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ABSTRACT

This paper derives a model of irregular or unplanned maintenance and repair outlays from an analytical framework based on rational economic behavior in which maintenance, utilization and service life decisions are appropriately integrated and estimates it with the help of data from 433 automobiles imported into Greece from various countries. On the theoretical plain it is shown that the model allows endogenously for most of the variables that have been identified in the relevant literature as important determinants of such expenditures. Also the model yields sharp sign predictions for the included variables and by doing so it sheds considerable light on several issues of theory and applied research in this area. On the empirical plain it is found that: a) there are two behavioral clusters of automobile owners, i.e. one that recommends pooling of the corresponding country data and another that suggests separate estimation of the model at the country level; b) as expected, the reported amounts of these outlays are related positively to the automobile's age, intensity of utilization, and road accidents, and c) even though the expenditures under consideration for Japanese made cars appear to be relatively more sensitive to road accidents than those of automobiles from all other countries, at least in the years of the sample and on this basis, they offered the best value for the money.

JEL classification: D12, E2, E22

Key words: maintenance and repair expenditures, utilization, service life, road accidents

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1. Introduction

At the time that Bitros (1976a, 1976b) emphasized the interrelated nature of operating and capital policies,[1] the literature did not offer a unified framework based on rational economic behavior to analyze their interactions. Moreover, even if such a framework did exist, these interactions would be extremely hard to estimate and test because the data on maintenance and repair outlays were extremely scanty, if at all available. In the decades that have elapsed since then, the literature makes reference only to a few relevant studies. The one by Smith and Cowing (1977) derived a three-equation model in which maintenance expenditures, gross investment and scrappage were interrelated. But it ignored the thorny issues associated with the firm's profit horizon and made no attempt at empirical implementation. The next noteworthy contribution was by Everson (1978, 1982). This gave rise to a four-equations model for a cost-minimizing railway firm and estimated it with the help of data for freight cars of the Class-I railways in the United States. However, on deeper examination it turns out that this model is marred by a grave inconsistency. To highlight it, consider the two-stage constrained cost minimization approach adopted to describe the behavior of the railway firm. In the first stage the firm chooses the utilization, maintenance, installations and retirements of freight cars, subject to an arbitrary rate of change in its outstanding freight car capacity. Then, in the second stage, by plowing the optimal values from the first stage back into the cost function, the firm forms its normalized restricted cost function. Finally, upon minimization of the later function, the firm is presumed to obtain the optimal path of the rate of change of its freight car capacity over an infinite horizon, and hence its level. But from Preinreich (1940) we know that the optimal lifetime of freight cars should be computed jointly with the economic life of freight cars in the chain of replacements extending as far into the future as the railway's profit horizon. By implication, in the first stage in which the firm solves for the optimal utilization, maintenance, installations and retirements of freight cars it must solve subject not to an arbitrary but to the optimal rate of change of freight car capacity in every future period; because as solved the model may not yield the optimal values of the variables under consideration.

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[1] Owners' decisions with respect to their durables may be classified into two categories. The first concerns the decisions that are primarily directed at changing the condition of durables themselves and includes replacement, scrapping, expansionary investment, overhauling and stripping, whereas the second category comprises the decisions that are associated with the utilization and maintenance of durables. In this paper I shall refer to the former as *capital policies* and to the latter as *operating policies*.

With the exception of the contributions by Hartl (1983) and Choi, Kollintzas (1985), the papers by Arnott, Davidson, Pines (1983, 1986), the doctoral dissertation by Smith (1987) and the paper by Kim (1988),[2] the relevant literature remained dormant until the second-half of the 1990s. From then on, and particularly from the publication of the paper by McGrattan and Schmitz (1999), which demonstrated that maintenance and repair expenditures is too big a component of Gross National Product (GNP) to be ignored, research activity intensified and made significant strides in three fronts. In the first front researchers introduced the above-mentioned operating and capital policies into one-sector dynamic general equilibrium models and analyzed their interactions in the steady state. The papers by Perez, Javier, Ruiz-Tamarit (1996), Collard, Kollintzas (2000), Licandro, Puch (2000), Licandro, Puch, Ruiz-Tamarit (2001), Leighter (2001), and Boucekkine, Ruiz-Tamarit (2003) fall in this category. However the planning horizon in these models is assumed to be infinite and this implies that in the steady state economic agents do not have an independent scrapping policy. In other words, they are prohibited from deciding at any time not to replace worn-out capacity.

Research work in the second front aimed precisely at addressing this limitation. In this the planning horizon is treated as an endogenous variable. By allowing economic agents to decide how many investment cycles, if any, and for how long in each investment cycle would be optimal to replace capacity, the policy of scrapping is brought back into the forefront. But this is made possible at a cost. This cost is that the simple one-sector models of the preceding studies, where there is only one representative firm applying continuously a replacement policy, is abandoned in favor of a two-sector dynamic general equilibrium model as follows. Initially, Bitros, Flytzanis (2002) set up a dynamic partial equilibrium model in which the capital using enterprise faces three options: to enter into business, to exit, if it is already in operation, or to replace its capital and continue doing so up to some profit horizon. Then, assuming that the firm plans to exit at the end of the useful life of its current capital stock,[3] Bitros, Flytzanis (2004) analyzed in depth the properties of utilization and maintenance. Lastly, drawing on the analytical results from the above studies, Bitros (2008a) presented a two-sector dynamic general equilibrium model with one representative firm in each sector, the main difference between them being that the firm in the more capital-intensive sector applies replacement, whereas the firm in the less capital-intensive sector applies scrapping.

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2 The analysis in Kim's (1988) paper is characterized by the same inconsistency that was pointed out above in regard to the paper by Everson (1982).

3 The model presented by Bitros, Flytzanis (2004) has not yet been extended to a capital replacing enterprise.

In the third front researchers have been studying the implications for capital policies of embodied technological progress as well as of various sources of uncertainty associated with the process of technical change. The papers by Boucekkine, Germain, Licandro, Magnus (1998), Boucekkine, Pommeret (2004), Cruz, Pommeret (2004), and Bitros(2008a), and Bitros give a representative sample of the growing literature in this field. But as of the time of this writing no attempts have been reported to highlight the influence of embodied technological progress on the interactions of operating and capital policies. As a result, in the presence of embodied technological progress and all other sorts of uncertainty, issues such as the degree of substitutability between maintenance and new investment, the trade-offs between utilization and maintenance under replacement and scrapping, the roles of regulatory and operating safety constraints, etc., remain in the promising agenda of future research.

In light of the preceding remarks this paper has three objectives. The first is to show how a consistent model of maintenance and repair expenditures for a firm operating under a policy of scrapping can be extracted from Bitros, Flytzanis (2004). The second objective is to substitute into the latter model reasonable analytic forms for the various functions involved so as to highlight the directions in which such expenditures are expected to change in response to changes in the other endogenous and exogenous variables. Thus past and new empirical results will become easier to interpret and more appealing to adopt in the design of maintenance and repair policies. Finally, in order to demonstrate the usefulness of the model, the third objective is to estimate it with the help of data from 433 passenger cars imported into Greece from various countries. The results that emerge are quite explicit. For example, it is found that: a) the best estimates are obtained when estimation takes place at the country level of the sample observations; b) the reported amounts of such outlays are related positively to the automobile's age, intensity of utilization, and road accidents, and c) even though the expenditures under consideration for Japanese made cars appear to be relatively more sensitive to road accidents than those of automobiles from all other countries, at least in the years of the sample and on this basis, they offered the best value for the money.

The paper is organized as follows. Section 2 lays out the theoretical model. Section 3 derives the model to be estimated. Section 4 describes the available data, as well as the definitions of the variables and the conventions that were adopted for their measurement. Section 5 presents and comments on the statistical properties of the estimated model and the experiments performed with it; and, finally, Section 6 provides a summary of the main findings and conclusions.

2. The model

Consider the owner of an automobile. The user's manual informs him how often he is expected to change oils, oil filters, sparkplugs, etc. If he wants to enjoy normal service and avoid the risk of major damages, he must follow the recommendations of the manufacturer of his car. As a result, these *regular* maintenance outlays may be considered mandatory. However, the same is not true with respect to the outlays for *irregular* or *unplanned* maintenance and repair (henceforth just maintenance, unless stated otherwise for comparison purposes), because to some extent and depending on the circumstance these are under his control. So the problem that he faces is when and how much to spend in undertaking such activities.[4]

According to the model presented by Bitros, Flytzanis (2004), which is briefly summarized in the Appendix, the automobile owner would be expected to decide according to equation A(8). This has several merits. One of them is that it constitutes an equilibrium relationship derived from an analytical framework based on rational economic behavior in which operating and capital policies are properly integrated. As such it gives theoretical support to past results and at the same time it provides a model of choice for related empirical applications at various levels of aggregation and for all kinds of consumer and producer durables. Moreover, since from propositions A(2.i) and A(2.ii) we know how the operating policies depend on the relative magnitude of the two discount rates, we are able to trace their time paths as well as all their possible shifts. This is a nice result because it highlights the potential of the model for dynamic analyses of the policies under consideration.

Another merit is that A(8) features endogenously most of the variables that have been considered in the relevant literature to be important determinants of maintenance expenditures. What this implies is that we gain some understanding of past findings in this area. For two cases in point consider first the results obtained, for example, by Bitros, Panas (1988), according to which the quality of cars is positively related to their size. Clearly if larger cars have more quality, they may tend to break down less frequently than smaller cars, so that on the average they may cost less to maintain. To capture this effect, in previous endeavors researchers included a proxy variable for size without any guidance regarding the sign of its coefficient. By contrast, the prediction from A(8) is that the sign of K_0 depends on the balance

[4] Aside from *regular* and *irregular* or *unplanned*, in the literature and in everyday life one comes across references to *preventive* maintenance. The latter applies mainly to durables like jet engines and ships, which are subject to sudden failure with potentially catastrophic consequences. For the analysis of preventive maintenance, a source to begin with is Jorgenson, McCall, Radner (1967).

of two effects, i.e. relating respectively to the quality and the scale of the car. If the effect of quality is larger than that of the scale the sign will be negative, and vice versa.

The second case has to do with the role of salvage value and it has a long story. In the past S_T was introduced into maintenance equations by reference to three arguments. The first of them drew heavily on the work by researchers who explored the impact of financial market imperfections. What these authors found is that such proxy variables of credit availability as interest rates, term to maturity, down payment, transactions costs, collateral, and probability of turndown, influence the demand for consumer durables in the same direction. Thus, since the amount one would need to borrow in order to purchase a new car depends negatively on the amount one would expect to collect from selling one's old car, the proponents of this argument found it natural to conclude that changes in salvage value should be related inversely to maintenance expenditures.

Contrary to the above is the conclusion of those like myself who subscribed to the second argument. To explain it, assume, as it happened in Greece for many decades, that because of credit rationing consumers do not have access to bank loans for buying new cars.[5] In this suppressed financial environment, aside from their transport services, passenger cars are considered good stores of value. As matter of fact in times of rapid inflation the latter function of cars may be the main reason for owning them. But if so, as salvage value appreciates, car owners would be expected to go out of their way to maintain them in prime condition.[6] On this basis then, salvage value and maintenance expenditures should be related positively.

Lastly, those who adhered to the third argument arrived at the same conclusion but through another train of thoughts. Their conceptualizations suggested that, if increases in the prices of new cars raise the prices of older cars, S_T should enter into the maintenance equation with a positive sign, because the cost of maintenance becomes relatively cheaper than before. In other words, as the prices of old cars increase, maintenance becomes a better substitute for

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[5] Before Greece entered the Eurozone in 2001, not only households but also several large sectors of the economy (e.g. housing) had no access to bank credit. Over the postwar period and through the end of the 1990s, the environment of financial markets remained pretty much as described by Halikias (1978, 211). In particular, the limited amounts of credit that were advanced to these sectors were distributed indirectly via manufacturing. To buy a car at the time of the sample, buyers had to pay in cash or expect to receive at most some small credit accommodation by the car importer.

[6] In pre-Eurozone Greece, rapid domestic inflation forced the Bank of Greece to undertake frequent devaluations of the Drachma. When devaluations occurred, the prices of imported cars increased by a corresponding percentage and raised the salvage value of older cars. As a result, the average service life of automobiles in Greece increased gradually to over two times the average service life of cars in the advanced economies, thus rendering the ownership of cars very maintenance intensive.

a new car, so the owners of older cars, who otherwise might have scrapped them, are induced to maintain them. Consequently, they argued, since all evidence from the movement of prices in second hand markets shows that increases in new car prices do raise the prices of older cars, a shift in S_T would be expected to increase maintenance expenditures.[7]

In light of the preceding remarks it is clear that the appearance in A(8) of K_0 and S_T from theory resolves two issues that have been clouded in uncertainty for many years. But these are not its only novel features. In addition it includes two key variables, i.e. utilization u_t and service life T. Turning first to the latter, from A(8) we observe that as service life increases maintenance expenditures are predicted to increase.[8] So what we have here is solid theoretical evidence in support of the ad hoc arguments that are occasionally adopted to rationalize the introduction of service life into partial and general equilibrium analyses of capital.[9] However, whether maintenance expenditures increase faster with increasing service life, as hypothesized, say, by Brems (1968, 37-41), or not is a question that can be resolved only on empirical grounds. For this reason the importance of empirical research in this respect can hardly be overstressed.

Next let us return to the utilization rate. From A(8) it emerges that an increase (decrease) in the intensity of utilization u_t would be expected to increase (decrease) maintenance. What this implies is that the operating policies move from the region of less intensive policies, i.e. less utilization and less maintenance, to the region of more intensive policies, i.e. more utilization and more maintenance, and vice versa. The reason for this result is found in two choices: the decision to restrict attention in this paper solely to the equilibrium solution of the model, and the specification of the operating function in A(6.i). For, as propositions A(2.i) and A(2.ii) succinctly state, the operating policies move from softer (less utilization and more maintenance) to harder (more utilization and less maintenance), and vice versa, when the relative magnitudes of the two discount rates σ / ε and $\sigma - \eta$ differ, whereas if A(6.i) were speci-

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7 Since at the same time the change in salvage value would influence scrappage in the opposite direction, this implication is fully corroborated by the empirical evidence, which, as in Bitros (1976a, 1976b), shows that maintenance expenditures and scrappage are related negatively.

8 The available evidence shows that both *regular* and *irregular* or *unplanned* maintenance and repair afford owners of automobiles some wide margins of flexibility when choosing the timing of the corresponding activities. But this evidence relates to automobile fleets with relatively low average service lives, say 6 years or so. When fleets consist of automobiles having an average service life of, say, over 12 years, as it was the case in Greece in the said period, maintenance and repair could hardly be postponed, because the breakdowns were more frequent and more severe.

9 For an example in this regard see Karplus, Paltsev, Babiker, Reilly (2013).

fied as linear no determinate equilibrium policies would exist.

To summarize the discussion so far, the model that was just presented yields sharp sign predictions for most of the main variables that determine irregular maintenance expenditures. As a result it sheds some light on several long-standing issues in the relevant literature and may stir interest for more applications using data from different durables, time periods, and countries.

3. From the theoretical to the estimating model

As it was stressed above, equation A(8) includes the main variables that economic theory considers important determinants of maintenance expenditures. However, the model derived from theory may be too narrow to account for several other factors, which may influence their timing and amount of such expenditures. By implication equation A(8) ought to be expanded to allow for additional factors that have been shown or are suspected to influence them significantly, irrespective of whether the identification of these important factors originates in the theoretical or empirical literature.

Thinking along these lines, it seems reasonable to assume that maintenance expenditures may be related positively to the number and the severity of car accidents. Of course, since both the salvage value S_T and the intensity of utilization u_t may act as proxies for past and contemporaneous car accidents, one may be tempted to surmise that allowing separately for such occurrences is superfluous and liable to introducing specification errors. Yet the impact of accidents that is transmitted to maintenance through these two channels is obscured, if at all discernible, because it operates together with other influences working in the same or different directions. Therefore, the decision to account separately for accidents is justified, at least on an experimental basis. For this reason I shall introduce the dummy variable $Dacc_i$ for car accidents.

The model should be expanded also to include two additional dummy variables: one for multiple-ownership of cars, $Down_i$, and another for rating the owner's memory regarding irregular maintenance incidences, $Dmem_i$. Referring to the former, its influence on maintenance expenditures was expected to be negative on the presumption that owning more than one car may afford owners the freedom to be lax about their maintenance. As for the latter, this was entered with a positive sign because, when car owners reflected and reported on their relevant historical records, it was natural for them to remember more accurately the more recent maintenance bills that they had paid.

Finally, since the passenger cars in the sample are imported into Greece from various countries, it was deemed pertinent to insert into equation A(8) a series of dummy variables,

$D_1, D_2 ... D_n$, so as to allow for the possibility of different country effects. The rationale for this specification is twofold. First, that automobiles manufactured in different countries may require different amounts of maintenance services, and second, that spare parts are priced differently by automakers in various countries. In particular, according to the views prevailing in the maintenance shops in Greece, cars imported from Germany and Japan would be expected to be less demanding in maintenance expenditures in comparison to those imported from Italy.

On account of these extensions, the cross-sectional nature of available data, and the grouping of countries from where passenger cars are imported into Greece, the model for maintenance expenses took the form:

$$m_i = [\alpha u_i^{\beta} \cdot \frac{S_{T_i}}{(K_{0i} e^{-\omega T_i})^{\varepsilon}}]^{\gamma} e^{\zeta_1 Dacc_i + \zeta_2 Down_i + \zeta_3 Dmem_i + \xi_1 D_{Fi} + \xi_2 D_{Gi} + \xi_3 D_{Ii} + \xi_4 D_{Ji} + \xi_5 D_{Oi}} . \quad (1)$$

where *F*=France, *G*=Germany, *I*=Italy, *J*=Japan, and *O*=Other countries. Finally, taking logarithms gave the following estimable form of the model:

$$\begin{aligned} \log m_i = \theta_0 &+ \overset{(+)}{\theta_1} \log u_i + \overset{(+)}{\theta_2} \log S_i + \overset{(+)}{\theta_3} T_i + \overset{(?)}{\theta_4} \log K_{0i} + \\ &+ \overset{(+)}{\zeta_1} Dacc_i + \overset{(-)}{\zeta_2} Down_i + \overset{(+)}{\zeta_3} Dmem_i + \\ &+ \overset{(?)}{\xi_1} D_{Fi} + \overset{(-)}{\xi_2} D_{Gi} + \overset{(+)}{\xi_3} D_{Ii} + \overset{(+)}{\xi_4} D_{Ji} + \overset{(?)}{\xi_5} D_{Oi} + \upsilon_i , \end{aligned} \quad (2)$$

with υ_i denoting a residual error term.

So, by way of passing to the next section, it is worth concluding that (2) constitutes a compromise between a narrow maintenance model like A(8) derived from rational economic behavior and a statistical model that could be formulated on purely ad hoc grounds.

4. Data and measurement of variables

The data used in the estimations were obtained through a questionnaire mailed in June 1986 to the subscribers of the magazine published by Hellenic Automobile and Touring Association, known in Greece as ELPA. In particular, at the request of the research team, ELPA offered to include our questionnaire in one of the regular mailings of their magazine, together with a letter requesting from their subscribers to complete it to the best of their records and recollections about the maintenance of their cars. Within days the completed questionnaires started arriving anonymously to our university premises. The waiting period closed in December 1986 and the database was assembled shortly thereafter. Up to the closing date we received a total of 441 questionnaires. However, 8 of them were deemed unusable due to various gaps and conflicts in the responses and this left us with a sample of 433 questionnaires, relating to cars imported into Greece from various countries and sold to households exclusively for private use.[10]

Those who responded answered a series of questions regarding the type and features of their car, the timing and extent of *regular* and *irregular* or *unplanned* maintenance bills they paid in recent years, the resale price of their cars, etc. In particular, to obtain information about the type and features of the automobiles, the respondents were asked to indicate: the model of their car, its manufacturer and country of origin, the year of its first circulation, its engine capacity, and the number of kilometers the car was run on the average per year. To gauge regular maintenance experience, the questions referred to the frequency with which engine oil, oil filter, air filter, petrol filter, points, spark plugs, brake pads and windscreen wipers were replaced. On the other hand, in order to obtain information about irregular maintenance events, the questions required the respondents to report: the years and the amounts they had spent for repairs of such major car components as engine, cooling system, electric circuits, brakes, suspension, steering system and exhaust pipe. Finally, additional information that was considered necessary in the research was obtained from questions referring to the record of accidents, the resale price of the cars, the number of cars owned, etc.

However, since the questionnaire was addressed to subscribers of a particular motoring association and not to all car owners in Greece, a few qualifications regarding the nature of the sample are in order. Car owners subscribe to motoring associations to minimize the financial cost and the cost of discomfort from an unexpected breakdown of their car, particularly when riding far from home. Hence they are motivated to subscribe by the condition of their car, the reliability of its maintenance, and the mode in which they use it. If the car is of average to old age and is used frequently over long distances, it will pay not only to maintain it meticulously but also to subscribe to the motoring association because of the extra insurance it provides. On

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[10] This aspect of the data is emphasized for the purpose of the following clarification. From a methodological point of view the modelling of maintenance and repair expenditures by car leasing and other firms would not be much different than the one adopted here for households. For example, since the tax treatment of such expenditures is different between businesses and households, (2) might include certain additional variables to capture their deductibility for the former but not for the latter. However, otherwise all main variables would be present irrespective of the type of ownership and utilization of the vehicles.

the contrary, if the car is relatively new and is used in short trips within the city, subscribing may not be worthwhile. Therefore, our hunch was that the data in the sample came from a population of car owners with above average age cars who maintained them with care and who used them regularly over relatively long distances. For these reasons the magnitudes of effects that will turn up in the statistical analysis should be interpreted with caution as they might not be representative of such effects in the fleet of all passenger cars in Greece.

The variables which enter the statistical analysis are based on information extracted from the questionnaire and are defined and measured as follows:

m_i = Expenditures for *irregular* or *unplanned* maintenance calculated as an average of such outlays in the last three years leading to the year of observation and deflated by the Consumer Price Index (CPI).

u_i = Average number of kilometers run by the car per annum in the last three years leading to the year of observation.

T_i = Age of the car measured in months from the date of its first circulation.

S_i = Resale price of the car as reported by its owner.

K_{0i} = Capacity of engine. This variable takes on integral values of which the smallest, (7), corresponds to cars with engine capacity between 600-700cc and the highest, (26), depicts cars with capacity above 2500cc.

$Dacc_i$ = Record of accidents. This variable takes the values 0 for no accidents, 1 for no serious accidents, 2 for accidents of average seriousness and 3 for serious accidents.

$Down_i$ = Multiple car ownership taking the value of 0 if the owner does not own other passenger cars and the value of 1 if he does.

$Dmem_i$ = Owner's memory with respect to the expenditure for his automobile's maintenance. This takes values equal to the number of intervening years from the earliest for which some irregular maintenance was reported to the most recent.

D_i = Dummy variables indicating the countries from where the automobiles are imported into Greece. The index i stands for the following countries: *F*=France, *G*=Germany, *I*=Italy, *J*=Japan and *O*=Other.

Finally, in order for the reader to obtain a better understanding of the structure of the data, **Table 1** displays some further information about the sample. In particular, the data in the first two left–hand columns show its breakdown by the country of origin of the cars. From this it follows that the composition of the sample corresponded roughly to that of the population, since

Table 1: Descriptive statistics of the data sample

Cars imported from:	Number of cars	Means and standard deviations of the main variables:[1]			
		m_i	u_i	T_i	S_i
France	80	11.3 (12.5)	18.1 (11.9)	95.9 (54.4)	1087.2 (648.5)
Germany	121	9.6 (14.0)	18.0 (18.5)	110.7 (71.4)	1508.4 (1310.6)
Italy	63	14.4 (18.9)	15.8 (6.3)	105.1 (53.5)	937.3 (530.2)
Japan	63	2.8 (3.7)	15.7 (7.9)	71.2 (40.3)	1015.5 (444.7)
All other	106	8.2 (8.5)	14.9 (9.4)	101.8 (57.6)	785.9 (587.2)
Total	433	9.3 (12.8)	16.6 (12.6)	99.2 (59.7)	1098.9 (884.5)

Notes

1. These are means and standard deviations of the variables measured in the original untransformed data. This clarification is necessary because later the variables m_i and u_i are transformed into logarithms.

at the time the cars from France, Germany, Italy and Japan topped the list of countries from where the cars in the fleet had been imported. Moreover, from the descriptive statistics reported in the other columns emerge several interesting observations. For example, notice that while German made cars had roughly the same average age with those made in Italy, i.e. 9.2 versus 8.7 years, relative to the latter, the former were operated for 12% more kilometers but required 33% less maintenance expenditures per annum. Or, for another example, observe that cars imported from Japan, even though younger that those imported from all other countries, required disproportionately lower annual maintenance expenditures. To be sure, the sample dates way back in time. But if car owners in Greece were confronted with these findings, most likely they would find them consistent with their present day experiences.

5. Statistical tests, results and interpretations

The variable S_i depends on T_i and K_{0i}. Thus three variables in (2) are endogenous, whereas the rest are exogenous. The endogenous variables are m_i, u_i and T_i. In the data section it was indicated that the service life would be measured by the age of the cars in the sample. This approximation is necessary because the service life of cars is an unobservable variable. However, age itself is not a decision variable. For this reason in the estimations T_i and S_i have been included in the subset of exogenous variables. Consequently, unless indicated otherwise, only m_i and u_i are considered as endogenous.

Another methodological issue was whether to estimate (2) separately for each country or by pooling the entire data set. Drawing on the contributions by Maddala (1991), Pesaran, Smith

(1995), Baltagi et al. (2000, 2008) and others, we adopted a two-stage approach. In the first stage we estimated the model both ways. In particular, we hypothesized initially that, apart from some fixed effects associated with the countries of origin of the cars, the coefficients of the model are homogeneous across countries. This enabled us to estimate the model by pooling all 433 observations. Then, adopting the view that the behavior of Greek automobile owners regarding maintenance expenditures differs according to the import origin of their cars, we hypothesized that the coefficients of the model are heterogeneous across countries and estimated it at this level of the data. In the second stage we confronted the question how to select between the two sets of estimates. The relevant literature offers several criteria for this purpose. Some, for example, are the Root Mean-Square Error (RMSE), the Mean Absolute Error (MAE), the Akaike Information Criterion (AIC) and Schwarz's Bayesian Information Criterion (BIC). In the present case we shall employ the unitless ratio $\sigma_i / \overline{m}_i^e$,[11] where σ_i is the RMSE and $\overline{m}_i^e$ stands for the absolute value of the mean of the estimates of the dependent variable.[12] The rationale for choosing this criterion is not hard to establish. Clearly, the smaller σ_i the more efficient the estimating approach from which it derives. But country-based estimates might give lower σ_i compared to those from pooling, because the latter approach places relatively little weight on any particular country. To counterbalance the possibility of such bias σ_i is divided by $\overline{m}_i^e$, which is a country related scale measure of the accuracy of the models from the two estimating approaches. Hence, those estimates will be selected for further analyses that give lower values for this criterion.

Table 2 in the next page shows the estimates that were obtained using all 433 observations in the sample. The ones reported in the column (1) resulted by applying Ordinary-Least-Squares (OLS).[13] From them it turns out that all coefficients have the anticipated signs and are statistically significant at comfortable levels of significance. Also, observe that the explanatory power of the model, while not on the high side, it is not unusually low given the cross-sectional nature of the data. Moreover, from the values of various tests which are reported in

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[11] Henceforth σ_i and $\overline{m}_i^e$ will refer to statistics computed from the logarithmic transformation of m_i.

[12] This ratio is the so-called *coefficient of variation*. It is used widely in sciences, including, for example, *Budgeting* and *Portfolio Analysis*, for selecting among risky investments of various sizes.

[13] Linear estimations of the model can mask some important patterns of the relationship investigated. To guard against this possibility the model was re-estimated with data oriented nonlinear approximations, using the Box-Cox power transformation technique. However, neither this approach, nor inserting several interaction terms in the estimations improved the results in comparison to those reported in Table 2.

Table 2: Pooled estimates of equation (2)

VARIABLES[1]	OLS (1)	WLS (2)	IV[3] (3)	WIV[3] (4)	GMM[2,3] (5)
Constant	-1.634	-2.488	-1.232	-2.272	-1.255
	(-2.68)	(-3.33)	(-1.66)	(-2.71)	(-1.84)
$\log u_i$	0.681	0.872	0.521	0.789	0.539
	(3.83)	(3.21)	(2.09)	(2.84)	(2.24)
T_i	0.0088	0.0145	0.008	0.0143	0.0083
	(4.42)	(5.22)	(4.20)	(5.22)	(4.31)
$\log K_{0i}$	-0.356	-0.536	-0338	-0.530	-0.326
	(-2.03)	(-2.05)	(-1.93)	(-2.11)	(-1.85)
$Dacc_i$	0.221	0.360	0.229	0.366	0.228
	(2.27)	(3.11)	(2.35)	(3.05)	(2.31)
$Dmem_i$	0.187	0.208	0.191	0.209	0.187
	(4.01)	(3.29)	(4.14)	(3.38)	(4.00)
D_{Gi}	-0.637	-0.737	-0628	-0.735	-0.629
	(-2.88)	(-2.67)	(-2.86)	(-2.74)	(-2.97)
D_{Ji}	-1.088	-1.058	-1.089	-1.063	-1.11
	(-4.07)	-(3.79)	(-2.86)	(-3.84)	(-5.31)
$\overline{R}^2$	0.267	0.359	0.265	0.359	0.265
SSR	1417.18	1455.30	1419.87	1456.01	1419.55
LM het. test	1.27 (0.260)[4]				
Jarque-Bera	29.64(0.00)				
Ramsey's Reset	47.45(0.00)				
F (zero slopes)	23.44(0.00)	35.61(0.00)	0.18E+08(0.00)	0.25E+12(0.00)	
F (over-id. Rest.)			0.334(0.855)	0.933(0.444)	
Schwarz B.I.C.	895.38	951.00			
Log Likelihood	-871.10	-926.72			

Notes

1. The symbols $\overline{R}^2$ and *SSR* stand respectively for the adjusted coefficient of determination and the sum of squared residuals. The figures underneath the parameter estimates give the values of the t-statistic. The values of the t-statistic for all estimates are heteroscedasticity-consistent.
2. The t-statistics are robust to heteroscedasticity.
3. Aside of the constant and all exogenous variables, the list of instruments included $Down_i$ =multiple car ownership, frm_i =frequency of regular maintenance, and fms_i =frequency of car models in the sample, as well as several interaction terms.
4. The figures within the parentheses are the P-values.

the lower part of the same column we can surmise that the estimated model is characterized by absence of skewness and kurtosis in the disturbances and the specification of its functional form is consistent with the data. However, as the *LM Het.test* shows, the data suffer from heteroscedasticity, and hence, one cannot draw valid inferences.

To confront this hurdle, the model was re-estimated using the Weighted Least Squares (WLS) estimator, which is suitable when there is heteroscedasticity in the data and the disturbances in the regression differ systematically across observations. In applying this estimator we hypothesized that the values of a variable in the model were proportional to the inverse values of the variances of the disturbances in the regression and experimented with several such variables for weighting. Column (2) exhibits the best estimates from this experimentation. These emerged upon dividing the observations of the variables in both sides of (2) by the corresponding observations of the resale value of automobiles S_i. On closer look, we observe that the correction of heteroscedasticity not only confirmed the statistical significance of the coefficients, but also it improved markedly the explanatory power of the model by increasing the value of the adjusted coefficient of determination $\bar{R}^2$ almost 35%, from 0.267 to 0.359. However, in as much as these results were encouraging, the treatment of u_i as exogenous in the context of the WLS estimator left some uncertainty as to their robustness. For this reason, we sought to apply an estimator that could allow by design for both non-constant variances in the disturbances as well as endogeneity in certain explanatory variables of the model.

Standard econometric packages offer three such estimators. These are the Instrumental Variables (IV), the Weighted Instrumental Variables (WIV), and the Generalized Method of Moments (GMM).[14] In the presence of one or more endogenous variables, the WIV estimator allows for heteroscedasticity by following the above described approach to WLS, whereas the GMM estimator transforms the variables in the model by means of weights computed from the estimated covariance of the disturbances. The results that emerged from the application of these estimators are shown in the corresponding columns of Table 2. From them it turns out that the WIV estimates are better than those from either IV or GMM because the estimated model has much higher explanatory power without being worse in terms of the statistical properties of the estimated coefficients. Observe though that the WIV estimates are remarkably close to the ones from the WLS estimator, and hence, which of the two equations is a better representation of the model should not be decided on sheer impressionistic grounds. For this reason, we conducted a

[14] Cross-sectional applications of the GMM estimator are considered, for example, by Woodbridge (2001).

Durbin-Wu-Hausman test to compare the two sets of estimates.[15] In particular, to implement the first stage of this test, we run a WLS regression on u_i using all instrumental variables. Then, in the second stage, we introduced the computed residuals from the first stage and re-estimated the equation in order to find out whether the coefficient of the residuals was statistically significant or not. The test turned out to be negative and on this evidence we chose the WLS estimates as the preferred representation of the model, because in the absence of endogeneity both OLS and IV estimates are consistent, but the IV ones are inefficient.

The next task was to estimate equation (2) using the available data separately for each country. A set of results selected from these efforts on standard statistical criteria are shown in **Table 3**. Looking at them, a key feature is worth noting. In particular, while the estimated coefficients are roughly stable for cars imported from France and Germany, in the cases of cars from Italy,

Table 3: Estimates of equation (2) at the country level of the sample

VARIABLES	COUNTRY OF ORIGIN[1]				
	France **WIV**	**Germany** **WIV**	**Italy** **WLS**	**Japan** **WLS**	**All Other countries** **WLS**
Constant	-3.486	-4.677	-5.702	-1.229	-0.836
	(-3.25)	(-3.68)	(-3.61)	(-3.69)	(-1.95)
$\log u_i$	0.786	0.981	1.69	…	…
	(2.09)	(2.33)	(3.29)		
T_i	0.0099	0.019	0.015	…	0.019
	(1.77)	(4.78)	(2.38)		(5.64)
$dacc_i$	0.445	0.597	…	0.751	…
	(1.87)	(2.49)		(2.28)	
$dmem_i$	0.402	…	0.328	…	…
	(5.40)		(2.57)		
$\bar{R}^2$	0.364	0.287	0.426	0.107	0.338
SSR	229.9	518.2	180.4	218.9	215.8
F (zero slopes)	0.12E+7(0.00)	0.47E+7(0.00)	16.3(0.00)	8.4(0.005)	55.2(0.00)
F (over-id. Rest.)	1.41(0.247)	1.40(0.247)			
Schwarz B.I.C.			135.0	135.6	201.9
Log Likelihood			-126.8	-131.4	-198.9

Notes

1. See notes in Table 1.

[15] Details about this test can be found in Nakamura, Nakamura (1981).

Japan and Other Countries, they differ markedly. For example, observe that the variables of car utilization and age are missing from the equations for Japan and Other Countries, whereas the coefficient of utilization in the equation for Italy is way out of line by comparison to its value either for France and Germany or that from the pooled estimates. These findings suggest that the homogeneity hypothesis embedded in the results in Table 2 is rejected. However, following established research practices, the superiority in the performance of the two sets of estimates should be decided objectively.

Relevant to this end are the results in **Table 4**. The figures in the second row give the values of the ratio $\sigma_\iota / \bar{m}_i^e$ that were computed using the WLS estimates of the model from Table 2, whereas the figures in the third row show its values using the estimates from Table 3. Looking at them we see that the separate (pooled) country estimates are more efficient for some countries but not for others. In particular, for cars imported from France, Italy and Japan, the separate country estimates are more efficient than the pooled ones, whereas for

Table 4: Efficiency comparisons of the estimates at the overall and the country level of the data

Values of the ratio: $\sigma_\iota / \bar{m}_i^e$	**France**	**Germany**	**Italy**	**Japan**	**Other Countries**
Computed from Table 2, model WLS	1.255	2.312	1.124	6.908	1.054
Computed from Table 3	1.188	2.854	1.086	3.444	2.618

cars from Germany and Other Countries it holds the opposite. Expressing this finding in reference to the homogeneity and heterogeneity hypotheses of the coefficients, which are embedded in the estimates of Table 2 and Table 3, respectively, the results in Table 4 indicate that there are two clusters of Greek automobile owners with respect to the maintenance expenditures of their cars. In the first cluster there are those with cars from Germany and Other Countries who behave similarly, and in the second there are those with cars from France, Italy and Japan who behave differently. Hence, given that the debate among econometricians about the pros and cons of pooling has not settled,[16] in the sequel we shall follow a middle of the road approach by adopting those estimates that are most efficient for cars imported from the particular countries under consideration.

[16] Exempting of course the situations where the researcher is compelled to pool the available data due to insufficient cross-section and/or time-series observations relative to the estimated parameters.

Having dealt with the above technical aspects, the next task was to employ the estimates so as to demonstrate the usefulness of the model's practical implications. For this purpose we turned to the differences of cars from various countries in withstanding wear and tear, which gives rise to differences in the bills for their maintenance. In doing so, we sought to highlight these differences in terms of the reported and expected maintenance outlays and how the latter might change if an independent variable changed by a certain percentage? Illuminating in these respects are the figures shown in **Table 5**. Looking at the mean values of the expected maintenance expenditures across the $\bar{m}_i^e$ row, we observe that the owners of Japanese made cars were expected to pay for maintenance not more than 48% relatively to owners of cars imported France, Italy and Other Countries. By implication, this finding may go a long way

Table 5: Reported and estimated means, standard deviations and selected elasticities of maintenance outlays in thousand Drachmae of 1980 prices

	France[1]	Germany[2]	Italy[1]	Japan[1]	Other Countries[2]
$\bar{m}_i$ [3]	3.51(8.03)	2.05 (10.2)	4.38 (8.04)	0.74 (7.45)	3.47 (5.70)
$\bar{m}_i^e$	4.16 (4.47)	2.00 (4.68)	5.00 (4.73)	1.80 (3.53)	3.49 (3.73)
$\eta_{m_i^e u}$	0.79(2.09)	0.75 (2.09) [4]	1.69 (3.29)		0.75 (2.09) [4]
$\eta_{m_i^e T}$	0.96 (0.54)	2.15 (1.39)	1.64 (.83)		1.98 (1.12)
$\eta_{m_i^e Dacc}$	0.43(0.41)	0.48 (0.45)		0.67 (0.70)	0.46 (0.44)

Notes

1. Computed from the corresponding estimates of Table 3.
2. Computed from the following WIV estimated model using the pooled data for cars imported from Germany and Other Countries:

$$\log m_i = \underset{(-3.09)}{-3.107} + \underset{(2.09)}{0.750} \log u_i + \underset{(5.99)}{0.019} T_i + \underset{(2.63)}{0.461} Dacc_i \underset{(-2.77)}{-0.875} D_{Gi}$$

$$\bar{R}^2 = .31 \quad D.F. = 227 \quad \text{Wald } \chi^2(4) = 75.24$$

3. The means derive from the logarithmic transformation of m_i. Hence, they are geometric.
4. These elasticities are similar because they derive from the coefficient of $\log u_i$ in the estimates displayed in note 2 above.

towards explaining the spectacular success of Japanese car manufacturers in the intervening decades, since by producing and marketing exceedingly low maintenance cars at competitive prices, they enjoyed a significant advantage, which helped them capture large market shares in all categories of automobiles worldwide. However, in comparison to cars from Germany, Japanese made cars may not be as competitive as indicated for two reasons. The first one is that maintenance expenditures are positively related to the age of cars and the Japanese cars in the sample are over 30% younger than those from Germany, most likely because of faster rates of new registrations. Hence, for equal age cars, the difference in the maintenance bills between German and Japanese made cars would have been smaller or even in favor of the German cars. As for the second reason, this stems from the realization that the segment of German cars in the sample is weighted toward higher end automobiles.

Of interest are also the differences in the means of the reported and predicted amounts of maintenance expenditures. By comparing the figures in the $\overline{m}_i$ and $\overline{m}_i^e$ rows, we see that in the cases of France, Italy and Japan those in the upper row are significantly lower than those in the lower row, whereas in the cases of Germany and Other Countries the figures in the two rows almost coincide. Does this evidence reveal substantive differences in the maintenance behaviour in the respective clusters of car owners? We believe that it does. For if, for example, German cars retain their resale value better than Italian cars, as they do in reality, the owners of the former cars would have an incentive to spend as required for their proper upkeep, whereas the owners of the latter cars would have an incentive to cut corners. At the same time though it is reassuring to note that these behavioural differences are consistent with the earlier findings regarding the homogeneity and heterogeneity hypotheses of the model's coefficients.

Turning to the second leg of the question, the figures in the three bottom rows from the bottom of the table display the elasticities of expected maintenance expenditures with respect to the three main independent variables. Those in the row $\eta_{m_i^e u_i}$ suggest that, if the average kilometers run by automobiles per annum increased by 10%, expected maintenance outlays would remain unchanged for cars imported from Japan, they would increase roughly by 7.5% for those imported from France, Germany and Other Countries, and they would rise by 16.9 % for cars from Italy. Thus, in combination with the figures in the $\overline{m}_i^e$ row, maintenance sensitive car buyers were faced with four options in the following declining order of preference: Namely, to purchase: a) Japanese made cars that require very low maintenance outlays with nil responsiveness to usage; b) German cars that combine low maintenance outlays with a moderate degree of sensitivity to car usage; c) Cars from France and Other Countries that give rise to high maintenance costs with a moderate degree of sensitivity to usage, and d) Italian cars that involve very high maintenance expenses with very high responsiveness to usage. Would this ranking change in view of the elasticities with respect to service life and road accidents? To find out, observe from the rows $\eta_{m_i^e\,Dacc}$ and $\eta_{m_i^e\,T}$ that, when Japanese cars were involved in road accidents, they tended to produce higher maintenance bills relative to the other automobiles in the sample. This is a disadvantage. But on the other hand the same cars would outlast in service the cars from all other countries without raising maintenance outlays and this is a major advantage. On balance, therefore, cars made in Japan would top the list of options for maintenance sensitive buyers. With analogous reasoning it may be argued that in all likelihood Italian cars would remain at the bottom of the above preference ranking, with cars from the other countries falling in between.

However, the above remarks regarding the relationship of maintenance expenditures to the automobile's service life and road accidents should not create the impression that it is that simple. This warning is warranted for several reasons. One stems from the indications in official and casual reports that the lack of sufficient maintenance contributes to road accidents. In the context of the model presented above, allowing for them would require D_{acc_i} to be treated as an endogenous variable. We did so but unsuccessfully, perhaps because of the cross-sectional nature of the data. Another complexity derives from the tax regime that Greek governments applied on automobiles at the time. Due to the level and the structure of the acquisition and usage related taxes that were levied, automobile owners extended the service lives of their vehicles through maintenance well beyond the limits that might be considered safe. As a result, it was commonly hypothesized that, by forcing car owners to drive old and hence unsafe vehicles, taxes were responsible to some extent for the heavy toll of road accidents in Greece. Bitros (1990, 1992) tested this hypothesis with data from the *Statistical Yearbook* of the Association of Hellenic Insurance Companies and found some tentative evidence in its favor. Lastly, it should be noted that since the decision on how much to spend on maintenance is taken by weighing several other variables, in the future and as richer data sets become available the single equation model adopted here should be supplanted by a simultaneous equations approach. That is why, until such research attempts become possible, the estimates and the inferences presented above should be considered only as indicative and subject to further scrutiny.

In short, what has been established is that the proposed theory of irregular or unplanned maintenance expenditures offers a flexible and potent mechanism for tackling significant issues stemming from the process of maintenance of such highly complex engineering systems like, for example, cars, houses and ships. It is flexible because interested researchers can substitute analytical functions to suit their problem at hand and it is potent because it can shed considerable light on the complex relationship linking maintenance expenditures to determinant that are very important in the decision making process of households, manufacturers and policy makers. Having tested a particular specification of this theory on automobile data from Greece, and having experimented extensively with the estimated model, the results confirmed both these claims about the merits of the proposed theory.

6. Conclusions

This paper had three objectives. The first was to derive a model of maintenance expenditures from rational economic behavior. This was accomplished by drawing on the research by Bitros and Flytzanis (2004) who modeled the behavior of a capital using enterprise operating under a policy of scrapping. The second objective was to employ the model to highlight the responses of these expenditures to changes in the other endogenous and exogenous variables. To this effect, the general revenue and wear functions in the model were specified further by substituting for them certain reasonable analytic forms. In turn, there resulted an equilibrium model of maintenance expenditures comprising all the variables that have been identified as important in the relevant literature and giving sharp sign predictions. Finally, the third objective was to highlight the usefulness of the model by means of an application. For this purpose the model was estimated and tested with the help of data from a questionnaire answered by 433 automobile owners in Greece.

In view of the unsettled controversy in the econometric literature regarding the approach to the data, the model was estimated by pooling all 433 observations in the sample as well as separately at the level of the countries from where the automobiles had been imported. Both approaches gave satisfactory estimates on standard statistical criteria. However, on account of the results from a pertinent test, we selected as more efficient the separate country of the model. As expected from theory, the estimates showed that the outlays for maintenance are related positively to the automobile's intensity of utilization, service life and road accidents. Also the estimates showed that Japanese made cars may be least demanding in maintenance outlays, followed by cars from Germany, and, lastly, by cars imported from Italy and Other Countries. Overall, and even though their maintenance appeared to be relatively more sensitive to road accidents than those of automobile from all other countries, the result showed that on this basis, Japanese made cars offered the best value for the money.

7. Appendix

The representative car owner would be expected to act in line with the precepts of economic theory. This implies that he would be expected to decide as if he were guided by the rules emanating from the solution to the problem:

$$\text{Choose } [T, u(t), m(t)] \text{ so as to maximize:}$$
$$A = \tilde{Q} + \tilde{S} = \int_0^T q(u,m,K)\phi(t)dt + \phi(T)S(K_T,T) \qquad \text{A(1)}$$
$$\text{s.t.} \quad \dot{K} = -s(u,m,K), \text{ with } K(t_0) = K_0, \text{ and}$$
$$0 \le u \le 1,\ 0 \le m \le 1,$$

where the various symbols are defined as follows:

$\tilde{Q} = \int_0^T q(u,m,K)\phi(t)dt$ *:* Expected net operating revenue for operating horizon *T*.

$K = K(\text{t})$: Used car measured in efficiency units, reflecting its size and age since first put in operation. New or unused car will be denoted by $K_0 = K(0)$.

$u = u(t)$: Utilization intensity relative to some extremal values, with $0 \le u \le 1$.

$m = m(t)$: Maintenance intensity expressed as expense relative to some extremal values, with $0 \le m \le 1$.

(u,m): Operating policy factors.

$q(u,m,K)$: Flow of net operating revenue.

$s(u,m,K)$: Flow of net capital wear.

(q,s): Operating policy flows.

$S = S(K_T,T)$: Scrap value of used car at T. For the scrap value of unused car we set $S_0 = S(K_0,0)$.

$\varphi(t) = e^{-\sigma t}$: Effective discount factor. Let $F(t)$ denote the probability of a *technological breakthrough* by time t, with $F(0) = 0$ and $F(t) < 1$ for all t. Assuming a constant discount rate ρ, the discount factor would be $e^{-\rho t}$. To account for technological uncertainty this is multiplied by $[1 - F(t)]$. In keeping with the specification of time invariance, attention is limited to the usual exponential case: $F(t) = 1 - e^{-\theta t}$. Then, since $\varphi(t) = e^{-(\theta+\rho)t}$, the effect of uncertainty is equivalent to introducing a revised *effective discount rate*, expressed by $\sigma = \theta + \rho$.

Expression **(1)** describes the general setting of an optimal control problem. Instead the analysis focuses on a more specific model by assuming q and s of the following type:

$q = rK^{\varepsilon}$: Where $r = r(u,m)$ is the operating net revenue rate. Usually positive, but it can also be negative. Increasing in *u,* decreasing in *m,* concave in *(u, m).*

$s = wK$: Where $w = w(u,m)$ is the capital wear rate; Increasing in *u,* decreasing in *m,* convex in (u,m). It expresses the effect on car of *maintenance* and *utilization*, including *aging*. Usually positive but it can also be negative, if aging causes upgrading or if investment type of maintenance overbalances the wear of equipment, allowing K to even rising above the original K_0.

(w,r) *: Operating policy rates*

These rate functions characterize the operating features of the equipment. They have been taken to be time invariant. However, prices are allowed to vary by setting:

$S = p_K e^{\eta T} K$: Scrap value of car at time T, where:

η : Relative rate of price change. It is the difference between equipment price change and operating revenue price change, because any common part can be subtracted from the discount rate σ. It can have either sign, or be zero.

p_K : Price of a new car.

With the help of these specifications in Bitros and Flytzanis (2004) we investigated the dependence on the parameters $\{\varepsilon, \sigma, \eta, p_K, K_0\}$ of: a) the *operating policies,* defined by the optimal rates of *utilization* and *maintenance* as functions of time*:* $\{u = u(t), m = m(t)\}$, and b) the *scrapping policy,* defined by the optimal duration or service life T^*. From that investigation it turned out that the solution to **(1)** yields several conditions that the optimal operating and scrapping policies must obey. In particular, the ones for *utilization*, *maintenance* and *service life* are given by:

i. For operating policies: $\{r = r(w),\, r'(w) = \mu\} \Rightarrow \{w = w(\mu),\, r = r(\mu)\}$
ii. For capital stock: $\dot{K} = w(\mu)K$, with initial condition $K(0) = K_0$
iii. For logistic value: $\dot{\mu} = \varepsilon\mu[\sigma/\varepsilon - i(\mu)]$, with final condition*:* $\mu_T = pe^{\eta T} K_T^{1-\varepsilon}$ A(2)
iv. For service life, the terminal scrapping condition: $i(\mu_T) = \sigma - \eta$,
v. For profitability*:* $\sigma - \eta < i(\mu_0)$, where $\mu_0 = pK_0^{1-\varepsilon}$.

and the logistic value μ stands for the car owner's shadow cost per unit of operating capital.

Looking at **(2)** we observe that **2(iii)** is autonomous. Moreover, since μ is continuous it will move in time monotonously. The sign of the derivative $\dot{\mu}$ determines the direction of monotonicity at any time, in particular at the terminal time T, given that cars are scrappable. Substituting from **2(iv)** into **2(ii)** we find:

$$\dot{\mu}_T = \varepsilon[\sigma/\varepsilon - (\sigma-\eta)]\mu_T \text{, where } \mu_T = pe^{\eta T}K_T^{1-\varepsilon} > 0\,. \qquad \text{A(3)}$$

Observe that the monotonicity property depends on the relative magnitude of the discount rate σ/ε, for operating capital K^{ε}, and the discount rate $\sigma-\eta$, for scrapping capital K. Drawing on this finding in Bitros and Flytzanis (2004) we established:

Proposition 1: Time shift of operating policies
If the equipment is scrappable, then we distinguish three cases: A(4)

i. If $\sigma/\varepsilon > \sigma-\eta \Rightarrow \eta > (1-1/\varepsilon)\sigma$, i.e. if the operating discount is higher than the scrapping discount, then $\mu(t)$ increases in time from harder (more utilization and less maintenance) to softer (less utilization and more maintenance) policies.

ii. If $\sigma/\varepsilon < \sigma-\eta \Rightarrow \eta < (1-1/\varepsilon)\sigma$, i.e. if the operating discount is lower than the scrapping discount, then $\mu(t)$ decreases in time from softer (less utilization and more maintenance) to harder (more utilization and less maintenance) policies.

iii. If $\sigma/\varepsilon = \sigma-\eta \Rightarrow \eta = (1-1/\varepsilon)\sigma$, i.e. if the operating discount and the scrapping discount are equal, then $\mu(t)$ stays fixed in time at the equilibrium policy.

Hence, since the focus in this paper is on the equilibrium operating policies applied by car owners, the analysis will be limited to Proposition A(1.iii).

Under this stipulation, the value of $\mu(t)$ stays fixed up to scrapping time *T*. By implication it must hold that:

$$r'(w_t) = p_K e^{\eta T} K_T^{1-\varepsilon}\,. \qquad \text{A(5)}$$

This suggests that the representative car owner should retain his car up to the time when the extra operating revenue realized from its use is equal to the car's scrap value per unit of operating capital. Consequently A(5) provides a rule of optimal conduct on his part, as well as a model to gauge his behavior. But before it can be adopted for empirical analysis, two modifications are in order.

The first of them is required because A(5) has been derived on the hypothesis that the representative car owner knows the analytic form of the operating function $r(w)$. But in actuality this is rarely the case, at least with regard to households. Hence, in order to obtain an estimable model, it is necessary to assign to this function an analytic form and at the same time to express it in terms of variables that can be observed. To this end, and in order to allow for the most general specification of the model, I adopted the following assumptions:

$$\begin{aligned} &\text{i.} \quad r_t = a_0 w_t^{\alpha_1} - \alpha_2, \ \text{for } \alpha_0, \alpha_2 > 0 \text{ and } 0 < \alpha_1 < 1, \\ &\text{ii.} \quad w_t = \beta_0 u_t^{\beta_1} m_t^{\beta_2}, \quad \text{for } \beta_0, \beta_1 > 0 \text{ and } \beta_2 < 0. \end{aligned} \qquad \text{A(6)}$$

Thus, substituting A(6.ii) into the derivative $r'(w)$ from A(5.i), introducing the result into A(3), and rearranging, yields:

$$\begin{aligned} &m_t = [\alpha u_t^{\beta} \cdot \frac{p_K e^{\eta T} K_T}{K_T^{\varepsilon}}]^{\gamma}, \\ &\alpha = \frac{\beta_0^{1-\alpha_1}}{\alpha_0 \alpha_1} > 0,\ \beta = \beta_1(1-\alpha_1) > 0,\ \gamma = \frac{1}{\beta_2(\alpha_1 - 1)} > 0. \end{aligned} \qquad \text{A(7)}$$

As for the second modification this is recommended by the observation that the services remaining in a car at any time cannot be measured directly. From our analysis in Bitros and Flytzanis (2004) we know that, if the average wear of a vehicle is given by: $\omega = \frac{1}{T}\int_0^T w(t)dt$, the amount of services left in it at T is: $K_T = K_0 e^{-\omega T}$. Thus substituting the latter expression into A(5) and recalling that $S_T = p_K e^{\eta T} K_T$ gives rise to:

$$m_t = [\alpha u_t^{\beta} \cdot \frac{S_T}{(K_0 e^{-\omega T})^{\varepsilon}}]^{\gamma}. \qquad \text{A(8)}$$

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