% hybrids) in 2035, their associated impacts remain small in the overall impact profile (2–17%, except for the electricity related categories, where their combined contribution reaches 40%).

In Figure 10 a comparison of the three scenarios is presented with 2020 as the reference year. It clearly shows that the evolution according to Scenario 1 represents the worst-case scenario, with impacts up to 3.2 times higher than the reference year. These high values are due to the linear increase of car numbers due to any lack of controlling the import of old polluting vehicles. These impacts can be partially avoided or even mitigated by introducing a series of fleet management rules that limit the use of old-generation vehicles and stimulate the uptake of cars with a low environmental footprint.

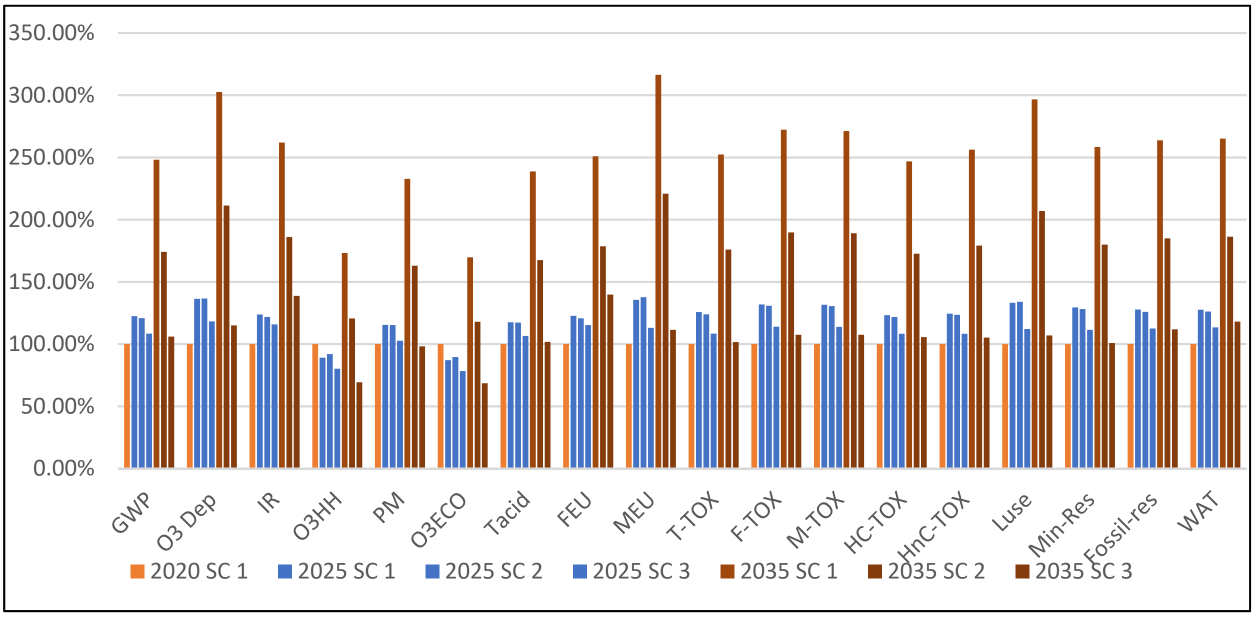

Figure 10. Environmental impacts scenarios comparison.

4. Conclusions

This study presents an in-depth analysis of the environmental performance and evolution of the passenger car fleet in Iasi County, which is representative of Romania in the period from 2020 to 2035. The analysis is based on historic statistical data regarding the car fleet number and structure and particularly on the dynamics of used car imports which were used to estimate the future of this fleet according to three scenarios. The environmental performance evaluation was made by means of a life cycle assessment, which was focused exclusively on the use-phase of passenger cars. The use phase was specifically modeled to estimate the exhaust emissions in various driving situations (rural, urban, hot-cold operation and peak—off-peak traffic values) and by considering the actual environmental performance and age of the vehicles comprising the fleet.

The results show that the current car fleet structure and evolution in a business-as-usual context will represent a worst-case scenario, with the global warming impact growing by 2.5 times by 2035. Furthermore, our analysis shows that the adoption of a series of car fleet management and regulating instruments can help to mitigate and even reverse some of these impacts. Thus, the accelerated rate of hybrid and electric vehicles uptake represents the main driver for improving the overall environmental performance (especially in the air-related categories), while only increasing the share of newer ICEVs (and eliminating the old cars) is not sufficient to limit these growing impacts.

From a methodological point of view, it is important to note that considering and modeling specific usage scenarios generates a localized impact profile and the results should be treated accordingly. Additionally, is it important to mention that this study needs to be continued with an investigation into the end-of-life phase of these vehicles because, as they are progressively replaced, their final fate needs to be properly managed.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su14148443/s1, Figure S1. Environmental profile of a 1 km urban drive of a EURO 4 petrol passenger car; Figure S2. Environmental profile of a 1 km urban drive of a EURO 4 diesel passenger car; Figure S3. Environmental profile of a 1 km urban drive of a EURO 5 hybrid passenger car; Figure S4. Environmental profile of a 1 km urban drive of an all electric passenger car; Table S1. Passenger car use inventory–urban scenario, hot emission, off peak operation; Table S2. Iasi County Passenger car fleet evolution; Table S3. Iasi county car fleet age dynamics; Table S4. Iasi County passenger cars distribution by type of fuel.

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Abbreviations

Global warming	GWP, kg CO_2 eq
Stratospheric ozone depletion	O3DEP, kg CFC11 eq
Ionizing radiation	IR, kBq Co-60 eq
Ozone formation, Human health	O3HH, kg NOx eq
Fine particulate matter formation	PM, kg PM2.5 eq
Ozone formation, Terrestrial ecosystems	O3ECO, kg NOx eq
Terrestrial acidification	T acid, kg SO_2 eq
Freshwater eutrophication	FEU, kg P eq
Marine eutrophication	MEU kg N eq
Terrestrial ecotoxicity	T-TOX, kg 1,4-DCB
Freshwater ecotoxicity	F-TOX kg 1,4-DCB
Marine ecotoxicity	M-TOX kg 1,4-DCB
Human carcinogenic toxicity	HC-TOX kg 1,4-DCB
Human non-carcinogenic	HnC-toxicityTOX kg 1,4-DCB
Land use	Luse m^2a crop eq
Mineral resource scarcity	Min-Res kg Cu eq
Fossil resource scarcity	Fossil-res, kg oil eq
Water consumption	WAT m^3

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