Evolution of the Exergetic Efficiency in the Transport Service

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Abstract

Transportation service is one of the main pillars of today's society and in 2018 it 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. During this period, energy efficiency increased in rail and aviation but decreased in road transports, with exception for 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.

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.

I. Introduction

To address the environmental challenges, and accordingly to the ETP2017 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. In 2018 transports were responsible for 24% of direct CO_2 emissions from fuel combustion[2]. 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]. According to Cullen *et al.*[4], *"The efficient use of energy is a key component of current efforts to reduce carbon emissions*."

According to Sorrel and Dimitropoulos[5], 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, acceleration and prestige. The combination of useful work (S) with these associated attributes (A) provides the full energy service: ES=es(S,A)*".

Cullen [6], 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. 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.

However, transports are more than the fuel they consume, all the life cycle of a vehicle contributes to its environmental impact. 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.

When talking about materials, one must separate them between stocks or flows and estipulate what information each one provides. 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.

Ana Gonzalez PhD. thesis was focused on *"Site-level resource efficiency analysis"*[42], an industry focus analysis of resource efficiency and her results show that an exergy-based metric is a suitable method to collect the interaction between energy and materials.

Carmona *et al.* [43] discuss how the stock-flow-service (SFS) nexus can contribute to broader form of resource accounting, reflecting some its limitations and how they can be tackled. 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.

II. Methodology

- 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.

The majority of service data, expressed in billion-kilometre (pkm) or tonne-kilometre (tkm), was taken from *Department for Transport (DfT)* web platform[45] with exception for aviation that obtained from the Civil Aviation Authority annual statistics documents [57].

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.

Road

Heavy Goods Vehicles (HGVs) includes all goods vehicles over 3.5 tonnes gross weight and light vans goods vehicles not exceeding 3.5 tonnes. Due to changes in methodology, data for HGVs from 2004 onwards are not fully comparable with previous one[54].

The occupancy rate is calculated by dividing passenger-kilometre by vehicle-kilometres from *DfT* [50]. To convert 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 [51], and the number of seats for each type of bus from a specification sheet[52].

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 [54].

Aviation

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, so missing values were estimated based on them.

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

- Energy

Domestic energy values 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.

Road

To separate the energy consumed by HGVs from the remaining vehicles (cars, motorcycles, buses and vans), it was calculated the percentage of petroleum derivatives used by each road vehicle category, from [61]. The remaining fuels (biofuels and electricity) were added to the car, taxis and vans category

Rail

To distinguish the amount of energy allocated to freight or passenger transport from the total amount, I used information on the amount of electricity and diesel consumed for passenger and freight rail transport from 2005 to 2017 taken from table 2.101 [65]. Pre 2005 values were estimated by assuming 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.

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 [66]. To 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].

Aviation

The data for air transport has a "corrupted" section from 1970 to 1990, were the kerosene energy values are too high., which contradicts the information about aviation fuel consumption [68]. 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.

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 defined by $y = 5 \times 10^{-5x} - 0.0444$. 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 III.

Energy consumption data for international passenger was obtained by subtracting domestic consumption from the total consumption provided by table 2.01 ECUK 2018 data tables [69].

- 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, to obtained the annual percentage of steel, aluminium and plastic for new cars; and to use such value to estimate stocks, inflows and outflows of each material following the stock model developed by Carmona *et al.* [35].

Material percentage per Car

Curb weight and percentage of steel and aluminium 1970 to 2012 were obtained from Serrenho and Allwood [70] values until 2014 were estimated through a linear approximation. To correct incorrect 1970 to 1985 steel values, I used the average ratio between GB and U.S.A. values (from MacKenzie *et al.* [71]) from 1985 to 2010, to estimate GB values form 1975 to 1985. From 1960 to 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 equal to the 1975 percentage. 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 [71] and the American Chemistry Council (ACC) 2017 report [73] provided the values, in mass, from 2010 to 2014, and from 1960 to 1975. To calculate the percentages I used the curb weight of cars, converted to pounds, provided by MacKenzie *et al.* [71].

Stocks, Outflows and Inflows

Stock and flows data were obtained through the same stock model that Carmona *et al.* used in [35]. The model that follows is supported an inflow-driven and stock-driven method.

The inflow-driven method follows equation (1), and the stock-driven approach is used to validate the results

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

- Energy Efficiency

The indicator used (equation (2)) will follow similar methodology as Carmona el al.[35].

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

- Material Efficiency

Material Replacement Efficiency, represented by equation (3) .

$$\eta_{replace} = \frac{Service}{Outflow} = \frac{pkm}{tonne} \vee \eta_{replace} = \frac{pkm}{MJ} \quad (3)$$

Stock Degradation Efficiency, represented by equation (4).

$$\eta_{stock} = \frac{Service}{Stock} = \frac{pkm}{tonne} \vee \eta_{stock} = \frac{pkm}{MJ} \quad (4)$$

Another indicator will be referred as Energy Intensity of Operation in-use Stocks (equation (5).

$$a_{stock} = \frac{Fuel\ Energy}{Stock} = \frac{MJ}{tonne} \vee a_{stock} = \frac{MJ}{MJ} \quad (5)$$

- ### 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 of each material and fuel.

The chosen indicator is represented in equation(6)).

$$\eta_{resource} = \frac{Service}{Fuel\ Exergy + Outflow\ Exergy} = \frac{pkm}{MJ} \quad (6)$$

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 exergy were taken from chapter [75] while steel and Aluminium exergy values were obtained by consultation of chapter 6 of *"Sustainable Metals Management"* [76].

For plastic it was used the formulation and values by Eboh *et al.* paper [77]. It was chose the relevant plastics available from the category. The percentage of each type of polymer in a car was taken from ACC 2017 report [73]. There was 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.

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 (7).

$$\eta_{embodied} = \frac{Service}{(Fuel+Outflow)CO_2\,emission} = \frac{pkm}{tonnes} \quad (7)$$

III. Results and Discussion

- ### Service

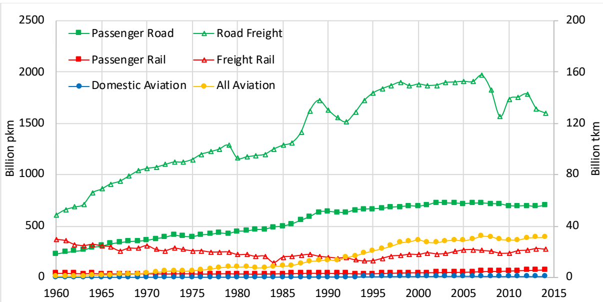

Figure 1 - Transport service with separation of air between domestic and international, and separation of road and rail goods and passenger transportation. Left axis in billion pkm and left in billion tkm.

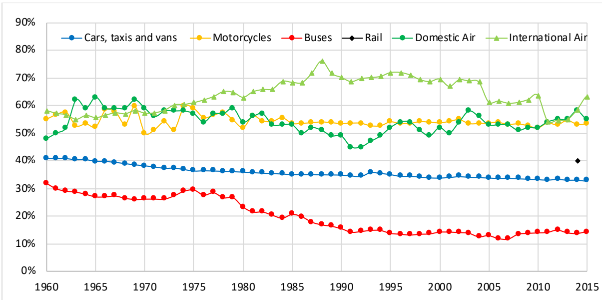

Figure 2 - Occupancy in percentage for each sector and vehicles.

Figure 1 presents service quantities for all sectors. 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. Since 1960, both road goods and passengers service are increasing, freight started with 612.50x10^6 pkm and reached 1598.56x10^6 pkm in 2014, having a steep reduction in 2008 due to the financial crises, passenger road service went from 229.00x10^6 pkm in 1960 and reach 698.78x10^6 pkm in 2014.

Rail freight and passenger transport behaved differently through the years. Freight oscillated, it had a shrinking tendency from 375.00x10^{6}pkm in 1960 to 166.25x10^6 pkm in 1995, with a discontinuity in 1984 due to workers strike. From 1995 on, it grew until 277.59 $x10^6$ pkm in 2014. Passengers service was roughly constant from 1960 to 1995 at 40.6$x10^6$ pkm and rose until 73.77$x10^6$ pkm in 2014.

Comparing aviation, both services expanded from 1960 until 2014. International had the biggest growth from all sectors, going from 10.47$x10^6$ pkm to 389.990$x10^6$ pkm. Domestic aviation service grew slower, starting with 0.91$x10^6$ pkm, having a peak of 10.40$x10^6$ pkm in 2005 and finishing 2014 with 8.77$x10^6$ pkm.

On Figure 2 - Occupancy in percentage for each sector and vehicles. 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 of efficiently used is the space for aviation and motorcycles, the latter expected due to only be available two seats. For cars and buses, occupancy has been decreasing through the years. It is highlighted how bus occupancy rate had a much steeper decrease than cars, which represents a shift from bus to other transportation means. The occupancy percentage of rail, 40%, is higher than in cars and buses but lower than aviation.

- Energy

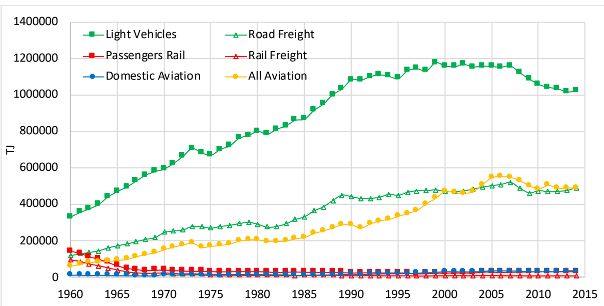

Figure 3 - Energy consumption with separation of air between domestic and all transport, and road and rail between goods and passengers' transportation in TJ.

Separating energy between the sectors (Figure 3), it stands out how much energy light road vehicles consume. 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.

- Energy Efficiency

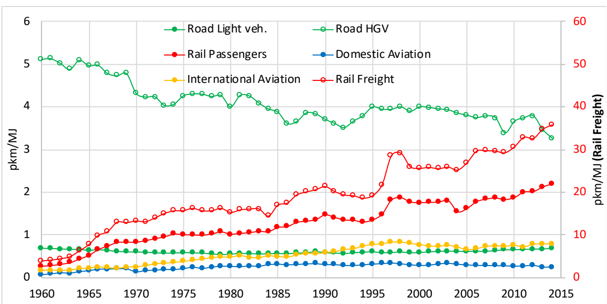

Figure 4 - Energy efficiency for three sectors. Separation of air between domestic and international, road and rail between goods and passenger's transportation in pkm/MJ. Right axis for rail freight.

Figure 4 presents the efficiency results. Separating goods from passengers, 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. However, HGV 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

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

Analysing the energy efficiency of passenger transport by road and rail, rail is more efficient after 1966. The difference is not as dramatic as in freight, but 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 an occupancy rate of 40% while cars is 33.6%. The global average efficiencies are 6.03, 1.60 and 0.26 pKm/MJ for rail, road and air respectively. Air transport is the least efficient, an expected result since they consume a lot more fuel for the service they provide. HGVs have a high efficiency and are the only that present a decreasing efficiency.

- Material Efficiency in Cars

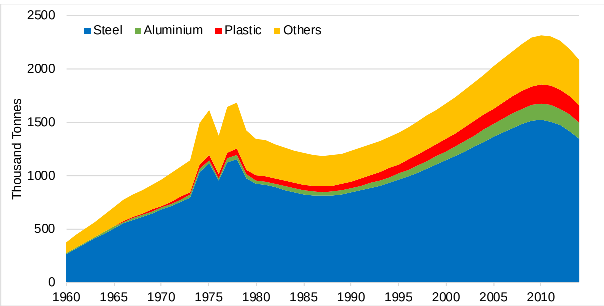

Figure 5 - Material outflows for cars in tonnes.

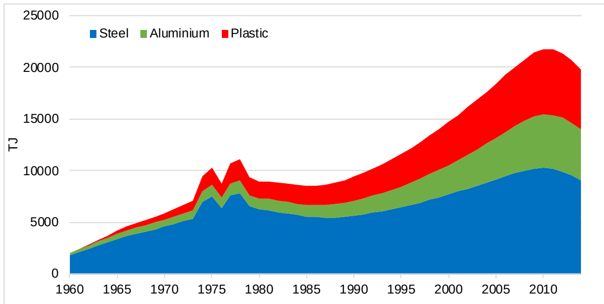

Figure 6 - Material outflows for cars in exergy units (TJ).

Figure 5 and Figure 6 presents the evolution of material outflow 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 assumed saved in fuel consumption because the shift enhanced the energy consumption in material production.

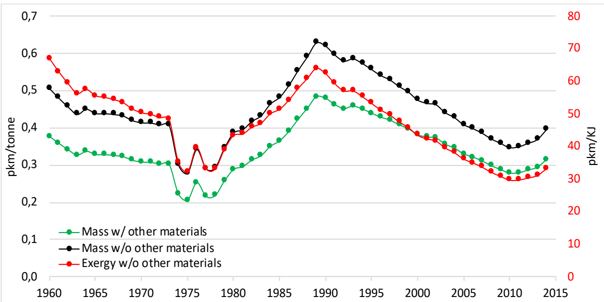

Figure 7 - Material outflows efficiency, in mass with and without others materials contribution and in exergy. Right axis in pkm/Kg, left axis pkm/KJ. Main materials include steel, plastic, aluminium. Other materials include everything else.

Material outflow service efficiency is represented in Figure 7. It is not possible to estimate the exergy content of "other materials" so they are not included in the efficiency calculation in exergy units. Outflows efficiency values have declined since 1989, meaning that the amount of service has declined for the amount of outflow that exist. Combining results from Figure 1, Figure 3 ,Figure 5 and Figure 6, where service, ouflows and energy have been increasing, one can conclude that the reduction of efficiency results from more stagnant vehicles. This idea is supported by John Bates & David Leibling RAC Foundation report [95] "...the typical car is only on the move for 6 hours in the week: for the remaining 162 hours it is stationary " for U.K.

- Resource Efficiency in Cars

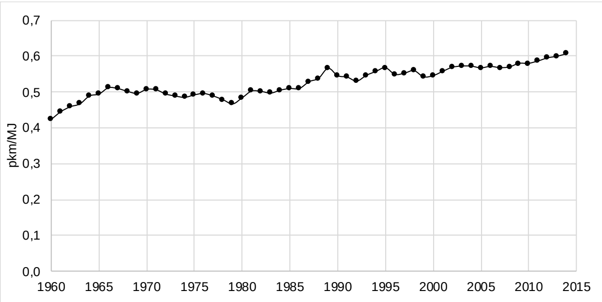

Figure 8 - Resource efficiency in pkm/MJ.

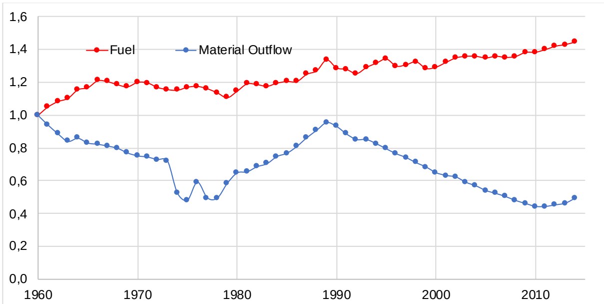

Figure 9 - Outflow Material and Fuel service efficiency, normalized to 1960.

Figure 8 presents the evolution of resource efficiency and shows that it has been increasing since 1960. It means that in 2014 fewer resources were consumed into providing on unit of service.

Figure 9 represents a normalization for material and fuel consumption service efficiency to analyse how both efficiencies evolved since 1960. There was an increase in service efficiency for fuel consumption, cars started providing more service (pkm) for less fuel consumption. 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.

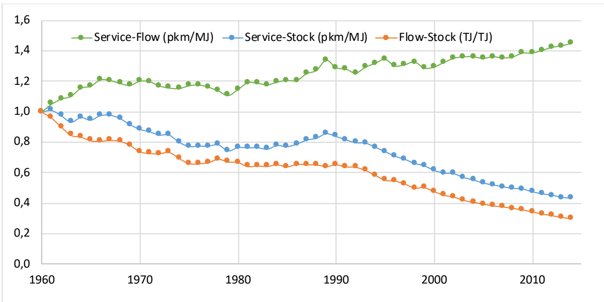

Figure 10 - Stock Flow Service Nexus, normalization to 1960.

Figure 10 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, stock grows much faster. Service-flow (resources) is growing, which means that the relation between the two has improved, and its known that is mainly due to an increase in service.

- Emissions

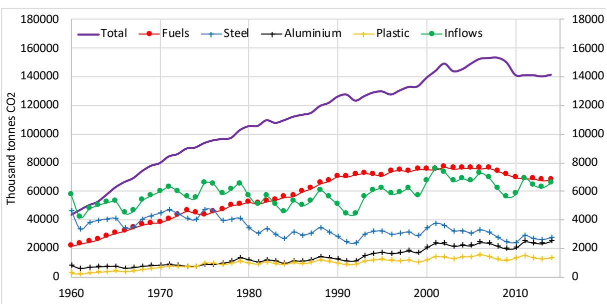

Figure 11 - CO2 emissions by inflows and consumed fuels in thousand tonnes.

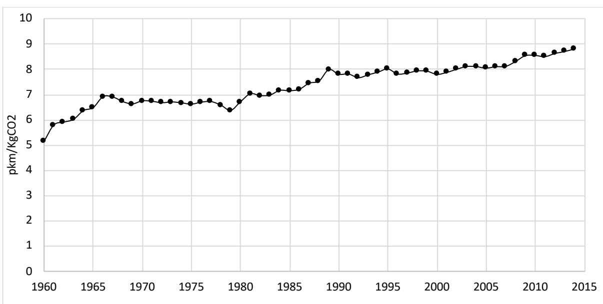

Figure 12 - Embodied Impact Rate, CO2 emissions by fuel and inflows to provide one unit of service in pkm/KgCO2.

It is important to study CO_2 emissions (Figure 11) because a higher energy consumption does not directly imply a bigger environmental impact. 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.

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 and vehicles acquisitions, but the stabilization for the following year is a positive sign.

Figure 12 represents the embodied impact of cars transportation. It has been almost steadily growing, so 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 .

- The conversion device and passive system in new cars

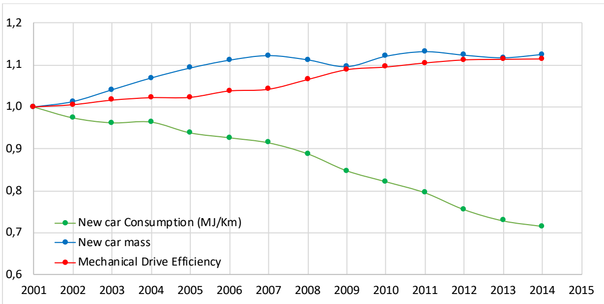

Figure 13 - New car mass and consumption, normalized to 2001.

Figure 13 presents the influence of changes in new cars. The car consumption represents the passive system while the mechanical drive represents the final-useful conversion. With this, it is possible to compare the evolution of both systems through a normalization of the values. It shows that the increase in weight did not increase its consumption. Bigger weight implies 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. Consumption decreases faster that mechanical drive efficiency and 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.

IV. Conclusions

In relation to energy efficiency, cars were the only ones to increase its efficiency, going from 0.46 pkm/MJ 0.68 pkm/MJ in 2014. Buses present the biggest reduction, a decrease of 2.87 pkm/MJ from 1960 to 1990, from where it remained rather stable. Heavy Goods Vehicles had an oscillating reduction in efficiency, starting in 1960 with 5.19 pkm/MJ and ending with 3.25 pkm/MJ in 2014. 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. For passengers it grew from 0.28 to 2.2 pkm/MJ, and freight from 4.01 pkm/MJ to 35.93 pkm/MJ. The increase in rail efficiency results from a change in consumed fuel, going from coal in 1960 to mainly diesel and electricity in 1970, 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.

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).

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 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.

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. There is a steep decrease of material efficiency after 1989, caused by the increase in the parked time of cars.

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.

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.

For the conversion device/passive system, results show that even with increasing mass, both mechanical efficiency and mileage improved, in different scales, indicating that technological improvements were made both at the conversion device as at the passive system level.

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