Evolution of the Exergetic Efficiency in the Transport Service

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Abstract

In 2018 the transportation service was responsible for 24% of direct CO_2 emissions from fuel combustion. This thesis analyses the evolution of the transportation service efficiency in United Kingdom from 1960 to 2014 considering energy and materials and the split between the conversion device and passive system in cars. Additionally, it proposes the use of a Resource Efficiency indicator.

During this period, energy efficiency increased in rail and aviation but decreased in road transports, with exception for cars. Regarding passenger transportation, cars efficiency grew from 0.46 to 0.68 pkm/MJ while bus had a reduction from 3.63 to 0.76 pkm/MJ; rail grew from 0.28 to 2.20 pkm/MJ; domestic aviation from 0.08 to 0.28 pkm/MJ and international aviation from 0.17 to 0.80 pkm/MJ.

For freight, rail is more efficient increasing from 0.32 to 2.87 tkm/MJ, while road decreased its efficiency from 0.41 to 0.26 tkm/MJ.

Regarding material efficiency it was showed that since 1989 the stock grew far more that the service provided, implying that cars became parked for longer time periods.

Resource efficiency had an almost constant grow, which means it was possible to provide more service while consuming less resources. A direct comparison between fuel and material efficiency demonstrates that the improvement in fuel efficiency allowed the increase in total resource efficiency despite a lower material efficiency.

The analysis on the evolution of the conversion device and the passive system showed that even with increasing mass, both mechanical efficiency and mileage improved.

Resumo

Em 2018 o serviço de transporte foi responsável por 24% das emissões de CO_2 provenientes de queima de combustível. Esta tese analisa a evolução da eficiência do serviço de transporte no Reino Unido de 1960 até 2014, considerando energia e materiais, e a divisão entre o sistema ativo e passivo nos automóveis. Adicionalmente, também propõe um indicador de eficiência de recursos.

Durante este período, a eficiência energética aumentou no transporte ferroviário, de aviação e apenas em carros nos transportes rodoviários. Para o transporte de passageiros, a eficiência dos carros aumentou de 0.46 para 0.68 pkm/MJ enquanto que os autocarros reduziram de 3.63 para 0.76 pkm/MJ; nos comboios aumentou de 0.28 para 2.2 pkm/MJ; na aviação doméstica de 0.08 para 0.28 pkm/MJ e na internacional de 0.17 para 0.80 pkm/MJ.

Para a carga, o transporte ferroviário é mais eficiente, progredindo de 0.32 para 2.87 tkm/MJ, enquanto que o rodoviário diminuiu de 0.41 para 0.26 tkm/MJ.

No que se refere à eficiência dos materiais foi demonstrado que desde 1989 o stock cresceu mais que o serviço prestado, ou seja, os carros ficaram estacionados por maiores períodos de tempo.

A eficiência de recursos teve um crescimento quase constante. Comparando a eficiência de combustível e de materiais demonstra que melhorias na eficiência energética permitiram o aumento da eficiência de recursos, mesmo com menor eficiência de materiais.

A análise da evolução do sistema ativo e o sistema passivo mostrou que houve melhoria em ambos mesmo com o aumento da massa dos carros.

Table of Contents

List of Tables

List of Figures

Nomenclature

ATF	Aviation turbine fuel
CO_2	Carbon Dioxide
CO_2e	Emitted Carbon Dioxide
DfT	Department for Transportation
ETP	Energy Technology Perspectives
GHG	Greenhouse Gases
Gt	Giga tonnes
GtC	Giga tonnes Carbon
HGV	Heavy Goods Vehicles
IEA	International Energy Agency
LDV	Light duty vehicles
LPG	Liquefied petroleum gas
M_{inflow}	Inflow mass
M_{stock}	Stock mass
Mpg	Miles per Gallon
PE	Polyethylene
pkm	Passenger-kilometre
PP	Polypropylene
PU	Polyurethane
PVC	Polyvinyl chloride
Tkm	Tonne-kilometre
2ºC(B2DS)	Beyond 2ºC Scenario

1 Introduction

To address the environmental challenges, and accordingly to the ETP 2017 p.19-20 report [1], to achieve the beyond 2ºC(B2DS) scenario, profound reductions of CO_2 emissions should occur across the sectors of transport, industry and building. According to Cullen *et al.* [2], *"The efficient use of energy is a key component of current efforts to reduce carbon emissions*.", and although efficiency presents a big advantage for emission reduction, it is neglected as consequence of the excitement for renewable energy and nuclear power.

It is focus on the transport sector because mitigating the emissions from the transport sector is a challenge due to its low energy efficiency and reliance on oil products. Transport presents multiple impacts on the environment: direct impacts with immediate consequences such as noise and CO_2 and other pollutants emissions [3]. In 2018 transports were responsible for 24% of direct CO_2 emissions from fuel combustion in the European Union [4]. Indirect impact are secondary effects that could have higher consequence than direct ones, due to incomplete combustion, particles are emitted and are indirectly connect with respiratory and cardiovascular problems [3].

Transport is fundamental to our economy and society. Mobility is vital for the internal market and for the quality of life of citizens as they enjoy their freedom to travel. Transport enables economic growth and job creation: it must be sustainable in the light of the new challenges we face. Transport is global, so effective action requires strong international cooperation. [5]

Transport has become more energy efficient, but EU transport still depends on oil and oil products for 96% of its energy needs [6]. Transport has become cleaner, but increased volumes mean it remains a major source of noise and local air pollution. New technologies for vehicles and traffic management will be key to lower transport emissions in the EU as in the rest of the world. By 2050, key goals to achieve 60% cut in transport emissions by the middle of the century include [6]:

-No more conventionally fuelled cars in cities.

-40% use of sustainable low carbon fuels in aviation; at least 40% cut in shipping emissions.

-A 50% shift of medium distance intercity passenger and freight journeys from road to rail and waterborne transport.

But transports are more than the fuel they consume, all the life cycle of a vehicle contributes to its environmental impact. Most environmental challenges that we face today, from raw material exhaustion to ecosystem degradation, comes from the unsustainable form in which we use resources [7]. Therefore, an analysis of the vehicle resources comes as really important. From the current stock that is used to comply with the service to the amount that is consumed every year as outflows to permit continuity of the transport service.

1.1 Aims

The goal of this project is to analyse the energy, exergy and material efficiency of transport service from 1960 to 2015 adopting passenger.km/TJ and ton.km/TJ as the units of transport service. To answer the question: *How efficient is the material and energy supply in transports for the service that they provide?*

An additional goal of the project is to join both energy and material in one single measure and to test whether the new indicator is a valid and useful approach for a resource efficiency analysis of the transport service provision. Whenever possible, to better understand the evolution of the efficiency indicators from 1960 to 2015, the data available will be used to separate the efficiency between conversion devices (engines), and the passive system (e.g. car without engine), from which energy is lost in exchange for final service. Insights will be used to discuss the efficacy of different approaches, policies and economic incentives to decrease CO_2 emissions associated with the transport service.

1.2 Structure of the thesis

The first chapter of the thesis focus on the principles of energy and material services and resource efficiency. Regarding energy, it goes into detail about conversion devices and the concept of passive service, as well as the definition of exergy and the attributes it possesses when analysing resources. For material services, it is analysed commonly used indicators as well as material analysis strategies. In the end it is described how some values will be validated.

Following, comes the methodology chapter, where it is described how and from where data was collected and treated as well as the formulation used. The obtained results are presented in the next chapter with followed by discussion of pertinent results.

The final chapter concludes the thesis, gathering all important results and re-analysing the most important ones. It is also mentioned improvements that could be made and proposes future work originated from topics presented in this thesis.

2 Bibliographic Review

2.1 Energy flow stages

Energy is a basic human need that is presented in all societies, from unelectrified ones that use biomass to cook, to industrialized ones were all mechanisms that sustain modern human needs, are built on converted energy forms.

All the existent perspectives on energy classification are based on the law of conversion of energy: energy can be transformed but never created or destroyed. The most frequent used stages are primary, final and useful [2], [8], [9].

Primary energy relates to forms of energy extracted from nature, it refers not only to the heating value of fuels like coal and crude oil, but also to sunlight, wind or water at high elevation, as they are provided by nature [9], [10].

The form of energy that is available to be used by final consumers such as households and industries, after conversion from primary carriers, is called final energy, examples are: electricity, refined fuels and heating [9].

However, what society wants is services, and not energy itself, the drivers for energy systems is its outputs and not its inputs [10]. Characterizing the energy system dynamics by an output measure such as useful energy, that incorporates the actually available energy after final conversion, comes as highly advantageous. That said, useful energy is the final common stage, the energy necessary to fulfil consumer needs, from light, motive power to heat and others. Useful energy is the stage of energy that is closest to the provision of the service and to the creation of economic value [11].

2.1.1 Energy Aggregation

To allow a valid comparison between sources and studies, it is fundamental to analyse how the aggregation of final and useful energy data is done. Sectoral aggregation refers to the division of energy into sectors, being summarized into industry, transport, and residential plus commercial. Each subdivided in smaller categories such public or governmental and including subsectors like agriculture.

In this aggregation, there are allocations that are debatable, for example, energy for powering tractors that could be under transports or agriculture (industry). There are other possible aggregation forms such as end-use aggregation, where the nature of the useful energy output defines the aggregation process. For example: radiant energy includes lightening purposes; kinetic energy including all mechanical power; or heating and cooling as thermal energy. Other form, is aggregation by energy carrier; where each carrier is attributed for product categories like coal, biomass or electricity [10].

Given the nature of this study, the sectoral aggregation of transports, divided in subsectors of type of transportation is the obvious choice.

2.2 Energy Services

There are multiple positions on the definition of energy services, depending on the author and purpose of the study. Michael Fell [12] proposed that *"Energy services are those functions performed using energy* *which are means to obtain or facilitate desired end services or states".* His proposal comes after a compilation of different concepts through a literature review. One of the main observations of the author is that "*energy services are widely considered either not to need a definition, or in some cases that they may be best 'defined' by simply providing a list of examples such as: 'energy service, for example, increase in room temperature, or more generally changes in comfort levels'*" [12].

According to Sorrel and Dimitropoulos [13], energy services on transports have more characteristics than just delivering passengers mobility, *"...all cars deliver passenger-kilometres, but they may vary widely in terms of features such as speed, comfort, entertainment, acceleration and prestige. The combination of useful work (S) with these associated attributes (A) provides the full energy service: ES=es(S,A)*".

As defined by Chu *et al.* [14], efficiency is the relation between inputs and outputs, a measure of resource utilization. Nakicenovic *et al.* [15], defined service efficiency as, *"...the provision of a given task with less useful energy (the output from conversion devices) without loss of 'service' quality".*

On the other hand, effectiveness is the use of outputs to achieve service consumption, to captivate passenger interest, which involves the quality characteristic identified by Sorrel and Dimitropoulos [13].

2.3 Exergy

The first complete definition of exergy was given by Baehr [16] in 1965, "*Exergy is that part of energy that is convertible into all other forms of energy*", in other words, the exergy of a system is the amount of mechanical work that can be maximally extracted from the system in its specific environment [17].

In 2006, Hermann carried out a study with the solo purpose of quantifying global exergy resources [18]. He pointed out how exergy is a model for the theoretical extractable work in a resource, rather than the capacity for exploitation. Exergy stands as a convenient measure of the usefulness of resource for technological and economic benefits.

Ayres *et al.* [19] suggests that exergy is the most suitable indicator for resource accounting. The common use of different units for each flux blocks a valid evaluation and comparison of all inputs, outputs and non-fuel flows that are first to be overlooked. An exergy balance combines both mass and energy flows, making it the ideal indicator for resources analysis.

Cullen [20], included exergy as a quality measure, asserting that exergy combines both quantity and quality, and an example for such is the fact that energy at a higher temperature can perform more work that the same amount of energy at a lower temperature. Work is a higher quality of energy than heat because work can be completely converted into heat, which does not occur for the opposite conversion.

The formulation for energy efficiency and exergy efficiency in terms of useful output is described in Table 1. It also presents the equation for quality factor, a dimensionless representation of the loss of energy quality in the conversion process.

Attached to these definitions, Cullen created a table with energy and exergy efficiencies of end-used conversion, Table 2 presents the values for motion devices.

Table 1 - Energy and Exergy Efficiency Formulation [20].

Energy Efficiency	Exergy Efficiency	Quality Factor
$\eta = \frac{\text{energy output(useful)}}{\textit{energy input}}$	$\epsilon = \frac{\text{work output}}{\textit{maximum possible work output}}$	$\upsilon = \frac{\epsilon}{\eta}$

Table 2 - Energy and exergy efficiencies of motion end-use conversion devices, adapted from Cullen [20], with total motion as a weighted average of all motion engines.

End-use device	η %	ϵ%	υ%
Diesel Engine	22	21	95
Petrol Engine	13	12	99
Aircraft Engine	28	27	99
Other Engine	47	25	53
Electric Motor	60	56	93
Total Motion	**26**	**24**	**90**

2.4 Conversion devices, Passive Systems and Efficiency

Current analysis fails to distinguish between the conversion devices that convert energy into useful form (engines, electric motors, furnaces, light-bulbs) and the system that transforms this form of energy into final services (vehicles, buildings, and factory systems). With his work, Cullen [20] introduces the concept of *passive systems*. It emphasizes the distinction between conversion devices, which transform energy into more suitable forms, and passive systems, from which energy is lost as low temperature heat, in exchange for final services.

Passive systems are the final technical components in every energy chain, and do not convert energy into another useful form, it is where the useful energy is lost as low-grade heat, in exchange for the final service. Examples of such systems are a car, without the engine, which deliver transportation, or a house, without heat exchanger and lighting devices. According to Cullen's conclusions [20], the challenge for passive systems is to design technologies that make better use of energy, increasing thermal isolation in buildings, improving materials etc.

Therefore, improvements can be done both in conversion devices and in passive systems. For transports, improving the conversion devices includes measures such as increasing the efficiency of the diesel motor or switching to an electric motor while improving the passive system is reducing drag and friction losses. Additional measures related with consumer behaviour such as increasing the occupancy of transports might also contribute to increase the efficiency of the transport sector.

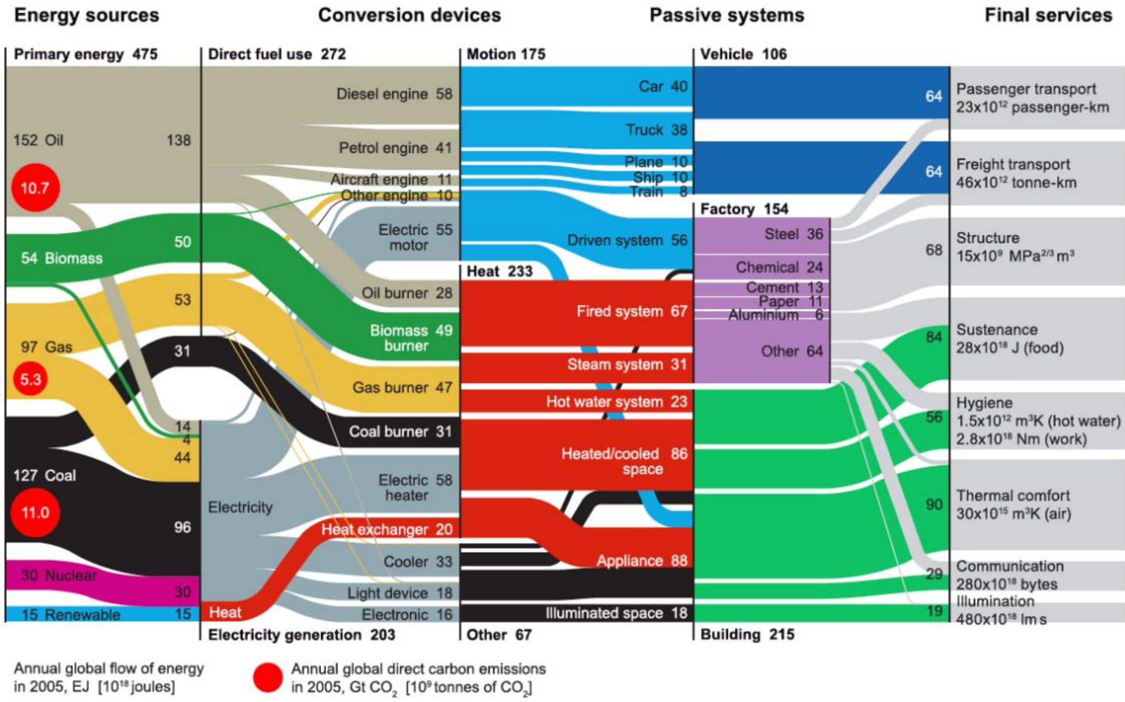

Figure 1 - Sankey diagram of energy global flow, from fuel to service. From Cullen's Phd. Thesis [17, p. 58].

Cullen [20] developed a Sankey diagram with the global flow of embedded primary energy (Figure 1), from energy sources to the final services. From the chart, is important to highlight that transportation is mostly powered by crude oil, and that over 90% of energy sources are fuels, so the attention for efficiency improvements should be on the improving the combustion process, or a largely transition to electric vehicles. The chart also shows what are the materials used in the different services.

Analysing the transport service, the focus of my research, it stands out how bigger is freight transport compared to passenger transport. Converting to the same unit of passenger-km, by an average of 80 Kg per passenger, freight transport equals to $57.5x10^{13}$, that is 25 times bigger than passenger transport. According to Cullen, the passenger and freight transport added together dominate the final services.

To analyse the chart, he resorts to two approaches. A vertical approach, that allows a comparison of the scale of energy flow between components at the at the same level of the energy transformation process; and a horizontal one, that enables an analysis of the different technical options, in each column category, into providing a service when an energy chain is traced from source to service.

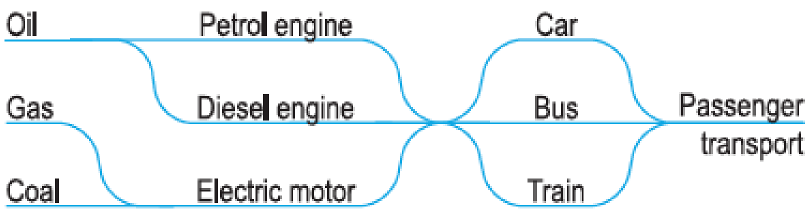

Figure 2 - Alternative energy chains for passenger transport[21, p. 62].

Cullen [21, p. 62] gives a visual example of how to consider different energy chains as a way to improve efficiency (Figure 2). When not looking at the global energy chain one is susceptible to miss the consequences caused by an efficiency change in the beginning of the chain. Using the same example as

Cullen, a switch in all engines from petrol (12% efficiency) to diesel (20% efficiency) would save 4 EJ worldwide, but it does not take into consideration the upstream efficiency changes. An abrupt change in petrol consumption would have a direct impact on oil distillery industry, an impact that is not simply compensated for the fact that diesel engines are more energy efficient.

A vertical analysis is useful for prioritizing potential efficiency improvements, within each vertical group. The energy use and potential gains cannot be added between different vertical groups (an example justification is given in the end of this section). Separating into vertical groups facilitates the identification of potential improvements, and the estimation of the impact of modifications.

In spite the commonly known fact that devices and systems are interconnected, current analysis fails to separate energy conversion devices, that convert energy into useful forms (engines, etc.), from the passive energy systems that transform the useful energy into final services (vehicles, etc.).

When this interconnection is not considered, the fact that energy savings in one system reduces the saving potential in the other is not obvious. To explain how, it will be used another example from Cullen [20], whom described this issue invoking two efficiency measures to improve cars operation by 2054 described by Pacala and Socolow [22]. The first measure requires an increase of fuel economy in cars, saving 1 billion tonnes of carbon (1 GtC). The second measure involves a decrease in the average annual travel per car, also saving 1 GtC. Both options would imply a reduction of 50% from total carbon emission by cars. Although each measure would result in savings of 1 GtC, if implemented perfectly, the reduction in carbon emission of both would not be 2 GtC. The true value would be 1.5 GtC (reduction=2*0.5+1*0.5), instead of 2 GtC (1+1). This is a simple example of how easy is to overestimate energy savings, because savings in one step of the chain reduces the potential for savings in the other. The separation between conversion devices and passive systems can contribute to clarify these issues.

Based on this problem, Nakicenovic *et al.* [15] introduced the term "service efficiency", with the intention of separating technology improving measures from service providing ones, such as improving the flow of traffic. On his work, Nakicenovic *et al.* [15] mentions that "low efficiency of the last link in the chain, namely the provision of energy services, drastically reduces the overall efficiency".

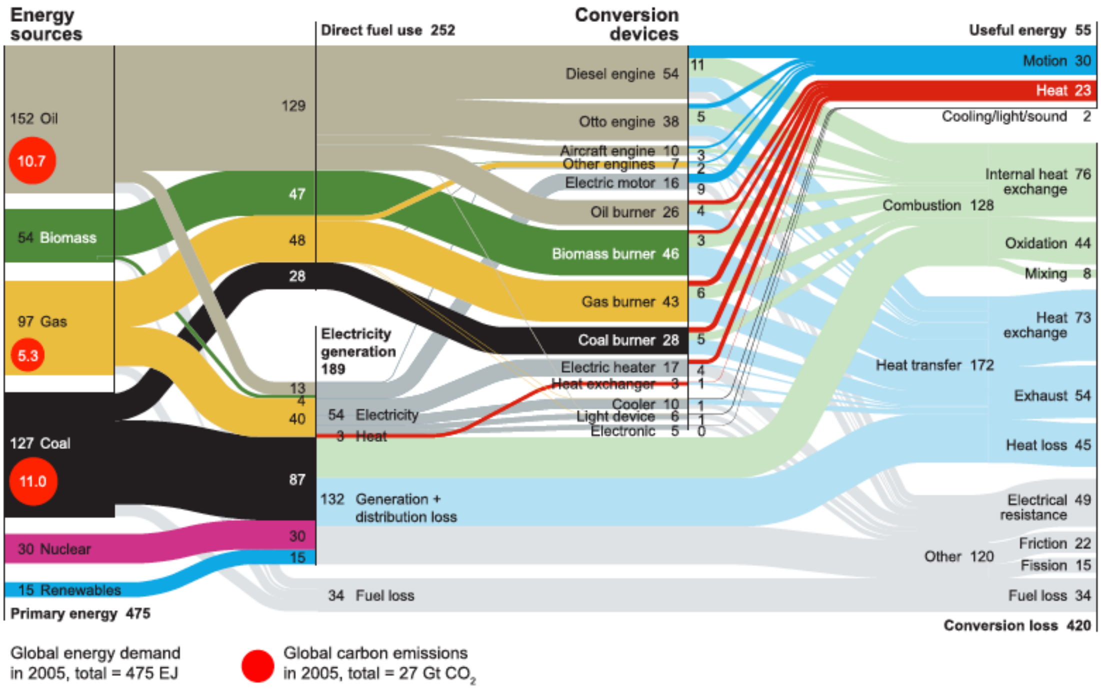

Figure 3 - Sankey diagram of the global energy conversion efficiency. From Cullen's Phd. Thesis [17, p. 79].

Figure 3 presents other really important result from Cullen's work, a Sankey diagram of the global energy conversion, making a separation between primary-final and final-useful by the "Conversion devices" division. When analysing such diagram, one must not compare directly individual devices efficiencies from different parts of the diagram. Saying that an electric motor (60%) is more efficient than a diesel engine (22%) does not take into consideration the larger upstream energy losses from electricity generation linked to the electric motor [12, p. 80].

To address this issue, it is possible to calculate a compound efficiency ($\epsilon_c = \epsilon_f \times \epsilon_e \times \epsilon_d$) that takes into account the consecutive device efficiencies along an energy chain. The subscripts indicate the type of device: c=compound efficiency, f=fuel efficiency, e=electricity generation/distribution and d=device efficiency (end-use). Efficiency values for the motion energy chain are shown in Table 3, taken from Cullen results. The compound efficiency expresses the theoretical efficiency limit for each chain. In most cases, the end-use device efficiency is the main cause of inefficiency, electric engines differ by having the engine itself has the main cause.

Table 3 - Compound efficiency of motion devices, ϵ_f=fuel efficiency, ϵ_e=electricity generation/distribution ϵ_d=device efficiency (end-use) and ϵ_c=compound efficiency

Energy Chain	ϵ_f	ϵ_e	ϵ_d	ϵ_c
Diesel Engine	93	100	21	**20**
Petrol Engine	93	100	12	**12**
Aircraft Engine	93	100	27	**25**
Other Engine	92	78	25	**18**
Electric Motor	93	32	56	**17**

When analysing passive systems, is not possible to calculate theoretical efficiencies limits like in conversion devices, because there is no conversion of energy. However, it can be determined a practical efficiency limit, measuring the minimum energy required to deliver a unit of final service [12, p. 88]. For that, it is necessary to explore the energy saving available in passive systems. Cullen presents several measures for each sector (building, factories and vehicles), due to the specific focus of this work on transports, only passive systems related to transports will be analysed.

2.4.1 Passive systems in Cars.

When analysing passive systems in transports, the source of energy losses is resistive forces. The main forces acting on a vehicle are exemplified in Figure 4 with some changes when going from road vehicles (cars) to trains or airplanes.

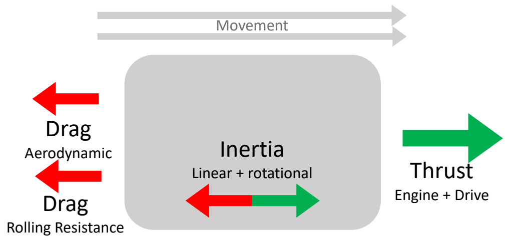

Figure 4 - Schematic of forces presented in a car motion.

The powertrain of a car includes the components (engine, drive system) that generate power and deliver it to the road surface (conversion device), converting energy to vehicle motion (passive system).

As shown in Figure 4, the thrust force (provided by the powertrain) is opposed by two drag forces, mechanical rolling resistance and aerodynamic drag. Following Newton's laws of motion, if drag and thrust are balanced, the car remains at a constant speed, so an additional thrust is needed to "overcome inertia" and accelerate the car. The vehicle motion is a balance between thrust and drag, and in case of acceleration with inertia. The energy (petrol, diesel or electricity) needed to provide the thrust is converted into low temperature heat delivered to the road, air and braking system [21].

Resistive forces depend on the passive system, thus, analysing them is relevant. In cars, **mechanical drag** is essentially a consequence of rolling resistance, the dissipation of energy due to tyre deformation, energy needed to flex the tyre. The losses depend on the vehicle weight and have a small contribution from its speed [21].

The friction losses in the engine, drive-train and wheel bearings are considered part of the conversion device.

Aerodynamic drag occurs in all vehicles types, it is a result of the shear stresses created by air flows around the vehicle body, both in laminar and turbulent regime [21]. It is influenced by air density, vehicle velocity, vehicle projected frontal area and by the drag force.

Inertia, the resistance of any mass to change in its velocity, must be overcome to accelerate the vehicle. Therefore, vehicles must have a reserve power to accelerate, implying a lower efficiency operation from the engine in normal loads. In the case of cars, this energy loss is bigger in urban driving, due to the frequent brake/accelerating cycles. In ideal cases, inertia energy could be recovered by deceleration without braking or by a regenerative braking system [21].

There are measures and improvements that can be made into reducing the dissipation of energy in cars. According to Cullen [21], the amount of energy saving is constrained by the limitation of engineering materials and available design options.

Using data from Zachariadis and Samaras [23] and Hickman [24] which assesses the performance of vehicle types across 15 European Union countries in 2000, Cullen concluded that the most energy gain comes from reducing the car mass to 300 Kg. Reducing the car frontal area is hard to achieve due to the requirement of carrying passengers, it is assumed a practical minimum limit of $A=1.5m^2$. For tyres, the limit was established by Santin *et al.* 176, with the 45-75R16 radial ply tubeless Michelin tyre, that has a rolling resistance coefficient only fractionally higher that train wheels (steel-on-steel contact).

When referring to trucks, it is not as easy to apply certain reductions, once the purpose of trucks is to carry heavy loads of goods a reduction in its empty load would directly influence the support needed to perform its function. Reduction in aerodynamics would also be difficult due to the volume needed to carry goods, but some of these possible measures are represented in Figure 5. Because trucks are mainly driven in extra-urban routes, the fraction of energy use for acceleration is lower, resulting in only small saving in inertia force from mass reduction [21]. Cullen [21] presents for all main transport modes tables of how each change would affect the energy efficiency of each vehicle.

Figure 5 - Possible aerodynamic improvements for trucks [101].

Melody L. Baglione PhD. thesis [25] refers how important is to understand the energy demand within the vehicle in order to develop more fuel efficient vehicles. She describes and quantifies the different causes for efficiency losses, from combustion inefficiency and thermal losses to aerodynamic and rolling resistance. It is used the specific case of a 2700 kg full-size 4x4 pick-up truck with a V8 engine and 5-speed transmission. Baglione [25] shows how the energy needed to provided service by a transport mode goes far beyond the simple conversion of energy by an engine.

To quantify the energy demand, Baglione created an energy analysis tool using MATLAB®/Simulink® based on used drive cycle data, component efficiencies, and basic physics equations.

Figure 6 taken directly from Baglione's work, it shows the distribution of the energy out of the engine. The noticeable result is that only 24.6% of the total fuel energy supplied answers to the vehicles demand, showing a remarkably high thermal loss of 63.5%, mainly cause in losses to the coolant and to the exhaust.

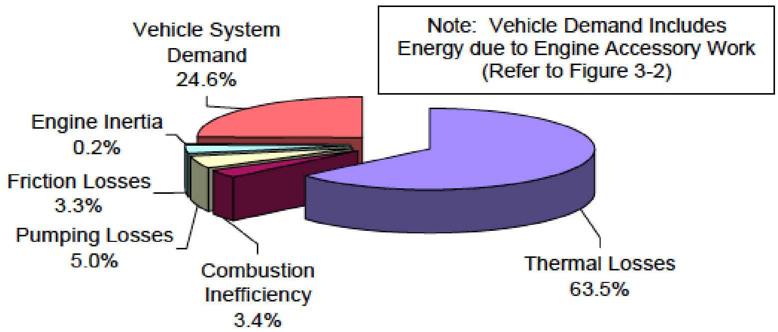

Figure 6 - Analysis of engine energy supply, taken from Baglione's PhD thesis [27, p. 53].

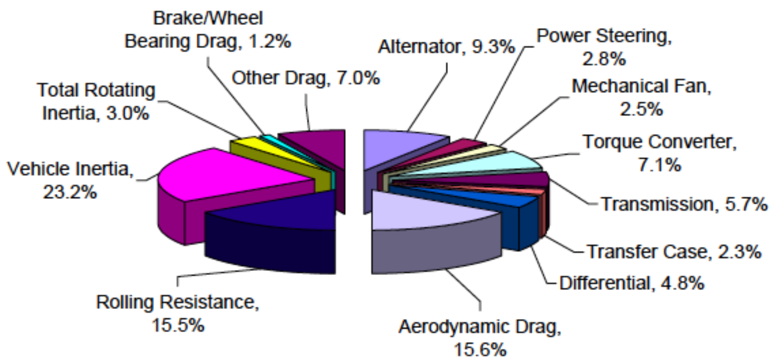

Figure 7 - Analysis of Percent Vehicle System Energy Demand, from Baglione's PhD thesis [27, p. 55].

From the 24.6% vehicle demand, Baglione sub-divided it into subsystems, and quantified how the energy was distributed (Figure 7). As these values are percentages from the total vehicle system demand, it is important to refer that, as example, 15.6% of aerodynamic drag shown on the chart represents 3.84% from the total energy supply.

2.4.2 Passive systems in airplanes.

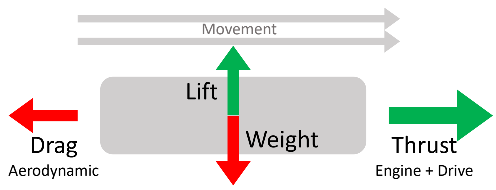

Figure 8 - Schematic of forces presented in an airplane motion.

Regarding airplanes, the approach has to be different due the different forces acting and needed for its movement (Figure 8). The passive system analysis is more complex, for two main reasons: there is no mechanical drag force acting on the airplane once in the air, instead the lift is needed to support the plane weight, and can be included in the aerodynamic drag; and the fact that the mass of the fuel composes a large proportion of the aircraft total mass, meaning it will change during the course of the full journey, the energy necessary for the entire trip will be a function of the distance.

There are multiple studies on the effect of distance, and weight on energy efficiency of airplanes [26], [27], [28]. For short distances, a significant fraction of the fuel is burnt during take-off and taxiing. For an optimum range of distance (dependent on aircraft type), the fuel efficiency is almost distance independent. For long distance flights (>8,000Km) the trade-off between fuel, weight and distance lead to a poor fuel efficiency. The "fuel for fuel" effect is predominant in long distance journeys, additional fuel has to be carried to be available at the end of the trip, increasing weight and consequently the amount of burned fuel [28].

There are two main drag components acting on the plane: profile drag that results from skin friction (friction between object and air), pressure drag (object shape moving on a fluid); and Vortex/lift drag, caused by the generation of lift, changes in lift vector direction that (backward push) [29]. Improvements on airplanes are mainly done by reducing its mass and by improving its aerodynamics.

2.4.3 Passive systems in Trains.

The big advantage of rail transport compared to road is that it is typically more efficient, resistive forces do not increase significantly with train length, allowing the transportation of more passengers or freight without a substantial loss of energy efficiency.

An analysis of the physics of rail is difficult to understand: the length; the difference between wagons shapes; the interaction with tracks, structures, platforms and tunnels are all factors that make the analysis more difficult.

Another challenge when analysing the service of trains is to separate the energy for freight and passengers because in many cases railways belong to private companies that do not disclose such type of information. To analyse how passenger or freight service can be improved energy wise is hard when there is not a clear distinction of how much each consume.

It is possible to set a limit to the practical limit using as example high speed trains, because this type of train is optimized with light-weight material and body designs that allow a minimal aerodynamic and mechanical drag. Beside these measures, coasting and regenerative braking can reduce the energy needed to overcome inertia, which are simple measures that can be applied in other types of trains [21].

2.4.4 Passive systems in Ships

In terms of goods transportation, ships are the most efficient mode. According to the international Chamber of Shipping [30], the international shipping industry is responsible for around 90% of world trade, but only accounts for 10% of primary energy for transport (Cullen [21]).

Ships velocity is limited due to fast increase of resistivity drag at high speeds, thus the shape of the hull and the design of the propeller. The design of the propellers is influenced by how minimal the drag can be while maximizing the lift that allows the ship thrust. For the hull, one can refer three main resistance forces: friction, due to shear stresses within the boundary layer; viscous pressure by variations in localized flow velocities or flow separation and wave resistance, by waves creates by the ship itself. Remaining resistance forces such's as climate variances, aerodynamic drag or hull maintenance (algae and rust) are not relevant.

According to Henningsen study [31], the choice of propeller can influence practical energy savings by 5 to 10%, depending on the type of ship. This author concluded that, improvements in hull design can result into up to 30% of energy saving. Henningsen also consider the effect of reducing the velocity of the ship by 10% (most resistance is caused by high velocities); this is an acceptable measure because a longer journey time will not significantly harm the transportation process and it would reduce CO_2 emissions by 23.3% which indicates large energy savings. This is the easiest measure to apply on current fleets.

2.5 Energy efficiency indicators

The publication of *"Energy Efficiency Indicators: Essentials for Policy Making"* [32] by IEA was developed with the intention of providing tools for initiating and developing energy indicators. According to IEA, well-founded indicators are an essential tool to aid decision makers into conceiving policies that are best suited to domestic and/or international objectives [33].

To better understand, it should be reviewed the difference between *energy intensity* and *energy efficiency*. In terms of service, something more *energy efficient* implies that it delivers more service for the same energy input. *Energy intensity* is the amount of energy consumed per activity (output), for specific sub-sectors and end uses [32, p. 17]. While an intensity indicator like energy/pkm is useful to assess the success of programmes like promoting carpooling, energy efficiency like vehicle fuel economy (l/Km) is more relevant to assess policies to improve efficiency of vehicles.

For the transport sector the preferred indicators are consumption of energy per passenger-kilometre (energy/pkm) or tonne-kilometre (energy/tkm).

As described by the report [32], one difficulty of the transport sector is that the energy consumption is not divided between passenger and freight transportation. Therefore, it is necessary to create indicators that perform a disaggregation of the total transportation energy. The level disaggregation will depend on the information available, the structure of the sector and the country situation/specificities [32, p. 104].

Level 1: Aggregate passenger transport energy intensity; accounts for the total passenger transport energy consumption per passenger-kilometre, it provides a general insight of the trend. It has the disadvantage that no conclusion can be drawn on where efficiency improvements can be made and that comparison between countries can be deceptive, due to the many factors that influence these indicators.

Level 2: Passenger transport intensity by transport mode; expresses the amount of energy consumed per passenger-kilometre, for each mode of transportation (road, rail, water and air). Level 2 indicators are relevant to develop efficiency measures for rail, air and ships. For road, more careful is needed because it includes different types of vehicles, and their relative shares may have a relevant impact on the overall intensity of road transport.

Level 3: Passenger transport intensity by road vehicle type; an energy intensity showing the amount of energy consumed per passenger-kilometre, for each road vehicle type.

Road service can be disaggregated in several ways. By type of vehicle (Light duty vehicles [LDV's], buses, motorcycles and 3-wheelers); by service provided (personal, commercial and public services); or a combination of the two.

In the report [32, p. 109], level 3 only focuses on road transport. Notwithstanding the existence of level 3 indicators on other transport modes, e.g. dividing air by type of plane, splitting rail into urban, inter-city or high speed. The report expresses that although the level of disaggregation depends of the structure, the data available and the resources available for such studies in each country, at a minimum, a distinction between LDVs and buses should be made.

Freight transport covers the domestic haulage of goods, it excludes air transportation due to the difficulty in separating the energy allocated for passenger or freight, and to the lack of data separating domestic and international data.

The level separation is quite like the passenger transportation. *Level 1: Aggregate freight transport energy intensity; Level 2: Freight transport intensity by transport mode* (road, ships and rail) and *Level 3: Freight transport intensity by road vehicle type* (vehicle weight).

These indicators are an essential tool to explain changes in energy consumption in the transport sector. Nevertheless, they cannot be used as measures of the impact of energy efficiency improvements. A change in the mode of travel, from train to road, will increase energy consumption even if the transport mode improves its energy efficiency [32, p. 111]. The indicators do not have a direct relation with the evolution of the transport's efficiencies.

2.6 Material Services

It is hard to find a clear interpretation of material services. One of the possible justifications for it is stated by Carmona *et al.* [34], ”*the sub-discipline of sustainable materials is newer than its sustainable energy counterpart and awareness of the issue is limited.”.* The more common method is to define material services relative to mass terms and the final product stage.

Carmona *et al.* were the first to attempt defining material services from the angle of “end user service”, to define its units based on the purpose of the material. It could result into a compatibility between material and energy service, as the example by Carmona *at al.* [34] "*...provide the same thermal comfort with more material and less energy, if we have better insulation or vice versa.”*

Carmona *et al.* developed a project that analysed the use of steel in UK's transport sector. One part of the project examines the material stock efficiency, in $Service/M_{Stock}$ units. This indicator assesses the relation between the material stock and the provision of service.

Carmona defined material service as *"Those benefits that materials contribute to societal wellbeing, through fuels and products (...) when they are put to proper use."*

2.6.1 Material Efficiency indicators

When talking about materials, one must separate them between stocks or flows and estipulate what information each one provides. As said before, indicators can be manipulated and adapted into providing the information desired.

Carmona *et al.* [35] refers to four indicators linked to material service efficiency, as tools to study steel flows and stocks required for transportation in UK, operating from 1960 to 2015. These indicators are dynamic because they separate material flows into durables and consumables for multiple periods that constitute the whole lifecycle.

2.6.2 Sustainable material strategies

The evolution of humankind was only possible due to the use and transformation of resources from the planet. Fisher-Kowalski *et al*. [36] categorized resource materials into: "biomass", "fossil fuels", "industrial minerals and metal ores" and "bulk materials for construction".

Due to increase of population, scarcity of resources, and environmental impact of industrialization, scholars started drawing sustainable material strategies. The sustainable strategies for this study will be the ones used in the literature review done by Carmona *et al.* [34], as well as the strategy proposed by the authors.

In the book *Sustainable Materials With Both Eyes Open* [37], the strategy "one eye open" is defined as an approach only focused on the efficiency gains. The solution for the sustainability problem (the strategy "with both eyes open") has to include reduction in material use, improving product function, a re-design of the production process keeping in mind the increase of corporate profitability. A faulty strategy (based only on energy efficiency) will increase the demand of products in the future due to the "rebound effect" because a more efficient industry will cause a higher product demand that will have the same (or higher) environmental impact as the less efficient one with less production.

In the book [37], it is analysed the effect of material in society. They measure the industrial sector performance through energy and material efficiency analysis, using carbon emissions as the main environmental indicator. It suggests a strategy that is focused on the potential benefits of using less raw materials on the production phase. This strategy is identified as *"with both eyes open".*

Focusing on "doing more with less" diminish the unneeded consumption of rare and non-renewable resources in the present for assurance of prosperity of future generations, as implied by Ayres *et al.* [38].

The main concern with these strategies is that they do not take into consideration the service part of the material efficiency, how the end product is used, and what is its impact in society. The relation between product and consumer is in constant variation, there are changes of economic power, necessities, and in the experience with the product itself. For these reasons, Carmona *et al.* [34] felt the need for a more ample strategy.

The strategy proposed by the authors of [34] is called "eyes wide open" and according to the author, *"It breaks the paradigm of seeing materials as products and emphasizes the services behind them."*.

Measuring material efficiency is more challenging that energy efficiency due to the log life cycles of the stocks. It is easier to follow the flow of energy due to limited sources, the same cannot be said about materials. As said by Carmona *et al.* [35] *"All material services are provided by flows (or stocks) but not all flows (or stocks) provide material services".*

2.7 Resource Efficiency

The elemental definition of resource comes as "*a stock or supply of money, materials, staff, and other assets that can be drawn on by a person or organization in order to function effectively*", according to oxford dictionary [39]. In other words, resource efficiency is the relationship between a specific benefit or result and the deployment of resources required to achieve this [40]. The definition by the European commission is "*Resource efficiency means using the Earth's limited resources in a sustainable manner while minimising impacts on the environment. It allows us to create more with less and to deliver greater value with less input.*" [41]

Ana Gonzalez PhD. thesis was focused on *"Site-level resource efficiency analysis"* [42], an industry focus analysis of resource efficiency, a study on joining typical disconnected indicators, energy efficiency and material efficiency using exergy. Results show that an exergy-based metric is a suitable method to collect the interaction between energy and materials. In this case, the focus was on material (steel) output thus the efficiency indicators vary from the service-oriented ones previously described. These indicators are measured in units of joules per tonne of material output.

On "*The Use Of Steel In The United Kingdom's Transport Sector: 1 A Stock-Flow-Service Nexus Case Study*" [43] Carmona *et al.* discuss how the stock-flow-service nexus can contribute to broader form of resource accounting, reflecting some its limitations and how they can be tackled. The nexus is analysed through 5 indicators: stock efficiency, stock degradation efficiency, stock maintenance rate, stock expansion rate and specific embodied impact. The nexus purpose is to allow an analysis of the complex interaction that occur within socioeconomic metabolism, where restricting resource accounting to one indicator could lead to misleading conclusions. Using the same example as Carmona *et al.* [43] "*...if one only follows the trend of stock efficiency without taking into consideration both the stock maintenance and stock expansion (contraction) rates, one might be led to believe that service is improving at the expense of a shortage of stock, which in fact is not the case."*

2.7.1 Which units for measuring/comparing?

A big obstacle of energy system analysis is to find one unit with a universal acceptance. Although the physical unit of Joule (J) is widely use and the official unit, it only presents most advantageous for energetic analysis when conversion is needed from one energy form to another. New units were developed through time, units that could also include information about quality, purpose and economic measures of the quantity of energy used [20].

For this project it is pertinent to discuss normalized units like *Energy Intensity*, and quality measures like *Exergy.* Normalized units allow a more serious comparison of energy data between data groups like countries, sectors, material etc. In statistics, normalisation refers to the method of adjusting values measured on different scales to a universal common scale[44], it allows a comparison between data characteristics without influence of the isolated variables. The most commonly used unit is energy intensity, it refers to the energy consumed per unit of activity. An example of such unit is energy consumption per unit of economic output [J/€].

In this project, I will use a normalized unit to analyse how efficient is the energy consumption in providing the transportation service [pKm/J], it will be stablished as an efficiency unit.

3 Methodology

This chapter describes data sources, the procedures to process such data, indicators and formulation used to achieve the desired results. The chosen country is United Kingdom due to its data availability regarding provided service.

Regarding data collection and treatment, this methodology is organized in three main sections: service, energy and materials. On the other hand, to describe the methods behind the used indicators the document is divided between energy efficiency, material efficiency and resource efficiency. Although characteristics like speed and so are extremely important when evaluating the transport service, they will not be considered in my study. It will be focused on the efficiency of the sector, in terms of passenger-kilometres, and not on the effectiveness of the sector (service quality).

3.1 Service

The scope of the study will be mainly domestic transportation from 1960 to 2014, with exception of air transport where reliable data for all transport is available (domestic plus international). The maritime sector will not be included since there is not sufficient data to quantify the service.

For domestic service, transportation that starts or ends outside United Kingdom borders is excluded. There is not enough information about passenger numbers and distance to pursue an international sphere study.

The majority of service data was taken from *Department for Transport (DfT)*, by U.K government web platform [45].

While I am aware people's mobility and freight transport are two different services, for comparison purposes, all tonne-kilometres data will be converted to passenger-kilometre by an average of 80Kg per passenger.

3.1.1 Road

For cars, vans, buses and motorcycles, service is expressed in billion passengers-kilometres (10^9 pkm). Information was obtained from the file "*Passenger transport, by mode: annual from 1952*" [46]. For heavy goods vehicles (HGV), service is expressed in billion tonne-kilometres (10^9 tkm) and came from "*Domestic freight transport, by mode: 1953 to 2017*" [47] file. Both files were obtained through DfT platform. HGVs includes all goods vehicles over 3.5 tonnes gross weight and light vans goods vehicles not exceeding 3.5 tonnes.

Passenger-kilometre is obtained through the traffic data (originally in vehicle miles) and the average occupancy rate, derived from national surveys. In 2017, the average occupancy rates for each year were revised and replaced by the three years average to improve the consistency of the series, [48]. Vehicle-kilometre data used in this calculation is based on nearly ten thousand manual counts, that are combined with automatic traffic counters (ATC) data and road length. These manual counts are done by trained enumerators that count the number of vehicles for each category in a specific segment of road form 07h00 to 19h00. On the other hand, the ATCs record the traffic with information about vehicles properties, which are used to classify them by type, [49].

To analyse the occupancy behaviour in passenger road vehicles, it was estimated the occupancy rate by dividing passenger-kilometre by vehicle-kilometres. The vehicle-kilometre data was obtained from *"Road traffic (vehicle kilometres) by vehicle type in Great Britain, annual from 1949"* [50] also from DfT platform. To convert such values into percentages, it is assumed total occupancy of cars as 5 and motorcycles as 2. For buses it is done a weighted average based on the percentages of different buses from "*Licensed buses and coaches at the end of the year by body type, Great Britain from 1994*" [51], and the number of seats for each type of bus from a specification sheet [52].

Heavy goods vehicles data is derived from the Continuing Survey of Road Goods Transport Great Britain [53], for light goods vehicles from surveys carried out in 1976, 1987, 1992/93, and from 2003 to 2005, with data being interpolated for the intervening years. Due to changes in methodology, data from 2004 onwards are not fully comparable with previous one [54]. Prior to 2004, the sample was selected on a weekly basis from a weekly update sample, from 2004 on, the weekly sample started to be selected from a sample that is updated quarterly, which makes the sampling frame more out-of-date through the quarter [55].

3.1.2 Rail

The data for freight was obtained from the same document as the one for HGVs [47]. After the 1996 privatization, data for rail freight transportation is not comparable with previous one as indicated in "*TSGB 2018 Notes and Definitions: Freight"* [54].

For the passengers-kilometre the data came from *"Length of national railway route at year end, and passenger travel by national railway and London Underground, annual from 1900"* [56].

3.1.3 Aviation

The data was collected from the Civil Aviation Authority annual statistics documents [57]. The relevant data is “used service” in tonne-km. The documents present data divided between domestic and total service, then between scheduled and non-scheduled, and finally by available and used. The only data available for the interval 1960 to 1974 is available service, both for domestic and total.

To estimate the missing values for scheduled flights, I calculated two percentages for the existing years: $\%\frac{Scheduled\ available}{Total\ available}$ and $\%\frac{Scheduled\ used}{Scheduled\ available}$. Then, I estimated by exponential function (visually more suitable) the percentages for 1960 to 1974. Through the approximation, the missing values were estimated, first for schedules available service, then finally for scheduled used service. The same was done for non-scheduled service and total service. The final total service by domestic aviation was determined by adding the calculated used scheduled service with the non-scheduled.

The occupancy rate was calculated by dividing the service use by the available.

3.2 Energy

Domestic energy values from 1960 to 2014 for UK were obtained through the International Energy Agency IEA [58]. The original values are exhibited by type of product in kilo tonnes and in gigawatt-hours for electricity. All values were converted into terajoules using the calorific value for each product on the corresponding year (KJ/Kt), also provided by IEA [58], and by standard conversion of 1GWh to 3.6 TJ. To convert mileage (mpg) of diesel vehicle to units of MJ/Km, the density considered was 10^6L=35.571 TJ/L.

IEA data is obtained through annual questionnaires submission from national administrations, for the United Kingdom the responsible administration is the *Department for Business, Energy and Industrial Strategy* (BEIS) [59].

Prior to 2004, data for electricity was not divided by sub-sector, being included in non-specific transport. It included data from road, non-industrial rails, and consumption for non-traction by railways and bus stations and airports. This technicality will be ignored for the development of this thesis.

3.2.1 Road

The data combines fuels for road vehicles, agricultural and industrial highway use. It excludes military use, stationary engines and tractors that are not for highway use [60]. The flows are by type of product and not type of vehicles, so it is not possible to know from the original data the quantity of energy used for passenger or freight transport.

The consumed energy, by type of fuel, for road transportation is shown in Figure 9. It is possible to see that from 1990 onwards there was a shift from petrol vehicles to diesel ones. After 2005 electricity started to increase, but due to such small values (69TJ in 2005 to 245 TJ in 2014), it is not visible in the graph.

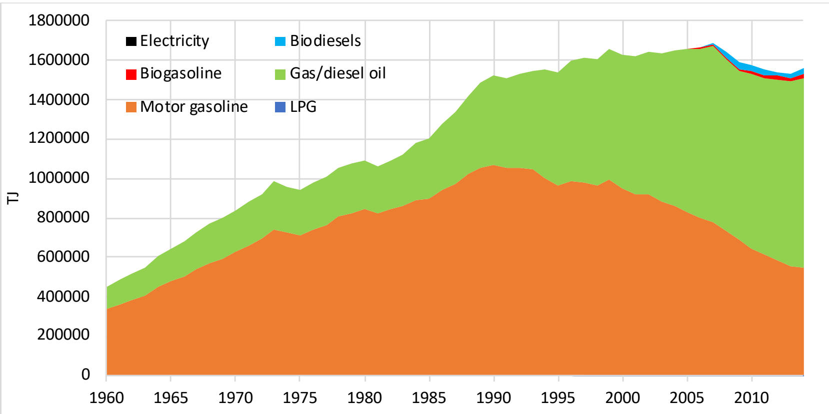

Figure 9 - Cumulative road energy consumption by product type in TJ[58].

To separate the energy consumed by each road vehicle (Heavy Goods Vehicles, cars, motorcycles, buses and vans), it was calculated the percentage energy from total petroleum derivatives used by each road vehicle category and then multiplied by the original petroleum derivatives values from IEA. The remaining fuels (biofuels and electricity) were added to the car, taxis and vans category.

Percentages of petroleum derivatives used by each road vehicle were determined using the file "*Petroleum consumption by transport mode and fuel type: United Kingdom, from 1970*" by the Department for Transports Statistics of United Kingdom [61]. It contains the amount of petrol, diesel and liquefied petroleum gas (LPG) consumed for the different road transport categories. A linear extrapolation for each type of transport category was done from 1960 to 1969 because data only starts in 1970 (see Figure 10). The final values for energy consumption by each road transport category are shown chapter 4

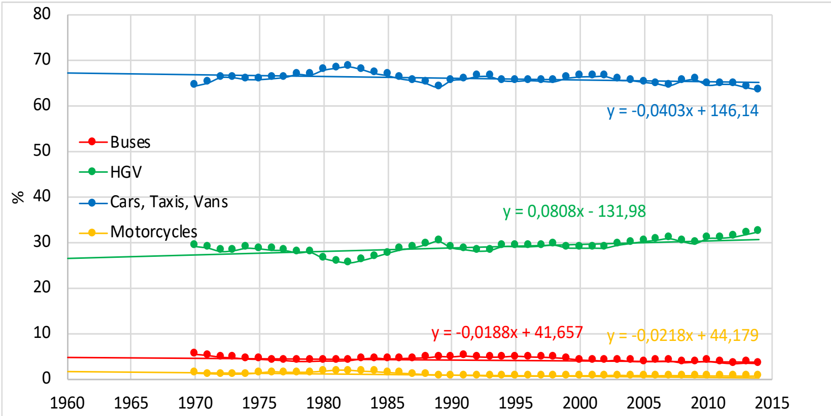

Figure 10 - Percentage of energy consumption for each road transport category.

3.2.2 Rail

Figure 11 is a representation of consumed energy quantities used in rail traffic, containing industrial railways and public rail transport in urban and suburban systems, like trams and metro [60]. Before 2004, electricity consumption refers to industrial rail only. From 2004 onwards it includes both industrial and urban rail, justifying the break in the electricity series from 2003 to 2004.

Analysing Figure 11, it stands out the steep decline from the 1960 to the 70's. The lower graph shows that the type of fuel that most contributes to the decrease in energy is coal. It also shows that as energy originated from coal decreases there is also an increase on energy derived from gas/diesel, electricity and fuel oil, suggesting a shift in the type of technology used in rail transport.

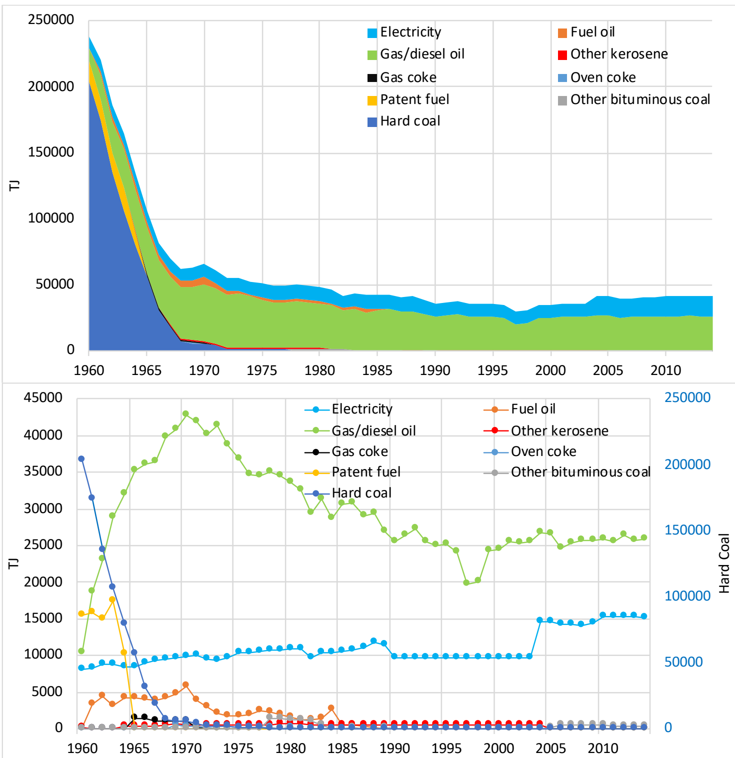

Figure 11 - Rail energy consumption by product type in TJ, with coal represented on the right axis bottom image[58].

In Great Britain, rail modernization started in 1950, with the replacement of steam locomotive (coal), by diesel ones, and in 1960 by the electrification of the British rail system [62]. In respect to these historical facts, and the high consumption of coal by steam locomotives, there is a justification for the steep decrease of energy consumption on train transportation after 1960. Steam locomotives are inefficient (≈6%) and have a high maintenance cost while diesel locomotives represent a more efficient fuel consumption solution (≈36%) [63][64].

To distinguish the amount of energy allocated to freight or passenger transport from the total amount, I used information on the amount of electricity (10^6kWh) and diesel (10^6L) consumed for passenger and freight rail transport from 2005 to 2017 taken from table 2.101 *"Estimates of passenger and freight energy consumption and carbon dioxide equivalent (CO_2e) emissions"* [65]. This data was used to make an estimation of the amount of energy allocated to freight or passengers transport prior to 2005. First, I estimated the fractions of electricity (from total electricity) and diesel (from total diesel) allocated to passenger transportation for the available data (2005-2017), and then the fraction of passengers' service from total service. I assumed that the fraction of total rail energy allocated for passengers prior to 2005 would behave in the same manner as the fraction of passengers' service from total service[1]. A similar assumption was made for freight. The estimation and real values are shown in Figure 12.

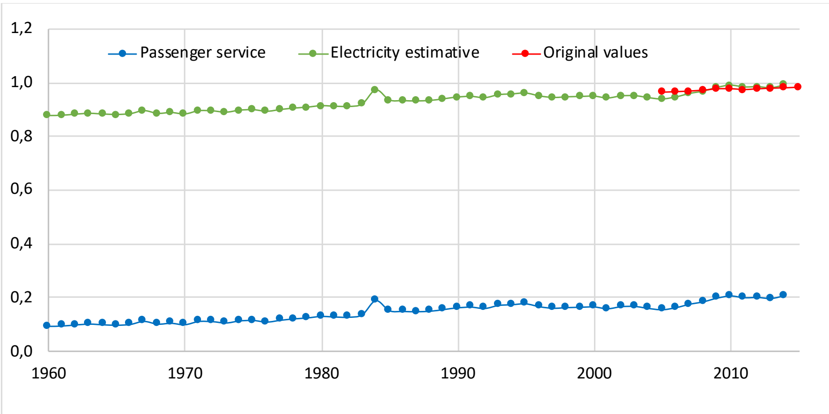

Figure 12 - Fraction of passenger service (from total service) and electricity (from total electricity) from 1960 to 2014.

Although electricity and diesel are the main power source for trains traction, from 1960 to 1985, there were other fuels used to power rail transport (Figure 11 - Rail energy consumption by product type in TJ, with coal represented on the right axis bottom image[58].). These were included in the fraction belonging to diesel because locomotives that used to be powered by different fuels evolved into current ones powered by diesel. The energy consumption of passengers and freight is presented in chapter 4.

It was only possible to measure the occupancy rail for 2016, and such value is assumed for 2014. The passenger/vehicle rate is taken from "*Regional and Suburban Railways Market Analysis Update*" [66]. To

[1] To correlate the service and energy fractions it was assumed that deviation between the two trends for the missing years would be equal to the average deviation of the existing years (2005-2014). The deviation values are 0.78 and 0.5 for electricity and diesel, for passenger transportation.

convert this rate into percentage it was used the average seat number per train as the same as France, which is calculated by dividing passenger/vehicle rate [66] by the occupancy percentage [67].

3.2.3 Aviation

Figure 13 shows the domestic aviation consumption from IEA database, it includes commercial, private and agricultural. It also includes fuel for bench testing of engines. It excludes fuel for road transport used by airlines.

The data for air transport has a "corrupted" section from 1970 to 1990, were the kerosene energy values are too high (see Figure 13, green data series). It presents a discontinuity in 1970 and 1989, and does not shows values for kerosene prior to 1970, which contradicts the information about aviation fuel consumption [68].

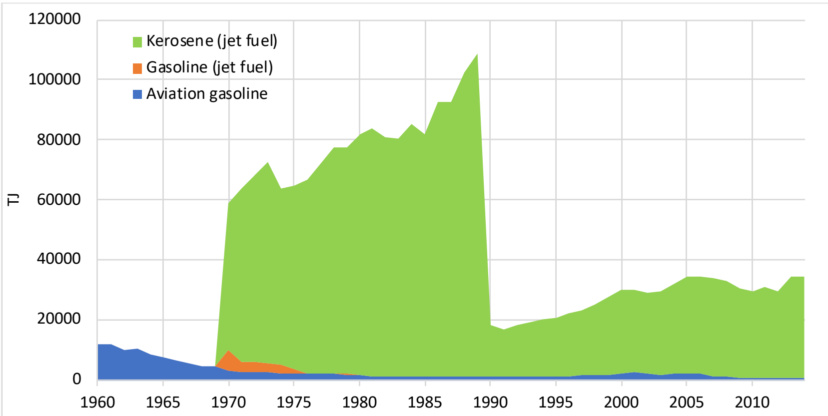

Figure 13 - Cumulative aviation energy consumption by product type in TJ [58].

There is no justification for this discrepancy. According to the report "*The UK oil industry over the past 100 years*" which presents a graph of fuel consumed by all aviation, aviation turbine fuel (ATF) kerosene have pass deliver of aviation gasoline in 1962 and continued to rise to the present day (green curve, Figure 14). There is no reference to the discontinuities. The original data also points to a gasoline (jet fuel) consumption for a short period, from 1970 to 1985. The report does not justify the inexistence of data on gasoline and kerosene consumption prior to 1970. This lack of data can be justified by the fact that from 1960 to 1969 data was estimated using population growth rates [60], being a probable source of error.

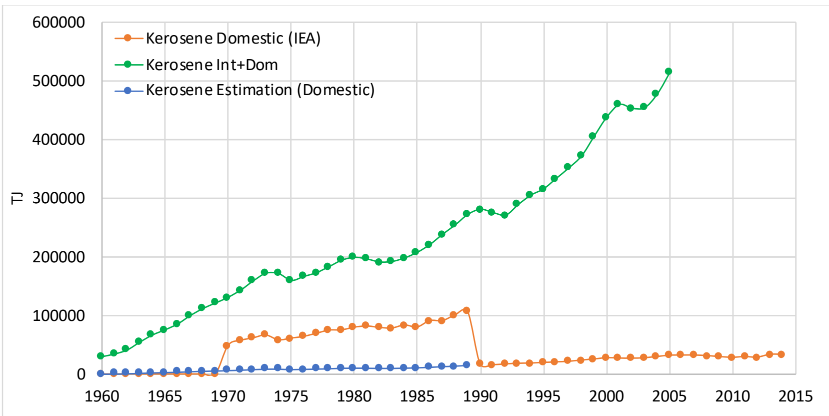

Figure 14 - Kerosene Consumption in TJ.

To estimate the [1960-1990] erratic values, it was assumed that the percentage of domestic kerosene from total (international plus domestic) kerosene consumption would follow a tendency. To find such tendency, I calculated the domestic fraction from 1990 to 2014, which resulted in a trend line defined by $y = 5 \times 10^{-5x} - 0.0444$, that was used to determine the [1960-1990] values. The estimated values are presented in Figure 14 in colour blue, and they show a more credible trend for the domestic kerosene consumption. The final energy domestic consumption values where calculated by adding the new kerosene values to the other fuels from the original data and are shown in chapter 4.

Energy consumption data for international passenger was obtained by subtracting domestic consumption from the total consumption provided by table 2.01: *"Transport energy consumption by type of transport and fuel 1970 to 2017"* from Energy Consumption in the UK (ECUK) 2018 data tables [69]. Because it is available domestic and total aviation data for both service and energy variables it will be done an efficiency analysis for both services.

3.3 Materials

It was not possible to find material data per year for all the sector. Material percentage evolution per vehicle per year was only available for cars.

The data was obtained in two separated steps: First, the annual percentage of steel, aluminium and plastic was obtained for new cars; and then the percentages of each material per car were used to estimate stocks, inflows and outflows of each material in tonnes for each year following the stock model developed by Carmona *et al.* [35].

3.3.1 Material percentage per Car

Serrenho and Allwood [70] published an analysis of *"Material stock demographics: cars in Great Britain"* where the average curb weight and percentage of steel and aluminium were calculated from 1970 to 2012, values until 2014 were estimated through a linear approximation and pre-1970 values were assumed as the same as 1970. According to Serrenho *et al.*, due to missing data from 1985 to 2009, composition percentages of USA cars were used as a proxy for the British average, the remaining missing values were obtained by linear interpolation. In Serrenho *et al.* data, steel and aluminium percentages have a constant value from 1970 to 1985, which is not correct. To correct steel values, I used the average ratio between great Britain and U.S.A. values (from MacKenzie *et al.* [71]) from 1985 to 2010, to estimate GB values form 1975 to 1985. In the remaining period between 1960 and 1975, the percentage of steel from 1975 was assumed. For aluminium, values from 1975, 1980 and 1985 were obtained from *Ducker Analysis* [72] and in-between years through a spline interpolation, prior to 1975 the value was considered the constant and equal to the aluminium percentage in 1975.

There was no historical information about cars' plastic constitution for European countries, so U.S.A. values were used. From 1975 to 2010, percentage data was taken from MacKenzie *et al.* [71]. American Chemistry Council 2017 report [73] provided the values, in mass, from 2010 to 2014. The same report presented a chart with the trend of amounts, in pounds, of plastic per vehicles in 5 years intervals from

1960 to 2016. To calculate the percentages I used the curb weight of cars, converted to pounds, provided by MacKenzie *et al.* [71].

The percentages of the three materials are presented in Figure 15. Figure 16 shows the materials in kilograms, using Serrenho and Allwood [70] curb weight data, representing the weight of new cars per year. To reduce energy consumption and pollutant emissions it is expected a reduction in car mass, however, what stand out from the graph is the increase in curb weight. It also stands out and the shift from steel to plastic, aluminium and other material.

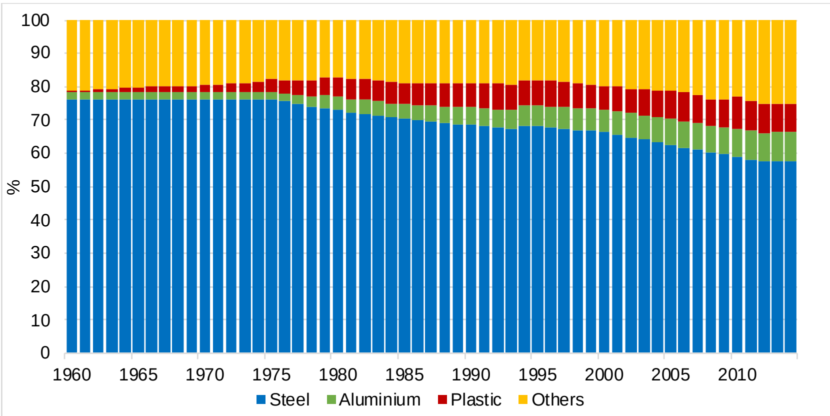

Figure 15 - Percentage of steel, aluminium and plastic in new cars, per year.

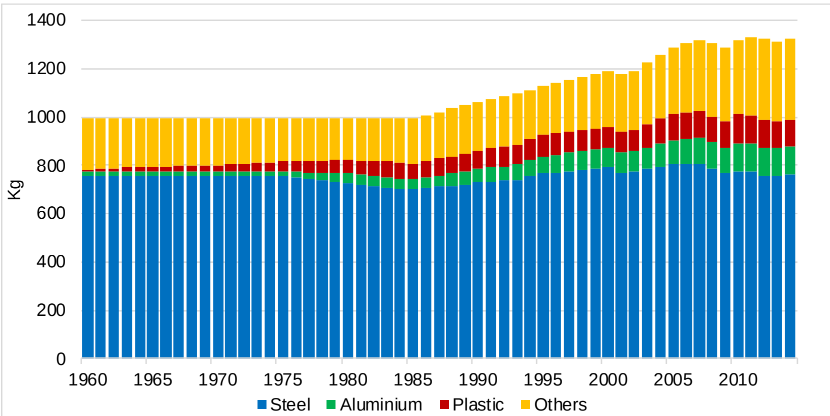

Figure 16 - Amount of steel, aluminium and plastic in kg in new cars, per year[70].

3.3.2 Stocks, Outflows and Inflows

Stock and flows data were obtained through the same stock model that Carmona *et al.* used in "*From flows and stocks to material services: the use of steel in the United Kingdom's transport sector*" [35]. The model that follows is supported by two methods: inflow-driven where material stocks are calculated by adding the annual difference between inflows and outflows and the stock-driven method, which adds the quantities of materials in a specific stock at a given time based on data describing the stock.

Equation (1) is the representation of the inflow-driven approach. For inflow it is used the amount of annual steel consumption allocated to the manufacturers responsible for UK registered vehicles. Outflows, on the other hand, are determined through a residence time model using a convolution integral and are derived from $\mathrm{M}_{\mathrm{Inflow}[\mathrm{n}]}$ and the probability density of a lifespan distribution function assigned to each vehicle category (f [n]). It is assumed a life expectancy for cars of 11 years from 1960 to 1980 and 13 year from 1981 to 2015.

$$M_{Stock[N]} = \underbrace{M_{Stock[0]}}_{Initial\ Stock} + \underbrace{\sum_{n=1}^{N} M_{Inflow[n]}}_{Inflow} - \underbrace{\sum_{n=1}^{N} M_{Inflow[n\rightarrow n']} \cdot f_{[n']} \cdot (1-\gamma)}_{Outflow} \quad (1)$$

Stock-driven approach is used to validate the values result from the total number of vehicles registered and the average steel composition for each category. For years where the annual difference, between inflow-driven and stock-drive, of the same category were more than ±20%, they adjusted the outflow for the previous year so that the inflow-driven model's values matched those of the validation.

Such correction is visible in outflow from 1973 to 1980, where two peaks of excessive disposal came from a specific inventory where a big quantity of vehicles is discarded.

3.4 Energy Efficiency

Energy efficiency indicators include a wide formulation that is adapted in accordance to the purpose and meaning desired for the indicator. The IEA published *"Energy Efficiency Indicators: Essentials for Policy Making"* [32] as a tool for initiating and developing energy indicators.

For transport service, they propose equation (2) as a measure of the amount of energy provided to a specific service. For this study, and following the example given by IEA, the analysed service is transportation with passenger-kilometre [pkm] and tonne-kilometre [tkm] as unit.

$$\varepsilon_F = \frac{Energy}{Service} = \frac{J}{pkm} \vee \varepsilon_F = \frac{J}{tkm} \quad (2)$$

Because my thesis will follow similar methodology as Carmona el al. [35], I will use equation (3), the inverse of equation (2).

$$\varepsilon_F = \frac{Service}{Energy} = \frac{pkm}{J} \vee \varepsilon_F = \frac{tkm}{J} \quad (3)$$

3.5 Material Efficiency

The indicator purpose is to measure how much material is needed to provide a unit of service.

To compare the relation fuels-service and material-service is not simple. Fuels are "short term" consumables, and it is possible to measure how much fuel is needed into providing a service in a time interval (one year). Materials on the other hand, can be separated between stock and flows (inflows and outflows).

The amount of stock for one year is the amount of material existent in current vehicles, plus new material added by purchases, subtracted by the amount that is removed from circulation – the average service life for cars is approximately 12.6 years, accordingly to Carmona *et al.* [74] so a percentage of one year stock account contributes for the next year account.

Flows are the form of measuring materials as consumables, they quantify an amount for a specific time frame. However, it is not obvious whether one should choose between inflows or outflows to measure material consumption in a way that is comparable to energy consumption. Inflows represent how much material is added to the vehicle stock in one year, part of the inflows will replace outflows while the rest will increase the stock of vehicles. Outflows quantify the amount of material that leaves the system either for recycling or landfill. Although the discarded materials were put into the system in years prior to the studied one, outflow data is the most adequate to represent the amount of material consumed for each transport service over a year.

One can distinguish the following known indicators for material efficiency:

Material Degradation Efficiency, to determine the material consumed to provide one unit of service. It accounts for the amount of material that needs to be replaced and is discarded. It is represented by equation (4).

$$\eta_{replace} = \frac{Service}{Outflow} = \frac{pkm}{tonne} \; or \; \eta_{replace} = \frac{pkm}{MJ} \tag{4}$$

Stock Efficiency, represented by equation (5), quantifies the amount of stock necessary to provide the corresponding service.

$$\eta_{stock} = \frac{Service}{Stock} = \frac{pkm}{tonne} \; or \; \eta_{stock} = \frac{pkm}{MJ} \tag{5}$$

Another indicator that will be analysed will be referred as **Energy Intensity of Operation in-use Stocks** (equation (6)), it accounts for the amount of energy used to activate the stock, that is, how much fuel is used to drive the current stock:

$$a_{stock} = \frac{Fuel\ Energy}{Stock} = \frac{MJ}{tonne} \; or \; a_{stock} = \frac{MJ}{MJ} \tag{6}$$

3.6 Resource Efficiency

To study material and energy resources, it is necessary to use a standard unit that allows a valid comparison between both flows. Exergy is the chosen unit due to its capability to characterize both flows and it will be used the final exergy content in each material and fuel.

Material outflows do not represent a consumption type equal to the one that fuel consumption does, the long lifespan of cars' materials do not allow it, this is the challenge of accounting for resource efficiency for such a large system. Nevertheless, I joined in one indicator both variables, calculating the service efficiency by assuming the total exergy consumption as the sum of fuel exergy with materials exergy. Equation (7) represents the formulation for such indicator.

$$\eta_{resource} = \frac{Service}{Fuel\ Exergy + Outflow\ Exergy} = \frac{pkm}{MJ} \tag{7}$$

The resource efficiency analysis will only be made for cars because it is the only vehicles where it was possible to find historical data for the material composition.

Petrol and diesel values were taken from chapter 19 of Dincer and Rosen "*Exergy*" book [75]. Steel and Aluminium exergy values were obtained by consultation of chapter 6 of *"Sustainable Metals Management"* [76]. All values are taken as constant throughout time.

To compute an exergy value for plastic it was used the formulation and available values by Eboh *et al.* paper on *"Estimating the specific chemical exergy of municipal solid waste "* [77], the relevant plastics available from the category are: Polyethylene (PE); polypropylene (PP); polyvinyl chloride (PVC) and polyurethane (PU). The percentage of each type of polymer in a car was taken from American Chemistry Council 2017 report [73], establishing the average of 2006 to 2016 values as a constant for all the analysed years. Because there were not exergy values information for all plastic/polymers in a car, the existing ones were considered has the sole constituents of plastics in a car, and from there considered the contribution of each type of plastic for the total exergy. Table 4 presents exergy values and coefficient for each type of material and fuels.

Table 4 - Exergy values and coefficients of fuels and materials

Compound	Exergy (MJ/Kg)	Exergy coefficient
Electricity	-	1.00
Common Diesel	44.70	1.07
Common Petrol	46.80	1.07
Steel	6.75	-
Refined Aluminium	32.80	-
Plastic	35.76	-

The final approach to resource efficiency is to analyse the CO_2 emission by fuels and outflows, through an **Embodied Impact Efficiency** represented by equation (8).

$$\eta_{embodied} = \frac{Service}{(Fuel+Outflow)CO_2 emission} = \frac{pkm}{tonnes} \quad (8)$$

Fuel values in tonnes were taken from DfT file "*Carbon dioxide emissions by transport mode, United Kingdom: 1970 to 2016*" [78][61]. For the material CO_2 emission factor values, it was only possible to find historical values for steel [79]–[81]. It was obtained the emission factors for 2013 for steel, plastic and aluminium from RICARDO-AEA "*Current and Future Lifecycle Emissions of Key 'Low Carbon' Technologies and Alternatives*" report [82], such values presented in Table 5. To estimate the historic values for aluminium and plastic it is assumed that the ratio between steel and aluminium or plastic from 1960 to 2015 will be the same as the value for 2013. It was not possible to apply CO_2 emission factors to the stock model, and it would be incorrect to apply the factors directly to the outflows because it would not consider the real impact of improvements done to reduce such emissions. For these reasons, inflows are used as a proxy to the outflows' emissions.

Table 5 - CO_2 emissions conversion factors for fuels and materials

Compound	$\frac{KgCO_2e}{Kg}$
Steel	1.24
Aluminium	7.28
Plastic	4.18

3.7 Cars efficiency analysis

3.7.1 Fuel efficiency

It was consulted consumption values of new cars published by authorities, as a form to validate energy efficiency values for cars. There are available two sets of data referring to cars from UK, the first was taken directly from Department for transportation file, "*Average new car fuel consumption, Great Britain: 1997 to 2017*" [61], where consumption was computed from average carbon dioxide emissions data for new petrol and diesel cars and presented in litres per 100 kilometres.

The second set of data, also on litres per 100km, was obtained from *"European Vehicle Market Statistics - Pocketbook 2018/2019"* [83] from ICCT, based on New European Driving Cycle (NEDC) procedure, with data from 2011 to 2018.

Data from DfT was separated between diesel and petrol cars, so the conversion to MJ/Km was done simply through each fuel caloric value. For the pocketbook data, it is necessary to separate between diesel and petrol fuelled cars, to be able to convert in energy units, for that it was used DfT data to calculate the percentage of petrol fuel cars, and diesel, from the total consumption.

The efficiency calculated in this project is in MJ/pkm. To be able to compare directly with other consumption values it is needed to remove the passenger information. For that, occupancy rates data were taken from DfT National Travel Survey [84] (2002 to 2017) and from European Environment Agency [85].

3.7.2 Mechanical Drive Efficiency

To analyse the engine efficiency, data regarding to mechanical drive efficiency was collected from Miller *et al.* [86] paper on "*Exergy Accounting: A Quantitative Comparison of Methods and Implications for Energy-Economy Analysis*". Between the two methods presented in the paper, in thesis it is used values from the "proxy" method where exergy efficiency values of a mechanical drive is based on its service efficiency.

4 Results and Discussion

This chapter presents and discusses the obtained results. Firstly, it is discussed the Energy Efficiency results, separated between transport sectors and a final analysis on the specific case of cars. Then comes a Comparison section, to compare between each sector the Service, Energy and Energy Efficiency. Following, comes Material Efficiency in Cars, divided between Stocks and Outflows and then the Resource Efficiency section that includes an Emission Subsection. The chapter ends with an analysis on the conversion devices and passive systems in a car.

4.1 Energy Efficiency

4.1.1 Road

Figure 17 represents graphically the data for service in road transports. It stands out an almost continuous growth in the categories with higher service quantity such as cars and HGVs. Contrarily, the bus services present a decrease justified by the reduction in occupancy rates, buses are emptier now than in 1960 (Figure 18). Heavy goods vehicles (HGV) represent a higher volume of services than other vehicles, it comes from the ability of carrying much higher masses, order of tonnes, while others carry a quantity in an order of hundred kilograms.

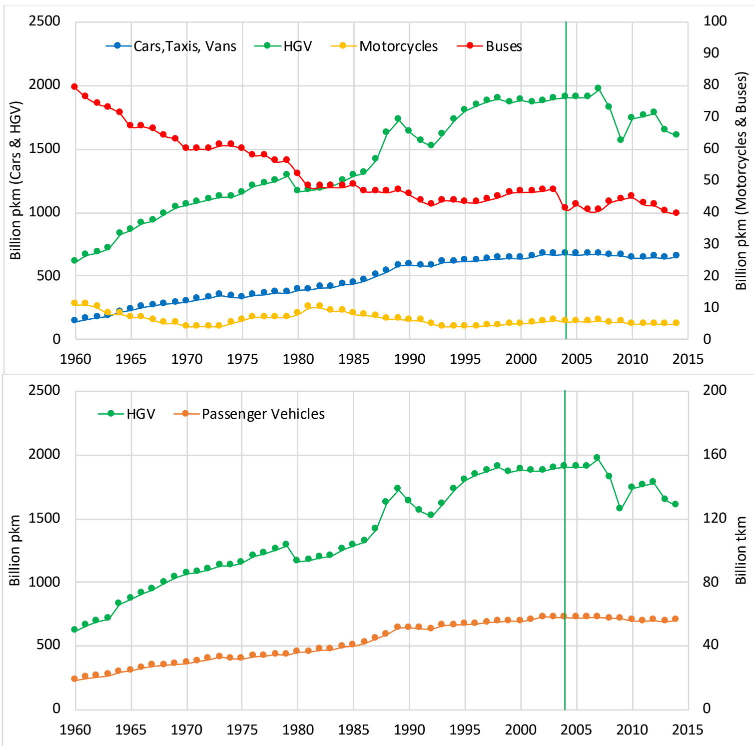

Figure 17 – Transport service by road. The top graph has service separated by vehicle type in billion pkm with motorcycles and busses in the right axis and cars and HGV on the left axis [46]*, while the second graph has service separated between heavy goods vehicles*[47] *and the remaining ones (passenger vehicles) with the left axis in billion pkm and the right in billion tkm.*

Figure 18 presents the passenger occupancy rate for road transport. Motorcycles had a stable occupancy rate (around 1) because only two seats per vehicle are available. For cars, vans & taxis and buses, occupancy has been decreasing through the years with exception of buses from 2007 onwards that showed a slight increase, probably associated with the 2008 global economic crisis when population looked for cheaper transportation options. On the figure, the right and left axis are differentiated by a factor of x10, which facilitates a direct tendency comparison between cars, taxis & vans and bus transportation. It is highlighted how bus occupancy rate had a much steeper decrease than cars, looking at the percentage graphic it is clear that this is the result of a reduction in passenger number and not an increase in buses fleet. The steep decrease represents a shift from bus to other transportation mean.

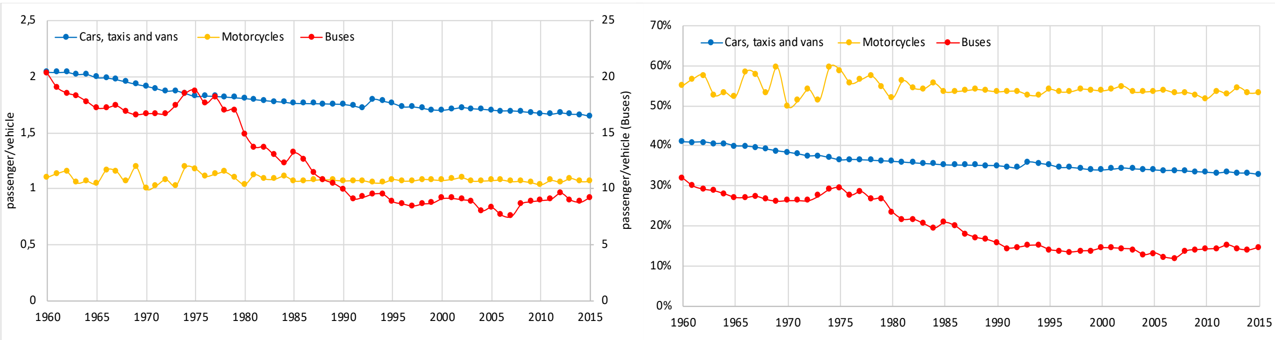

Figure 18 - Occupancy rate for road transports. The graph on the left is in passenger/vehicle with buses scale on the right axis and the right on in percentage including.

The results for energy consumption for each road vehicle type are plotted in Figure 19. When comparing these values with the ones from Figure 17, there is an "inversion" of two curves' positions, the consumption by cars, taxis & vans is far bigger than HGV's (while in service it is the opposite. Cars consume significant more energy to provide far lower service than HGVs. However, the type of service (passenger vs. freight) is not comparable. Apart from the transportation of persons, cars also provide other services such as comfort, safety, and full adaptability for routes or schedules.

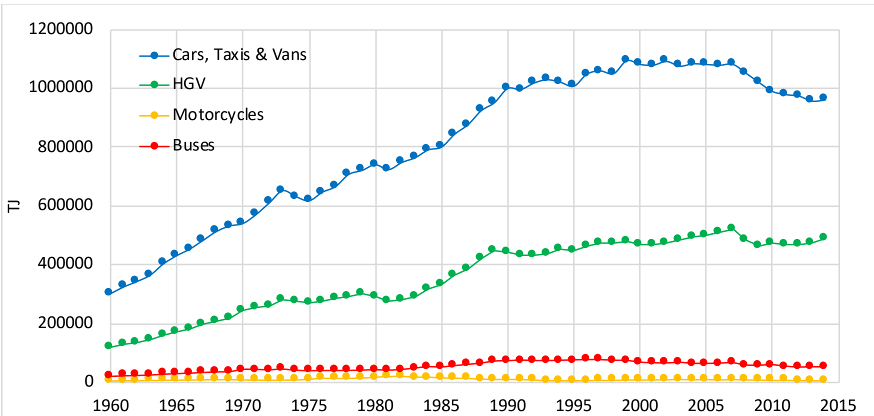

Figure 19 - Energy consumption for road transport by vehicle category in TJ.

The efficiency of road transport is presented in Figure 20. Heavy goods vehicles are, by far, the most efficient ones, approximately 6 times more efficient than passenger vehicles. This is in fact the expected result since the amount of goods the HGVs carry is a lot bigger than the increase in energy consumption. The efficiency for cars, taxis and vans increased slowly through the years, going from 0.46 in 1960 to 0.68

in 2014. For buses there is a decrease of efficiency, from 3.63 to 0.59 until 1991, justified by the decrease in service without a significant change in energy consumption. A reduction in bus service demand does not imply a direct reduction in bus fleet, buses must guarantee a geographic and logistic range that supports the population needs, and it is a challenging service in terms of optimization.

In the total, passenger road transportation is rather inefficient, with an average value of 0.6 pkm/MJ. An interesting result is the fact that all passenger vehicles converge to values close to 0.8 pkm/MJ, however, a better efficiency would be expected, at least for buses, since they have the capacity of carrying more passengers. Going back to Figure 18, it is possible to verify that buses present the lowest occupancy percentage which means that bus service is not optimized. Knowing this, this analysis suggests that the efficiency results could be improved by an increase in ridership. A shift from car to public transportation buses would reduce the necessity for such large numbers of cars in circulation, increasing cars efficiency as well.

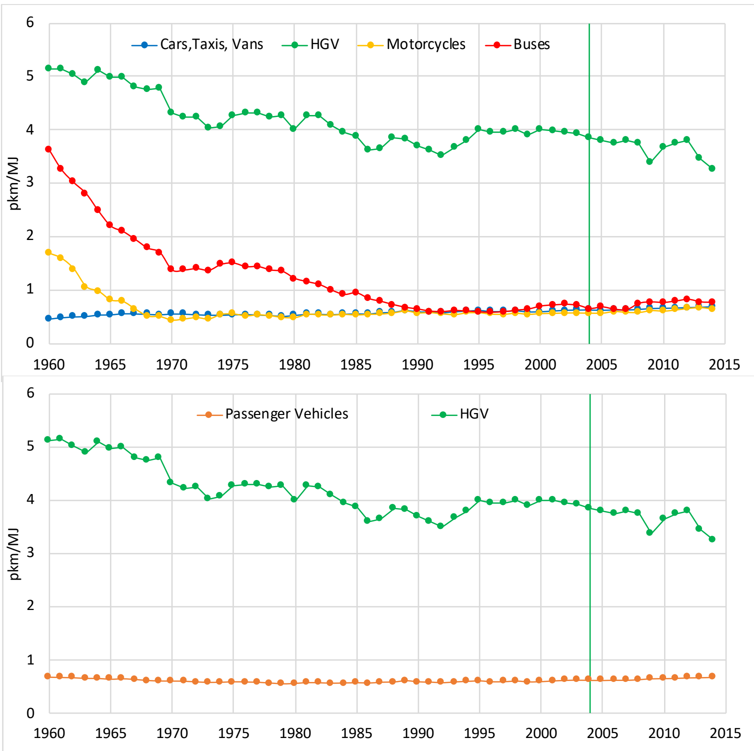

Figure 20 - Efficiency of road transport in pkm/MJ. Green bar represents a break in the series explained in the methodology chapter.

4.1.2 Rail

Figure 21 represents the data for rail service, separated between total, passengers and goods transportation. Until 1996 it presents a reduction in freight service, with passenger remaining stable. After the 1996 privatization, both freight and passenger ridership increased until 2014.

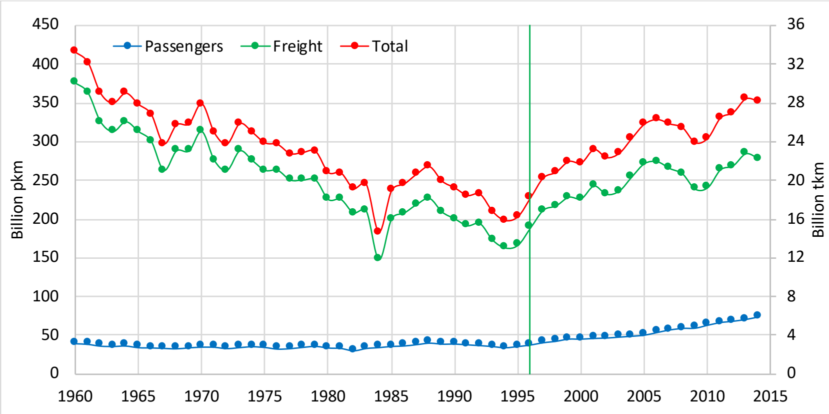

Figure 21 - Passengers-Km rail transportation, passengers[56]*, freight* [47] *and total. Left axis in billion pkm, right axis in billion tkm.*

"*Domestic freight transport, by mode: 1953 to 2017*" [47] includes data for goods lifted (tonnes) and goods moved (tkm). In Figure 22, the available data (tkm and tonnes) and the estimated kilometres travelled by a tonne of goods were normalized to the first value (1953). Results show that, after 1996, there is an abnormal increase of kilometres numbers which is coincidental with the privatization of British Railways and according to the metadata, exact comparison pre and post privatization is not possible. Contacts established with the Office of Rail and Road [87], obtained no response regarding the tendency of rail freight transportation, and reports published by the same entity ([88], [89] and [90]), also do not explain the difference in the kilometre data.

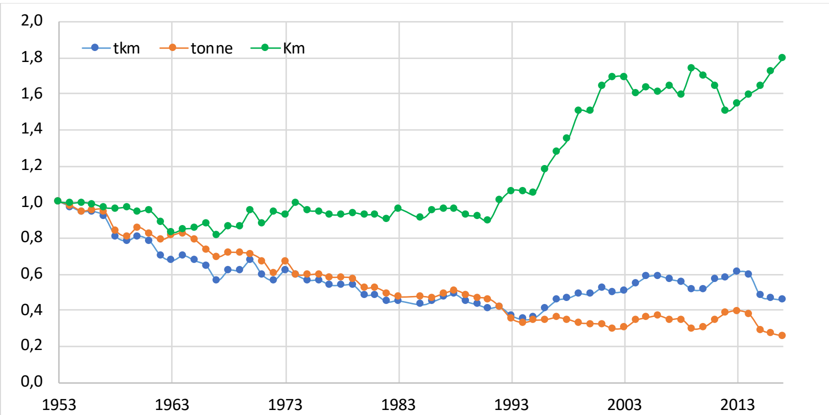

Figure 22 - Normalization of freight values to 1960. Goods moved (tkm), lifted (tonnes) and kilometres travelled by a tonne of goods.

Final energy consumption by rail freight (Figure 23) does not have the same evolution as the service, it remains approximately constant after 1996 implying an increase in the service efficiency that is not consistent with reality.

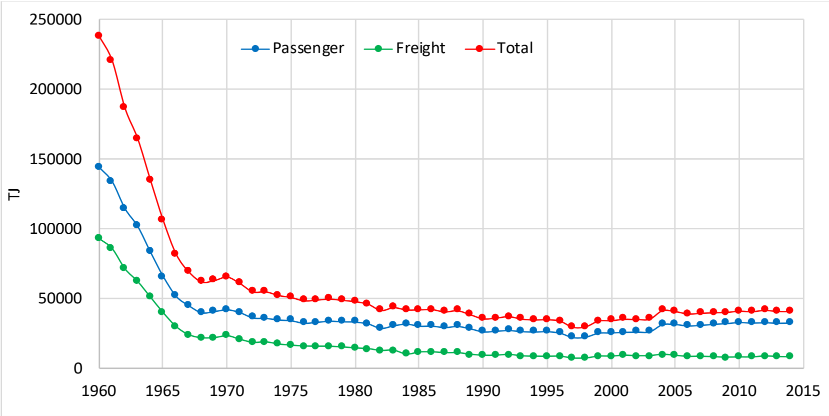

Figure 23 - Energy consumption by rail separated between passengers, freight and total in TJ.

Figure 25 displays the efficiency of rail service. It has become more efficient through the years, with a four unit grow from 1960 to 1975, and a twofold growth from 1995 to early 2000's for the total service. The prominent growth after 1995 was due to privatization of the rail industry in UK, unfortunately there is not a reliable comparison between pre and post privatization. There is an exception on growth tendency: in 1984 there was an acute decrease caused by a strike of coal workers that reduced the rail service for that year [54].

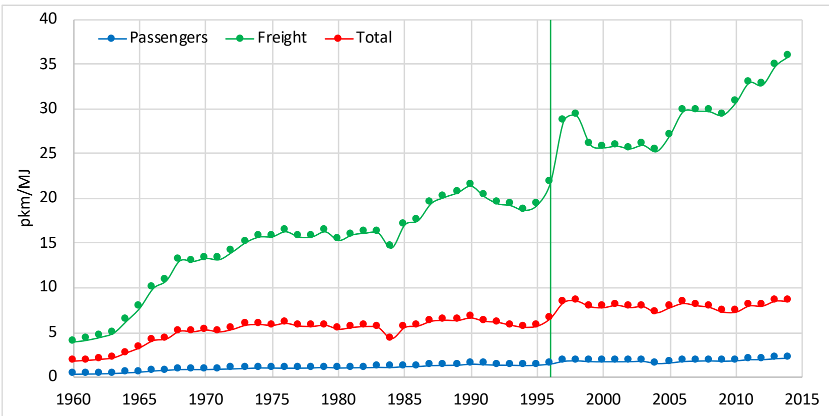

Figure 25 - Efficiency of rail transport in pkm/MJ. Green bar represent break in data.

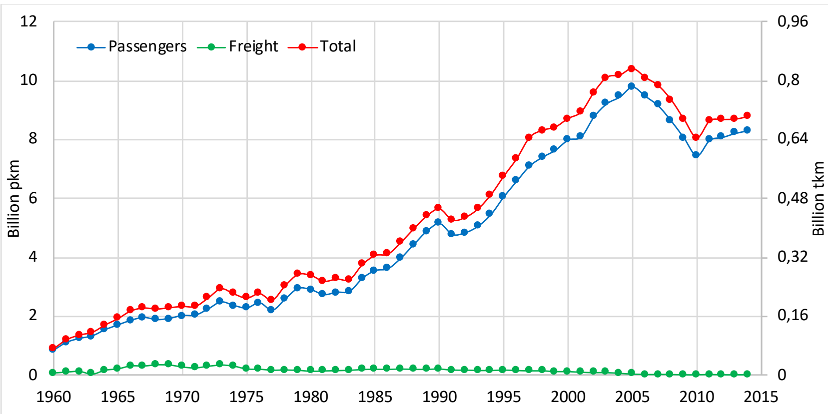

Figure 24 - Service domestic aviation in billion pkm (right axis) for passengers and tkm for freight (left axis) [93].

4.1.3 Aviation

The service data for domestic aviation is shown in Figure 24, it is separated between freight, passengers and total. It was not possible to separate the energy consumption between freight and passenger transportation, hence it is only relevant to present the data service separated between domestic and international as shown in Figure 26.

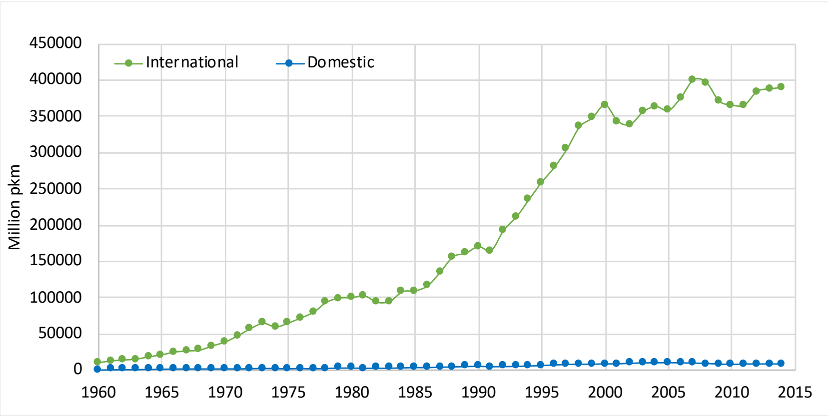

Figure 26 - Domestic and international service in million pkm.

Figure 27 presents the energy consumption data for aviation, it shows the domestic estimative (in blue), the original domestic data (in orange) and the international aviation consumption (in green).

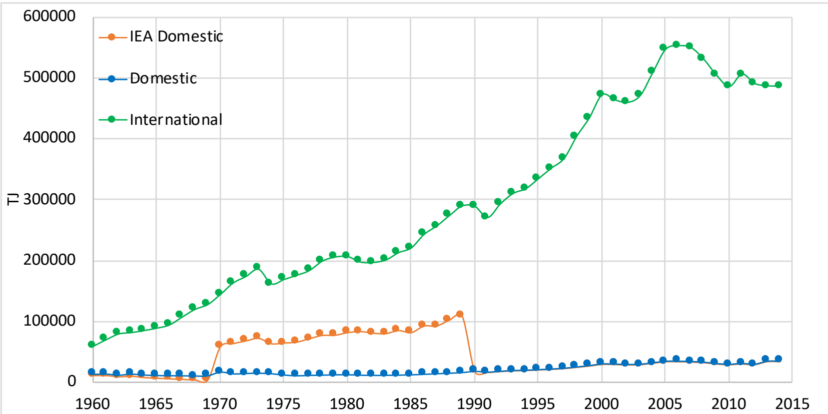

Figure 27 - Energy consumption by aviation in TJ.

Figure 29 presents the efficiency values for air transport, for both international and domestic service. There is a drop in 1970 for domestic service that indicates a discrepancy of the data, it is justified by the gasoline jet fuel values. The visible result for air transport is that international travel is significantly more efficient that the domestic one, rising from 0.26 pkm/MJ in 1970 to 0.77 in 2014, while domestic had 0.14 pkm/MJ in 1970 and only reached 0.25 pkm/MJ in 2014.

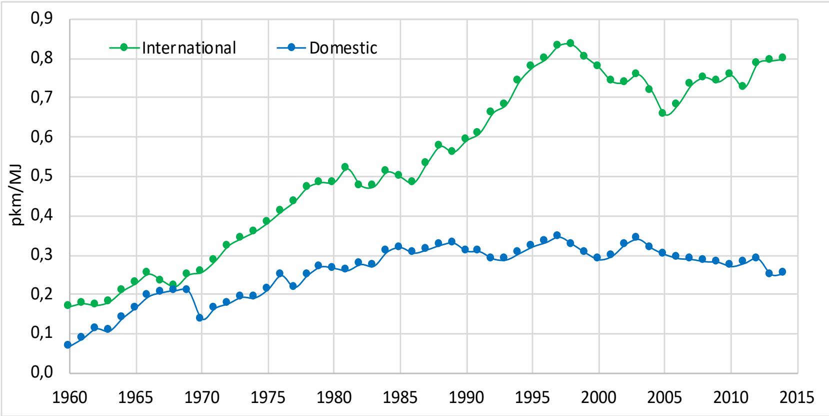

Figure 29 - Efficiency of air transport. Comparison between domestic and international service in pkm/MJ.

Figure 28 represent the fraction of energy and service of domestic aviation from total aviation. It is possible to see that the difference between domestic and international efficiency is caused by the passenger-km variable. The fraction of energy maintained generally constant through the years while the service decreased significantly. International aviation has higher efficiency because it possesses higher service quantities, not because international consumes less that domestic. According to the *"UNWTO Annual Report 2017"* [91], by World Tourism Organization, tourism has grown above average, at around 4% per year, for eight straight years, corroborating the increase of international travelling shown in the collected data.

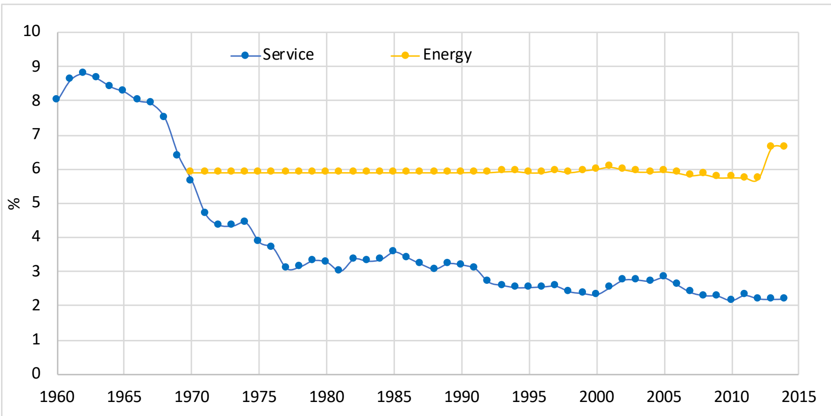

Figure 28 - Percentage of energy and service of domestic aviation travel from total (domestic + international).

4.1.4 Cars Efficiency

Figure 30 presents trends of fuel consumption in cars by different sources. In red, for the totality of cars per year calculated in this project. In blue, for new cars, separated between extra-urban and urban, and in green, for new cars published by department for Transportation. The occupancy values used to estimate the efficiency in red in Figure 30 are from DfT national travel survey [84]. For comparison purposes, I did not use the occupancy values estimated in chapter 4.1.1. To calculate efficiency values in MJ/MJ it was multiplies the service efficiency in MJ/pkm by the cars occupancy rate.

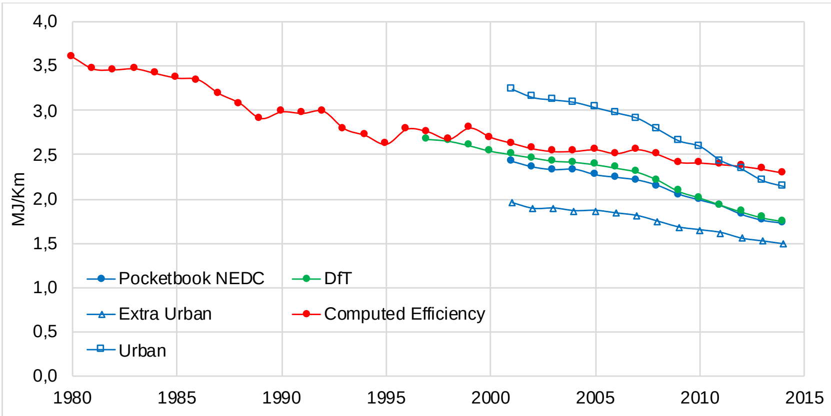

Figure 30 - Fuel consumption by cars. Comparison between computed values and new cars published ones in MJ/Km.

Comparing these trends is possible to validate the computed values in this project since they are quite similar to the "theoretical" ones. They present a lower efficiency (higher MJ/Km), associated to the reality of consumption, and to the fact that is taken into consideration all current cars and not solely new ones.

For a better comparison of the calculated values with new car consumption, Figure 31 presents a shift of ten years to the pass of computed efficiency values where it is made the assumption that the new cars take 10 years to affect the total consumption. The result is an overlapping of values from 2001 to 2004, suggesting that the energy efficiency values estimated in this thesis are reliable.

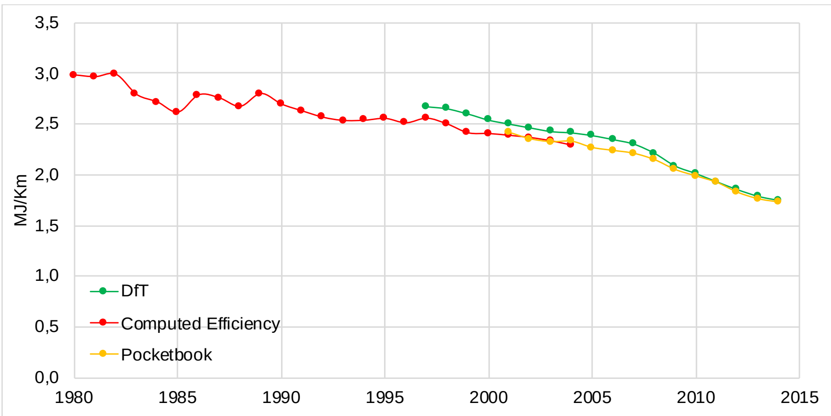

Figure 31 - Fuel consumption by cars, with lifespan adjustment to computed efficiency values in MJ/Km.

4.2 Comparison between sectors

4.2.1 Service

Figure 32 presents the figures for passenger-km for each transport sector. It is noticeable the distance in values of road transportation from the other sectors, demonstrating how much society relies on road transportation, and how much it grew since 1960, going from 841.50 to 2297.34x10^9 pkm in 2014.

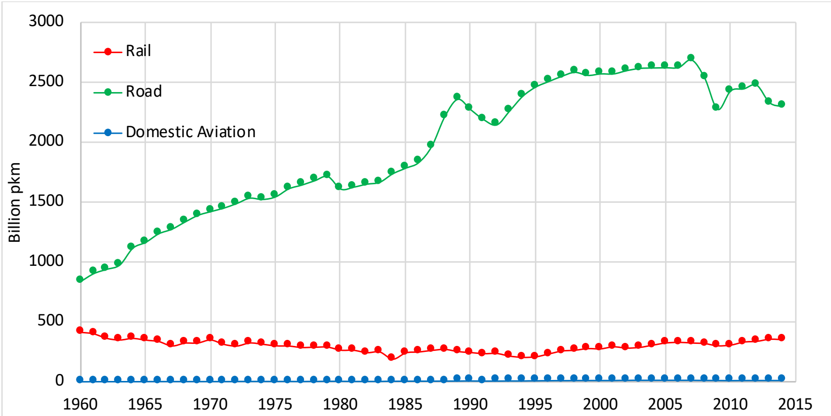

Figure 32 - Domestic transport service for three sectors: aviation, road and rail transport in billion pkm.

It is of the most importance to separate goods from passenger services due to the distinct service they provide. Figure 33 shows the data separated between freight and passengers for road and rail, and between domestic and international for aviation. The road service has the biggest values for the three sectors, the road sector is so frequently used that the passenger transport surpasses the rail freight service.

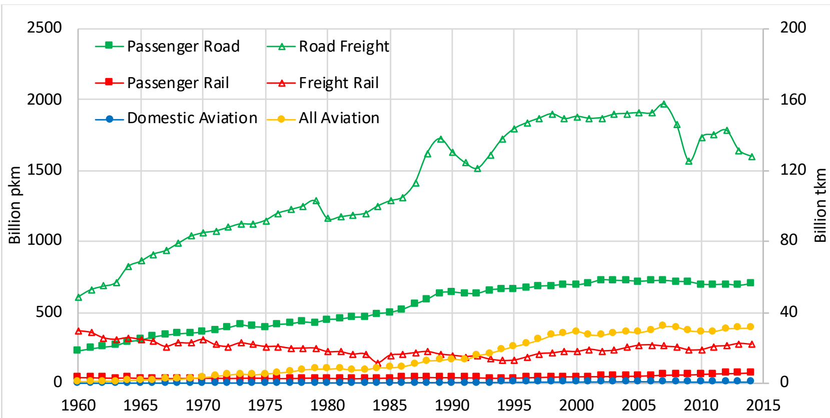

Figure 33 - Transport service with separation of air between domestic and international, and separation of road and rail goods and passenger transportation. Left axis in billion pkm and left in billion tkm

Since 1960, both road goods and passengers service are increasing, freight started with 612.50x10^9 pkm (32x10^9 tkm) and reached 1598.56x10^9 pkm (128.89x10^9 tkm) in 2014, having a steep reduction in 2008 due to the financial crises, passenger road service started with 229.00x10^9 pkm in 1960 and grew almost constantly until 2014 reaching 698.78x10^9 pkm.

Rail freight and passenger transport behaved differently through the years. Freight oscillated, it had a shrinking tendency from 375.00x10^9 pkm (37.00x10^9 tkm) in 1960 to 166.25x10^9 pkm (13.30x10^9 tkm) in 1995, with a discontinuity in 1984 due to workers strike. From 1995 on, it grew until 277.59 x10^9 pkm

(22.21x10^9 tkm) in 2014. Passengers service was roughly constant from 1960 to 1995 at 40.6x10^9 pkm and rose until 73.77x10^9 pkm in 2014.

Comparing domestic and international aviation, both services expanded from 1960 until 2014. International had the biggest growth from all sectors, going from 10.47x10^9 pkm in 1960 to 389.990x10^9 pkm in 2014. Domestic aviation service grew slower, starting with 0.91x10^9 pkm, having a peak of 10.40x10^9 pkm in 2005 and finishing 2014 with 8.77x10^9 pkm.

Figure 34 shows the share of passenger service that each sector possesses, it stands out how big is the cars service, having its lower value in 1960 at 52%, with buses at 29% and rail at 15%. From then on cars grew until reaching a maximum in 1992 at 87% share, declining slightly until 2014 at 84% where rail grew slightly, from its minimum in 1993 at 5% to 9% in 2014. Buses decreased it share slowly, having a small increase in 1992 and reaching 5% in 2015.

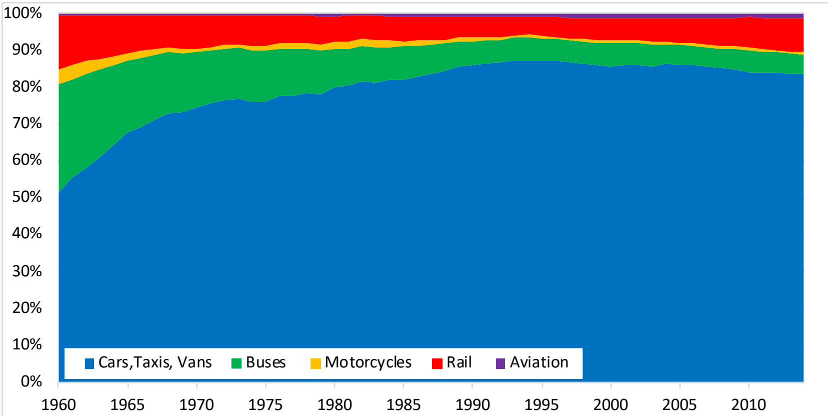

Figure 34 - Passenger transportation share for each sector.

In relation to freight shares (Figure 35), it is only compared between road and rail. Once again road presents the majority faction of freight transportation, starting with 62% in 1960, reaching it maximum of 92% in 1992 and ending in 2014 with 85% share. Rail decreases it shares until 1992 at 8% from when it started growing until reaching 15% in 2014. Based on the timing, the main reason for the increase in rail share was the railways privatization.

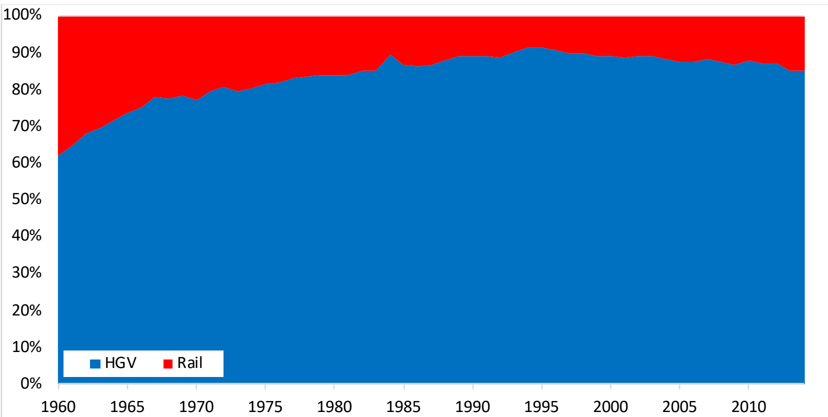

Figure 35 - Freight transportation share for road and rail.

On Figure 36 it is presented the occupancy rate of all sectors with exception for rail where it was only possible to find one value. It stands out how efficiently used is the space for aviation and motorcycles, the latter expected due to only be available two seats. It is seen once again the low occupancy in buses and in cars, as explained in the road section. The occupancy percentage of rail, 40%, is higher than in cars and buses but lower than aviation.

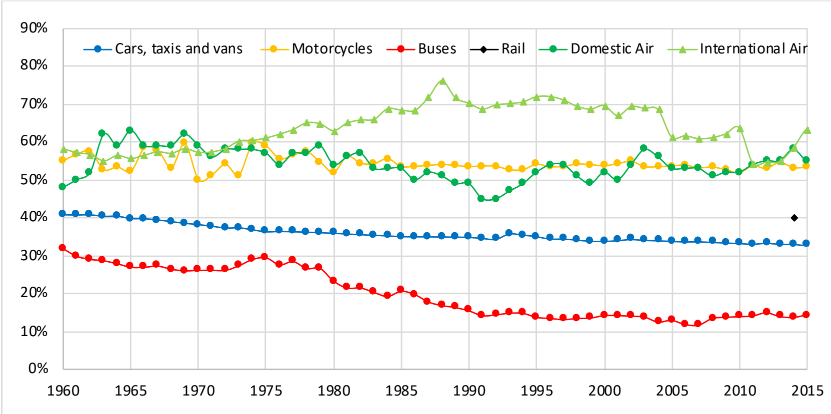

Figure 36 - Occupancy in percentage for each sector and vehicles.

4.2.2 Energy

Figure 37 presents the energy consumption for the three sectors. The main highlight from the figure is how much road transportation consumes when compared with the other sectors.

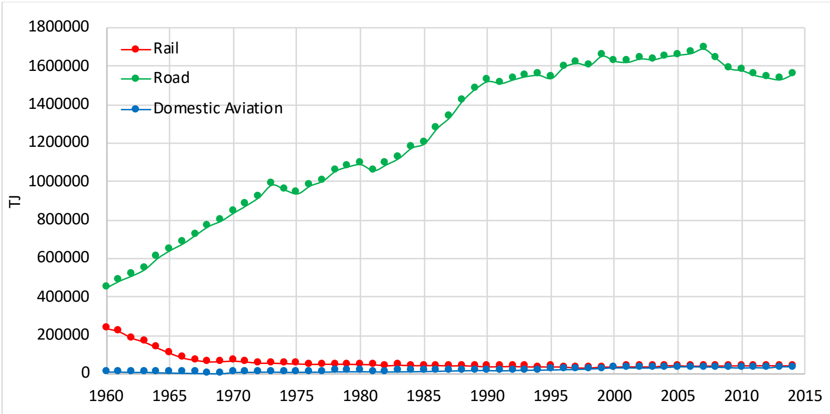

Figure 37 - Energy consumption by transports for three sectors: aviation, road and rail transport in TJ

Separating road and rail sector between goods and freight (Figure 38), it stands out how much energy light road vehicles consume in order to deliver its service. Electricity as power source contributes with less than 1% for road light vehicles, making them the main source of CO_2 emissions in the transport sector. It is also important to highlight how much energy international aviation consumes, knowing that its service is far lower than the other sectors, airplanes transport far less goods and passengers and it consumes too much for the available service it can deliver.

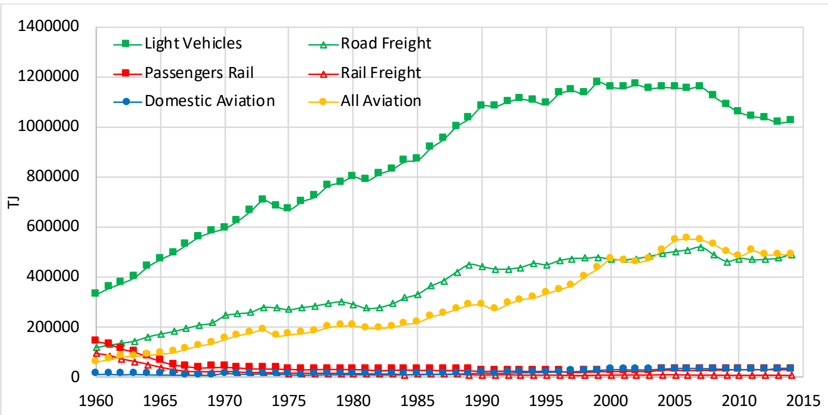

Figure 38 - Energy consumption with separation of air between domestic and all transport, and road and rail between goods and passengers' transportation in TJ.

4.2.3 Energy Efficiency

The average efficiencies are 6.03, 1.60 and 0.26 pKm/MJ for rail, road and air respectively. The sector that is more efficient, by a considerable difference, is the rail transportation (Figure 39).

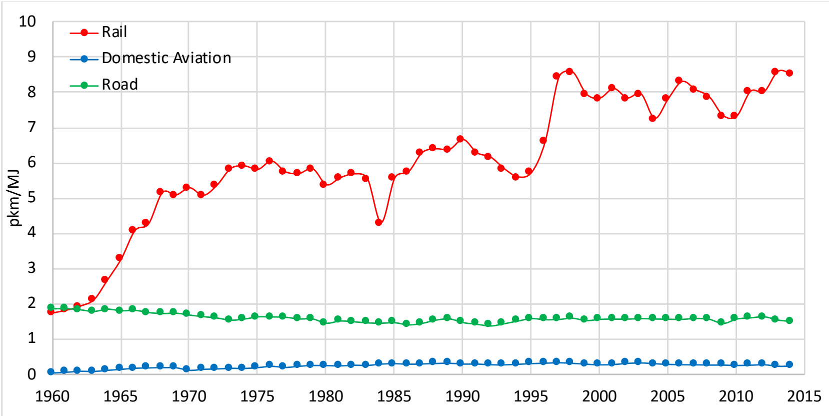

Figure 39 - Energy efficiency for domestic transport in three sectors in pkm/MJ.

Rail has the capacity to transport high quantities of goods, increasing significantly its efficiency. Figure 40 presents the efficiency for the different sectors separated between passenger and freight for road and rail. Rail freight has the highest efficiency, having to be shown on a secondary vertical axis.

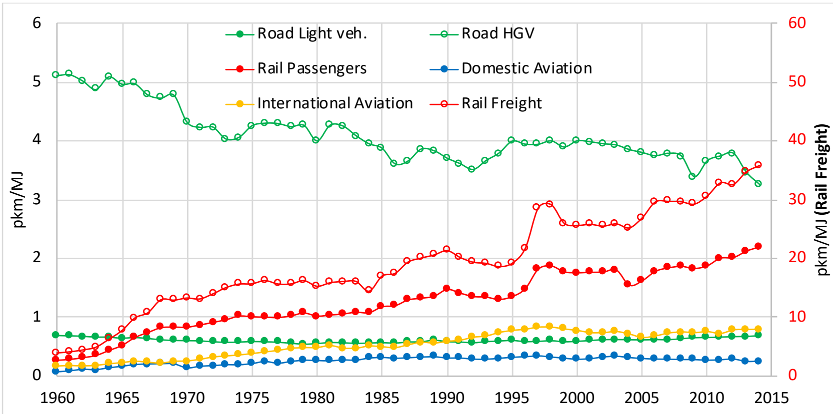

Figure 40 - Energy efficiency for three sectors. Separation of air between domestic and international, road and rail between goods and passenger's transportation in pkm/MJ. Right axis for rail freight.

Air transport is the least efficient, an expected result. Although airplanes commonly travel significantly larger distances than the other sectors, they consume a lot more fuel for the number of transported passengers and cargo.

Road transportation has a low efficiency when is taken into consideration both heavy goods and passengers' vehicles in the same unit. When separated, heavy goods vehicles have a high efficiency but still lower than rail freight, HGV's is the only that present a decreasing efficiency.

Separating goods from passengers (Figure 41 and Figure 42), there is an average efficiency of 19.44 pkm/MJ for rail and 4.10 pkm/MJ for road in goods transportation, and 1.27 pkm/MJ for rail and 0.61 pkm/MJ for road in passengers transportation. It is clear and expected that goods transportation is far more efficient than passengers. Goods transportation allows the transportation of huge masses with an exceptional use of the assigned space without significant increase in energy consumption. This type of transport uses planned quantity forecasts and delivery schedules that make it easier to maximize the quantity of goods and distance for a unit to travel. However, such characteristics could hardly be applied to passenger transportation, since it is defined by different attributes, for example, comfort and safety needs do not allow a condensation of mass as in freight transportation. Nevertheless, these attributes do not hinder the possibility of increasing passenger transportation efficiency, higher occupancy and better scheduling are some of those possible measures.

The transportation of goods by rail is much more efficient than by and road (Figure 41). The justification is that rail transportation needs less energy to provide the same amount of service as road.

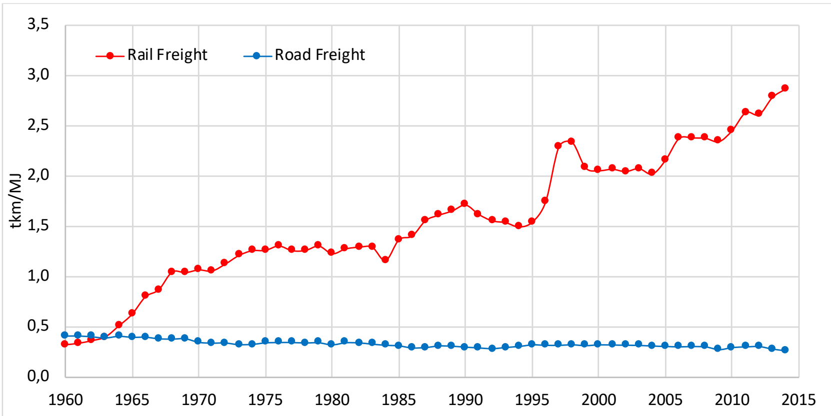

Figure 41 - Comparison between road and rail of goods transportation efficiency in tkm/MJ.

Table 6 presents the impact of rail freight on road haulage, the values are obtained from *Office of Rail and Road* using the moved and lifted goods data from *Dft* [45]. The table shows how many truck journeys are avoided by using rail, and how many kilometres road vehicles would have to travel to move the amount of freight transported by rail.

The CO_2 emission by road freight amount to, 2.4 Gt worldwide while rail only emits 0.1Gt (2018), according to IEA [92]. According to Nam Kim [93], when comparing CO_2 emissions between truck-only and rail-based intermodal freight, rail-based intermodal systems emit less CO_2 than truck-only systems, regardless of the type of locomotive. However, in the case of electricity powered locomotives, if the power plant works exclusively with fossil fuels, the emissions could be higher than road vehicles. All this information leads to the conclusion that rail is a better option, environmental and efficiency wise, for freight transportation when logistically possible, and incentives should be focused into promoting this type of transportation.

Analysing the energy efficiency of passenger transport by road and rail (Figure 42), rail is more efficient after 1966. The difference is not as dramatic as in freight, but it has grown throughout the period and in 2014 the efficiency of passenger transport by rail was already 3.21 times higher than by road. An important reason for the higher rail efficiency is the occupancy rate. According to DfT data [84], the average occupancy rate for cars based on surveys is 1.68 from 1980 to 2014, which represents 33.6% of occupancy considering that most cars have five available seats, while the calculated rail average occupancy is 40%.

Table 6 - Impact on Road haulage from Office of Rail and Road [94].

Year	Avoided lorry journeys (millions)	Rail freight lorry kilometres equivalent (billions)
2004-05	9.61	1.99
2005-06	9.15	2.03
2006-07	9.40	1.95
2007-08	8.94	1.94
2008-09	8.72	1.92
2009-10	8.73	2.06
2010-11	7.83	1.85
2011-12	9.05	2.13
2012-13	9.71	2.03
2013-14	9.11	1.98
2014-15	10.46	2.19

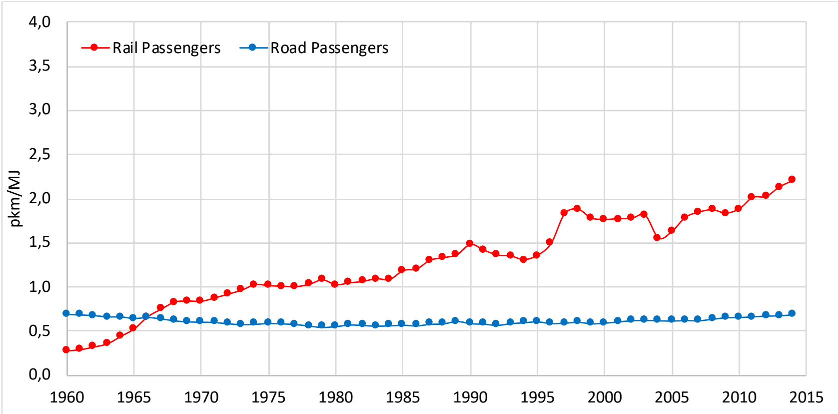

Figure 42 - Comparison between road and rail of passenger transportation efficiency in pkm/MJ.

The occupancy is the main contributor for the low efficiency of road passenger vehicles but does not fully justify the inferior values. Figure 43 presents efficiency values with the assumption of 100% car occupancy. Results show that even if the occupancy was maximized it would not surpass the efficiency values for train. The justification is similar to the one for freight, in rail is possible to transport more passengers and a bigger distance without a significant increase in energy consumption.

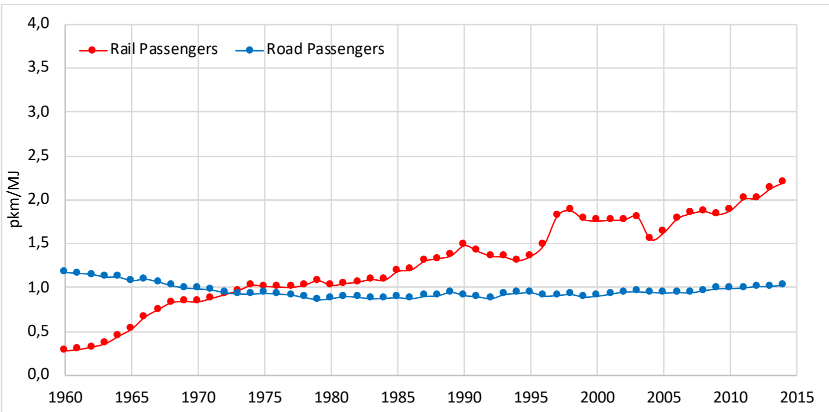

Figure 43 - Energy efficiency of passenger transport for rail and road with 100% cars occupancy rate, in pkm/MJ.

4.3 Material Efficiency in Cars

4.3.1 Stocks

Figure 45 and Figure 44 presents the evolution of material stocks in cars in mass and exergy. In terms of exergy the contribution of plastic and aluminium for the total is far greater than when analysed in terms of mass. It indicates that a shift to lighter materials could have a broader impact than the saves in fuel consumption because the chosen materials present higher exergy contents than previous materials (steel) which suggests that the shift enhanced the energy consumption in material production.

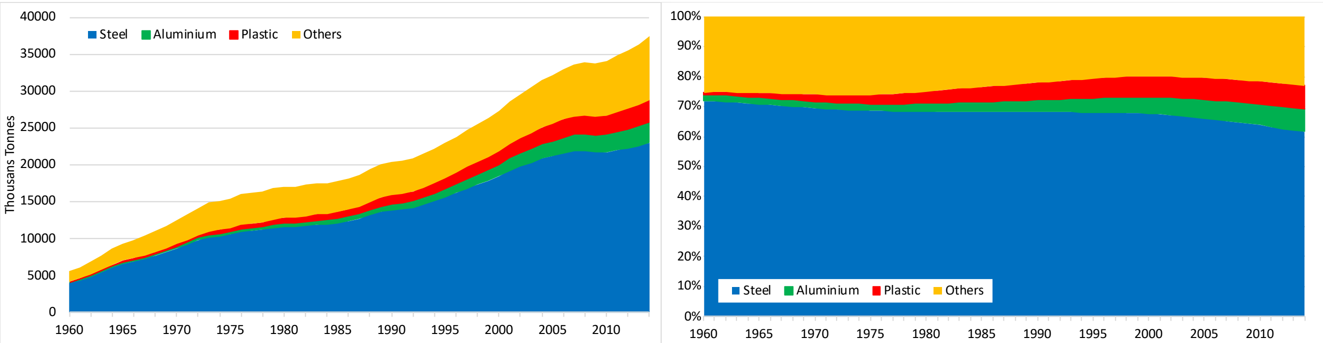

Figure 45 - Material stocks for cars in tonnes and percentage.

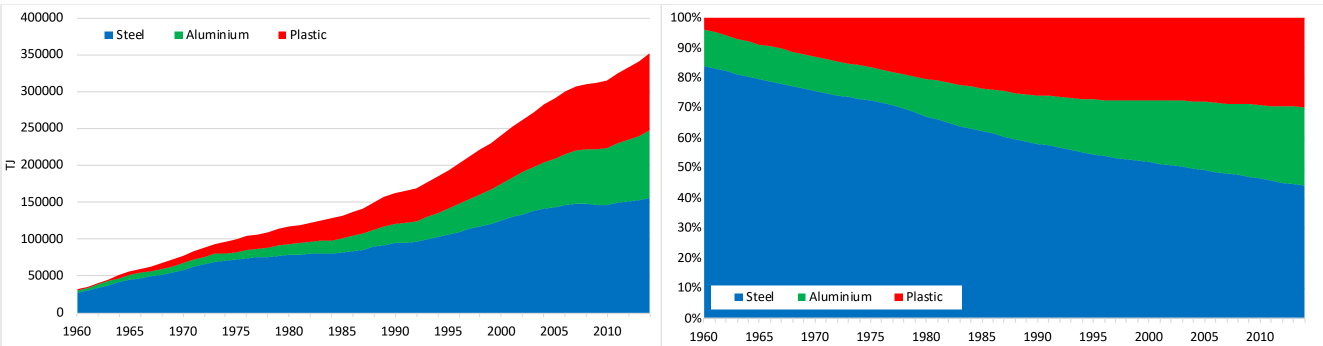

Figure 44 -Material stocks for cars in exergy units (TJ) and percentage.

Material stock service efficiency is represented in Figure 46 both in mass and exergy units. It is not possible to estimate the exergy content of "other materials" so they are not included in the efficiency calculation in exergy units. For a better comparison, efficiency values in mass units are represented both with and without the contribution of "other materials" for the total weight.

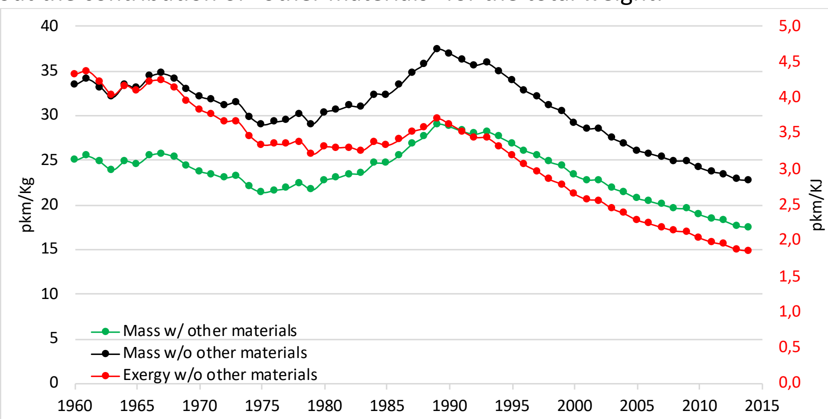

Figure 46 - Material stock efficiency, in mass with and without others materials contribution and in exergy. Right axis in pkm/Kg, left axis pkm/KJ. Main materials include steel, plastic, aluminium. Other materials include everything else.

Stock efficiency values have declined since 1989 until current days, meaning that the amount of service has declined for the amount of stock that exist. Combining results from the two previous graphs and Figure 17, where service, stocks and energy have been increasing, one can conclude that the reduction of efficiency results from more stagnant vehicles since the growth in vehicles stocks did not produce a parallel increase in service. The idea of more stagnant vehicles is supported by David Z. Morris magazine article [95] that states that in U.S.A. cars are parked 95% of the time, and by John Bates & David Leibling RAC Foundation report [96] "...the typical car is only on the move for 6 hours in the week: for the remaining 162 hours it is stationary - parked" for U.K.

4.3.2 Outflows

Figure 47 and Figure 48 shows the evolution of cars' material in units of mass and in exergy units, respectively. The difference between the mass and exergy analyses are similar to the stocks case.

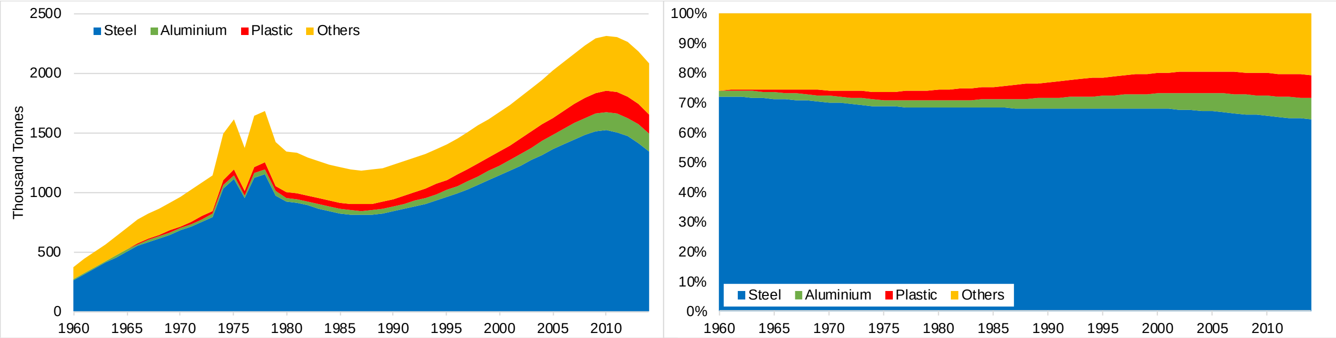

Figure 47 - Material outflow for cars in tonnes and percentage.

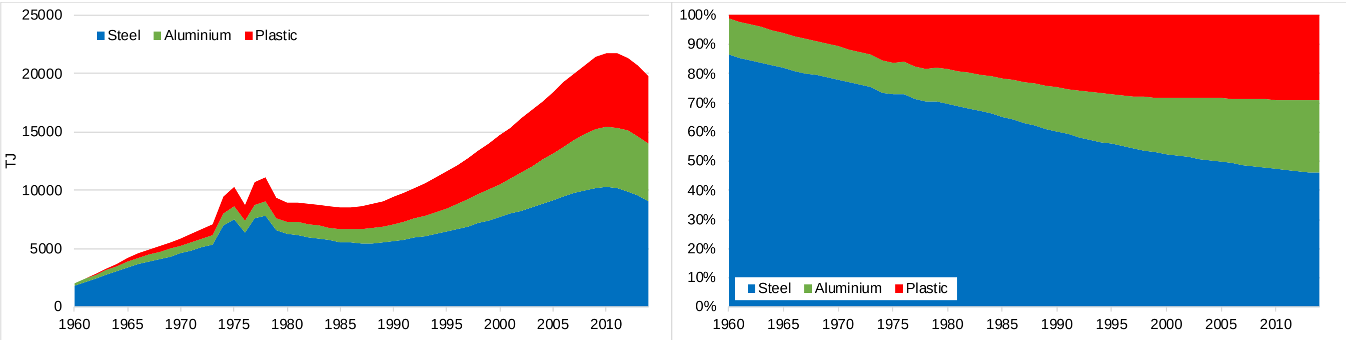

Figure 48 - Exergy outflow for cars in exergy unites (TJ) and percentage.

Material replacement efficiency in represented in Figure 49. From 1989 onwards the efficiency started to decrease, as it did, in the stocks case. The major difference, beside the irregularity from 1973 to 1980, is an increase after 2011. The growth in efficiency is caused by the reduction in discarded materials (outflow) as shown in Figure 47 - Material outflow for cars in tonnes and percentage., justified by the 2008 economic crises where population delayed the dispose of vehicles as a form of financial economization [97].

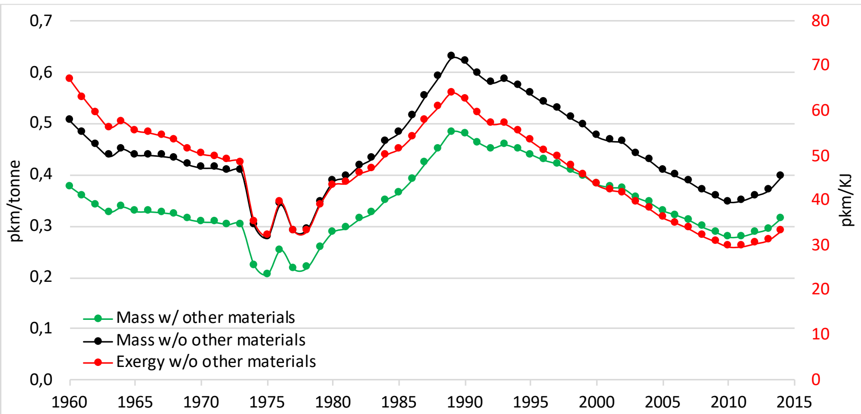

Figure 49 - Material replacement efficiency, in mass with and without others materials contribution and in exergy. Right axis in pkm/tonne, left axis pkm/TJ.

4.4 Resource Efficiency in Cars

Figure 50 presents the exergy values for cars' material outflow (consumed materials), and for consumed fuel, for each year. The magnitude of consumed energy by fuel is such that it is necessary to represents the two data sets in different axis. It shows how massive is the consumption of energy for powering cars, and in this case powered by fossil fuels, which leads to enormous CO_2 emissions.

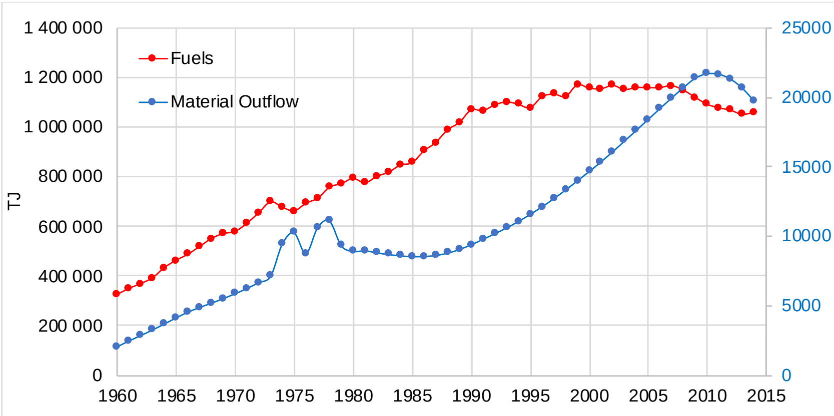

Figure 50 - Fuel and Material exergy consumed in TJ. Left axis for fuels and right axis for material outflows.

To better analyse the evolution of material and fuel consumption, a normalization was made in respect to the exergy values of 1960 for: fuel consumption, material outflows and stocks (Figure 51). Although the consumption of fuel is far bigger than material ones, its consumption did not increase dramatically, at least when compared with material stocks and outflows. From 1985 onwards, stock and outflows (in exergy) increased significantly due to a shift from steel to lighter materials which possess higher exergy contents.

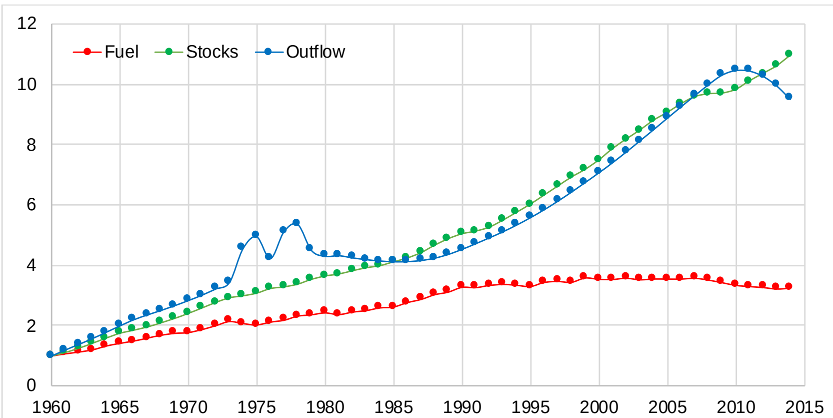

Figure 51 - Fuel, material outflow and stock exergy normalization to 1960.

Figure 52 presents the evolution of resource efficiency, it is defined by the amount of consumed exergy (fuel plus material) needed to provide a unit of service. This indicator is a tool to study how the resources are being used to provide the transport service. Results show that resource efficiency has been increasing since 1960

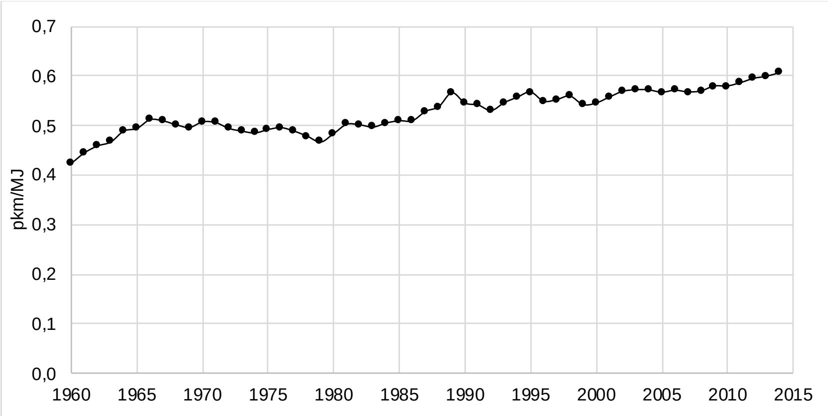

Figure 52 - Resource efficiency in pkm/MJ.

To better study resource efficiency, Figure 53 represents a normalization of the service efficiency in terms of MJ/pkm, for material and fuel consumption and it allows to analyse how both efficiencies evolved since the first year of the study. There was an increase in service efficiency for fuel consumption, cars started providing more service (passenger-kilometre) for less fuel consumption, having a constant grow since 1999. In contrast, material consumption service efficiency decreased significantly from 1989 to 2010, which is justified by the rise of lighter material that possess higher exergy (plastic and aluminium) and by cars parked for longer time periods. After 2010 it starts to increase, as a result of the 2008 crisis where less material where discarded.

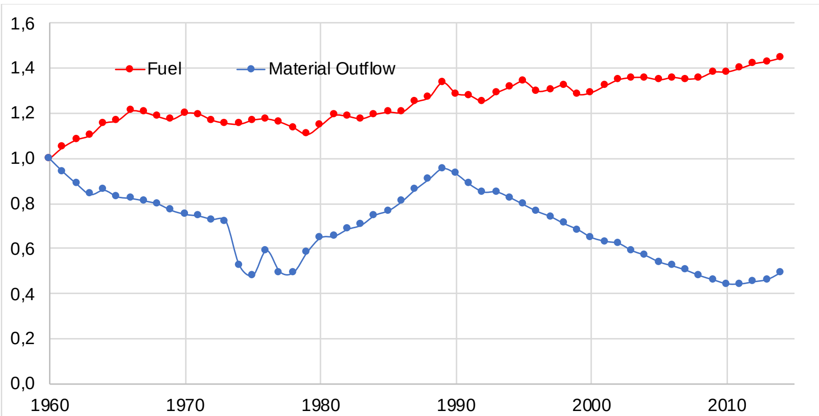

Figure 53 - Outflow Material and Fuel service efficiency, normalized to 1960.

A pertinent approach to these sets of data is to find the energy intensity of operation in-use stocks , that is, how much energy is necessary to make the existent stock active for service. Figure 56, shows the evolution of this indicator. Since 1992 the amount of energy necessary has decreased, such decrease in energy was caused by an accentuated increase in stock while fuel consumption had a smooth, and comparatively, small growth (Figure 55). Services did not follow the same trend as material stocks (Figure 55) suggesting that a higher acquisition of cars did not result in a higher service, and the justification is the same as the decrease in material stock efficiency, cars are parked for longer time periods.

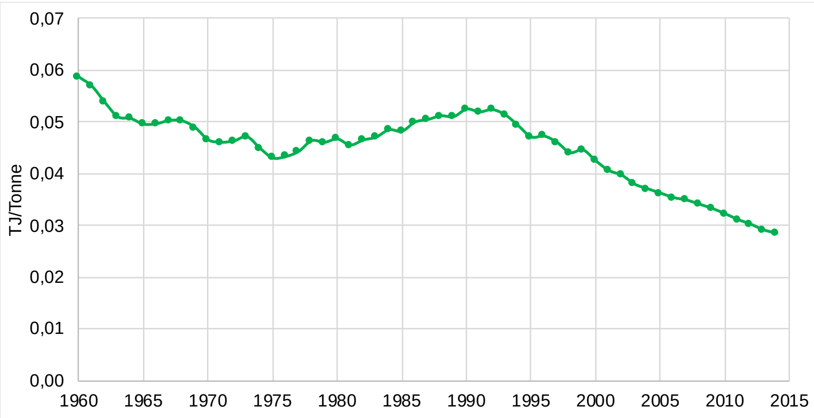

Figure 56 - Energy Intensity of Operation in-use Stocks.

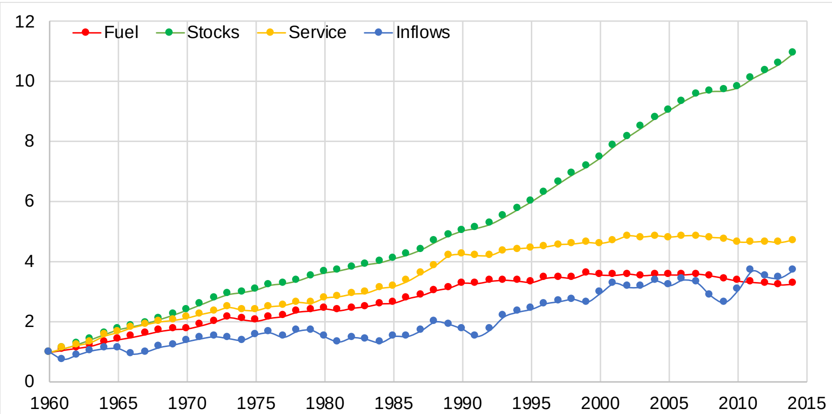

Figure 55 - Normalization to the service value of 1960 for fuel, stocks and inflows, the latter three in units of exergy.

Figure 54 represents three indicators essential for the relation stock-flow-service and their evolution. The stock related indicators are the ones that decrease through the year, indicating an inefficiency related to stock because stock grows much faster (Figure 55). Service-flow (resource efficiency) is growing, which means that the relation between the two has improved, Figure 54 emphasizes that the increase in service is the principal cause for the efficiency growth.

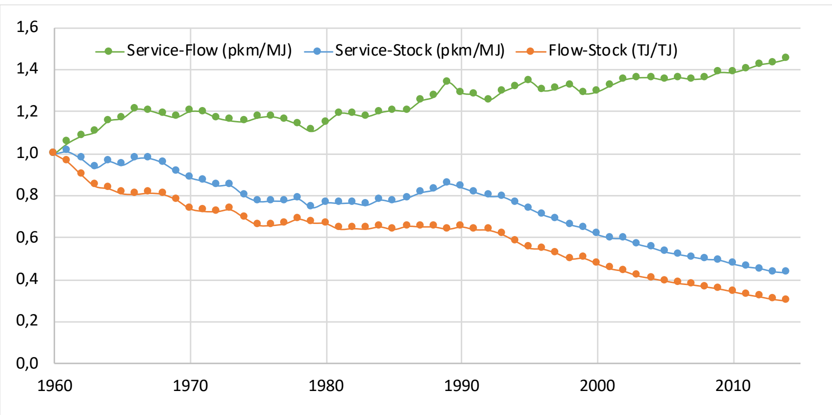

Figure 54 - Stock Flow Service Nexus, normalization to 1960.

4.4.1 Emissions

It is important to study CO_2 emissions because a higher energy consumption does not directly imply a bigger environmental impact. Figure 57 represents the amount of CO_2 emitted by fuels and by new materials (inflows), as well as the total impact. As explained before, it was not possible to determine the outflow CO_2 emissions by the stock model, instead inflows were used as a proxy to the outflows.

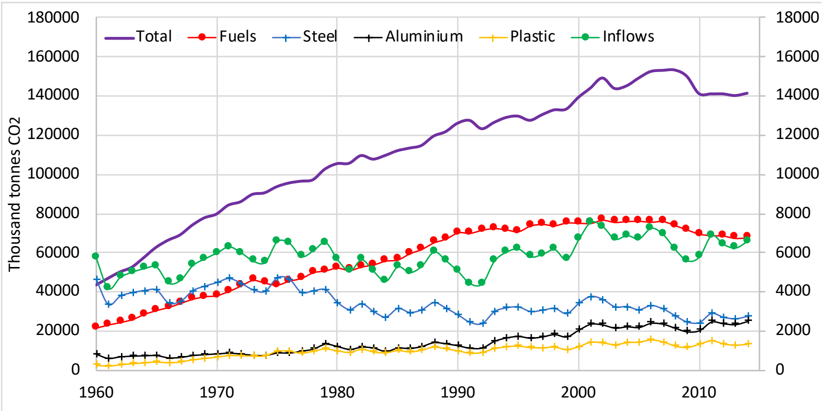

Figure 57 - CO_2 emissions by inflows and consumed fuels in thousand tonnes.

Although the results present an upward tendency since 1960, it ends in a good note with emissions decreasing and stabilization after the 2008 financial crises. After such events, it is expected some reduction in service (see Figure 17) and vehicles acquisitions, but the stabilization for the following year is a positive sign. Inflows emissions are smaller than fuel by one order of magnitude, thus it is correct to assume that fuel emissions is the total emissions tendency setter, and it is where more focus should be done regarding reductions and improvements.

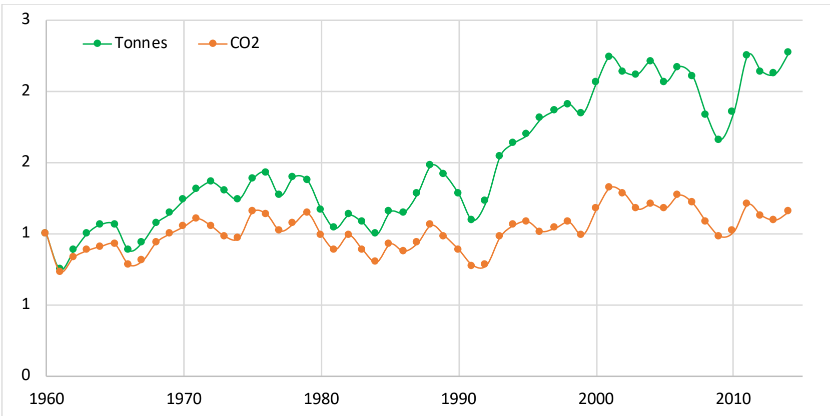

Figure 58 - Normalization to 1960 of inflows emissions and mass.

The total material emissions do not have a defined trend due to its oscillations. However, analysing each type of material, it is clear the reductions in emissions by steel while plastic and aluminium CO_2 emissions increased (Figure 57). To clarify the impact of this shift, a normalization of the emissions and the inflows mass (Figure 59) was done. The graph shows that although the emissions kept increasing, they do not follow the same growing behaviour as the inflow mass, that is, CO_2 emissions do not increase significantly despite a significant increase in consumed material. This is a good result, because even if consumption increased, the changes in the production process and type of material allowed to suppress emissions.

Figure 59 represents the embodied impact of cars transportation, and how the emission of CO_2 evolved in relation to the service. The conclusion is that it has been almost steadily growing, and in recent times it is possible to provide more service while emitting less CO_2. This increase is a positive indicator for a more environmental stable future, however it is known that it is not good enough, cars emit far too much CO_2 when compared to other transport modes, and for this reason it is imperative that both a reduction in consumption as well as an improvement in the service provided occur.

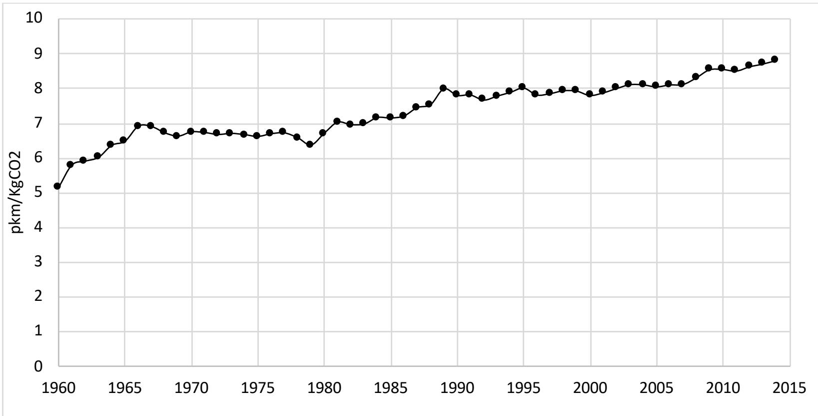

Figure 59 - Embodied Impact Rate, CO_2 emissions by fuel and inflows to provide one unit of service in pkm/KgCO_2.

4.5 The conversion device and passive system in new cars

Figure 60 presents the influence of changes in new cars. The car consumption represents the passive system while the mechanical drive represents the final-useful conversion. Although it is not possible to calculate the real efficiency of the passive system, it is possible to compare the evolution of both systems through a normalization of the values as illustrated in the figure.

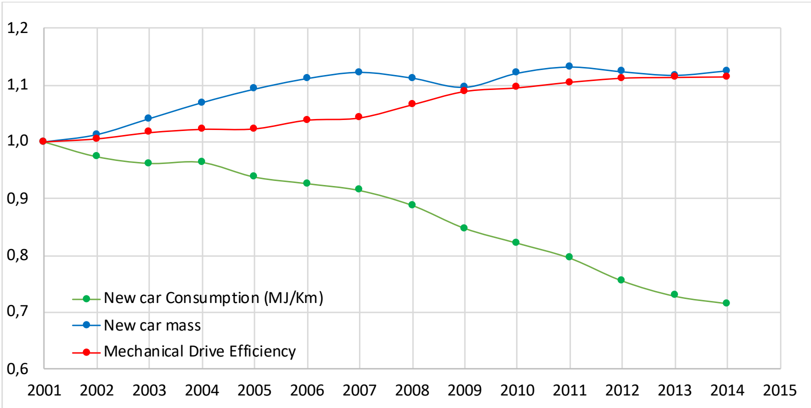

Figure 60 - New car mass and consumption, normalized to 2001.

Comparing the mass and the consumption of new cars, it shows that the increase in weight did not increase its consumption. A higher mass will imply higher weight and consequently higher resistance by the car, resulting in more consumption if no changes are done to the car technology. Because the consumption did not increase it means that the car became more efficient, and such is proven by the growth in mechanical drive efficiency. Because consumption decreases faster that mechanical drive efficiency it allows to conclude that improvements were made both at the engine level and at the passive system level. If improvements were done only at the engine level both curves would have a symmetric behavior, consumption would decrease as much as mechanical efficiency would increase.

5 Conclusions

The purpose of this thesis is to analyse the evolution of the transport sector service from 1960 to 2014. It is focused on resource efficiency which led to the proposal of a new indicator that sums the contributions from fuels and materials. Additionally, it also addresses separately energy and material efficiency. The resource analysis is done on a specific vehicle, cars, which led to a further study on the evolution of its passive system and conversion device, from 2002 to 2014.

In relation to road transport, car, vans & taxis were the only ones to increase its efficiency, going from 0.46 pkm /MJ in 1960 to 0.68 pkm/MJ in 2014. Buses present the biggest reduction, a decrease of 2.87 pkm/MJ from 1960 to 1990, afterwards efficiency remained rather stable until 2014. Heavy Goods Vehicles had an oscillating reduction in efficiency, starting in 1960 with 5.19 pkm/MJ (0.41 tkm/MJ) and ending with 3.25 pkm/MJ (0.26 tkm/MJ) in 2014. Motorcycle decrease from 1.67 to 0.55 pkm /MJ in 1975, maintaining until 2017 an efficiency close to its 1975 values. The substantial reduction of bus efficiency comes from an increase in its consumption, probably by an increase in its fleet, without resulting in a boost in its service, which is supported by the reduction in its occupancy.

Rail transportation shows a growth in its efficiency from 1960 to 2014. For passengers it grew from 0.28 to 2.2 pkm/MJ, and freight from 4.01 pkm/MJ (0.32 tkm/MJ) to 35.93 pkm/MJ (2.87 tkm /MJ). Freight transportation presents a growth peak in 1997, from 6.60 to 8.42 pkm/MJ justified by the privatization where pre and post values are not comparable. The increase in rail efficiency results from a change in consumed fuel, going from coal in 1960 to mainly diesel and electricity in 1970, afterwards, the mix did not change significantly until 2014, combined with a continuous growth in passengers service. Freight presents a decrease in service until 1996, but because the reduction in energy consumption is bigger it allowed an increase in efficiency.

In aviation, both domestic and international present and increase in its efficiency. Domestic from 0.08 to 0.28 pkm/MJ, and international from 0.17 to 0,80 pkm/MJ in 2014. Both increases are justified by high occupancy rates and by an increase in service, both variables higher in international than domestic.

The best approach for energy service efficiency results is to separate between passenger and freight, due to the difference in service that each represents. For passenger transportation, rail is the most efficient because it can carry more passengers without significant increases in energy consumption. Besides being the most efficient form for passenger travel, trains provide schedule and route stability that others do not. When compared to road transports, trains do not have to deal with the uncertainties of traffic and end up by offering more comfort and safety. Considering all variables, rail as main transportation mode should be encouraged and promoted, and financial incentives should be directed towards its improvement. The less efficient mode was aviation. Aviation requires high energy consumption which results in large greenhouse gases (GHG) emissions, according to the European Aviation Safety Agency [98], in 2016 aviation contributed to 3,6% of the total European GHG emissions. For a service that is not capable of transporting high passenger numbers, its environmental impact is too big. Whenever possible, trains should be chosen as a substitute of air travel.

In 2014 rail only represented 9% of total passenger service, with cars representing 84% and buses 5%. From 1960 to approximately 1975 there was a shift from bus and train to cars, the fractions of passenger service provided went from 29% to 14% for bus and from 15% to 8% in 1975 for trains. Only after the 1997 privatization, a small increase in rail is observed with a corresponding decrease in cars; buses did not suffer much change since 1984 at 9%.

Although trains come across as the most efficient transport mean, a complete shift is not realistic. As so, improvements in others means should be done. An important measure that should be encouraged is to increase the occupancy rate, for example, by car sharing, or by incentives for public transports use (bus).

Regarding freight, it was only analysed for road and rail. In terms of shares, road freight had majority, going from 62% in 1960 to 85% in 2014, reaching its peak in 1995 at 94% share. Rail presented its higher fraction value in 1960 at 38% ending in 2014 at 15% after its minimum in 1995 before privatization. Rail is the most efficient in terms of the service it provides, with 35,93 pkm/MJ in 2014, while road freight was kept at 3.25 pkm/MJ in 2014. As said by Nam King [93], rail-based intermodal system emit less CO_2 than truck only systems, regardless the type of locomotive, and according to a Department for Transportation document [99], each freight train removes the equivalent of 25-76 HGVs from the roads which would improve road congestion, particularly from long-distance truck movements. However, rail does not allow the same flexibility as trucks, so the solution is to increase intermodal transportation. Following Milan Janic [100] paper, in Europe, intermodal freight transport has been seen as a probable competitor for road transportation and to environmentally friendlier in many contexts.

The reason for why passengers choose more inefficient transport means comes from quality characteristics that they provide. Cars for example, give the passenger an autonomy, liberty and comfort that other public choices do not have to capacity to offer. Another example is the velocity that airplanes provide that makes extremely difficult for trains to compete with. Regarding freight, trucks allow a mobility freedom that trains could never achieve.

Based on continuous technological developments it would be expected that all analysed vehicle/sectors had improved their efficiency. Nevertheless, the analysed indicator is service efficiency and the dynamic of service kept changing through the years due to its complexity and strong connection to human behaviour. A clear example is buses, where efficiency was expected to increase due to better engines; however, occupancy rates declined, and technologic improvements could not compensate for such drastic behaviour changes. This inherent connection of service with human behaviour is what makes impossible for service efficiency to achieve values as the ones permitted by technological evolutions. Other reason is incentives, even if new technology that could turn the service much more efficient could be developed, the cost/benefit is not good enough to allow investments.

When analysing stock and outflows it emerges how important is to analyse materials apart from its mass. The results show that the shift from steel to lighter materials (aluminium and plastic) could have a broader impact than the reduction in mass. By looking at the exergy content, plastic and aluminium present a much bigger impact than they would if analysed in terms of mass only. There is a steep decrease of material efficiency (service per unit of stock or outflows) after 1989, caused by the increase in the parked time of cars. It means that there was material consumption (more purchases) that did not result in increasing service, on a big scale it represents a mismanagement of resources.

A new indicator was proposed for resource efficiency in transport of passengers in cars. Resource efficiency had an almost constant grow until 2014, which means it was possible to provide more service while consuming less resources. A direct comparison between fuel and material efficiency demonstrates that the improvement in fuel efficiency allowed the increase in total resource efficiency despite more materials being consumed to provide the service. Due to its large scale, fuel consumption is the trend setter.

The exergy intensity of operation in-use stocks accounts for the amount fuel exergy that is consumed to activate the stock to provide service. Between 1992 and 2014, this indicator decreased because less energy was needed to make the stock useful. This is not caused, by a sudden improve in cars consumption efficiency, but due to longer parked periods. In this context, such indicator could be misleading, just because it indicates lower energy consumption, it does not mean that there is a positive evolution. To better understand the evolution of stock-flow-service nexus, each pair, service-flow/ service-stock/ flow-stock, was normalized to 1960. Stock related indicators are the ones that have a decreasing tendency, indeed the increase in stock was not followed by increasing service or fuel consumption. The service-flow pair (energy service efficiency) is the only one that rose through the years, because service grew while there was less fuel consumption.

Regarding the environmental impact of resource consumption, fuels consumption is the main source of CO2 emission, with material having a minimal contribution for the total emission. By looking at a normalization of mass of materials and associated emissions, it is evident that the amount of consumed materials grew a lot faster than the associated CO_2 emissions, which implies that production of materials being consumed in the passenger transport service in cars has been partially decarbonized.

From all the indicators some transmit more relevant and pertinent information than others. Due to the magnitude of fuel consumption, resource efficiency does not bring much extra information into the table when compared with energy efficiency, as so it is crucial to accompany Resource Efficiency with Fuel Consumption and Material Consumption Efficiency separately. Another important indicator is Material Stock Efficiency because it has the ability to show how the stock is utilized by the service, the higher the value of this indicator, the lower the number of vehicles that are not used and lower the spoilage of materials. The final relevant indicator is the Embodied Impact Efficiency, in this case in terms of CO_2 emitted, it is a proxy of the environmental impact of the service beyond its exergy value.

To untangle the evolution of the conversion device from the passive system in cars from 2001 onwards, the mileage, the mass and the mechanical drive efficiency were compared. Mechanical drive efficiency is a representation of the final to useful conversion, and the mileage the useful to passive system losses. Results show that even with increasing mass, both mechanical efficiency and mileage improved, indicating that technological improvements were made that allowed an increase in weight without reducing efficiency or increasing consumption. Additionally, it was observed that the mileage decreased more than the increase in mechanical efficiency, suggesting that, the technological developments in the passive system were more significant than in the conversion device mechanics.

The methodology used comes with some limitations. The split between rail freight consumed energy and passengers was estimated based on values from 2005 to 2017, with no real values from the missing years to confirm, being a significant source of error of rail efficiency results. Regarding service, the fact that several data sets had a survey and estimate component creates a possible variance between the data and reality. Other limitation was the inability to separate aviation energy consumption between freight and passenger transportation. For materials, the main limitation comes from the inability for obtaining historical information for more transport modes. For cars, it was the lack of information for more materials and by the fact that its exergy content refers to the final exergy and not embodied exergy.

For the specific case of freight transport, it was not possible to do a thorough examination of why there where so many variations of the service. In the future, it would be interesting to correlate information regarding the type of material transported and geographic distribution with economic parameters, that represent the consumers behaviour.

The most relevant limitation for this thesis was the inability to find more information regarding the evolution of the engine efficiency for all transportation modes, making it impossible to analyse how its passive system evolved in comparison with the device efficiency. The main difficulty was to find historic values for all data, nowadays most relevant data for this type of analysis is already collected. Even so, I think that it would be important to collect the occupancy rate for each vehicle in public transports. It would also be valuable if every producer would publish every year the percentages of each material used in the making of its vehicles.

5.1 Future Work

In futures works, there should be an analysis on the Embodied Resources Efficiency, which would take into consideration all the exergy involved in the whole life cycle of the transport sector. Due to the lack of historical information it was only possible to analyze in more detail cars. Future investigations should extend the resource analysis and device efficiency/passive system for all transport means. Regarding the environmental impact, it should be done a study on other pollutants, as well as an assessment of other environmental downfalls that emerge from all the life cycle of the transport sector. To further corroborate this study, an economic analysis should be done in relation to the evolution of the transport service, where a study of cost/benefit, cost/quality, cost/effectiveness and cost/efficiency could result in a better comprehension of passenger behavior.

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7 Appendix

Table - 1 - CO2 factors for each material per year.

	tonne CO_2e/tonne		
	Steel	Aluminium	Plastic
1960	4,64	27,22	15,63
1961	4,50	26,41	15,16
1962	4,34	25,48	14,63
1963	3,99	23,44	13,46
1964	3,87	22,71	13,04
1965	3,92	23,03	13,22
1966	3,96	23,24	13,35
1967	3,83	22,47	12,90
1968	3,88	22,76	13,07
1969	3,87	22,72	13,05
1970	3,74	21,94	12,60
1971	3,69	21,65	12,43
1972	3,37	19,80	11,37
1973	3,28	19,24	11,05
1974	3,37	19,80	11,37
1975	3,57	20,98	12,04
1976	3,41	20,00	11,48
1977	3,32	19,52	11,21
1978	3,10	18,19	10,44
1979	3,24	19,04	10,93
1980	3,24	19,00	10,91
1981	3,26	19,16	11,00
1982	3,31	19,42	11,15
1983	3,06	17,98	10,32
1984	3,01	17,69	10,16
1985	3,02	17,72	10,18
1986	2,84	16,66	9,57
1987	2,68	15,74	9,04
1988	2,61	15,33	8,80
1989	2,51	14,75	8,47
1990	2,48	14,58	8,37
1991	2,52	14,77	8,48
1992	2,21	12,95	7,44
1993	2,21	12,95	7,44
1994	2,23	13,11	7,53
1995	2,19	12,87	7,39

1996	1,91	11,21	6,44
1997	1,89	11,12	6,38
1998	1,91	11,22	6,44
1999	1,81	10,63	6,10
2000	1,91	11,24	6,45
2001	1,96	11,49	6,60
2002	1,98	11,60	6,66
2003	1,80	10,55	6,06
2004	1,75	10,28	5,90
2005	1,80	10,55	6,06
2006	1,83	10,76	6,18
2007	1,79	10,53	6,05
2008	1,83	10,73	6,16
2009	1,80	10,57	6,07
2010	1,63	9,56	5,49
2011	1,60	9,37	5,38
2012	1,56	9,17	5,27
2013	1,53	8,99	5,16
2014	1,50	8,80	5,05