Characterization of the evolution in the efficiency and quality of lightweight passenger vehicle services

João Barata

joaoabarata@tecnico.ulisboa.pt

Instituto Superior Técnico, Universidade de Lisboa – Portugal

November 2019

Abstract

Car efficiency is one of the decisive factors when implementing policies and trends in the transportation sector. This efficiency is usually quantified considering the main service that vehicles offer, the movement from one location to another, in relation to the energy consumed, i.e. fuel consumption. The main objective of this work is to propose and test a new methodology to analyze the transportation service offered by lightweight vehicles. Rather than analyzing it as a whole, it is intended to look at the evolutionary behavior of the services it provides. To achieve this objective, a comprehensive work on a select sample of the European car fleet was done where the vehicle was divided in five services: base, comfort, safety, emission control and performance. These were analyzed by studying the correspondent mass variation and indicators evolution (kW/l, gCO2/km, safety ratings, etc.) over time. The results obtained helped to reach a better understanding of the recent developments in the automobile sector. Both the average mass and quality of each service have increased since 2001 but the only service where the mass increase directly resulted in a better quality was comfort. In the other services, the improvements in quality are a consequence of technological development. Even though each segment reduces his average mass, the average lightweight vehicle mass registered in 2017 was 80 kg heavier than the one verified in 2001. This event is happening due to a shift in consumer trends, where the SUV's market share rose from 2% to over 34% nowadays. This change is cancelling out emission savings from developments in technology. Due to this shift, prospects on the compliance with the 2020/2021 CO2 emission limit (95 g/km) aren't positive for a great number of manufacturers.

Keywords: Transportation, Services, Comfort, Safety, Emissions Control, Mass Analysis, Environmental Impact.

1. Introduction

The number of light passenger vehicles circulating in Europe (EU28) is about 257 million (data from 2016). Together with the rest of the automobile sector they contribute with a significantly large number of jobs, 6,1% of the European work force. On the other hand, because of their dependence on fossil fuels, they contribute largely to GHG emissions and pollutants, such as soot, which has a negative impact on human health. Nowadays 14% of global GHG emissions are associated with transportation (EPA, [s.d.]). With this increasing and worrisome numbers, the advancements in technology and policy makers decisions, transportation is already showing some signs of this transformation.

Car efficiency is one of the decisive factors in implementing policies and trends. This efficiency is usually quantified considering the overall service that lightweight vehicles offer, the movement from one location to another, related to the energy required, i.e. fuel consumption. However, the transportation service can be subdivided into several services, which allows a more complete characterization of this efficiency. Moreover, fuel consumption and pollutant emissions resulting directly from this consumption do not represent the full environmental impact caused by cars. Raw material extraction, vehicle production and assembly, maintenance and disposal of materials in the end of the vehicle life also contribute to the environmental impact. It's estimated that about 6% to 22% of a vehicle's life cycle emissions are related to raw material extraction and production

(Weiss *et al.*, 2009) depending mainly on energy consumption, production site and useful lifetime. Vehicles in the US usually are closer to 6% and in the EU to 22% due to trends in both energy prices and environmental policies. With the expected decrease in the use of fossil fuels to power automobiles, the percentages of emissions related to production and disposal of the vehicle's life cycle will certainly increase, which in turn increases the importance of this issue.

Fuel consumption is dependent directly to vehicle mass. More mass equals more fuel consumption and vice-versa. Research between the correlation of these values has been done over the years. The work of L. Cheah (Cheah, 2010) evaluates the potential energy savings and cost changes related to mass decrease. It was estimated that with a 10% reduction in mass, fuel consumption would decrease by 7% or, in absolute values, for every 100 kg reduction, equals a saving of 0,39 l/100km. This relationship between fuel consumption and mass was analyzed once again in Knittel's work (Knittel, 2011). The results obtained were that for every 10% of mass reduction a 4% reduction in fuel consumption follows. The objective of this paper was to also estimate the technological advance. As a consequence of developments in technology, and although in 2006 cars were on average heavier and more powerful than in 1980, there was a 15% reduction in fuel consumption. The results of this work also indicated that, with this technological advance, and if vehicle mass and power had been maintained at values observed in 1980, the reduction in fuel consumption would be 60%.

The UE publishes yearly reports where a detailed statistical assessment of the European car fleet and its efficiency is made (ICTT Annual Pocketbook (ICCT, 2018)). Following the 2009 decisions on the CO2 emissions limits this was one of the measures to inform the public about the evolution or setback made in the automotive market. There is also work where the impact of the change in vehicle mass is evaluated by separating them into four services: base car, comfort, safety and emission control (Zoepf, 2011). This mass breakdown focused on the US market since 1975 until 2010. However, there is clearly a mismatch between these two types of analysis. Two cars of the same mass and efficiency remain very different for users, manufacturers and policy makers.

Regarding the secondary services and their characterization, the literature reviewed pointed the direction to how it could be accomplished. Nowadays the emission control characterization is obtained with the WLTP, Worldwide Harmonized Light Vehicle Test Procedure (Mock *et al.*, 2014). This is a procedure used globally to determine the GHG levels emitted by vehicles as well as the fuel consumption of conventional and hybrid cars and the autonomy of electric vehicles. It was developed to replace NEDC, New European Driving Cycle procedure, which included a large number of tolerances and flexibilities in the results obtained, as well as not being adapted to the most recent technologies. This would give car manufacturers better results than in real situations. This new procedure was a great measure to help enforce the limits in CO2 emissions set by the EU. It should be noted that these limits are evaluated according to the average mass of vehicles registered by each manufacturer. This means that heavier vehicle manufacturers may have higher emissions than lighter car manufacturers. Due to the fact that NEDC procedure was being used in the study timeframe, the values obtained in this work to characterize the emission control service were collected using NEDC procedure.

The EU over the years has been able to establish what can be considered as the most widely accepted characterization of the security service, the Euro NCAP tests. These tests have been in existence since 1997 and are supported by the EU, International Automobile Federation, and other national federations. Over the years a number of upgrades have been made to reduce road accidents accordingly with EU's proposed objectives. Vehicles are assessed under various impact conditions and about the consequences of such impacts on their occupants, adults or children, pedestrians and, in a recent future, cyclists. In addition, driving assistance and active safety systems are also evaluated. A rating of 0 to 5 stars is attributed to each vehicle.

Comfort, as defined by M. Gameiro da Silva (Gameiro da Silva, 2002), can be divided into five types: thermal comfort, air quality, sound, vibration and others of minor importance. Using recent technologies, the author also suggests methods to evaluate them. These factors are objectively measurable but comfort feeling is subjective for each person which complicates its characterization.

Car performance and its evaluation is generally accepted in the sector by measuring some objective attributes. The most common, and where information is usually public, are top speed (km/h), acceleration time 0-100 km/h (s), maximum torque (Nm), specific power (kW/l) and weight to power ratio (kg/cv).

Putting all of this together, the objective of this thesis is to reassess the efficiency of the transport service and the quality of the services provided by cars through a more detailed characterization.

It is also intended to analyze which service contributes the most to the mass increase of the vehicle and whether the increase in service quality is proportional to the one observed in the mass.

The proposed methodology in order to achieve these objectives is an analysis of the fleet of vehicles registered in the EU during the twenty first century, analyzing in detail models that are representative of the different automotive market segments. The analysis for each model is divided into 5 services: base, safety, emission control, comfort and performance. Safety, base, emission control and comfort will be analyzed through a mass breakdown. Performance, emission control and safety will be characterized by the evolution in objective indicators of their quality. With the results of the analysis and data collected, it is intended to reach conclusions about the "added value" on the developments in these services for the user and whether or not this method is valid to evaluate and characterize the efficiency of the transport service.

2. Methods

This chapter will describe the methodology used in this dissertation.

2.1. Timeframe, Sample and Services

The timeframe of the analysis starts in 2001 and ends in 2017. This happens due to the fact that online data is more copious for recent vehicles. This factor is important due to the lack of collaboration of brands and companies in providing the desired data. Also, because it is the same timeframe that is being used on the reports available by the EU.

Vehicles analyzed were chosen because of their relevance in the automotive market and representativity on their segment. The market was divided into seven segments: Mini, Small, Lower Medium, Medium, Upper Medium, SUV and Luxury. The data collected for each vehicle was used as representative for the segment they belonged, except in SUV. A further explanation on this segment will be made in chapter 2.3. Table 1 shows which vehicles were studied.

The vehicles were divided into five services: base (all the components necessary to move from point A to point B), safety, comfort, emission control and performance.

Table 1 – Sample of Analyzed Vehicles

Segments	Vehicles
Mini	Fiat Panda 2ª Gen and 3ª Gen
Small	Renault Clio 2ª Gen, 3ª Gen and 4ª Gen
Lower Medium	Volkswagen Golf MK5, MK6 and MK7
Medium	Volkswagen Passat B5, B6, B7 and B8
Upper Medium	Mercedes E Class 3ª Gen and 4ª Gen
Luxury	BMW 7 Series 4ª Gen, 5ª Gen and 6ª Gen

To evaluate and characterize these services two methods were selected:

1. Mass breakdown of the vehicle divided by services;

2. Analysis of specific indicators that objectively evaluate the corresponding service.

After weighing the pros and cons and the importance of each service to the market, the mass analysis performed in this paper focused on 4 services: base, safety, comfort and emission control. Performance, where a mass breakdown is not feasible, was assessed for the added value of its development to the user through the evolution of vehicle performance indicators. These indicators were maximum speed (km/h), acceleration from 0-100 km/h (s), specific power (kW/l, l being the engine displacement liters), power (kW) and weight/horsepower (kg/hp). Safety and emission control were also analyzed through Euro NCAP tests rating and carbon dioxide emissions respectively.

2.2. Data Collection and Mass Analysis

The method for the mass breakdown was designed to reduce the impact on the lack of available information about vehicle components mass. Two starting points were used:

• Base list of 124 components stratified by the services they provide (according to a car lifecycle analysis model (Burnham, Wang e Wu, 2006) and online databases (Auto-Data, [s.d.]; Cars-Data, [s.d.]))

• Components mass for two vehicles, one with 893 kg and another with 1510 kg (Burnham, Wang e Wu, 2006).

For all the vehicles the procedure was:

1. Search for the exact mass of as many components as possible, placing more emphasis on searching components whose mass varies most from car to car.
2. Supplement missing values with weighted average or estimate using known values in the literature or data from the automotive life-cycle analysis model.
3. Verify the validity of the search by comparing the final mass with the publicly available mass assigned to the vehicle.

In order to assess how representative the results of the mass analysis were, it was estimated the error between the average mass resultant from this analysis, in relation to the values disclosed by the EU in its official documents (ICCT, 2018). Assuming that the mass of each vehicle represents the mass of the segment it belongs, the average mass of the car fleet was calculated as follows:

$$\sum_{i=1}^{n,m} ni \times mi \ = Average\ Regsitered\ Car\ Mass$$

Where *i* represents each segment, *n* the market share and *m* the mass.

To further analyze the results and for better data organization, groups of components were also defined within each service. The calculation of the average mass of each component and group of components was performed by the same calculation as the average mass of the car fleet.

2.3. SUV's

The SUV's segment, due to its particularities, was analyzed differently from the others. Generally, segments of the automotive market have vehicles with similar characteristics. The segments are precisely that, an attempt to group similar vehicles into one class. In some cases, for instance, the Toyota Aygo, Citroen C1 and Peugeot 107 vehicles share a great number of components as they result from collaborations between manufacturers (Carbuyer, [s.d.]). However, the SUV's segment does not exhibit this behavior. In fact, in this case, there are several sub-segments. Through contact with JATO (global provider of automotive market data), some data and information were provided in order to obtain answers on how to study this segment. According to these data, the division into sub-segments has been done since 2010, when SUV's began to expand in terms of supply with the introduction of various new models. Until then, with a few exceptions, SUV's were large and heavy vehicles. From 2010 onwards, it was decided that SUV's would be divided into four sub-segments (Small, Compact, Mid-Size, and Large) as verified in JATO data (JATO Dynamics Limited, [s.d.], [s.d.], [s.d.]). Thus, the study performed on SUV's was divided into two periods. The first period, between 2001 and 2009, in which market stability was considered. The second, between 2010 and 2017, where SUV's were treated as a set of four sub-segments; Small, Compact, Mid-Size and Large. The vehicles studied can be seen in Table 2.

Table 2 – SUV's Analyzed

Segments	Vehicles
Small	Dacia Duster
Compact	Nissan Qashqai I and II
Mid-Size	Volvo XC60
Large	BMW X5 and F15

In the first period, due to lack of available data, it was considered that the vehicles analyzed represented equal shares in the market. This means that, between 2001 and 2009 it was considered that the SUV's market was stagnant which is relatively in line with EU data (ICCT, 2018). In the second period, between 2011 and 2017, the approach was different. Here, with data from JATO, it was possible to divide the SUV's segment by the corresponding sub-segments and their market shares. With these data and vehicles corresponding for each sub-segment it was possible to estimate the average mass of SUV's in this time interval. Similarly, to the average mass of the lightweight vehicle fleet, the calculation used for this segment was:

$$\sum_{j=1}^{n,m} nj \times mj \ = Average\ SUV\ Mass$$

Where *j* represents each sub-segment, *n* market share and *m* mass.

The analysis performed in this segment followed the same structure that the one performed in the conventional segments.

3. Results and Discussion

The average mass of vehicles registered in the EU is increasing. The characterization of this phenomenon and the identification of the underlying causes was the motivation for this thesis. This chapter presents the results of the research and data collection performed throughout this work as well as an analysis of those results.

3.1. Transport Service Analysis

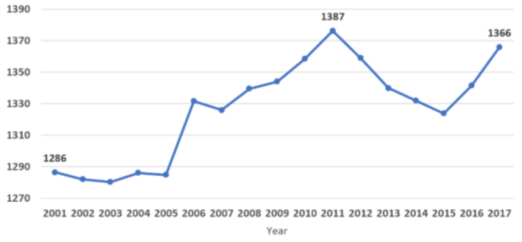

Figure 1 – Average Weight in kg of Vehicles Registered in the EU

As shown in Figure 1, the average mass of vehicles registered each year has increased since 2001. In 2001 the average mass was 1286 kg and in 2017 it was 1366 kg, i.e. a 6% growth. Without technological development and given studied estimates, the average consumption would have increased by 0,31l/100km. With annual registrations of 15,2 million (ICCT, 2018) and the average distance traveled by approximately 12000 km (ODYSSEE-MURE, [s.d.]), the mass increase would correspond to an extra consumption of about $20{,}15 \times 10^6$ GJ and extra emissions of $1{,}48 \times 10^9$ kg of CO2 annually. However, 2017 is not the year with the highest mass. In 2011 it was 1387 kg, 7% higher than 2001, and 1,5% higher than 2017. This peak in 2011, and subsequent mass reduction, can be justified by the fact that in 2009 the EU agreed on carbon dioxide emission limits per km between 2015 and 2030.

Despite the constant increase in mass, which in the timeframe of the analysis was 80 kg, consumption decreases significantly year after year totaling a decrease of 32% (Figure 2). The main reason for this reduction was the technological development in combustion engines. The sharpest drop in consumption after 2011 comes after car emission limit values had been set and the European public debt crisis had begun (Lane, 2012). After these events, car manufacturers implement an even stronger policy of reducing fuel consumption. This policy was in line with consumer demand at the time, due to the costs associated with energy, and with the aim of reducing emissions. Adjusting the previous estimate, and considering this technological development, the results were a consumption of around $16{,}15 \times 10^6$ GJ and emissions of $1{,}24 \times 10^9$ kg of CO2. These values are 20% lower than previously estimated.

The results obtained for mass evolution are in line with EU data, where a significant rise was also found, in this case around 9%. In the EU Pocketbook (ICCT, 2018) the increase goes from 1268 kg to 1395 kg. In relation to the North American market (Zoepf, 2011), the differences are smaller. In 2001 the average mass of the American vehicle was 1540 kg and in 2010 it was 1590 kg. Unlike the EU, where there was a 7% increase in this period, the US increase was only 3%. One of the reasons that may explain this difference is that historically the US has a fairly high SUV market share compared to the EU.

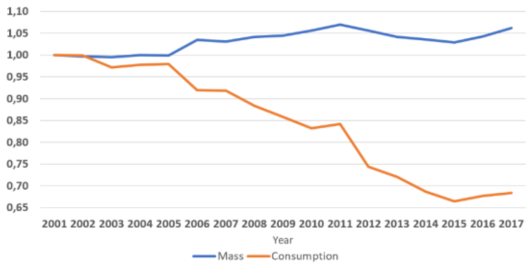

Figure 2 – Massa vs. Energy Consumption of Vehicles Registered in the EU

Due to the dichotomy between the SUV's and the other segments it seemed appropriate to study the differences between mass evolution in these groups. The results show that mass reduction is present in both groups. This helps to substantiate what has been said before. Despite further technological development in engines, there has also been a focus on mass reduction. The decrease is even more significant in SUV's due to the fact that they are expanding to smaller vehicles. Then, how is the increase in average total mass in the EU explained if in all segments a reduction was verified? In 2001, the share of SUV's sold in the EU was 2%, in 2017 it was 28% and now it is over 30%. While all segments are reducing mass, consumers are increasingly opting for higher mass vehicles. In order to understand the impact of this shift it was estimated that at 2001 market share levels and with the existent technological development, the emissions in 2017 would be 101 gCO2/km instead of 115 gCO2/km and average mass would be 1280 kg instead of 1366 kg. This estimate shows that even by imposing a change in the trend, the 2020/2021 emission limits would not be immediately met.

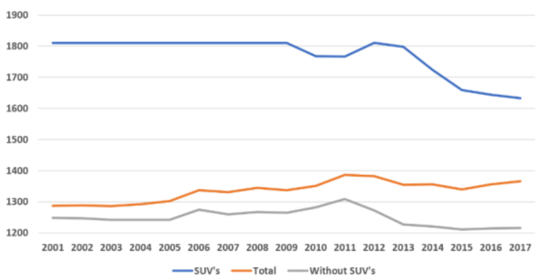

Figure 3 – Evolution of All Segments Mass vs. SUV'S vs. without SUV's

3.2. Service Analysis

The mass breakdown of services highlights three main trends. Comfort undergoes a considerable increase in absolute and relative mass. The base service decreases the relative mass and slightly increases the absolute mass. Other services tend to increase absolute mass and maintain relative mass (Figure 4).

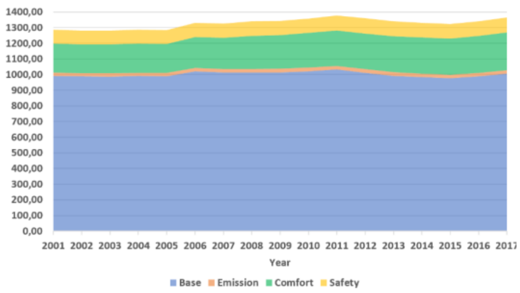

Figure 4 – Absolute Mass in kg of the Services Provided by Vehicles Registered in the EU

The mass of the base car, between 2001 and 2017, increased by 13,9 kg, about 1,4%, but the relative mass dropped from 77,1% to 73,6%. This difference of 13,9 kg, considering the total mass of the base service of around 1000 kg, can be considered insignificant. This service accounted for only 17,5% of the increase in the average mass of cars registered in the EU.

Comfort, between 2001 and 2017, increased from 185 kg to 240,3 kg, an increase of 29,9%. These values correspond to a rise in relative mass from 14,4% to 17,6%. It is also responsible for 68,8% of the 80 kg increase in the average mass of cars registered in the EU. This trend in comfort is justified by an increased consumer demand for aspects related to this service, particularly supplementary accessories, reduced noise and vibration, increased thermal comfort and increased space inside the vehicle.

Regarding safety and emission control, both change insignificantly in relative mass, from 6,87% to 7,06% and from 1,68% to 1,75% respectively. However, absolute mass values increase. Safety rose from 88,4 kg to 96,5 kg, an increase of 9,2% and emission control rose from 21,6 kg to 23,9 kg, an increase of 10,6%. These increases in both services have a 10% impact and 3,7% respectively in relation to the absolute mass increase. Both services also improved their quality Table 3. In the zero to five-star rating of Euro NCAP tests there is an increase of approximately one star. This improvement in the Euro NCAP assessment is even more significant if we consider that the tests are currently more demanding than in 2001. Emissions also decrease by 50 gCO2/km. This 30% decrease, although significant and positive, still does not allow car manufacturers to relax in view of the 2020/2021 legislation. User demand for safety, EU road accident targets and legislative tightening in emissions, are the main reasons for the changes on the quality of these services.

Table 3 – Safety and Emission Control Indicators

Year	Euro NCAP	Emissions (g/km)
2001	3,75	165
2003	3,99	150
2005	4,83	152
2007	4,80	148
2009	4,74	137
2011	4,86	130
2013	4,82	121
2015	4,76	112
2017	4,71	115

Similar trends were observed in US market (Zoepf, 2011). Between 2001 and 2010, services such as safety, emission control and base are characterized by small percentage changes, between 1% and 2%. The service where there is indeed a significant difference is comfort with an increase of 14%.

Again, it seemed appropriate to analyze the differences between SUV's and other segments. In both cases the base service is reduced by absolute mass and by percentage mass. SUV's reduced 174 kg mainly due to the widening in offer of smaller vehicles. In the remaining segments the reduction was 61 kg. This is the service where the use of lighter materials and reduction of components is more present.

In comfort, SUV's when compared to other segments are characterized by a higher percentage and absolute mass of components, which proves the idea that they are more focused on this service. Since 2001 it was estimated an increase of 22 kg in SUV's and 28 kg in the remaining segments. For the other services, both emissions and safety are relatively stable in percentage terms. In absolute mass, SUV's show significant differences, both emission control and safety reduce their mass by 5 kg and 20 kg respectively, while in the other segments this variation is less than 1 kg. Curiously despite the higher mass in safety, the Euro NCAP ratings since 2010 show that SUV's aren't safer than other vehicles Table 4. One of the most negative points that may contribute for these values is their tendency to roll over due to a higher center of gravity.

Table 4 – Euro NCAP Rating Evolution of SUV's vs. Without SUV's

Year	Euro NCAP Without SUV's	Euro NCAP SUV's
2010	4,77	4,66
2011	4,89	4,62
2012	4,88	4,67
2013	4,87	4,58
2014	4,88	4,47
2015	4,89	4,31
2016	4,89	4,31
2017	4,88	4,29

Grouping the components of each service also allowed a deeper analysis of vehicle evolution. Of course, due to the average mass increase of cars, most of these groups increased their mass. However, some other possible reasons should be mentioned.

Analyzing the base service of all segments in more detail, it can be noted the impact that the 80 kg increase in the average mass of vehicles has on the car's structural component groups.

Both Body and Chassis are increased by 4 kg and 13 kg respectively. Despite having to move a higher mass, the Powertrain is reduced by about 7 kg, which is another proof of the technological development in the engines, transmissions and other constituents of this group. The Battery and Interior show similar behavior increasing both between 1kg and 2 kg (Table 5).

Table 5 – Mass in kg of Base's Groups

Year	Body	Interior	Powertrain	Chassis	Battery
2001	352,68	37,16	336,13	253,23	15,89
2005	355,78	37,43	338,07	256,44	16,08
2009	353,02	39,36	328,34	275,10	16,12
2013	355,31	39,39	327,78	268,76	16,79
2017	356,53	39,43	328,99	266,75	17,29

Comfort component's groups are the most affected by mass increase. Mass growth of climate control, especially since 2009, is 12 kg. This increase is not due to the change in consumption trend towards heavier cars. As previously discussed, the shift in the market happens mainly from 2009/2010, however, Climatization has its peak in 2009. Another group with a high increase is Sound, a 120% growth. Weighing only 12,5 kg in 2001, this group reached 27,5 kg in 2017. In recent past most mid and small segment vehicles had a simple 2-4-speaker sound system. Today the reality is very distinct. A standard version of the Toyota Yaris has 8 speakers, which obviously affects the mass. In relation to the other groups of components, the increases are between 3 kg and 6 kg and in all of them the largest increases are made after 2009. This is followed by the trend of heavier vehicles. Examples of this are, for instance, Roof Rails and Panoramic Roofs that are part of the Interiors and Exteriors. Both are heavy components and more frequent in SUV's than in the other segments (Table 6).

Table 6 – Mass in kg of Comfort's Groups

Year	Climatization	Sound	Interiors	Exteriors	Sensors and Others	Ergonomics	Driving Aids
2001	51,60	12,53	20,19	18,54	16,27	39,26	26,61
2005	52,41	12,84	20,23	19,04	16,36	39,38	26,51
2009	64,46	18,34	22,11	20,98	17,10	41,75	26,10
2013	63,75	24,39	24,09	22,63	20,22	44,74	28,11
2017	63,86	27,54	26,68	24,57	21,47	45,90	30,28

The two emission control component's groups show a gradual increase in mass over time. Both variations are around 1 kg and correspond to an 8,6% increase for Electronics and Feedback Equipment and 14,2% for Catalyst, Valves and Particle Filter (Table 7). The reasons for this increase are once again the shift in the market for heavier vehicles, but primarily the tightening of CO2 emissions legislation and other pollutants.

Table 7 – Mass in kg of Emission's Groups

Year	Electronics and Feedback Equipment	Catalytic Converter, Valves and Particulate Filter
2001	13,89	7,74
2005	14,11	7,86
2009	14,70	8,25
2013	14,95	8,48
2017	15,09	8,84

Safety component's groups mostly follow the trend of mass increase in cars. The Retention group, which consists of seat belts and head restraints, is the only one that suffers a reduction, slightly over 1 kg and equivalent to 7,4%. The decrease in these components makes perfect sense because even with the switch to heavier vehicles, both seat belts and headrests in most cases remain five and same size. With the use of lighter materials, development of new mechanisms and decrease in size or number of components, a decrease in mass is naturally expected. The opposite happens in the other three groups. In Structural and Airbags, the passage to larger and heavier cars has an impact on mass, which is visible given the increase after 2010. Structural increases by 4 kg, or 20,4% and Airbags by 1 kg, or 2,7%. In addition to the change in consumption, the evolution of legislation and safety tests aiming to reduce fatalities also influence the increase of structural reinforcements and number of airbags.

Table 8 – Mass in kg of Safety's Groups

Ano	Estrutural	Airbags	Retenção	Sistemas Ativos
2001	18,44	31,98	19,99	17,95
2005	18,81	31,85	19,90	18,89
2009	18,70	30,70	19,61	20,66
2013	20,83	34,07	18,94	21,53
2017	22,20	32,83	18,51	22,87

The Active Systems increases by about 5 kg, i.e. 27,4%. Technological development since the late 1990's and the increasing use of systems such as ABS, traction control, stability control and others contribute to this gradual increase in mass over time.

3.3. Performance

The performance analysis performed in this work reveals a positive development. It can be seen in Figure 5 that the five indicators show substantial improvements despite the increase in mass that hinders vehicle performance in all aspects.

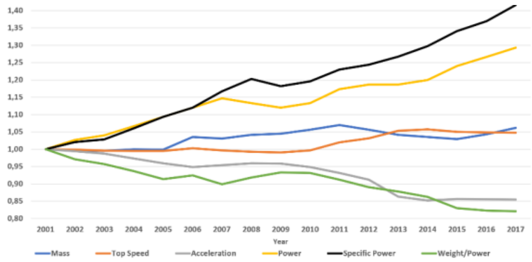

Figure 5 – Evolution of Performance Indicators vs. Mass

Maximum speed, probably the least important indicator of technological development, grows 5% and power grows 30%. The main reasons for this improvement, especially since 2009/2010, are the shift towards SUV's and the mass reduction achieved in each segment. Because SUV's are heavier, they usually have engines with higher horsepower. These two indicators are usually associated, a higher power produces a higher maximum speed. This association is confirmed by the correlation coefficient between the data, in the value of 0,81. Strongly correlated are also weight/power and acceleration, with a value of 0,92. These indicators show an improvement of 17,5% and 15% respectively. Specific power was the indicator with most progress, compared to 2001 it increased 42%. Usually, larger displacement volume results in more power. It is in this matter that the emission limit legislation has most influenced car manufacturers. These efforts in combustion engine development have to be enhanced. A few years ago, vehicles had typically thermal efficiencies in their engines between 20% and 30%. These numbers are now quite different. Top-selling vehicles, such as the Toyota Prius, have efficiencies of 40% (Voelcker, [s.d.]) and manufacturers like Hyundai already target 50% thermal efficiency for their road vehicles (Bruce, [s.d.]).

4. Conclusions and Further Research

4.1. Conclusions

The average mass of vehicles in the EU is increasing. The characterization of this phenomenon and the identification of the underlying causes was the motivation for this thesis.

Firstly, a mass breakdown on the evolution of services provided by vehicles was executed. This type of analysis was performed for the first time at European level. Also, the distinction between SUV's and other segments was innovative and introduced in the analysis in order to gain a better characterization and understanding of evolving market trends. The methodology used had some limitations, namely the difficulty of accessing data. Having access to teardown reports databases would be ideal. Secondly, an analysis to the evolution of indicators that characterize the various services, in this case, emission control, safety and performance was also executed. The remaining services were not analyzed due to the lack of objective indicators to characterize them

The conclusions on the evolution of the automotive market were the following. Automobiles and all the services provided by them increased their mass. However, each segment reduced its mass, which means the increase in the total market average mass is mainly due to the shift in consumer trends towards heavier vehicles. An increase in mass corresponds directly to an increase in consumption, which is associated with a decrease in efficiency. However, an increase in the mass of a secondary service may correspond to an increase in its quality, for instance, in comfort. Despite all this, both the quality of transportation as the quality of the secondary services improved. Vehicle performance greatly improved, with an increase of 40% in specific power. Also, emission control, which is closely related to fuel consumption, fell by 30% between 2001 and 2017, from 165 g/km to 115 g/km. This reduction is insufficient to meet the legislated limits for 2020/2021. Regarding the other secondary services, from the analysis performed in this work it is possible to say that cars have never been so safe and comfortable and never had such high-quality performances. The increase in quality observed in these services is not only associated with mass increase, but mainly with technological development. In safety, the average rating awarded rose from 3,75 in 2001 to 4,71 in 2017. In comfort, the sound systems, seat ergonomics, vibration, noise reduction and thermal sensation have been greatly improved. This is the service where the increase in mass was greatest, 68,8% of the 80 kg increase in the average vehicle mass came from comfort.

However, despite all this positive technological development, there are two questions that must be asked. Why has consumer choice led to mass increase that counters all this development? And what can be done to counteract this growing trend year after year?

According to the "Mission Impossible: How Car Makers Can Reach Their 2021 CO2 Targets and Avoid Fines" report (Transport & Environment, [s.d.]) the main reason is the aggressive marketing campaigns in favor of SUV's. These are associated with safety and comfort, but the results obtained show they aren´t as safe as the other segments, consume more fuel, consequently emit more GHG and generally have a higher price. In conclusion, if a change in consumer trends never had happened, the technological development would be even more evident, the average safety of Euro NCAP tests would be higher, the consumption and therefore the emissions would be reduced and the average mass, would also be smaller.

To reverse this trend towards heavier vehicles there are several measures that policy makers can implement. Firstly, CO2 emissions laws that are the centerpiece of EU transportation emissions policy, should be applied and not suffer any last-minute weakening under pressure from manufacturers or governments. However, these laws have an issue. The emission target for each manufacturer is calculated as a function of the average mass of vehicles sold by them. This gives the chance to have heavier fleets that consume more. Secondly, the tests performed by the European Commission, Member States and authorities must ensure that there is no manipulation of test results through an extensive conformity checking process. Finally, governments can help shift to zero GHG vehicles by reforming car taxation and helping high-mileage fleets, such as taxis and corporate fleets, move to zero-emission.

4.2. Further Research

There are several ways in which further research on this topic can be pursued. It is suggested an increase in number of vehicles analyzed in order to obtain a better representation of the European car fleet. Obtaining access to teardown reports of the vehicles analyzed would also be extremely important. This would make the data collection process manifestly faster, more reliable and would make the division of components into the respective services and groups more accurate.

Teardown reports would also be extremely useful in extending this type of analysis to all the vehicle life cycle. This analysis would make it possible to understand the trade-offs between increased quality of services and technologies in relation to the environmental impact of this improvement, and the trade-offs of mass reduction through the use of lighter materials that sometimes present another type of energy or environmental challenges.

It is also suggested that the analysis incorporates electric and hybrid vehicles, as their presence in the automotive market gains dimension year after year.

Finally, it is suggested to include design in this type of analysis. As a mass analysis of design is not feasible, the evaluation would have to be tested using an indicator. The functional design could be classified by the coefficient of aerodynamic resistance, however, for the aesthetic design the challenges in defining an evaluation measure would be a difficulty given its subjectivity.

References

AUTO-DATA - **Technical specs, data, fuel consumption of cars** [Em linha] [Consult. 2 set. 2019]. Disponível em WWW:<URL:https://www.auto-data.net/en/>.

BRUCE, Chris - **Hyundai Aims For 50 Percent Thermal Efficiency For Future Engines** [Em linha] [Consult. 21 out. 2019]. Disponível em WWW:<URL:https://www.motor1.com/news/184754/hyundai-future-powertrain-efficiency-plan/>.

BURNHAM, Andrew; WANG, M.; WU, Y. - Development and Applications of GREET 2.7 — The Transportation Vehicle-Cycle Model. **Energy**. 2006) 124. doi: 10.2172/898530.

CARBUYER - **Citroen C1 vs Toyota Aygo vs Peugeot 108 | Carbuyer** [Em linha] [Consult. 2 set. 2019]. Disponível em WWW:<URL:https://www.carbuyer.co.uk/news/142764/citroen-c1-vs-toyota-aygo-vs-peugeot-108>.

CARS-DATA - **Car specs database** [Em linha] [Consult. 28 ago. 2019]. Disponível em WWW:<URL:https://www.cars-data.com/en/>.

CHEAH, Lynette W. - Cars on a Diet : The Material and Energy Impacts of Passenger Vehicle Weight Reduction in the U . S . **Engineering**. 2010) 13.

EPA - **Global Greenhouse Gas Emissions Data** [Em linha] [Consult. 2 out. 2019]. Disponível em WWW:<URL:https://www.epa.gov/ghgemissions/global-greenhouse-gas-emissions-data>.

GAMEIRO DA SILVA, M. C. - Measurements of comfort in vehicles. **Measurement Science and Technology**. . ISSN 09570233. 13:6 (2002). doi: 10.1088/0957-0233/13/6/201.

ICCT - European Vehicle Market Statistics Pocketbook. 2018).

JATO DYNAMICS LIMITED - **B-SUV** [Em linha] [Consult. 2 set. 2019]. Disponível em WWW:<URL:https://www.jato.com/wp-content/uploads/2017/09/B-SUV.jpg>.

JATO DYNAMICS LIMITED - **C-SUV** [Em linha] [Consult. 2 set. 2019]. Disponível em WWW:<URL:https://www.jato.com/wp-content/uploads/2017/09/C-SUV.jpg>.

JATO DYNAMICS LIMITED - **D-SUV** [Em linha] [Consult. 2 set. 2019]. Disponível em WWW:<URL:https://www.jato.com/wp-content/uploads/2017/09/D-SUV-Premium.jpg>.

KNITTEL, Christopher R. - Automobiles on steroids: Product attribute trade-offs and technological progress in the automobile sector. **American Economic Review**. . ISSN 00028282. 101:7 (2011) 3368–3399. doi: 10.1257/aer.101.7.3368.

MOCK, Peter *et al.* - The WLTP: How a new test procedure for cars will affect fuel consumption values in the EU. **ICCT White Paper**. 2014:9 (2014) 1–20. doi: 10.1016/j.enpol.2013.12.013i.

ODYSSEE-MURE - **Change in distance travelled by car** [Em linha] [Consult. 11 out. 2019]. Disponível em WWW:<URL:https://www.odyssee-mure.eu/publications/efficiency-by-sector/transport/distance-travelled-by-car.html>.

TRANSPORT & ENVIRONMENT - How car makers can reach their 2021 CO2 targets and avoid fines. [s.d.]).

VOELCKER, John - **Next Toyota Prius Hybrid: 40-Percent Thermal Efficiency From Engine** [Em linha] [Consult. 20 out. 2019]. Disponível em WWW:<URL:https://www.greencarreports.com/news/1098429_next-toyota-prius-hybrid-40-percent-thermal-effiency-from-engine-toyota-says>.

WEISS, M. *et al.* - On the road in 2020—A life-cycle analysis of new automobile technologies, Energy Laboratory Report # MIT EL 00-003. October 2000 (2009).

ZOEPF, Stephen M. - Automotive Features: Mass Impact and Deployment Characterization. **Mechanical Engineering**. 2011).