Car ‘organ-transplant’: anticipating energy and environmental benefits of cleaner technologies

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Abstract

The transport sector faces multiple challenges including the accommodation of increasing fuel prices and environmental pressures. These hurdles become more important in road transport where cars hold a larger share of final energy consumption and emissions. Although not solved, the situation is improving in general and the question of accelerating the transition to new technologies is dominant, yet not sufficient.

Technological turnover of car fleets is determined by the replacement of older vehicles by new models. Depending on the diffusion of new cars and driving forces for technological change, the total displacement of older technologies can last 10 to more than 40 years. Car Organ Transplant (COT) is explored here as a complementary alternative to conventional technological turnover of fleets by which potential benefits are delayed as obsolete technologies continue to pollute at preceding levels. COT corresponds to replacing obsolete powertrain and ancillary equipments with cleaner technologies. Consequently, car’s service time is extended with upgraded and fully functional technologies.

We analyzed lifecycle environmental and economic benefits of COT by comparing different car-ownership approaches over 20 years: keeping car, buying new car, buying remarketed-car; buying transplanted-car or transplanting own car. We concluded that COT is potentially attractive for owners while improving energy and environmental performance of automobility. Additionally, we estimated the pervasiveness of COT in the Portuguese car fleet and corresponding impacts. We concluded that COT potentially yields significant energy and environmental benefits for society.

Barriers and implications of COT for the automotive industry were identified. Importantly, increased standardization, modularity-in-design and modularity-in-production are necessary. Lastly, new relationships between carmakers and customers may arise like ‘evolutionary car selling’ by which planned COT over time would be bundled to car purchasing or to the auto mobility service provided.

Introduction

The transport sector faces multiple challenges including the accommodation of increasing fuel prices and environmental pressures. These hurdles become more important in road transport where cars hold a larger share of final energy consumption and emissions. Under current market trends, car use will perpetuate the current pressure on natural resources and the environment if the automotive industry does not produce sufficiently high efficient and less material intensive vehicles or if the international demand for automobility continues its stunning growth – nearly 5%/year over three decades in the European Union (Eurostat, 2003) and higher growth rates (15% to 20%/year) currently occurring in China (Schipper and Ng, 2004).

In response, these energy and environmental efficiency challenges are stepping up research and development in the areas of propulsion technology (e.g., exhaust gas prevention, alternative fuels, and alternative propulsion systems, among others). Although the powertrain operation principle remained the same over the last century, it has undergone vast improvements ever since, by which fuel economy of cars has increased by a long way and specific emissions have decreased noticeably. Nonetheless, perfect combustion is still not obtained and, thus, together with large amounts of carbon dioxide (CO_2) and water (H_2O) in the exhaust gases, pollutants are still emitted: carbon monoxide (CO), non-methane volatile organic compounds (NMVOC), oxides of nitrogen (NO_X) and particulate matter (PM) – just to mention the regulated ones. Importantly as well, large amounts of material consumption and waste production are still involved in the production, use and final disposal of cars. Concomitantly, governments are implementing measures for pollution control (for the most part, regulatory instruments like the Euro standards in the EU) and to reduce carbon emissions by means of increased fuel economy of cars (e.g., voluntary agreement between the EU and the automobile manufacturers associations – ACEA , JAMA and KAMA – as well as policies to promote the decoupling of mobility growth from economic development – White Paper of the European Commission, 2001).

Despite the diffusion of more efficient new vehicles, the concentration of air pollutants in many urban areas often exceeds air quality standards (EEA, 2006) and there are strong evidences that climate change is being increasingly induced by anthropogenic emissions of greenhouse gases through global warming (IPCC, 2001, 2007). In reality, higher efficiency of cars is being offset by increased motorization and mobility and by diverting the technological improvement gains into non fuel saving vehicle features (e.g., larger vehicles and/or engine size, higher acceleration power, air conditioning, among others), while *technological breakthroughs take longer to diffuse and become effective*, also. In this sense, the situation is improving in general and in many respects the question of accelerating the renewal of fleets towards cleaner technologies seems dominant (Viegas, 2003), although not entirely sufficient. In this sense, the transition to a more sustainable transportation system requires a *fleet conversion policy that efficiently absorbs new, clean technologies and retires old, high-polluting technologies*.

Technological turnover of car fleets has been essentially determined by the retirement of older vehicles and replacement with new models. However, the total displacement of older technologies can last from 10 to more than 40 years (Grübler, 1990, Grübler and Nakicenovic, 1991). One environmental implication of slower diffusion rates is technological obsolescence of the running fleets and, therefore, benefits from best available technologies (BAT) are fully explored only after 10 to 40 years. Furthermore, an important share of today's motorized mobility is using older, obsolete and more polluting technologies (for example, refer to data presented by Davis and Diegel, 2006, for the USA), although older vehicles are expected to drive significantly shorter distances over time. If, on one hand, new vehicles are more fuel efficient (considering equivalent models) and include more and better pollution control devices, on the other, pollution control equipment deteriorates over time (Ross et al., 1995, Harrington, 1997, Ross et al., 1998) and so does the fuel economy of engines although to a lesser extent (Ang et al., 1991).

One possible way to reduce the delay of cleaner technologies' diffusion would be to make the average lifetime of vehicles shorter by accelerating the turnover of fleets (i.e., increase the entrance of new cars while anticipating the retirement of older vehicles, as mentioned above). However, overall environmental impacts of cars can potentially increase from a lifecycle accounting perspective, mainly due to additional consumption of energy and raw materials or generation of emissions and solid waste from new car production and retirement of older cars (ECMT, 1999, Kim et al, 2003). Therefore, reducing the lifetime of vehicles below a certain limit is not necessarily the best option if the environmental impacts are to be minimized holistically.

The present paper proposes one additional solution as part of an energy consumption and environmental impact reduction strategy for automobility. We named it 'car organ transplant' (COT) that aims to extending the service time of vehicles while keeping them technologically up-to-date. This paper is divided in five sections (including this introduction). After exploring the concept in the next section, we present the overall methodology used in our research. Finally, after presenting and discussing the results obtained, we draw the overall conclusions of this paper, in the last section. Finally, we highlight that the present paper presents some of the more important results and conclusions of the research work developed by Moura (2008) for the completion of his doctoral dissertation. As such, the research details are extensively developed in the dissertation.

The concept: Car Organ Transplant (COT)

COT is an analogy between organ transplant medical care in humans and car care. Organ transplant in cars corresponds to replacing parts, modules and systems of the powertrain (including depollution equipment) and other energy intensive ancillary equipments (e.g., air conditioning) of the car that are technologically outdated, downgraded or malfunctioning while keeping the remaining components and parts that are state-of-the-art and fully operative, in order to improve its energy and environmental efficiency and possibly reach 'like new' performance standards. We defined a kit of transplanting organs by including all parts and components that could directly and indirectly influence the cars energy and environmental performance (for details on the composition of the kit refer to Moura, 2008). The potential advantages of the concept proposed here, compared to existing conventional alternatives, relate to potentially consume less energy and raw materials and generate less emissions and solid waste. However, these advantages and uncertainties related to COT had to be analyzed.

Firstly, does COT reduce lifecycle energy and environmental impacts when compared to conventional car ownership approaches (e.g., buying new or remarketed cars periodically), and is it attractive for car owners when comparing its total ownership costs to those of conventional approaches? In fact, COT is effective only if the energy and environmental costs of producing the replacing organs and scrapping those substituted are offset by the gains in energy and environmental efficiency striving from the use of those transplanted organs. Otherwise, we would worsen the overall burden.

Secondly, to what extent are transplant technologies expected to diffuse in car fleets and, consequently, how is COT expected to foster the technological turnover of fleets? Accordingly, what are the corresponding energy and environmental impacts considering whole fleets? As mentioned previously, technological renewal of car stocks takes place by means of new models entering the stocks. Typically, the rate of diffusion of new cars is approximately 10% of the total car fleet and the corresponding technological turnover is expected to increase with transplanted-cars (our hypothesis). The extent of the diffusion of such technologies depends mostly on the competitiveness of transplanted-cars in the used car market considering that COT involves additional costs (i.e., 'is it sufficiently attractive to car consumers when other conventional options exist in the market place?'). The degree of energy and environmental benefits from organ transplants depends largely on the pervasive capacity of such technologies but also on the balance between the production of new equipments (and retirement of older ones) and the corresponding gains in efficiency (from using them).

Other concepts are similar or complementary to COT: *renovation* (i.e., restoring to a former better state as by cleaning, repairing, or rebuilding), *remanufacturing* (i.e., bringing car parts and components to their original state), *retrofitting* (i.e., installing new or modified parts or equipment in something previously manufactured or constructed), *conversion* (i.e., altering the physical or chemical nature or properties of some object or equipment for more effective utilization) – just to mention some more important. The reason for differentiating organ transplant from the remaining concepts is that it involves the substitution of several subsystems of the car and that it is expected to bring major improvements in energy and environmental performance.

COT has been explicitly or implicitly mentioned by other authors. For instance, the authors of the Foresight Vehicle Program (SMMT, 2004) refer that "*retrofit capability of technology is a challenge as an intermediate step before introducing more radical solutions*" and that "*technologies aiming to increasing service life, whilst enabling the upgrading of emissions and safety systems, will be needed*". Complementing this idea, Nieuwenhuis and Wells (2003) suggest that "*the latest powertrain items and other new technologies could be fitted at various points during the car's life*". They add that extending the lifetime of products is the expectable trend in view of the extension of the lifetime of car parts performed by the automotive industry and in face of more stringent environmental regulations that will arise. Complementarily, Graedel and Allenby (1997) suggested that "*in the future, it is likely that engines, transmissions, (…) and other parts will be designed so that they can be removed and replaced as easily as can today's portable radio batteries*". In a general sense, all authors argue that partial technological upgrading of cars during their service life would be an advantage in the future.

However, putting COT into practice requires a different, more modular, approach to building cars than the current mainstream in order to deal with possible mechanical barriers. With the significant technological improvements in cars, over the past decades, key mechanical components and bodywork are more reliable and last longer. Whereas intra-generational interchangeability is naturally planned when designing cars (e.g., spare parts), *inter-generational interchangeability* is not sought after. Dealing with incompatibility issues between model years involves increased standardization and modularity in order to ensure viability and wider impact of COT (Baldwin and Clark, 2002, Baldwin et al., 2006). Full compatibility between the main building blocks of the transplantable organs and the recipient vehicle through clearly defined standardized interfaces are essential, although physical limitations to full modularity may arise (refer to Whitney, 2003).

In practice, COT would involve new conceptions of car production and ownership: 1) *design and manufacturing* of cars; 2) greater awareness and credit to the *lifecycle total ownership costs* by car owners (including environmental costs), and 3) *serviceability* by which car makers, suppliers and the aftermarket agents would have to offer commercially viable transplantable organs (in packages or kits) while ensuring ease, duration and competitive costs.

In the next section, we describe the main methodological steps followed to analyze the potential energy and environmental advantages of COT from the car owner and fleet perspectives.

Methodology

Although it should be applicable to any country or regional circumstances, the potential advantages of COT are demonstrated in the Portuguese context, firstly, by analyzing the private car ownership over 20 years and, secondly, by exploring the possible diffusion of transplant technologies throughout the Portuguese car fleet until 2030. Both approaches include impact analysis on energy consumption, atmospheric emissions, raw material consumption and generation of solid waste. While in the first part, we are analyzing the concept in the car owner perspective, in the second we approach the problem from the car fleet perspective, and thus more systemically. As from now, we highlight that the economic analyses presented here (for instance, the Total Ownership Costs) were performed for the car owner context only. As such, we do not intend to extrapolate these results and consider the distribution of benefits and costs over society (i.e. by type of economic agent).

We used life cycle (LC) analysis to evaluate the possible energy and environmental impacts of organ transplant in cars. We included the following lifecycle (LC) stages in the LC inventory model of both cars and transplanting organs: material production; vehicle and organ manufacturing/transplanting; fuel refining, transportation and delivery; car use; maintenance and repair; end-of-life disposal. We calculate LC energy and environmental burdens by multiplying the number of cars with the respective energy/environmental coefficients and mileage curves or weight: when addressing the operation stage we used annual kilometers; for the remaining stages we used car or organ weight.

We also used total ownership costing (TOC) tools to evaluate the costs of car ownership. Importantly, the costs analyzed included: car and COT price, fuel cost, insurance, maintenance and repairs, damage environmental costs. To evaluate the cost of COT, we used the cost breakdown methodology by Delucchi *et al* (2000) for a Ford Taurus and obtained approximately 4,500 Euro per COT (for calculation details refer to Moura, 2008).

Emissions from car use are based on the EMEP/CORINAIR guidelines from the European Environmental Agency (EEA, 2007). Importantly, we adopted the car classification used in these guidelines (refer to Table 1). We estimated the evolution of fuel economy of cars based on data collected in the literature (Ntziachristos and Samaras, 2000, ACEA, 2003, Brink *et*

Table 1. Car classification and average annual mileage (in brackets)

	Engine Size (c.c.)		
Fuel type	Small (<1,400)	Medium (1,400-2,000)	Big (>2,000)
Gasoline	PCGS (8,800)	PCGM (9,200)	PCGB (9,400)
Diesel	PCDS (22,500)	PCDM (24,000)	PCDB (24,500)

Note: PC stands for Passenger Car; Mileage is expressed in (km/year).

Table 2. Damage costs from airborne emissions (adapted from Bickel and Schmid, 1999)

	Damage costs		
	(2 000€/ton of air emissions)		
Pollutants	Min	Max	Average
Carbon Monoxide (CO)	0.001	0.016	0.008
Nitrous Oxides (NOx)	0.298	7.578	3.938
Volatile Organic Compounds (VOC)	0.209	1.380	0.795
Particulates	140	940	540
Carbon Dioxide (CO_2)	0.012	0.034	0.023†

† This value is confirmed by the PointCarbon .

al., 2005, DGEMP, 2005, ACEA, 2006, Ceuster *et al.*, 2006, Zachariadis, 2006). Regarding the energy intensity and emission factors of the up and downstream stages to car use, we collected data from Kim (2003) that we compared (and validated) with other sources for the EU context (Worrell *et al.*, 1997, Choate and Green, 2003, IPPC, 2001, Moors, 2006, Utigard, 2005). Importantly, these factors evolve with time also as manufacturing procedures are expected to become more efficient, too.

Annual mileage is expected to decrease with the age. Still, for simplification purposes, we adopted constant mileage over time for each of car type and values were based on APA (2007). With respect to the weight of cars, we used data adapted from Delucchi *et al* (2000).

LCA AND TOC ANALYSES OF A MIDSIZE GASOLINE CAR OWNERSHIP OVER 20 YEARS

To tackle the first research question, we centered our analysis on a midsize gasoline powered car and considered five car-ownership strategies over a 20-years ownership period: (S 1) keeping car, (S 2) buying new car, (S 3) buying remarketed-car; (S 4) buying transplanted-car or (S 5) transplanting own car. While in the first strategy, the car is kept over 20 years, the remaining includes swapping (or transplanting) vehicles periodically for which we tested several periodicities (our base case considered a 7-years swapping periodicity). Based on the characteristics of the vehicle and its operation over the service time, we calculated the energy consumption, emissions, raw materials use and waste generation from a LC perspective, for each ownership alternative. As mentioned above we also used TOC analyses to evaluate the costs of each strategy and assess the respective payback periods, i.e., after the initial investment, when does payback occur for each strategy, considering that the accounted benefits are reductions in fuel consumption and emissions compared to the base case of keeping a car over 20 years (assuming that for equivalent models, buying a newer vehicle or transplanting a newer technology in a older model increases the overall efficiency of the car). In this sense, TOC of car ownership were complemented with a monetarized evaluation of the environmental impacts striving from air pollutant and greenhouse gas emissions. These environmental external costs associated with airborne emissions from transportation reflect the potential for pollutants to impact human health (mortality and morbidity), building materials, crops, global warming, amenity losses (due to noise), ecosystems and land use change (Bickel et al., 1997). Additional societal costs related to issues such as infrastructure, accidents (human health), fuel security, water pollutants, solid waste, and congestion were not evaluated. The following table presents the monetary unit-costs used in our analysis (the average values).

Energy and environmental impacts of COT for the car fleet

Regarding the second research question, we extended our analysis of COT to the entire fleet. The figure 1 illustrates the model used to simulate a reasonable approximation of the evolution of the Portuguese fleet with respect to its dimension and technological composition for the period 1995-2007 and analyse its performance. The model is composed by three main modules: vehicle stock, LC energy and emissions coefficients, and car mobility by vehicle type. The combination of the outputs of these three modules provides the overall energy and environmental performance of the car fleet.

The vehicle stock module is separated into four sub-modules: vehicle stock, new cars, remarketed used-cars (both conventional and transplanted) and End-Of-Life (EOL) disposal of vehicles. The model is described in the following paragraphs whereas methods and necessary data collection are explained in more detail in Moura (2008, Chapter 7).

In very aggregate terms, the car stock model follows the following equation: *Total cars (t)=Total cars (t-1)+New cars (t)-End-Of-Life(EOL) cars (t-1)*, where *t* stands for calendar year). Based on this model, we estimated the baseline evolution of the car stock until 2030. By doing so, we defined the basis for comparison (*Baseline Scenario*) with the scenario where transplanted cars pervade in the existing stock (*Transplant Scenario*) as from 2008.

The total annual stock of cars (i.e., running fleet) was estimated based on a regression curve of the Portuguese car density (*cars/1,000 license holders*), aka ownership rate. Based

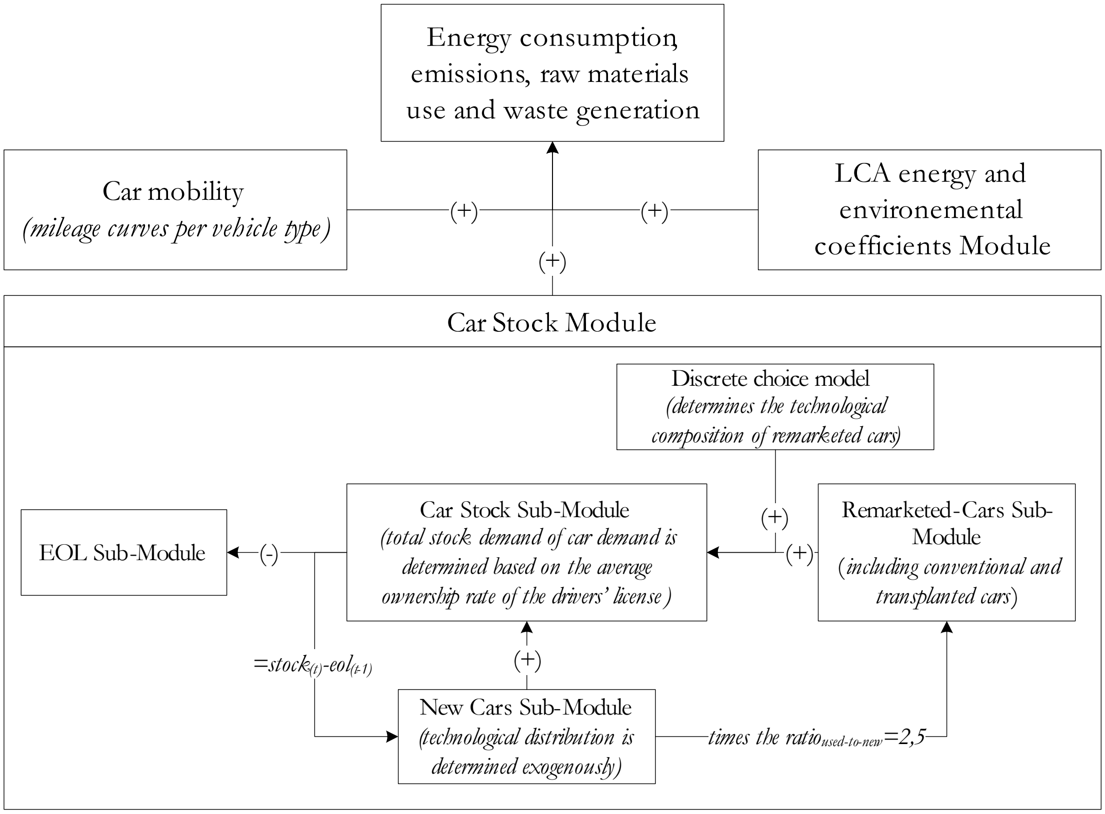

Figure 1. Simplified model of the car fleet dynamics (source: author)

on vehicle data provided by ACAP (2007) and demographic data provided by INE (2004, 2007), we calibrated the following logistic curve, for the period 1971 to 2007: $CD=893/[1+exp(-0.189+378.year)]$, with $R^2=0.99$. Future demand of cars was obtained by extrapolating the previous function from a time variable (plus constant) basis. As this extrapolation provides car density values, we used the demographic forecasts of the Portuguese population and respective driver-license holder's cohort composition from INE (2007) to calculate the overall car stock, annually. We did not include more explanatory variables (such as, purchasing power or division of urban/suburban/rural population) since we are want to test the aggregate impact of COT on a realistic baseline scenario and not a very accurate forecasted car stock evolution.

To estimate the amount of annual cars sales, we determined the quantity of new cars needed to match demand after deducting the retiring vehicles. The overall technological composition of the fleet over time is obtained by estimating which car types are retired and sold yearly. The retirement of older vehicles is calculated with "modified" Weibul curves suggested by Zachariadis et al. (1995), with the following expression: $S(k)=exp[-((k-\lambda)/\beta)^\wedge\lambda]$, where k represents the vehicle age. Parameters λ and β were calibrated with the time series available for the Portuguese fleet (ACAP, 2007) by which $\lambda=11$ and $\beta=31$ (although some variation occurs depending on the model years). The annual technological mix of new cars is determined exogenously based on the estimates by Ceuster *et al* (2007) in the TREMOVE model for Portugal.

After modeling the evolution of the Portuguese car fleet and estimating its baseline evolution until 2030, we estimated the diffusion of transplanted cars in the *Transplant Scenario*. The pervasiveness of a technology depends on the attractiveness of its characteristics and on the consumer's preferences and choice behavior. Accordingly, we developed a discrete choice model to simulate the options of consumers when facing a finite set of remarketed-car alternatives (conventional and transplanted), based on proxy-revealed preferences data provided by AB-motor (consultant of the Portuguese car market, http://www.abmotor.pt). We calibrated a 2-level nested Logit where each nest groups Diesel or Gasoline fuelled cars and elemental alternatives correspond to the engine size within each nest. We obtained the following parameters and statistics (in brackets) for the utility function. The Inclusive Value (IV) parameter for Gasoline cars was fixed to 1, while for Diesel cars we obtained 0.4735 (16.29).

$$V_j=\underset{(12.96)}{0.00159}\times ES-\underset{(-18.34)}{0.19714}\times AGE-\underset{(-28.96)}{0.00013}\times CP-$$

$$\underset{(-33.15)}{0.00002}\times TC-\underset{(-4.36)}{00536}\times CIRCT+\underset{(14.93)}{0.00932}\times NBRMOD$$

We made the following assumptions to calibrate the model:

1. Transplanted vehicles compete with remarketed cars and choices are basically influenced by the characteristics of cars (or attributes of the utility function): engine size (ES), age (AGE), car price (CP) - and/or COT cost, total operation costs (TC), taxes (CIRCT), and the number of makes and models of cars or transplanting kits available in the market (NBRMODS).

2. If a vehicle is transplanted with a newer propulsion system, its performance in terms of energy consumption and emissions is that of a new system. There is evidence on the potential losses of efficiency by adapting a new propulsion system to an older model, compared to its performance in a new car.
3. A used-car is transplantable once during its lifetime (applicable to the fleet-wide exercise, only).

There is an underlying assumption striving from the first assumption that is *new-car buyers do not become transplanters*. Complementarily, what we are assuming is that the attitude of potential transplanters is similar to the attitude of remarketed-car buyers and both are different from the attitude of the consumer of new cars. Indirectly, we are assuming that the consumer who wishes to buy a new car will value differently the criteria for decision-making (e.g., novelty/fashion, wear of the car/maintenance costs, etc.) that would be reflected in the set of variables of the utility function and respective parameters. Furthermore, if the transplanted alternatives compete with remarketed cars, these will replace used-cars only. Consequently, we estimated how many used-cars are remarketed every year. We adopted a simple approximation of the reality by calculating the moving-average ratio of used-to-new cars. Our results indicate that for each new car sold there are 2.5 cars remarketed, every year (this is consistent with the surveys by BCA, 2006).

Finally, we had to make two important mathematical specifications to our models:

- We imposed a restriction by which transplanted-cars would substitute its equivalent conventional used-car (and these are obviously retrieved from the total stock) in order to maintain our total stock of cars equal to the total demand we estimated yearly.
- We assumed that a transplanted car would have a longer service time compared to conventional cars. As such, we extended the car's lifetime by approximately 5 years and assumed a maximum service of 35 years.

The last specification had an indirect effect on the sales of new cars. As indirect consequence of extending car service time through COT is that the global demand for new cars is reduced over time. As a result, COT reduces the velocity of materials flow through the automotive sector and originates a reduction of materials use, energy consumed in manufacturing processes and emissions generated. We present now the main results obtained in our research by separating the analysis centered on the car ownership from the fleet's perspective.

Results

IMPACT OF COT ON THE CAR OWNERSHIP STRATEGY

With respect to the ownership of a midsize gasoline car over 20 years, our results show that, comparatively to keeping the car over 20 years (S 1), performing COT periodically provides significant reductions in overall energy consumption (-3.1%), air emissions (-6.2% for CO, -25% for NMVOC and -4% for CO_2) and solid waste production (-20%). Exceptions are made for PM and NO_X emissions. In the first case, PM emissions produced by gasoline-fuelled cars are not significant and, therefore, reductions from technological upgrades are null. This is not the case of diesel-cars for which COT contributes to the reduction of lifecycle PM emissions. In the case of NO_x, the additional emissions due to the production of transplanting kits and replaced equipment are not recovered over the vehicle service time, showing an increase of 34%. Conversely to other pollutants, NO_x emission factors are not reducing as strongly, over the last years. Hence, technological changes by COT are not reflected in more NO_x emission reduction. COT is logically more material-intensive (more 40%) as more parts and components are produced and used. Still, transplanting cars consumes half of the raw material used if cars are replaced by new cars periodically (every 7 years). Importantly, additional environmental burdens from technological transplant are recovered over a reasonable number of years, given the gains of efficiency achieved (3 to 4 years).

In addition, we concluded that COT contributes positively to the reduction of total car ownership costs (TOC) and transplanting the car twice over 20 years reduces overall costs by 4% when compared to keeping the car over the same period of time. The extent of the LC gains (whether environmental or economic) varies with the age of the transplanted car. All costs and pollutants considered, maximum benefits are reached at the age of 9 (and 5) for environmental damage (or economic costs). However, reasonable payback periods (less than 6 years) are obtained if cars are transplanted after the age of 5 (Figure 2). For transplants after 5 years, the payback periods decrease (almost linearly) as the transplanting age increases. We conclude that COT is potentially attractive for car owners, considering that the break-even of the initial investment is reached over a reasonable time horizon (6 years), while contributing to reducing LC environmental impacts.

Complementarily, the Net Present Value (NPV) indicates how much value is added by an investment over some period of time, discounting the future cash flows of the project. In the present case, they compare the alternatives of whether keeping the car as usual (S 1) or investing in COT (S 5), and the cash flows correspond to the cost reductions due to the reduction of fuel consumption and emissions after COT. Accordingly, NPV is maximized when the car is transplanted at the age of 5 if the investment is analyzed over 20 years. We note that NPV remains quite constant if cars are transplanted until the age of 15.

As shown in the following *radar* graph, the swapping/transplanting periodicity that minimizes all costs varies across ownership strategies but also across energy and environmental burdens. CO_2 emissions are minimized if new cars (S2) are swapped every 11 years, while they are minimized if 6-year old remarketed-cars (S3) are bought every 4 years or if cars are transplanted (S5), or bought transplanted (S4), every 7 years. In the case of CO emissions, transplanted-car emissions are minimized if cars are swapped every 7 years, which is faster than for new (10 years) or remarketed (11 years) cars. Interestingly, lifecycle solid waste generation is minimized if new cars (S2) are swapped every 9 years. On one hand, more materials are wasted during production stages if car swapping is more frequent (since more cars are produced) and, thus, swapping periodicity should be smaller to reduce material losses. On the

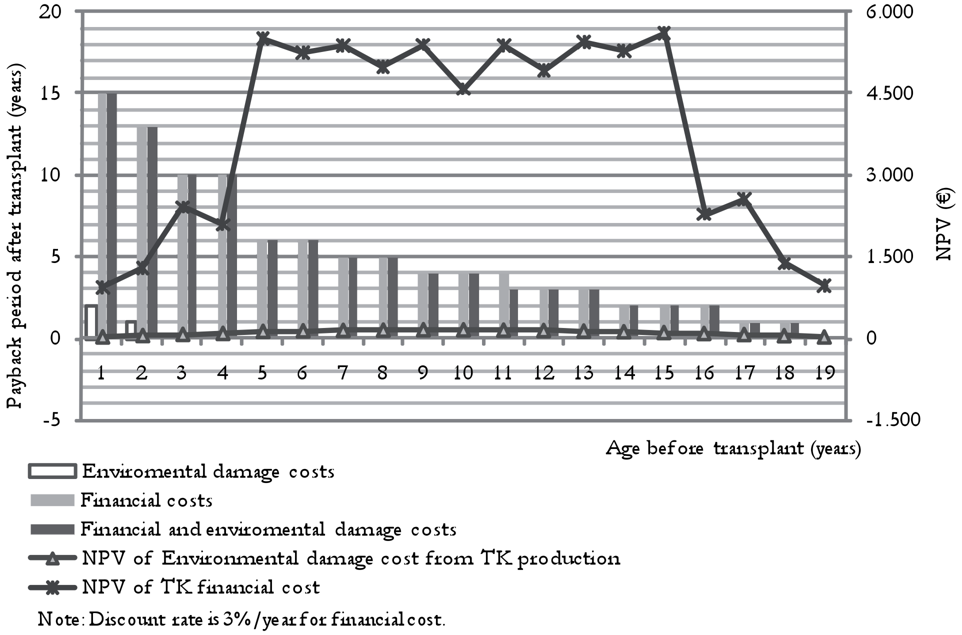

Figure 2. Payback period and net present value of transplant investment, including environmental damage costs (source: author)

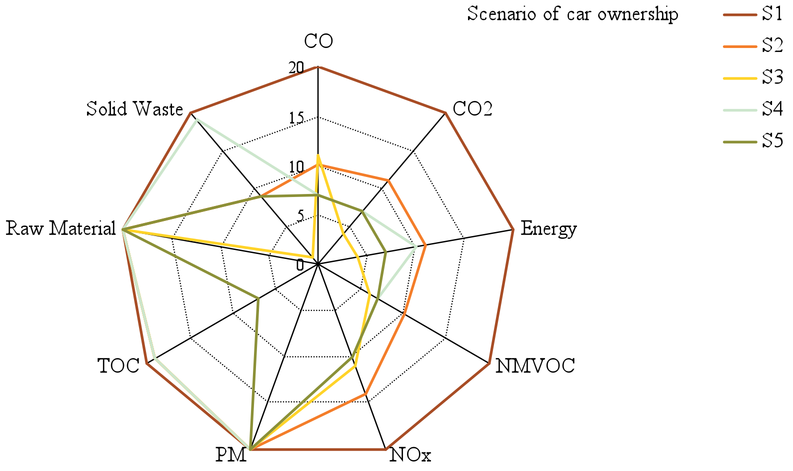

Figure 3. Optimal swapping periodicities to minimize TOC and environmental burdens (source: author). Notes: Remarketed cars are 6-years old. Swapping periodicity is fixed at 20 years for scenario 1.

other hand, the probability of car retirement increases if they are substituted later and, thus, the quantity of material disposed increases.

When comparing all car ownership strategies (multi-objective function that includes environmental damage costs), we conclude that transplanting the car twice over 20 years (S5) results in the smallest total ownership costs. Conversely, buying two new cars in 20 years (S2) is the least attractive option, according to the assumptions used here. Although the total environmental costs (consider alone) differ little between scenarios, the best alternative is to transplant cars (S5) or buy transplanted cars (S4) every 3 years, whereas the worst alternative is to buy a new car every 7 years (S2). On one hand, transplanted cars (S4 and S5) consume fewer materials than new cars (S2) and, on the other hand, they are more efficient than conventional remarketed cars (S1 andS3). We compared these results of optimal swapping periodicities to current sales habits of 2nd hand cars from 1st to 2nd owners and further on. Based on the used-car market survey by BCA (2006), we know that the age structure of remarketed cars varies from country to country. Anyway, in Portugal, we conclude that the majority of used-car owners keep their cars during 5 to 8 years. As such, we conclude that these owners might as well consider COT as it pays back after 3 years, considering environmental costs only, or 7 years, considering total ownership costs.

IMPACT OF COT ON THE TECHNOLOGICAL COMPOSITION AND ENVIRONMENTAL PERFORMANCE OF THE FLEET

According to our assumptions and considering transplant prices (for the final consumer) equal to transplant costs, the annual potential market share of the transplanted technologies would be nearly 50% of the consumers of remarketed cars. After estimating the optimal price that would maximize revenues for the transplant supply chain (price is necessarily higher than cost as it includes net revenues for the supply chain) and concluded that prices would be higher than transplant costs by a factor of 2.5. Consequently, demand would be lower and the potential market share of transplanted cars would become 30%. For example, according to our assumptions, a consumer who buys a 7-years old, midsize gasoline-powered car after being transplanted would pay 21,500 Euro that account for: the vehicle's residual value 11,500 Euro; 4,500 Euro of transplant costs; and 5,500 Euro of value added and other costs (e.g., taxes).

These are good grounds for the transplant business since the potential benefit (26%=5,500/21,500×100) would allow several stakeholders to participate in the value chain of transplanting services although we note that this profit margins are over-estimated since it did not include potential competitors, no economies of scale (due to lower material costs), and no benefits of a learning curve (due to gaining expertise in manufacturing and operating). We conclude that the share of transplanted vehicles would lie somewhere between 30% and 50% of remarketed cars.

We referred before that the payback period for a car transplanted at the age of 5 years, would correspond to 6 years, if transplant prices were 50% of base costs, i.e. roughly 7,000 Euro. In this case, the overall market share for transplanted vehicles we round to 40% of remarketed cars.

Transplanted cars are expected to diffuse at an annual rate of 3% of the total stock. Considering that new technologies were conventionally diffused through the entrance of new cars in the stock, COT increases the technological turnover from 7% to 10%, i.e. the full deployment of a new technology is potential cut down by 4 years. The main impacts related to the introduction of transplanted cars in the used-car market are:

- The average age of the baseline fleet is expected to decrease 1.5 years (from 8.5 to 7 years) where the percentile 60% decreases from 8 to 6 years of age and percentile 90% decreases from 16 to 14.
- The introduction of transplanted technologies in the market induces a shift towards smaller and diesel powered vehicles, i.e. potential downsizing of the car stock.
- After 2015, we estimate the production of new cars is cut down by 50 thousand new cars (i.e., a difference of -14% compared to the *Baseline Scenario*), while 155 thousand cars are transplanted (we recall that approximately 350 thousand cars are sold annually).
- In the longer run, more than 30% of the fleet would have been transplanted with new and cleaner technologies.

These impacts are potentially more expressive, considering that there are significant differences in fuel consumption and emissions between smaller and larger vehicles and that an older vehicles are normally higher emitters (although they have lower annual mileages). The stock dieselization has both an upside and a downside impact: whereas diesel cars consume less than equivalent gasoline cars (and, for itself, it emits less carbon dioxide), they generate more particulates and NO_X (although these can be solved with depollution equipment). The car stock technological transformation is also reflected in its Euro standards composition. Assuming that transplanted cars behave and are classified like new cars, COT could increase the number of Euro 5 and 6 vehicles by 20% until 2020, compared with the baseline scenario.

According to our assumptions, there is an overall saving of (-4%) of energy consumption, by 2020. Higher reductions are expected during the material production and car manufacturing (-20%) and EOL (-40%) stages, although these correspond to smaller shares of the global LC burden (13% and <1%, respectively). Similar results were obtained for the remaining parameters that we analyzed (CO_2, CO, NMVOC, NOx and PM). Additionally, COT could lead to a decrease of raw material consumption (-10%) and waste generation (-14%) by 2020. The majority of waste (nearly 80%) is reused or recycled. Although the global percent-variation is apparently low, it corresponds to expressive reductions in absolute terms. For example, in the case of CO_2 emissions, this percentage equals 555 Gg, 780 Gg and 660 Gg, in 2020, 2025 and 2030, respectively. This potential for emissions reduction is major when compared to the effectiveness of other transport policy instruments included in carbon reduction strategies. For example, COT could contribute more than any measure of the Portuguese National Program for Climate Change (Seixas and Alves, 2006), except for the introduction of biofuels that is expected to generate a reduction of 1,200 Gg of CO_2 emissions (according to our assumptions). Complementarily, the introduction of COT would also provide an annual reduction of nearly 1.5 Gg of NOx (~4% of total emissions of passenger cars) and 0.5 Gg of NMVOC (~4% of total emissions of passenger cars), after 2015. The measures included in the Portuguese National Emissions Ceiling Program (PTEN) are less outreaching than these results (APA, 2003).

Discussion and conclusions

Our results indicate that COT can bring energy and environmental benefits for the car owner and society. Although our economic analysis focused the car owner only, we would expect positive spillovers for the economy since additional business streams within the automotive aftermarket would arise. As we mentioned earlier, the downside for the car makers would be that the number of car sales (in a whole) would eventually decrease. However, it is expectable that OEMs would benefit from COT in the aftermarket since they remain the producers of the main powertrain sub-system and the strong cross-subsidization from the aftermarket sales (parts and components) would possibly compensate the reduction during the manufacturing stages.

One possible outcome for the auto industry would be the change of the current contractual relationship between car makers and customers. Today, the former lose control over their clients after the car leaves the retail store because they compete in the aftermarket for independent servicing and repairs. A new relationship could arise in the form of '*evolutionary car selling system*' by which OEMs would provide their customers the possibility of programmed COT over an extendable service time bundled to the car they sell or alternatively the mobility service associated to the vehicle they 'rent' or 'lease'(analogy to the 'evolutionary military acquisition system' of the US Department of Defense, 2003). As such, car makers would enhance customer's loyalty by postponing their investment in a new car over longer periods while the car maker would guarantee a periodic system refitting through COT. Importantly, COT would be encouraged if (and when) car owners would have to pay for their carbon and environmental footprints, in the sense that they would be running in fine tuned cars equipped with cleaner technologies.

References

ACEA (2003) Monitoring of ACEA's Commitment on CO2 Emission Reductions from Passenger Cars (2002), Brussels, European Commission.

ACEA (2006) Monitoring of ACEA's Commitment on CO2 Emission Reductions from Passenger Cars (2004), Brussels, European Commission, COM(2006) 463 final.

ANG, B. W., FWA, T. F. & POH, C. K. (1991) A statistical study on automobile fuel consumption. Energy, 16, 1067-1077.

APA (2003) Tectos de Emissão Nacionais, Agência Portuguesa do Ambiente, D.L. 193/2003, (http://www.apambiente.pt/ access in April 20th, 2006).

APA (2007) Portuguese National Inventory Report on Greenhouse Gases (1990-2005) Lisbon, Agência Portuguesa do Ambiente (Portuguese Environmental Agency).

BALDWIN, C., CLARK, K., RESEARCH, D. O. & SCHOOL, H. B. (2006) Modularity in the Design of Complex Engineering Systems. IN BRAHA, D., MINAI, A. A. & BAR-YAM, Y. (Eds.) Complex Engineered Systems. Cambridge, Massachusetts, Springer.

BALDWIN, C. Y. & CLARK, K. B. (2002) The Option Value of Modularity in Design. Harvard Business School, http://www.people.hbs.edu/cbaldwin/DR2/DR1Option.pdf, (09/09/2008).

BICKEL, P. & SCHMID, S. (1999) Externalities of Energy-Part II: External costs of transports. Stuttgart, Germany, Institute of Energy Economics and Rationale Use of Energy, http://www.externe.info/oldvolumes/vol9e.pdf, (06/05/2008).

38. BICKEL, P., SCHMID, S., KREWITT, W. & FRIEDRICH, R. (1997) External costs of Transport in ExternE, Seville, Funded by the European Commission, JOS3-CT95-0004.

BCA (2006) BCA Used Car Market Report – 2006 London, Sewells – Information & Research.

CEUSTER, G. D., HERBRUGGEN, B. V. & LOGGHE, S. (2007) TREMOVE BASELINE DATA version 2.52. Leuven, http://www.tremove.org/download/index.htm.

CHOATE, W. T. & GREEN, J. A. S. (2003) U.S. Energy Requirements for Aluminum Production: Historical Perspective, Theoretical Limits and New Opportunities, California, USA, BCS, Incorporated for the U.S. Department of Energy Energy Efficiency and Renewable Energy

DAVIS, S. C. & DIEGEL, S. W. (2006) Transportation Energy Data Book: Edition 25, Washington, D.C., Oak Ridge National Laboratory for the U.S. Department of Energy.

DELUCCHI, M., BURKE, A., LIPMAN, T. & MILLER, M. (2000) Electric and Gasoline Vehicle Lifecycle Cost and Energy-Use Model, Davis, California, Institute of Transportation Studies - University of California, UCD-ITS-RR-99-4.

DGEMP (2005) Consommations de carburants des voitures particulières en France (1988-2004). Paris, Direction Générale de l'Énergie et des Matières Premières, Observatoire de l'Énergie, http://www.industrie.gouv.fr/energie/statisti/pdf/consom_carbu_04.pdf.

ECMT (1999) Cleaner cars : fleet renewal and scrappage schemes, Paris, European Conference of Ministers of Transport ; OECD Publications Service.

EEA (2006) Transport and environment: facing a dilemma. TERM 2005: indicators tracking transport and environment in the European Union, Copenhagen, European Environment Agency.

EEA (2007b) EMEP/CORINAIR Emission Inventory Guidebook - Road Transport Methodology Chapter (5th version), Copenhagen, European Environment Agency),

EUROSTAT (2003) Panorama of transport: Statistical overview of transport in the European Union -Data 1970-2001 (Part 1), Luxembourg, Office for Official Publications of the European Communities, KS-DA-04-001-EN-N.

GRAEDEL, T. E. & ALLENBY, B. R. (1997) Industrial Ecology and the Automobile Prentice Hall.

GRÜBLER, A. (1990) The rise and fall of infrastructures – Dynamics of evolution and technological change in transport, Laxenburg, Austria, Physica-Verlal Heidelberg.

GRÜBLER, A. & NAKICENOVIC, N. (1991) Evolution of transport systems: past and future, Laxenburg, International Institute of Applied Systems Analysis, RR-91-8.

HARRINGTON, W. (1997) Fuel Economy and Motor Vehicle Emissions. Journal of Environmental Economics and Management, 33, 240-252.

INE (2004) Projecções de População Residente – 2000-2050, Lisbon, Instituto National de Estatística, ISSN: 1645-7633.

INE (2007) Estudos Demográficos. Revista dos Estudos Demográficos, 41, 79.

IPPC (2001a) Best Available Techniques Reference Document on the Production of Iron and Steel. Seville, Spain, Integrated Pollution Prevention and Control (IPPC), http://eippcb.jrc.es/pages/FActivities.htm, (01/04/2008).

168. IPPC (2001b) Reference Document on Best Available Techniques in the Non-Ferrous Metals Industries. Seville, Spain, Integrated Pollution Prevention and Control (IPPC),

KIM, H. C., KEOLEIAN, G. A., GRANDE, D. E. & BEAN, J. C. (2003) Life Cycle Optimization of Automobile Replacement: Model and Application. Environmental Science and Technology, 37, 5407-5413.

MOORS, E. H. M. (2006) Technology strategies for sustainable metals production systems: a case study of primary aluminium production in The Netherlands and Norway. Journal of Cleaner Production, 14, 1121-1138.

MOURA, Filipe (2008) "Car organ transplant – Anticipating the energy and environmental benefits of cleaner technologies " , Doctoral dissertation submitted for the PhD degree from the Transportation Systems Studies of the Instituto Superior Técnico of the Universidade Técnica de Lisboa, December 2008, Lisbon.

NIEUWENHUIS, P. & WELLS, P. (2003) The automotive industry and the environment: A technical, business and social future, Cambridge, UK, Woodhead Publishing.

NTZIACHRISTOS, L. & SAMARAS, Z. (Eds.) (2000) COPERT III - Computer programme to Calculate Emissions from Road Transport Methodology and Emission Factors (version 2.1), Copenhagen, EEA.

ROSS, M., GOODWIN, R., WATKINS, R., WENZEL, T. & WANG, M. Q. (1995) Real-world emissions from model year 1993, 2000, and 2010 passenger cars, Berkeley, California, Lawrence Berkeley Lab./Energy and Environment Division, LBL-37977.

ROSS, M., WENZEL, T. & WANG, M. Q. (1998) Real-World Emissions from Conventional Passenger Cars. J. Air & Waste Manage. Assoc., 48, 502-515.

SCHIPPER, L. & NG, W.-S. (2004) Rapid motorization in China: Environmental and Social Challenges, World Resources Institute, EMBARQ, ADB-JBIC-World Bank East Asia and Pacific Infrastructure Flagship Study.

SMMT (2004) Foresight Vehicle Technology Roadmap – Technology and Research Directions for Future Road Vehicles (Version 2), Cambridge, Society of Motor Manufacturers and Traders.

US DEPARTMENT OF DEFENSE (2003) Manager's guide to technology transition in an evolutionary acquisition environment, Washington DC, USA, US Department of Defense.

UTIGARD, T. A. (2005) Aluminium versus steel production trends – past, present and future. Aluminium International Today, Jan/Feb, 26-31.

VIEGAS, J. (2003) Transport Policy development in Europe 1950-2020. IN ECMT (Ed.) 50 years of Transport Policy. Paris, European Conference of Ministers of Transport.

WHITNEY, D. E. (2003) Physical limits to modularity. MIT Engineering Systems Division.

WORRELL, E. & BIERMANS, G. (2004) Move over! Stock turnover, retrofit and industrial energy efficiency. Energy Policy, 33, 949-962.

ZACHARIADIS, T. (2006) On the baseline evolution of automobile fuel economy in Europe. Energy Policy, 34, 1773-1785.

ZACHARIADIS, T., SAMARAS, Z. C. & ZIEROCK, K.-H. (1995) Dynamic Modeling of Vehicle Populations: An Engineering Approach for Emissions Calculations. Technological Forecasting and Social Change, 50, 135-149.