WHAT COULD BE THE COSTS AND BENEFITS OF TRANSPLANTING NEWER TECHNOLOGIES INTO OLDER CARS?

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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. 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. Consequently, there is a delay of potential energy and environmental benefits from more efficient technologies, while obsolete technologies continue to pollute at preceding levels although with some reduction as distances travelled by older cars tend to be smaller.

Our research explores one possible alternative to partially overcome this barrier through car organ transplant (COT). This corresponds to extending the car's lifetime while keeping its powertrain and exhaust after-treatment devices technologically upgraded by replacing obsolete components with best available technologies, during its service time.

The present paper presents our cost-benefit analysis of performing COT in a midsized gasoline car, over a period of 20 years of car ownership. Firstly, we propose a procedure to estimate the potential costs of performing COT. Then, we present the models we developed to estimate those costs and benefits: Total Car Ownership Cost model to evaluate the economic costs of car ownership and a Life cycle Inventory model to calculate the energy and environmental burdens (i.e., energy consumption, air emissions, materials' use and final disposal) from the lifecycle perspective (i.e., from "cradle to grave " and well-to-wheel").

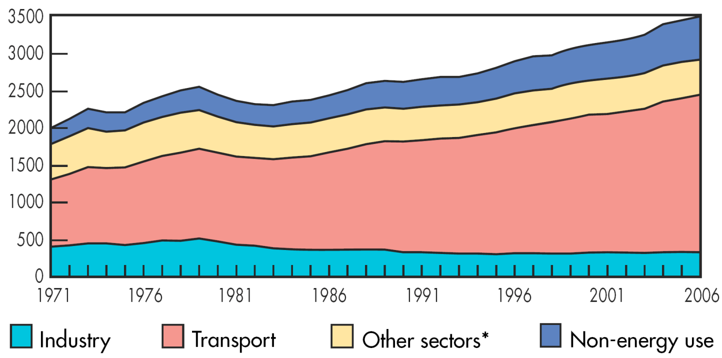
Importantly, we concluded that replacing the powertrain and exhaust after-treatment technologies could weigh as much as 20% of the car's curb weight and the full operation could cost about 25% of a new car and about 40% of a 6-years-old remarketed car. We concluded also that the payback of COT is reached after 6 years if the car is transplanted at the age of 5. Moreover, the additional burdens from COT (producing the replacing technologies and scrapping the replaced ones) are recovered after 3 to 7 years depending on the environmental burden under consideration. Based on a multi-objective function

(including economic and environmental damage costs altogether), we concluded that the payback period would be 5-6 years if the car were transplanted at the age of 5. Finally, we conclude by exploring the grounds for more radical transplantation of existing Internal combustion Engine models with electric-drive technologies, based on their predicted mass-production costs.

Keywords: Car use, organ transplant, technological diffusion, energy efficiency, cost-benefit analysis

INTRODUCTION

Current global challenges include, among others, the need to manage energy supply and security, raw material consumption, control solid waste generation, and reduce greenhouse gas emissions and local/regional pollution, while providing infrastructural, economic and social conditions for sustainable development. These challenges are particularly pronounced in the transport sector, where the current dependence on internal combustion engine (ICE) vehicles fuelled with petroleum from politically volatile regions remains a major barrier to overcome. The figure below illustrates clearly the higher growth rates of the world's transport energy consumption while the other sectors of the economy remain relatively stable.



Note: *Includes agriculture, commercial & public services, residential and non-specified other sectors.

Figure 1 - Evolution of Total Final Energy Consumption by Sector (1971 to 2006) (International Energy Agency, 2008)

Private cars account for a large share of those challenges. 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 3 decades in the European Union (Eurostat, 2003a) - and higher growth rates - (15-20%/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, including: exhaust gas prevention, alternative fuels (e.g., biofuels), alternative propulsion systems (electric drive vehicle – EDV - either pure, hybrid, or fuel-cell), and materials technology by which the use of lighter materials and developing reuse and recycling technologies is making the automotive industry (progressively) less material intensive. Importantly, passenger cars are in use for more than a hundred years, since the invention of the ICE - end of XIX century. Although the powertrain operation principle has basically remained the same, 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.

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 (GHGs) through global warming (IPCC, 2001, 2007). In reality, higher efficiency of cars is being off-set 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, air conditioning, among others), while technological breakthroughs take longer to diffuse and become effective, also. In this sense, although problems are far from solved and recognizing that technology isn't the panacea for all environmental impacts of transportation – for example, land occupation by the transport system remains one important issue to tackle – the situation is improving in general and in many respects the question of accelerating technological renewal of fleets towards more efficient technologies seems dominant (Viegas, 2003). 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 largely determined by the retirement of older vehicles and replacement by new models. However, depending on the motorization rate of countries and the driving forces for technological change (for example, accelerated end-of-life vehicle retirement policies), 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 after 10 to 40 years, only. 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 shortcut the delay in the diffusion of cleaner technologies 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). 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 older cars' scrappage

(ECMT, 1999). Kim *et al* (2003) concluded that, all lifecycle stages considered, cumulative emissions of regulated pollutants would be minimized by extending automobile service time: 7 to 14 years for 2000s model years and beyond, while a lifetime of 18 years would minimize cumulative energy consumption and CO_2 emissions. Therefore, reducing the lifetime of vehicles below these values is not the best option if the environmental impacts are to be minimized accounting for the overall lifecycle.

THE CONCEPT, RESEARCH QUESTION AND OUTLINE

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***' (hereon, referred to as COT) that aims to extending the service time of vehicles while keeping them technologically up-to-date (Moura, 2009). This is an analogy between organ transplant medical care in humans and car care. This concept corresponds to replacing any component of the powertrain and energy intensive parts of the car that are technologically outdated, downgraded or malfunctioning while keeping the remaining state-of-the-art and fully operative components and parts, in order to improve its energy and environmental performances and possibly reach 'like new' standards. ***Putting it simply, replace only what has to be replaced and keep the remainder running while no better options arise.*** Other authors suggested similar strategies (Ware, 1982, Nieuwenhuis and Wells, 2003, Maxton and Wormald, 2004, SMMT, 2004) such as repowering, retrofitting, among others. The potential advantages of the concept proposed here, compared to existing conventional alternatives, relate to potentially less energy and raw materials consumption and less emissions and solid waste generation.

This apparently simple and attractive proposal might have some drawbacks that we analyze partially in the present paper (refer to Moura, 2009, for a thorough and extensive analysis of the concept). Does COT reduce lifecycle energy and environmental impacts when compared to conventional car ownership approaches (for example, buying new or remarketed cars periodically), and is it attractive for car owners when comparing its total ownership costs to those of conventional approaches? This concept is effective only if the energy and environmental costs of producing the replacing organs (parts and components of a car) and scrapping of those substituted are offset by the gains in energy and environmental efficiency striving from the use of the transplanted organs. Otherwise, we would worsen the overall burden. Still, even if the concept is effective from the lifecycle energy and environmental perspectives, carrying out COT is believed to be largely dependent on its competitiveness in the market place (i.e., 'is it sufficiently attractive to car consumers').

In the next section, we present our methodology to estimate the potential attractiveness of car organ transplant for car owners and briefly present the model for lifecycle energy and environmental impacts analysis, followed by the presentation of another model for economic analysis. We end the paper with the presentation of our results and main conclusions.

METHODOLOGY AND MODELS FOR ANALYSIS

Methodology

When having to choose which car to buy, it doesn't matter if a car starts out cheaply (low acquisition cost) but costs more down the line (high running costs). Similarly, it is hardly preferable to choose a car that pollutes less if the start-up and operation costs are higher. This said, we could hardly conceive that a significant share of consumers would opt for transplanted cars if these are not competitive when compared to conventional alternatives, despite the potential efficiency improvements and corresponding operation cost reductions. Therefore, we check here if the costs of *cost of organ transplant* (COT) can compete in the market place with the remaining alternatives. If not, our hypothesis would have only fragile grounds for further analysis.

Effectively, consumers hardly (not to say *rarely*) consider environmental criteria when deciding which car to buy. Instead, they give priority to other attributes such as price, styling, reliability and safety. After reviewing many surveys on car type discrete choice modeling, Train (1986) found a surprising consistency in the attributes considered by households when choosing cars: price, operating costs (or fuel efficiency) and some measure of size (e.g., number of seats, weight, and/or wheel base). Furthermore, the UK used-car market survey by BCA (2006, p.76) reveals that environmental considerations were ranked 11th, in a set of 20 decision-making attributes. Although the RAC report on motoring (2006a) indicates that UK motorists recognize the environmental impacts of car use and that 50% of the inquiries would check emissions levels before purchasing their next vehicle, they also recognize that environmental attributes lag a long way behind the other criteria. By the end of this paper, we will have demonstrated that transplanted cars can be an attractive alternative for some segments of car consumers, under the assumptions of our analysis.

Firstly, we analyze the total car ownership costs (estimated in Euros) for the use of car over 20 years (our base case), then estimate what could be the car organ transplanting costs (that will constitute the alternative *transplant scenario*). After that, we analyze the optimal replacement of cars based on standard economic calculations, for each scenario. Thereafter, we compare the total economic costs of both scenarios, for different swapping intervals. We also test the impact of considering different horizons of analysis on the optimal replacement intervals. Finally, we analyze the same situation relative to the comparison of scenarios including environmental damage costs, also.

Models for analysis

We 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. Refer to the next table for the breakdown of total cost of car ownership by different authors. As we will present in the forthcoming section, our estimates fit within the intervals of others'.

Table 1. Total costs of car ownership

Motoring costs	Automobile de France [a]		RAC [b]	Edmunds.com [c]		TheAutoChannel [d]	Autopolis [f]		Average car
	France	UK	Germany	UK	USA	USA	Generic car	Average costs	%-Share range
	Renault Clio	Ford Focus	VW Golf	Generic car	Ford Focus	Ford Focus			
Depreciation	1,536 *(30%)*	2,569 *(36%)*	2,084 *(28%)*	3,035 *(44%)*	1,217 *(26%)*	1,128 *(24%)*	(36%)	1,928 *(28%)*	[24% - 44%]
Fuel costs	1,238 *(24%)*	1,897 *(27%)*	2,042 *(27%)*	1,395 *(20%)*	976 (21%)	1,278 *(27%)*	(21%)	1,471 *(22%)*	[20% - 27%]
Insurance	540 (11%)	560 *(8%)*	667 *(9%)*	516 *(7%)*	1,201 *(26%)*	857 (18%)	(11%)	724 (11%)	[7% - 26%]
Maintenance & repairs	639 (12%)	1,025 *(14%)*	1,136 *(15%)*	376 *(5%)*	680 (14%)	450 (10%)	(13%)	718 (10%)	[5% - 15%]
Financing	190 *(4%)*	279 *(4%)*	339 *(5%)*	1,304 *(19%)*	409 *(9%)*	351 *(8%)*	(13%)	479 *(7%)*	[4% - 19%]
Parking	489 (10%)	349 *(5%)*	607 *(8%)*					482 *(7%)*	[5% - 10%]
Fees & Taxes	338 *(7%)*	449 *(6%)*	333 *(4%)*	162 *(2%)*	215 *(5%)*	214 *(5%)*	(6%)	285 *(4%)*	[2% - 7%]
Opportunity cost						394 *(8%)*		394 *(6%)*	[8% - 8%]
Tolls	149 *(3%)*		256 *(3%)*					203 *(3%)*	[3% - 3%]
Other costs				158 *(2%)*				158 *(2%)*	[2% - 2%]
Total	5,119	7,128	7,464	6,946	4,698	4,672		6,840	
	27¢€/km	38€/km	40€/km	36€/km	25€/km	25€/km		32€/km	

[a] Automobile Club (2005)- Comparison of motoring costs of three equivalent gasoline-fuelled passengers cars from different EU countries. Depreciation is calculated by retrieving the remarketed car price after 4 years to its initial purchasing price. Annual mileage is approximately 19,000 km.
[b] Royal Automobile Club (RAC, 2006b)- The costs are an average from a set of 17 models (e.g., Toyota Yaris; Citroen C2; Toyota Prius; Ford Focus; VW Golf; BMW 3 Series; Peugeot 407; Mercedes C Class; Renault Espace; Porsche Cayenne). The item *'Other costs'* includes the RAC membership fee. Fuel costs consider a 12,000 annual mileage. Exchange rate is 1.254€ per £.
[c] Edmunds.com (2008)- Quotes for a 2008 Ford Focus obtained from the internet (04/04/2008). Fuel costs consider a 12,000 annual mileage. Exchange rate is 0.634€ per USD.
[d] AutoChannel.com (2008)- Costs calculation as previous note. Opportunity costs are considered using the cost recovery factor, $CRF = d / [1-(1+d)^{-n}]$, where *d* is the discount rate (3.8%) and *n* is the total time span before retiring the car.
[e] Maxton and Wormald (2004).

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€ per COT (for calculation details refer to Moura, 2008). Refer to the table next page for the cost breakdown we estimated and to Moura (2009, section 5.3, p. 161) for a detailed analysis and discussion of results.

Table 2. Transplanting costs breakdown (source: author)

Parts	Components	Materials Used	Materials cost	Labor time (Overheads)							Manufacturing costs (€)				
				Manufact.		Assembly		Mounting		Total	Materials Production	Labor costs			Total
		(kg)	(€/kg)	(hrs)	*(%)*	(hrs)	*(%)*	(hrs)	*(%)*	(hrs)		Manufact.	Mounting	Overheads	
Engine	Base engine	149	1.06	13.11	*250*	6.00	*250*			47.78	158	406	0	1,015	1,579
	Other components	39	0.71	2.20	*150*					3.30	28	47	0	70	144
	Module	188						6.00	*250*	15.00	0	0	128	319	446
Transmission	Clutch & controls	4	0.71	0.05	*150*					0.08	3	1	0	2	5
	Transmission	30	0.71	4.30	*150*	2.87	*250*			13.63	21	152	0	290	463
	Module	34						6.00	*250*	15.00	0	0	128	319	446
Chassis components	Engine electrical	14	1.32	0.53	*100*					0.53	19	11	0	11	41
	Engine emission Controls	8	5.29	0.70	*100*					0.70	42	15	0	15	72
	Exhaust system	23	1.06	1.40	*100*					1.40	24	30	0	30	84
	Catalytic converter	13	5.29	0.60	*250*					1.50	66	13	0	32	111
	Oil and grease	3	1.41	0.60	*150*					0.90	4	13	0	19	36
	Air conditioning	31	1.06	0.15	*150*					0.23	33	3	0	5	41
	Heating system	10	0.71	0.15	*150*					0.23	7	3	0	5	15
	Accessories equipment	2	1.94	0.10	*150*					0.15	4	2	0	3	9
Other transplant costs	Adaptation equipment	5	2.82	6.00	*250*			6.00	*250*	30.00	14	128	128	638	907
Total		330						18.00		130.41	422	824	383	2,771	**4,400**

The damage environmental 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).

Table 3. Damage costs from airborne emissions (adapted from Bickel and Schmid, 1999)

Pollutants	Damage costs (2000€/kg of air emissions)		
	Min	Max	Average
Carbon Monoxide (CO)	0.001	0.016	0.008
Nitrous Oxides (NO_x)	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 (http://www.pointcarbon.com)

Damage costs associated with individual emissions were calculated using the Impact Pathway Approach proposed by the ExternE project (Bickel and Schmid, 1999). Uncertainty is evident, since the maximum estimates are greater up to 25 times than the minimum estimates, and the values in Table 3 are considered illustrative and are used only to provide an indication of how the ranking of the different car ownership scenarios based on TCO including private motoring costs only may vary from those including external costs from air pollutants, also.

To calculate the environmental damage costs, we used a simplified life cycle (LCA). We included the following 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 energy/environmental coefficients with age-degrading mileage curves or weight: when addressing the operation stage we used annual kilometers; for the remaining stages we used car or organ weight. 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 al., 2005, DGEMP, 2005, ACEA, 2006, Ceuster et al., 2006, Zachariadis, 2006). Emissions during car use were based on the EMEP/CORINAIR guidelines from the European Environmental Agency (EEA, 2007). 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.

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).

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).

RESULTS: ECONOMIC ANALYSES OF CAR USE AND ORGAN TRANSPLANT

Vehicle lifecycle economic profile

We simulated the annual total ownership costs by summing cost estimates of the categories presented in the previous section, excluding environmental damage costs, for a 20-year service time. Figure 2 illustrates the life cycle profile of ownership costs for a 2000 midsize gasoline-powered car. The graph reflects the results obtained for a constant annual mileage (15,000 km), the base case scenario for maintenance and repair of the car and (fast) depreciation rates. We included a financing scheme of 3 years loan period with a down payment of 20% and an interest rate of 3%.

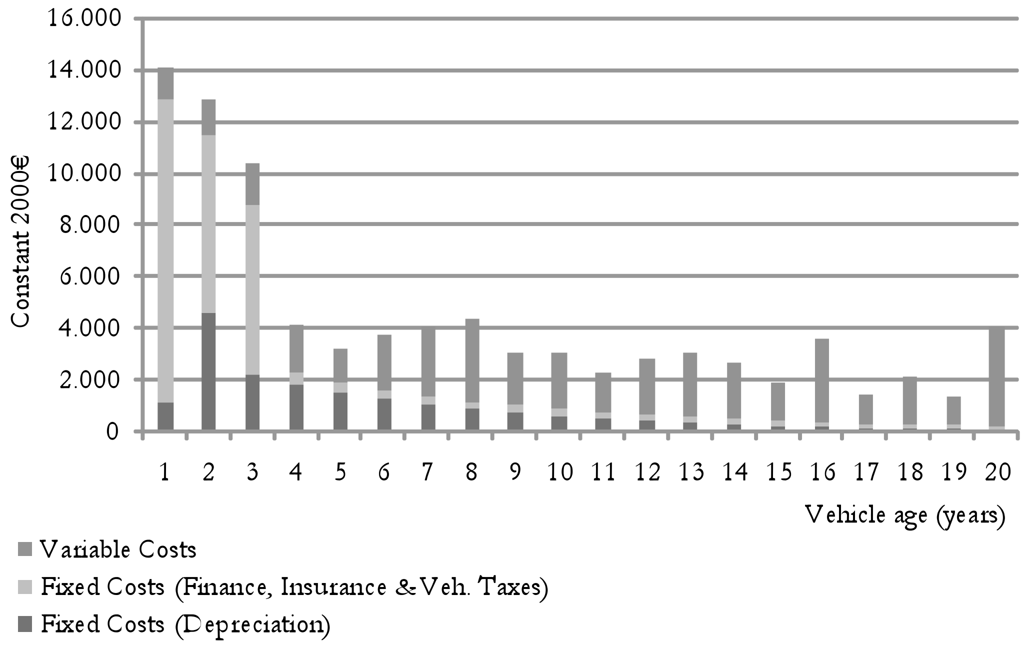


Figure 2. 20-year life cycle profile of ownership costs for a 2000 midsize gasoline-powered car (source: author)

We observe that fixed costs (including financing, insurance, and depreciation) exhibited a strong decrease with vehicle age (in constant 2000 Euros), principally due to the fact that we consider that the residual value of the used car depreciates strongly until its 7th year of age – we note that we assumed a payment period of 3 years with 3% interest rates. From the 7th year onwards, total ownership costs stabilize at approximately 2,000€/year (all costs included), although some variation can occur depending on the scenario of depreciation and maintenance and repair considered (this issue is addressed in the sensitivity analysis later, in this chapter). Interestingly, fuel costs correspond to more than 40% of annual ownership costs as from the 4th year of age. Therefore, any increase of fuel efficiency (possibly due to powertrain transplant) after this age is more evident, all costs considered. Repair costs generally increase over time. However, we opted to follow the approach by Spitzley *et al* (2004) by which the more random nature of these costs leads to substantial fluctuations from year to year.

The next figure illustrates the total per km life cycle ownership costs for different horizons of analysis: 5, 10 and 20 years of service time. These are 69¢€/km, 48¢€/km and 35¢€/km, respectively. Spitzley *et al.* (2004) estimated 30¢€/km and 20¢€/km per km costs for 10 a 20-year service time, respectively. These are below our results possibly due to the lower capital investment and fuel costs in the USA. Additionally, annual per km ownership costs from different sources presented in Table 1 (p.6) ranged from 25¢€/km to 40¢€/km. All in all, our results are consistent with these sources.

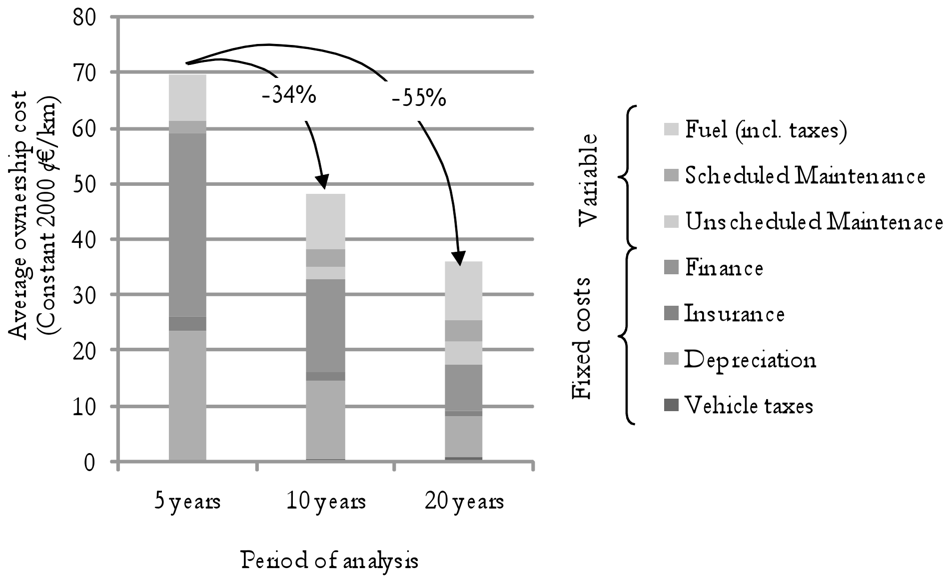


Figure 3. Per km life cycle costs of a 2000 midsize gasoline-powered car for different horizons of service time (source: author)

Fixed costs include financing, insurance and depreciation. Logically, as the service time increases, the higher capital investment costs (financing) are distributed over longer periods, since variable costs remain comparatively constant. In this sense, ownership cost can decrease more than 30% (and 55%) from 5 to 10 years (and 5 to 20 years) of car ownership. Still, we note that fixed costs correspond to 80%, 70% and 50% of total ownership costs depending on the service time considered (5, 10 or 20-years, respectively).

Transplant costs, payback period and net present value

At this point, we analyze how much savings the investment in organ transplant in a car adds to car ownership over a certain period. In this sense, we calculated two standard indicators of financial analysis of investments: payback period (PB) and net present value (NPV). In the first case, it indicates the amount of time (expressed in years) required for cumulative estimated future net benefits from an investment (here, savings in fuel cost, maintenance and repair cost and circulation tax) to equal the amount initially invested (here, transplant costs). NPV indicates how much value is added by an investment over some period of time, discounting the future cash flows of the project. These are used to compare alternative investment opportunities. In the present case, they are used to compare the alternatives of whether keeping the car as usual or to transplant it with Best Available Technology after some time.

The formulas used to estimate both PB and NPV are:

$$PB = \frac{TC}{\frac{1}{p.i.} \times \sum_{k=1}^{p.i.} \frac{CF_k}{(1+d)^k}} \qquad 1$$

and,

$$NPV = -TC + \sum_{k=1}^{p.i.} \frac{CF_k}{(1+d)^k} \qquad 2$$

where,

TC are the transplant costs (for the base case scenario, *TC* = 0, whereas for the transplant scenario , *TC* = 4,400€),

1. *p.i.* is the period of investment considered for the economic analysis (in the case of *PB*, we use the maximum expected service time of a car (20 years) to estimate the average annual cost and, in the case of NPV, we considered 5 to 10 years as intuitive time windows that people would consider when planning their private investment when considering private car swaping,

2. *CF* are the cash flows over one year and can be calculated by subtracting costs to benefits of some activity (here, benefits are intangible[1] and therefore CF refer to costs only),

3. *k* refers to calendar years, and

4. *d* is the discount rate (we considered 3% per annum).

Figure 4 (next page) presents the results of these indicators calculated for the differential between the alternatives referred in the previous paragraph and equations 1 and 2 are reformulated as follows:

[1] The benefits of car ownership can be: auto-mobility, accessibility, comfort, privacy, sense of control, etc.

$$PB = \frac{TC}{\frac{1}{20} \times \sum_{k=1}^{20} \left[\frac{-\Delta\left(fc_k + mr_k + ct_k\right)}{(1+d)^k} \right]} \quad 3$$

and,

$$NPV = -TC - \sum_{k=1}^{5\ or\ 7} \left[\frac{\Delta\left(fc_k + mr_k + ct_k\right)}{(1+d)^k} \right] \quad 4$$

where,

1. fc, mr and ct, refer to fuel costs, maintenance and repair costs and circulation taxes, respectively (we did not include the remaining cost items presented before since they are equal in both scenarios and, thus, their difference is null), and

2. Δ refers to the difference between those costs in both scenarios.

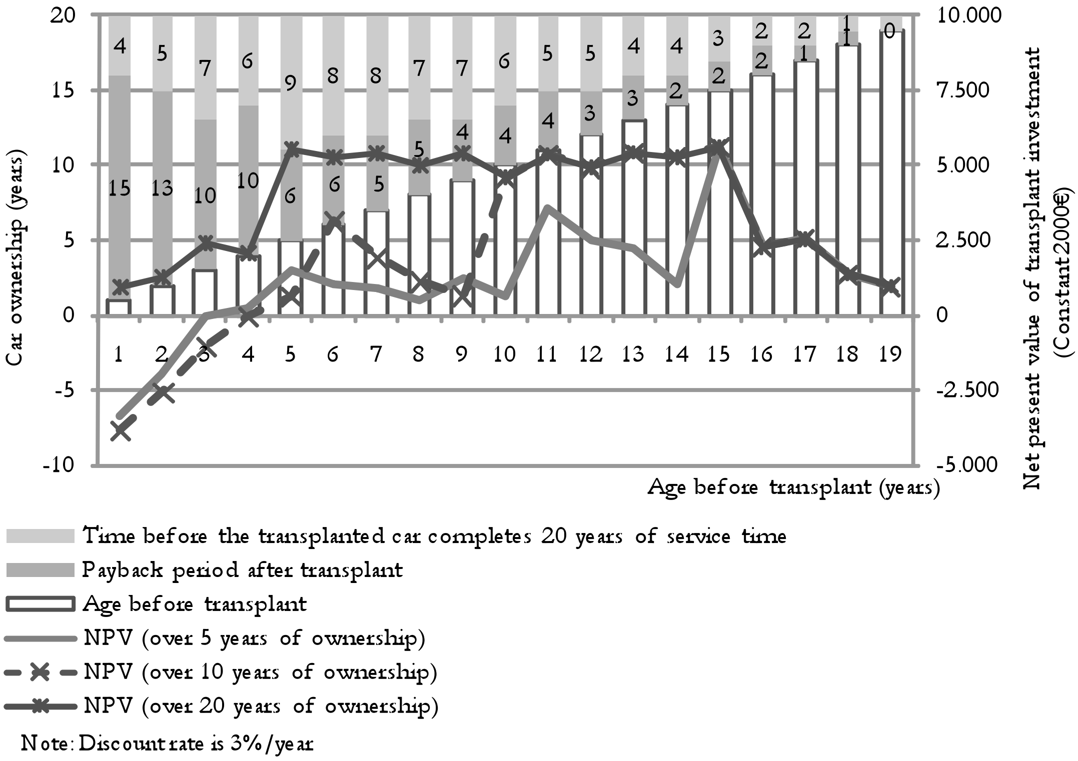


Figure 4. Payback period and net present value of transplant investment (source: author)

We will now analyze the previous figure providing a 'guided tour' on the various information we can take out.

1. The white bars in the graph correspond to the time when the car is transplanted and during which technology gets outdated and loses efficiency.

2. The dark-grey bars symbolize the period required to pay back the investment in organ transplant. We conclude that the payback period decreases as the age of transplant increases. As expected, the running costs of a car decrease as technology gets younger and updated (BAT) considering that all costs depend on the car's efficiency

(including circulation taxes that depend on its carbon efficiency). Therefore, the bigger the gap between the model year of the car and that of the transplanted components, the lower is the payback period. Furthermore, if we add the age of transplant to the payback period (white bars) we obtain the total service time required before the payback period is completed. Interestingly, we conclude that if the car is transplanted with 5 years of age, the investment is cost-effective after 6 years (considering economic costs only and under our assumptions), reaching a total service time of 11 years. In this case, the investment is cost-effective for a 6% fuel economy improvement from 8.6 liters/100km to 8.1 liters/100km (considering that the car is used during 6 years after being transplanted). This results are consistent with the findings by Greene and Duleep (1992) who estimated that fuel economy improvements in the order of 7% to 11% are probably cost-effective – in their case, they estimated fuel economy improvements of new models. Furthermore, the report "*Making cars more efficient-Technology for real improvements on the road*", by the ECMT (2005), refers that under the assumptions of a gasoline vehicle used in Europe (for example, fuel prices), there are several technological improvements in cars that are cost-effective from the consumer's viewpoint. For example, electric water pumps, efficient alternators, efficient air conditioners, automated (or shift indicator lights) manual transmission are paid for by fuel savings in 3 years or less, and should therefore be attractive to many consumers. According to the same report, the prospects for diesel-powered vehicles are not so promising party due to lower fuel cost savings and partly because diesel engines use less fuel during cold weather. Considering that the transplanting kit (as we conceived here) includes these technological improvements, we can conclude that our results are more conservative that those presented in the ECMT report.

3. <u>Light-grey bars</u> symbolize the time left after the payback period and before the car ownership period we considered in our exercise, finishes. Correspondingly, they indicate the time during which the car owner accumulates net benefits after the payback period of the transplant investment. Again, these benefits are maximized if cars are transplanted at the age of 5.

4. <u>Lines with stars</u> symbolize the Net Present Value for a horizon of analysis of 20 years. Accordingly, NPV is maximized when the car is transplanted at the age of 5. We note that NPV remains quite constant if cars are transplanted until 15 years of age. However, if we consider different horizons of analysis (for example, 5 and 10 years – illustrated by the solid line and the dashed line with crosses, respectively), the age of transplant that maximizes the NPV is 15 years of age. In this case, the payback period would be 2 years leaving 3 years to complete the maximum service time (20 years). Realistically, only a very small share of car owners would opt for this alternative. Hence, we analyzed the second best NPV for both period of analysis and concluded that the corresponding ages of transplant are:

    a. 11 years, if the car owner analyses her/his investment over 5 years, where the payback period is 4 years and the net benefits are obtained over 1 year (accounting for a minimum 16 years of service time); and

b. 6 years, if the car owner analyses her/his investment over 10 years, the payback period is 6 years, and net benefits are collected over 4 years (accounting for a minimum 16 years of service time, also).

After trying other periods of analysis (results not shown here), we conclude that the transplant ages that maximize NPV (other than 15 years) lie between 5 and 7 years, if the car owner analyses her/his decision up to 10 years. Importantly, if she/he considers investment periods of less than 5 years, the transplant ages raise to 15 years. Again, we think that only a very marginal share of consumers would opt for such an alternative.
We concluded from the sensitivity analysis to the transplant costs that our estimated are rather stable and would vary mainly if the labor costs involved would changed radically. However, transplant costs do not include any profit for the transplanter (i.e., those who perform organ transplant in cars – for instance, garages). As such, transplant prices are not expected to be the same as transplant costs. In this sense, we analyzed situations where profits are added to transplant costs – 10%, 25%, 50% and 100% more than base costs. The following figure illustrates the payback periods obtained for profit range. We conclude that only a few car owners would transplant their cars if transplant costs would double (i.e., +100%). For instance, transplanting a car at the age of 9 years, would require a payback period of another 9 years, leaving 2 years before the end of car ownership we considered, here. Yet, the payback period for a car transplanted at the age of 6 years, would correspond to 7 years, if transplant prices were 50% of base costs.

Figure 5. Payback periods for different profit ranges

We calculated payback periods and NPV indicators including environmental damage costs from both scenarios – we used the unit costs (€/kg $_{pollutant}$) presented in Figure 6 (next page). In previous sections, we explained that the environmental damage costs refer to air emissions, only, and that they include all lifecycle stages. As mentioned before, we calculate the gains from technological transplant on the operation emissions (including 'well-to-wheel' and maintenance related emissions), and estimate the payback period to recover the additional environmental damage costs from producing materials, manufacturing and assembling components, and handling the EOL of replaced components.
We note that the costs related to PM emissions were not included. According to the EMEP/CORINAIR Guidelines (EEA, 2002), PM emissions during the operation of gasoline-fuelled cars are minor. Conversely, these are important during the production of materials and manufacturing of vehicle components. If we include them in the present

calculation, we would distort our results and mislead our conclusions since there is no impact from technological transplant on PM emissions (i.e., infinite payback periods if PM were considered alone). The next figure illustrates the results of our calculations and includes the payback period for environmental damage costs (white bars), the payback period of financial costs (dark grey bars), and finally, all costs considered together (light grey bars).

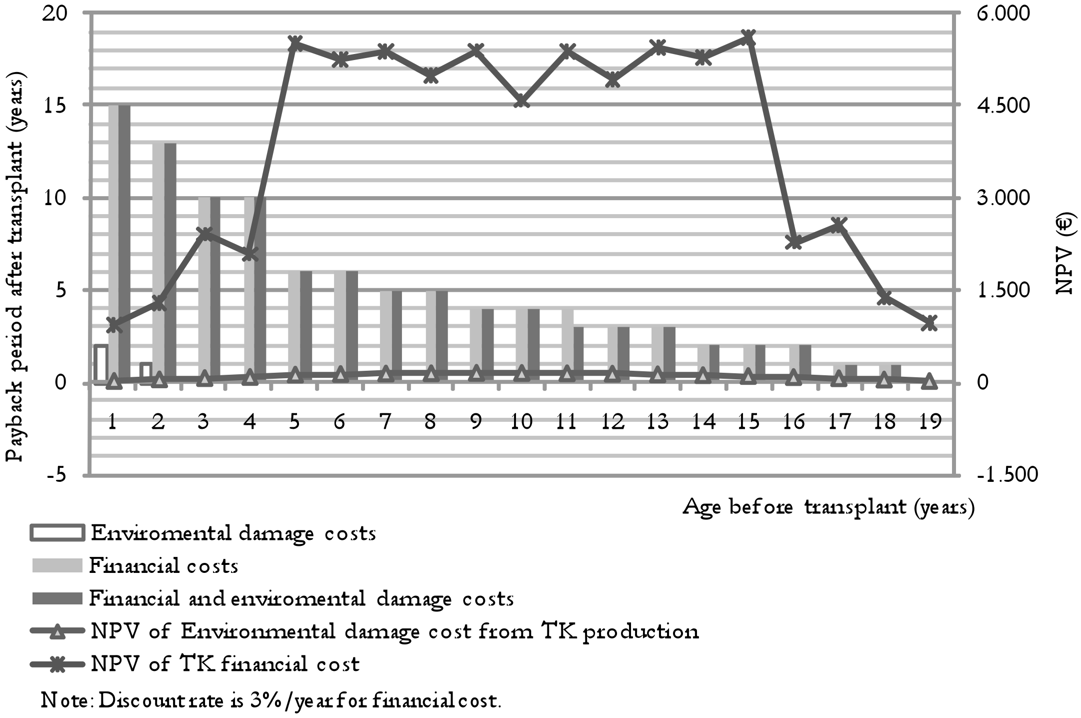


Figure 6. Payback period and net present value of transplant investment, including environmental damage costs (source: author)

Environmental damage costs are recovered sooner than economic costs, as from the transplant age of 3. In the case of younger used cars, the reduction of emissions striving from the gains of efficiency after technological transplant are not sufficient to offset the pollution from the production of transplanting kits. In reality, cars are not expected to be transplanted before 4 years of age. Figure 6 includes the NPV from both environmental costs (curve with triangles) and economic costs (curve with crosses) and shows the gap between them, in monetary terms. Environmental costs influence the payback periods from technological transplant only to small extent – i.e. one year increase of payback if the car is transplanted after one year. The remaining payback periods are mainly driven by the economic cost of technological transplant at different ages.

SUMMARY AND CONCLUSIONS

We described in this chapter, the total car ownership cost model and the cost estimates of technological transplant. We observed that the highest costs of car ownership are related to the depreciation of the car over its service time. Per km unit cost of car ownership (all costs considered) decreases significantly (up to 55% for a 20-years service time) as the car ages. Interestingly, the fixed costs (which include financing, depreciation, insurance and taxes) of car ownership are dominant during the vehicle's service time. During the first 5 years, these

correspond to more than 80% of total costs. Considering an ownership time of 20 years they correspond to 50% of total costs. These analyses suggest that, from the economic perspective, extending the service time of the car is a rational and more profitable option.
We conclude also from the previous analyses that technological transplant might be an interesting option for some car owners, since they can recover their investment after a reasonable period of time (i.e., approximately 5-7 years depending on the age of transplant, although this depends strongly on the transplant price to be adopted by transplanters). In addition, there are environmental gains from transplant operations by which increased emissions due to the production of transplanting kits and scrappage of replaced components are recovered after shorter periods of time (i.e., 4-5 years), as well. We recall that we do not include in this environmental damage accounts, the avoidance of raw materials consumption and waste production. Therefore, the payback periods should be even lower. Furthermore, if the transplanting kit includes remanufactured parts and/or components, the overall energy, environmental and economic burdens can be potentially lower. Refer to Smith and Keoleian (2004) for a detailed analysis on the lifecycle environmental impacts of remanufactured engines.

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