Analysis and prediction of private car ownership and use in Denmark: Part of the ELISA Project

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Publication date:
2020

Document Version
Publisher's PDF, also known as Version of record

Analysis and prediction of private car ownership and use in Denmark

Part of the ELISA Project

DTU Management for kommissionen for grøn omstilling af personbiler

18. September 2020

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Citeres som: Abegaz et al. (2020). Analysis and prediction of private car ownership and use in Denmark – Part of the Elisa Project. DTU Management Rapport. ISBN: 978-87-93458-91-8

Udgivet af: Institut for Teknologi, Ledelse og Økonomi, Danmarks Tekniske Universitet
Rekvireres: www.dtu.dk
ISBN: 978-87-93458-91-8

Foreword

This report documents the estimation and forecast of the levels of car ownership and use in Denmark. Car ownership and use is defined at aggregate national level and the estimation is performed using macro data for the period 1976-2018.

This work was funded by the Danish Energy Agency, the Ministry of Finance and the Ministry of Transport and Housing as part of the ELISA Project. The ELISA Project was carried out in the period January to September 2020 by the Transport Division under the Department of DTU Management.

Results have been discussed with the steering group of the ELISA Project with members from the Danish Energy Agency, the Ministry of finance and the Ministry of Transport and Housing. We thank the members of the Steering group for input and comments.

Kgs. Lyngby, September 2020

Jeppe Rich
Professor, Project Leader

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1. Introduction

This report documents the estimation and forecast of the national car ownership and use for Denmark. This work was funded by the Danish Energy Agency, the Ministry of Finance and the Ministry of Transport and Housing, and undertaken as part of the ELISA Project on improved projection tools for the Green Transition of the transport sector.

The current analysis is needed to update forecasts based on the 2004 car ownership and use model, known as the Aggregate Road Transport (ART) model, using additional and more recent data to take into account recent changes in travel behaviour and other economic conditions.

The rest of the report is organised as follows. First, we give an overall summary of the main results. Then, we provide a description of the data and outline the estimation methods. Finally, we present the estimation results and the resulting forecasts and conclude.

2. Summary

This report presents the main findings from econometric analyses of car ownership and use levels for Denmark using historical macro data for the period 1976-2018. We model car ownership and use levels as a function of other economic variables including GDP and official indices for car purchase prices and vehicle operating costs. The models are estimated using dynamic time series methods to obtain estimates of long run cointegration relations and coefficients reflecting short-run dynamics.

The car ownership model is estimated using an Error Correction Model (ECM), a model that assumes the existence of an equilibrium relationship that determines both short and long run relationships. It is formulated as the 2004 ART model (Fosgerau, Holmblad & Pilegaard, 2004), keeping the ratio between long run and short run elasticities equal for all explanatory variables. The validity of this restriction was tested statistically, and the restriction was accepted as an appropriate description of the data. With the restriction, we obtained a higher precision of the estimated elasticities compared to the case without the restriction. The estimated long run elasticities of GDP and purchase price from this model are 0.83 and -0.57, respectively. The implied long run elasticity of operating cost is -0.34, but it is not significant at the conventional 5% level (its p-value is 0.29). Forecasts based on this model show that car ownership is predicted to increase from 0.49 cars per capita in 2018 to 0.62-0.71 in 2040 depending on alternative assumptions about the growth rate of purchase prices.

Compared to estimates from the 2004 ART model (Fosgerau, Holmblad & Pilegaard, 2004), we now find higher long run income and purchase price elasticities while the operating cost elasticity is lower.

For the car use model, we considered two different measures – mileage per car and mileage per capita. Mileage per car is the measure used in the original 2004 ART model, but this choice had

to be reconsidered due to a change in the trend of mileage per car during the sample period. Mileage per car has shown an increasing trend until the early 1990s, after which it declined. This change could be explained by the general increase in the car fleet and especially the increase in the share of households with two or more cars. With other explanatory variables showing an overall upward or downward trend, it proved difficult to identify the effect of individual factors on this measure of car use. We therefore chose the model formulation with mileage per capita, which has a positive trend.

We model mileage per capita in terms of its lagged values and contemporaneous and lagged values of GDP, purchase price and operating costs, using an Error Correction Model. Our analysis shows a significant and negative long run effect of operating costs and purchase price on the extent of car use. In particular, a percentage increase in operating costs (resp. purchase price) is associated with a decline in mileage per capita by 0.61% (resp. 0.64%) in the long run. GDP has a positive and significant long run effect on car use - the estimated long run elasticity is 0.80. Our analysis shows that mileage per capita is predicted to increase from 7,500km in 2018 to 9,900km - 11,600km in 2040 depending on the alternative assumptions regarding the growth rate of purchase price in this period.

3. Data and stationarity

3.1 Introduction

The analysis is carried out using historical data covering a period of 43 years spanning from 1976 to 2018. While data for earlier years was available, this was not used in the analysis due to concerns over its reliability.

Table 1 provides definitions of the key variables in the analysis. Our definition of the car fleet includes conventional personal cars powered by diesel, petrol, hybrid or electric engines, vans (<2 tons), company cars that can be used for personal trips, and motorcycles.

Table 1: Definition of key variables

Variable	Description
Fleet size	By fleet size we refer to the number of motorcycles, personal cars and vans (<2 tons). We also use the term fleet size per capita (vehicle/person) to refer to the average fleet size per person.
Mileage	Mileage is the total kilometres driven by all private vehicles regardless of the rate of vehicle occupancy. In estimation, we used mileage per capita (km/person) which is the ratio of mileage to population size.
Vehicle purchase price index	Average vehicle purchase price relative to the price in a base year, which is 1964. The index includes the price of passenger cars and passenger vans, motorcycles and bicycles.
Vehicle operating cost index	Average vehicle operating cost relative to the price in a base year, which is 1964. The index includes the cost of spare parts and accessories, tyres, propellants, lubricants, maintenance, repair, parking fees, toll, driving lessons and tests, car inspection and car hire.
GDP	Real GDP in 2010 chained prices (million Danish Kroner).

Data on vehicle purchase price and operating cost indices, GDP and petrol price and the share of multi-car households is obtained from Statistics Denmark (see Table 11 in the Appendix for details).

3.2 Fleet size

The total fleet size has increased from 1.46 million in 1976 to 2.86 million in 2018 with an average annual growth rate of 1.62% during this period. The growth in fleet size is due to an increase in population and in car ownership per capita. The level of car ownership per capita grew from 0.29 in 1976 to 0.49 at the end of the sample period. Despite an overall upward trend, the stock of cars fluctuated over time registering negative growth rates at the beginning of the 1980s and 1990s. The highest annual growth rate was observed in 2007 where the car fleet grew by 4.7%, perhaps due to the change in taxation policy, while the lowest growth was observed in 1980 where the car fleet declined by 2.6%. Years with higher growth rate include 1984-1986, 1995-1996 and 2006-2007. On average, car ownership per capita grew at the rate of 1.3% in the sample period.

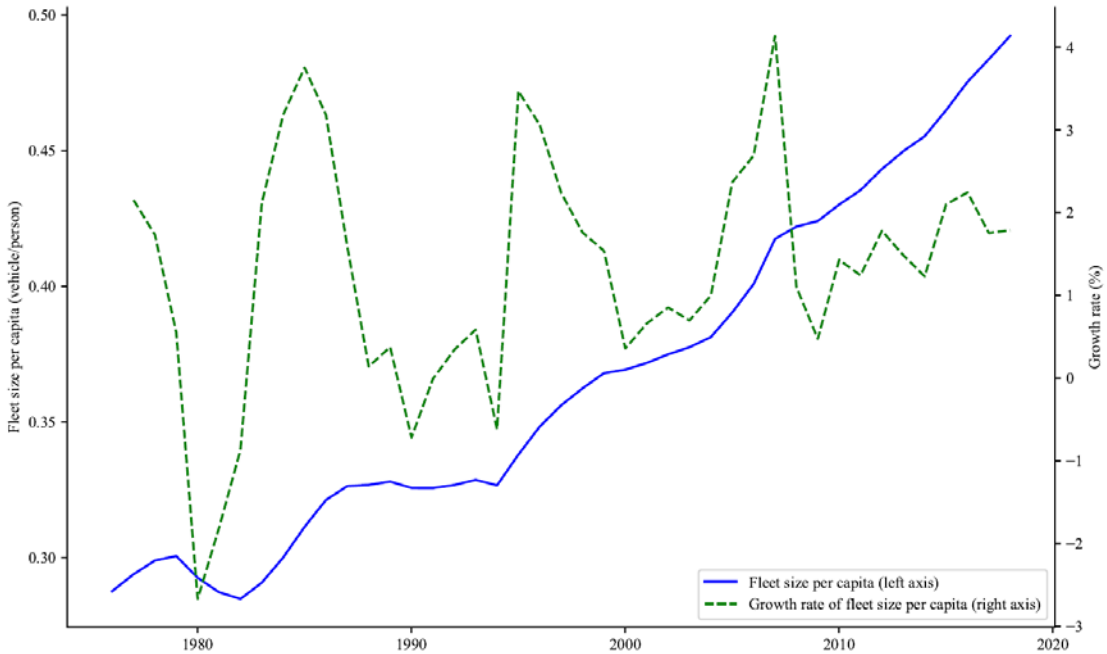


Figure 1: Fleet size per capita and its growth rate during the sample period

At the household level, while the share of households with one car or no car declined during the sample period, the share of households with multiple cars showed a clear upward trend. The latter rose from 6.7% in 1996 to 16.8% in 2018.[1] Hence, the growth in the car fleet in the recent years seems to be largely driven by the increase in multi-car households.

[1] Data on car ownership at the household level is available only starting from 1996.

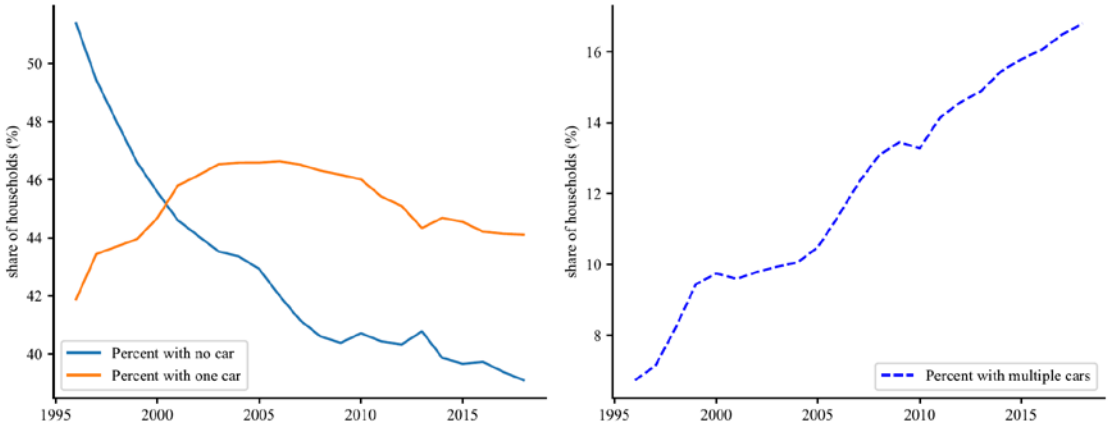


Figure 2: Share of households by status of car ownership

Saturation: The data supports our prior expectation that car ownership levels increase along with GDP. With GDP continuing to grow, an important question is how much that subsequently drives the level of car ownership. While the effect of income is expected to gradually fade, the data shows strong positive correlation between fleet size and income. This seems to suggest that a saturation level may not be that close.

The level of GDP per capita varies from about 192,000 to about 359,000 DKK during the sample period. It is interesting to note that there appears to be a shift in level relative to GDP in recent years.

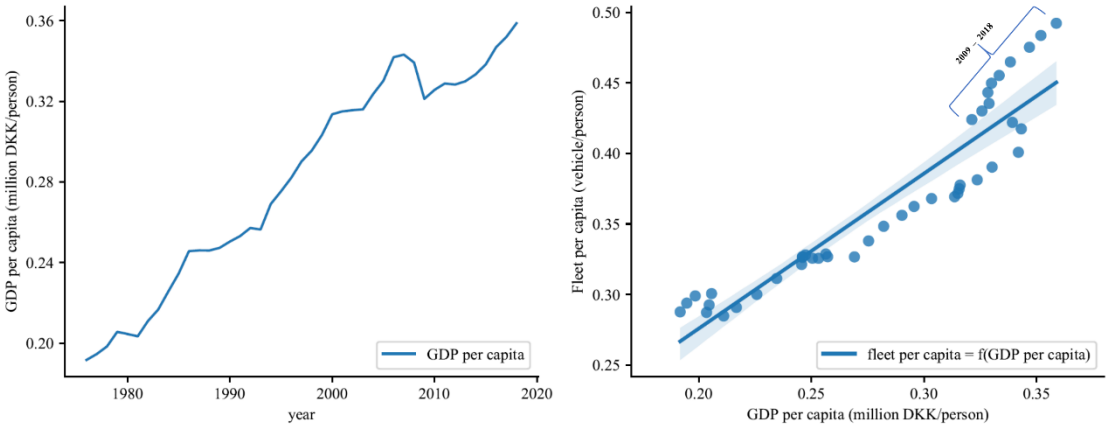


Figure 3: Trend in GDP per capita (left) and the relationship between fleet size and GDP per capita, along with a fitted regression line (right)

Vehicle purchase price and operating cost: While the purchase price declined during the sample period, operating cost showed an increasing trend. Over time, both series fluctuated around their respective linear trends. The purchase price index declined from a maximum value of 0.95 in 1976 to a minimum value of 0.56 in 2018 recording an average annual growth rate of -1.2% during the period. It declined faster at the beginning of the 1980s and after 2007. In contrast, the operating cost index increased at a rate of 0.9% per annum attaining a lowest value of 0.95

in 1976 and a highest value of 1.42 in 2012. Faster increases in the cost index have been observed in 1979-1981 (likely due to the oil crisis) and 1999-2000. Larger declines were seen in 1990, 2009 and 2015.

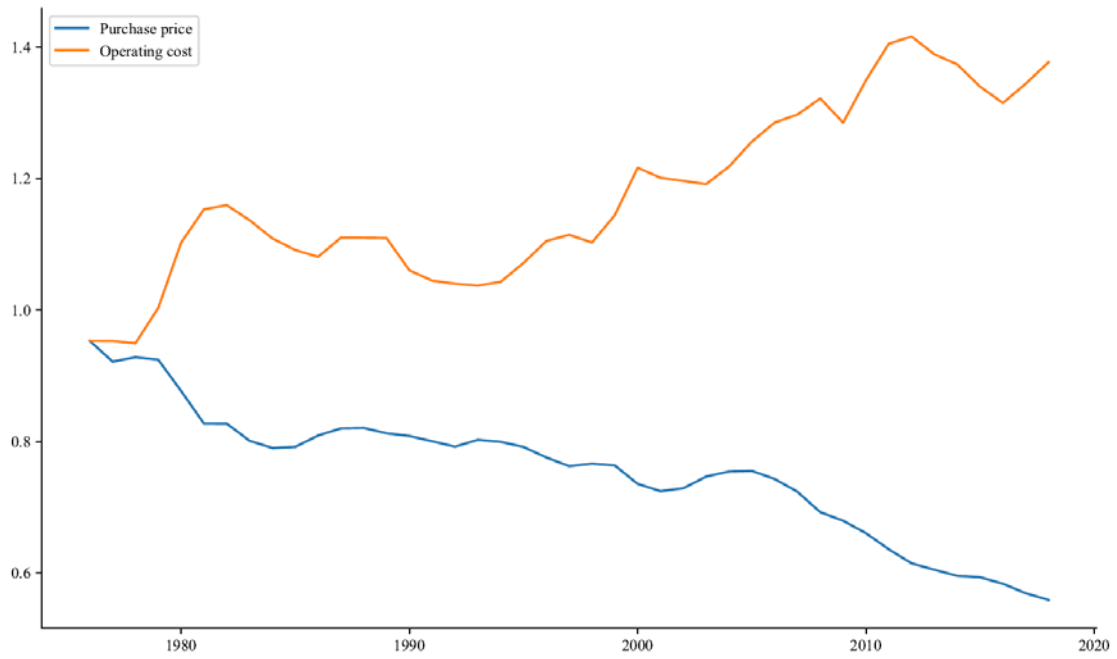


Figure 4: Trend of purchase price and operating cost indices

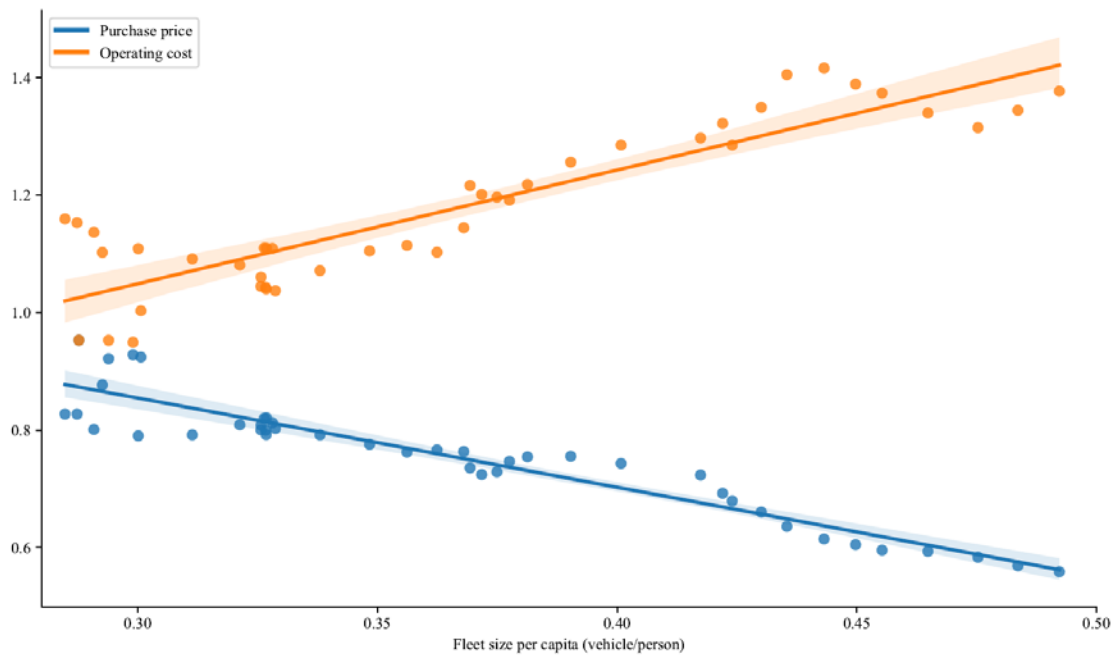


Figure 5: The relationship between purchase price and operating cost indices with fleet size

3.3 Mileage

As the total fleet size increased over time, so did the amount of vehicle kilometres driven. Total mileage increased from 22.7 billion km in 1976 to 43.5 billion km in 2018 thereby growing at the rate of 1.6% per annum. The proportional increase in total mileage is similar to the change in fleet size, implying a reduction in the average mileage per car. Mileage per car follows a trend similar to an inverted U-shape: It increased until early 1990s, after which it declined owing, in part, likely to an increase in the share of households with two or more cars that reduced reliance on one car. In contrast, mileage per capita increased over time after a small dip in the early 1980s (the second oil crisis). The vehicle kilometres travelled (VKT) by the average person increased at a rate of 1.3% from 4,500km in 1976 to 7,500 in 2018.

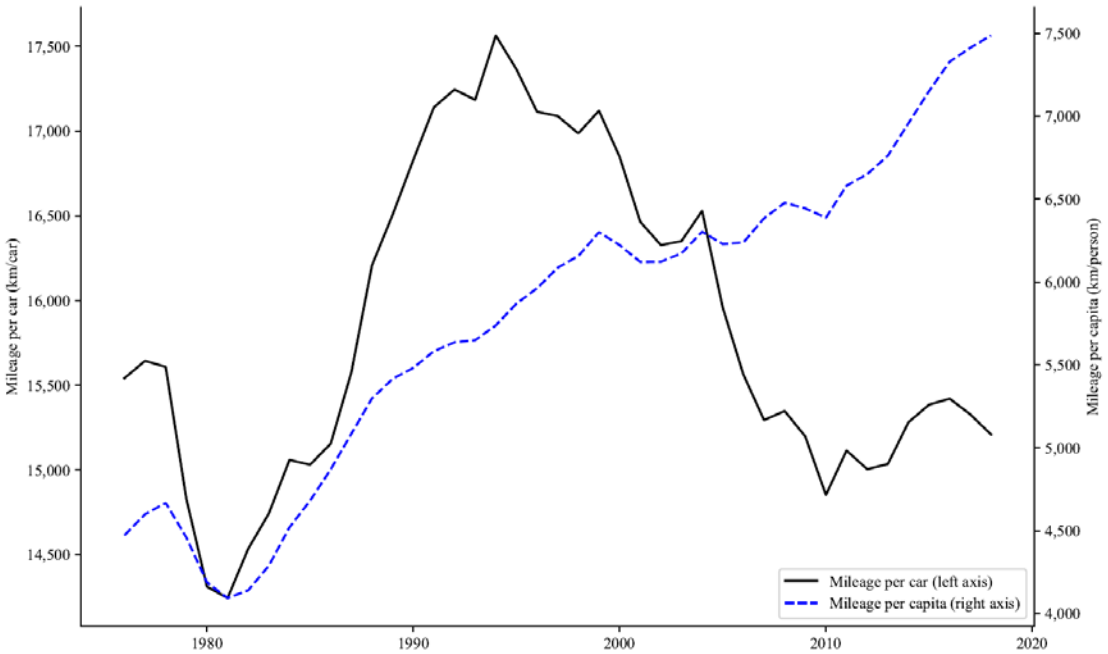


Figure 6: Trends in mileage per car and mileage per capita levels

3.4 Stationarity and cointegration analyses

We conducted a stationarity test for each series to determine its order of integration. The test is performed based on four widely used test methods: the Augmented Dickey Fuller (ADF) test, the Dickey Fuller Generalised Least Squares (DF-GLS) test, the Phillips-Perron and Kwiatkowski–Phillips–Schmidt–Shin (KPSS) test.

As we used the logarithm of each variable in our econometric analyses, the stationarity test is performed after a similar logarithmic transformation is applied to each variable. Test statistics from the four methods, each of which includes one augmenting lag and a constant term, are reported in Table 12. Results indicate that all series are non-stationary in levels; however, they become stationary in first difference. Hence, the variables are integrated of order one, denoted I(1). This means that we cannot apply standard time series regression analysis without checking whether the time series are cointegrated. Cointegration is the existence of a long term equilibrium relation between the variables.

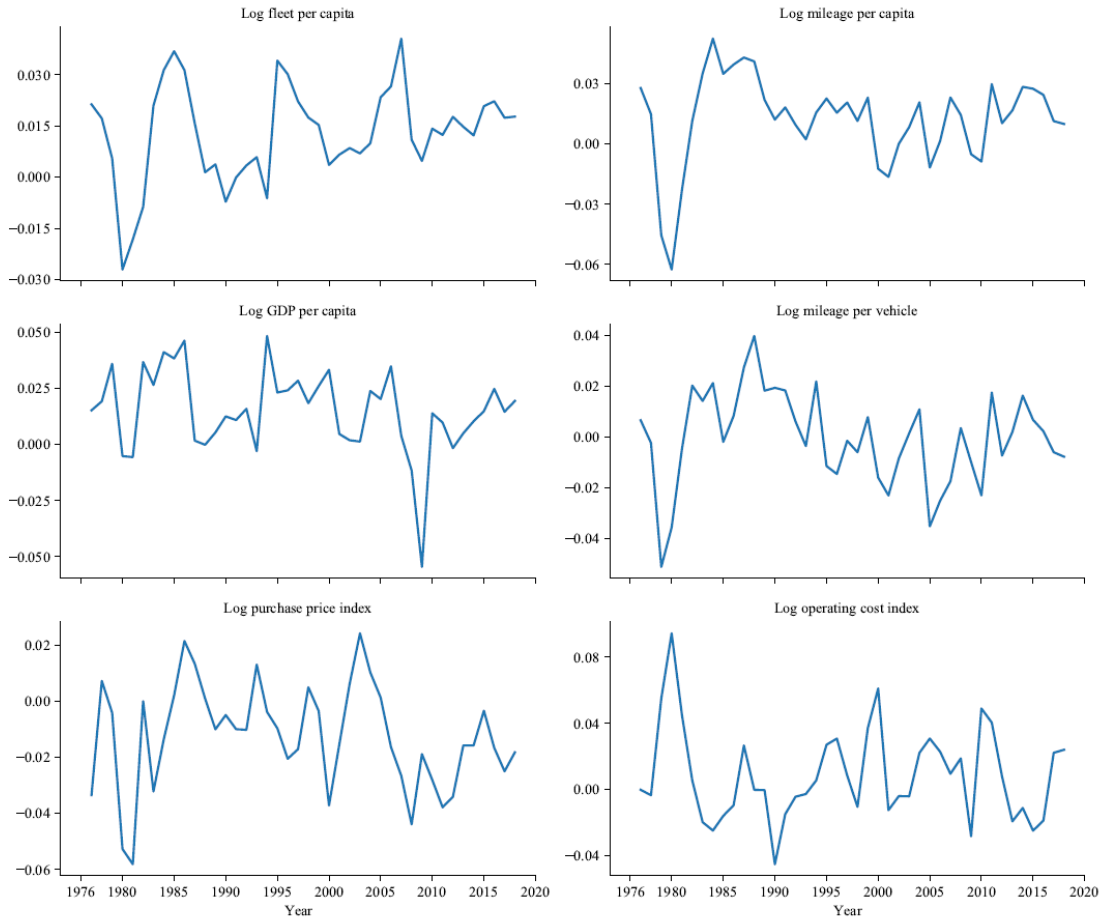


Figure 7: Trend of key series after first differencing

We test for the order of cointegration among the key series assuming no trend in each series and an unrestricted intercept in the cointegration relation. The test is performed using Johansen's Cointegration Test by allowing a maximum of three lags in the underlying model. The resulting trace statistics shows a maximum of 1 cointegrating relation among the logarithms of the following series:

- fleet size, GDP, purchase price and operating cost
- mileage per capita, GDP, purchase price and operating cost.

This result indicates a long run relation between the variables, which is a key requirement for our chosen econometric model.

Table 2: Number of possible cointegration relations among a set of variables

Fleet size per capita, GDP, purchase price and operating cost					
Maximum rank (r)	parameters	Log-likelihood	eigenvalue	trace statistic	5% critical value
0	36	457.39	.	57.64	47.21
1	43	472.40	0.53	27.60*	29.68
2	48	482.69	0.40	7.03	15.41
3	51	485.53	0.13	1.36	3.76
4	52	486.21	0.03		

Mileage per capita, GDP, purchase price and operating cost					
Maximum rank (r)	parameters	Log-likelihood	eigenvalue	trace statistic	5% critical value
0	36	436.95	.	50.51	47.21
1	43	453.79	0.57	16.83*	29.68
2	48	459.20	0.24	6.01	15.41
3	51	462.12	0.14	0.16	3.76
4	52	462.20	0.00		

* indicates failure to reject the null hypothesis that there are r cointegrating equations against the alternative hypothesis of $r-1$ or fewer cointegrating equations.

4. Econometric model

This section presents the econometric method employed in estimating the fleet size and car use models.

We formulate models for fleet size and for mileage per capita.

For fleet size, we formulate the model as being dependent on income and the prices of car purchase and use and we use lagged values of these variables to describe the dynamic structure. We start out with a more general model, but to improve the precision of the estimates we continue with a restricted model, where the ratio between long run and short run elasticities is assumed constant for all explanatory variables.

For the mileage model, we formulate the model for mileage per capita as being dependent on income and the prices of car purchase and use and lagged values of these variables. In this situation, the unrestricted model turns out to give satisfactory results. We note that this model specification differs from the ART MILES model in Fosgerau, Holmblad & Pilegaard (2004): Their mileage model has the mileage per vehicle as dependent variable, and does not include the purchase price index. The reason for this deviation is due to the observed complex trend for mileage per car as described in the data section.

The shift from analysing mileage per car to mileage per capita implies the formulation of a new model. Therefore, it is necessary to include the effect from fleet size, here expressed by the index for purchase price, as the models need to capture both fleet size and mileage per capita effects. The reformulation of the mileage model from mileage per car to mileage per capita also has implications for the interpretation of the results, which we will describe later.

We now turn to the formal description of the models.

4.1 Fleet size model

4.1.1 The general dynamic model

Let y_t be the logarithm of fleet size (in vehicles per capita) in year t. We model y_t as a function of its value in previous years and a set of explanatory variables (X_t), which include the logarithms of GDP per capita (x_{1t}), purchase price index (x_{2t}) and vehicle operating cost index (x_{3t}). The definition of variables and the units in which they are measured is given in Table 13 in the Appendix. As discussed above, y_t and X_t are I(1) time series, but since there is at most one cointegration relation between them, we can estimate the relation between them using an Autoregressive Distributed Lag (ARDL) model formulated directly in terms of y_t and X_t. The general form of this model is:

$$y_t = \delta + \sum_{i=1}^{p} \phi_i y_{t-i} + \sum_{i=0}^{q} \beta_i X_{t-i} + \varepsilon_t$$

where ε is a white noise error term and δ, ϕ_i and β_i are parameters to be estimated. While the above formulation suggests the same lag order for each series in X, in estimation, we can allow a different lag length for each series. This model can be re-written in the form of an Error-Correction Model (ECM):

$$\Delta y_t = \delta - \alpha(y_{t-1} - \theta X_{t-1}) + \sum_{i=1}^{p-1} \psi_{y_i} \Delta y_{t-i} + \psi_{X_0} \Delta X_t + \sum_{i=1}^{q-1} \psi_{X_i} \Delta X_{t-i} + \varepsilon_t$$

where $\alpha = 1 - \sum_i \phi_i$ is the speed of adjustment towards long run equilibrium after distortion, θ is a set of parameters where each parameter $\theta_k = \sum_i \beta_{k,i}/\alpha$ indicates the long run impact of x_k on y (which is the long run elasticity between the original variables without logarithms), and ψ represents a set of coefficients. Specifically, ψ_{X_0}(=β_0) is the contemporaneous (short run) impact of X_t on y_t, which is the short run elasticity between the original variables. The ARDL and ECM are equivalent models that produce identical elasticities and forecasts for given values of p and q.

A formal test allowing up to 3 lags for all series indicate that one lag or two lags would be sufficient to capture the dynamic structure. Our most general model specification therefore has 2 lags of both the dependent and independent variables (p=2, q=2). For ease of later reference, we label this model as FM1. As described below, we also consider two other models in addition to FM1.

4.1.2 Unrestricted ART FLEET model

Two of our analysed model specifications are the unrestricted and restricted versions of the 2004 ART FLEET model (Fosgerau, Holmblad & Pilegaard, 2004), modified slightly by including a constant term and excluding a dummy indicator for the scrappage premium policy in 1994. Both

models can be written in ECM form, as we show below. The ART FLEET model has 2 lags of the dependent variable and 1 lag of the other variables. The unrestricted version of this model is:

$$\Delta y_t = \delta + c_1 y_{t-1} + c_2 y_{t-2} + (c_3, c_5, c_7) X_t + (c_4, c_6, c_8) X_{t-1} + \varepsilon_t \quad (1)$$

To write this in ECM form, we use the following equivalents:

$$y_{t-2} = y_{t-1} - \Delta y_{t-1} \qquad \text{and} \qquad X_t = X_{t-1} + \Delta X_t$$

Inserting this into eq. (1) and re-arranging, we arrive at the ECM model with p=2 and q=1:

$$\Delta y_t = \delta - \alpha(y_{t-1} - \theta X_{t-1}) + \psi_{y_1} \Delta y_{t-1} + \psi_{X_0} \Delta X_t + \varepsilon_t \quad (2)$$

with $\alpha = -(c_1 + c_2)$, $\psi_{y_1} = -c_2$, $\psi_{X_0} = (c_3, c_5, c_7,)$, and $\theta = \frac{1}{\alpha}(c_3 + c_4, c_5 + c_6, c_7 + c_8)$.

We label this model FM2. Provided that the chosen lag length (p=2, q=1) is sufficient to capture the dynamic structure in the data, such that the residuals are not serially correlated, this is a general formulation which allows the estimated elasticities to vary independently of each other.

4.1.3 Restricted ART FLEET model

Fosgerau, Holmblad & Pilegaard (2004) recommended using a restricted version of the model above, keeping the parameters $(c_2, c_3, c_4, c_5, c_7)$, but restricting (c_1, c_6, c_8) to be functions of the other parameters:

$$c_1 = \left(\frac{c_2 c_3}{c_4} - \frac{c_4}{c_3} - 1\right),\ c_6 = c_5 c_4 / c_3,\ c_8 = c_7 c_4 / c_3$$

With this formulation, the ratio between the long term and short term elasticities is restricted to be identical for all explanatory variables. In terms of the parameters of the ECM, the restricted ART model has

$$\alpha = -\left(\frac{c_2 c_3}{c_4} - \frac{c_4}{c_3} - 1 + c_2\right),\ \psi_{y_1} = -c_2,\ \psi_{X_0} = (c_3, c_5, c_7), \text{ and } \theta = k(c_3, c_5, c_7),$$

with the proportionality factor $k = \frac{1}{\alpha}(1 + \frac{c_4}{c_3})$. We label this model FM3.

This formulation with the restriction on the relationship between short and long run elasticities corresponds to assuming the so-called capital stock adjustment model (see the derivation in Fosgerau, Holmblad & Pilegaard (2004)).

4.2 Mileage model

Let m_t be the logarithm of the level of car use (mileage per capita in km/person) in year t. We model m_t as a function of its value in previous years and a vector of explanatory variables (X_t), which includes the logarithms of GDP per capita (x_{1t}), the purchase price index (x_{2t}), and the vehicle operating cost index (x_{3t}).

As shown, m_t and X_t are I(1) series, so it only makes sense to estimate ARDL and ECM models as the above, if the variables are cointegrated. Given at most one cointegrating relation, we can

use the ARDL model as described in Section 4.1.1 or its equivalent ECM formulation, replacing the dependent variable by m_t.

A formal test allowing up to 3 lags for all series indicate that one lag or two lags would be sufficient to capture the dynamic structure. Our most general model specification therefore has 2 lags of both the dependent and independent variables (p=2, q=2), and can thus be written in ECM form as:

$$\Delta m_t = \delta - \alpha(m_{t-1} - \theta X_{t-1}) + \psi_{y_1}\Delta m_{t-1} + \psi_{X_0}\Delta X_t + \psi_{X_1}\Delta X_{t-1} + \varepsilon_t \quad (3)$$

where, as before, α is the speed of adjustment towards long run equilibrium after distortion, θ is a set of parameters where each parameter $\theta_k = \sum_i \beta_{k,i}/\alpha$ indicates the long run impact of X_t on m_t (equal to the long run elasticity between the original variables without logarithms), and ψ are the short run coefficients. Specifically, ψ_{X_0} is the short run impact of X_t on m_t, which is the short run elasticity between the original variables.

5. Estimation results and discussion

5.1 Fleet size model

In this section, we present and discuss estimation results from the model for fleet size. As stated earlier, this model analyses the number of cars per capita as a function of its past values and contemporaneous and lagged values of variables for income (GDP per capita) and cost of buying and using a car. Estimation is carried out using the logarithms of the dependent variable and each explanatory variable.

We start out with FM1: an Error-Correction model with 2 lags of both the dependent and independent variables ($p = q = 2$). This model passes the required validation tests: the errors are homoscedastic, normally distributed, and serial uncorrelated, and the hypothesis of a unit root in the residuals is rejected at the 10% level, indicating the existence of a cointegrating relationship (i.e., long run relationship in levels). However, many of the estimated parameters have rather large standard errors, including all the long run elasticities. For this reason, we prefer a more parsimonious model with fewer lags.

Our next model is the FM2: an Error-Correction model with 2 lags of the dependent variable and 1 lag of the independent variables (p=2, q=1), i.e. the model in Section 4.1.2. For easy comparison with the original ART FLEET model from 2004, we estimate the model in the form of eqn. (1). Table 3 provides estimation results from this model. This model also performs well in the validation tests: We can accept that errors are homoscedastic and serially uncorrelated, and the hypothesis of a unit root in the residuals is rejected.[2] However, still some parameters have rather large standard errors, including the long run elasticities of purchase price and operating costs, which means that the estimates are somewhat inaccurate.

[2] Normality of the error terms is rejected, meaning that standard errors are valid asymptotically, but may be biased in small samples.

Table 3: Estimation results from FM2

Dependent variable: change in log fleet size per capita					
Variable		Estimate	Standard error	t-statistic	Prob.
Log fleet size per capita [t-1]	c_1	0.409	0.13	3.05	0.00
Log fleet size per capita [t-2]	c_2	-0.522	0.09	-5.85	0.00
Log GDP per capita	c_3	0.207	0.11	1.86	0.07
Log GDP per capita [t-1]	c_4	-0.149	0.13	-1.12	0.27
Log purchase price	c_5	-0.001	0.10	-0.01	0.99
Log purchase price [t-1]	c_6	-0.059	0.11	-0.56	0.58
Log operating cost	c_7	-0.043	0.11	-0.40	0.69
Log operating cost [t-1]	c_8	0.074	0.12	0.64	0.53
Constant	δ	-0.060	0.07	-0.87	0.39
R-squared		0.59			
Number of observations		41			

Like Fosgerau, Holmblad & Pilegaard (2004), we therefore proceed with a restricted model, where the ratio between long run and short run elasticities is assumed to be constant across all explanatory variables. This is the model FM3 in Section 4.1.3. Table 4 provides the estimation results. Comparing this restricted model to the unrestricted model above using a likelihood ratio test shows that the two models are not significantly different (LR =5.05, 3 degrees of freedom, p-value=0.17), i.e. the restriction is not against the data. Moreover, the restricted model passes the validation tests: Errors are homoscedastic, normally distributed, and serially uncorrelated, and the hypothesis of a unit root in the residuals is rejected.

Table 4: Estimation results from FM3

Parameter	Estimate	Standard error	t-statistic	Prob.
c_2	-0.513	0.10	-5.35	0.00
c_3	0.233	0.11	2.15	0.04
c_4	-0.166	0.11	-1.55	0.13
c_5	-0.160	0.08	-2.03	0.05
c_7	-0.095	0.10	-0.99	0.33
Constant	-0.004	0.03	-0.14	0.89
R-squared	0.54			
Number of observations	41			

As we see in Table 5, the short run elasticities have the expected signs, though the elasticity for operating cost is not significantly different from zero. The implied long run elasticities of GDP, purchase price and operating cost are 0.83, -0.57 and -0.34, respectively. While the other two elasticities are significantly different from zero even at the 1% level, the elasticity of operating cost is not significantly different from zero at conventional levels (its p-value is 0.29). However, we choose to keep the operating cost in the model for the following reasons:

- Theoretically (from a micro-economic perspective), it is more likely that operating cost has a negative effect on the fleet size, rather than no effect.
- The original ART model from Fosgerau, Holmblad & Pilegaard (2004) also included operating cost, and all their model estimates were significantly different from zero.

Figure 8 shows that the model provides a good fit to the data.

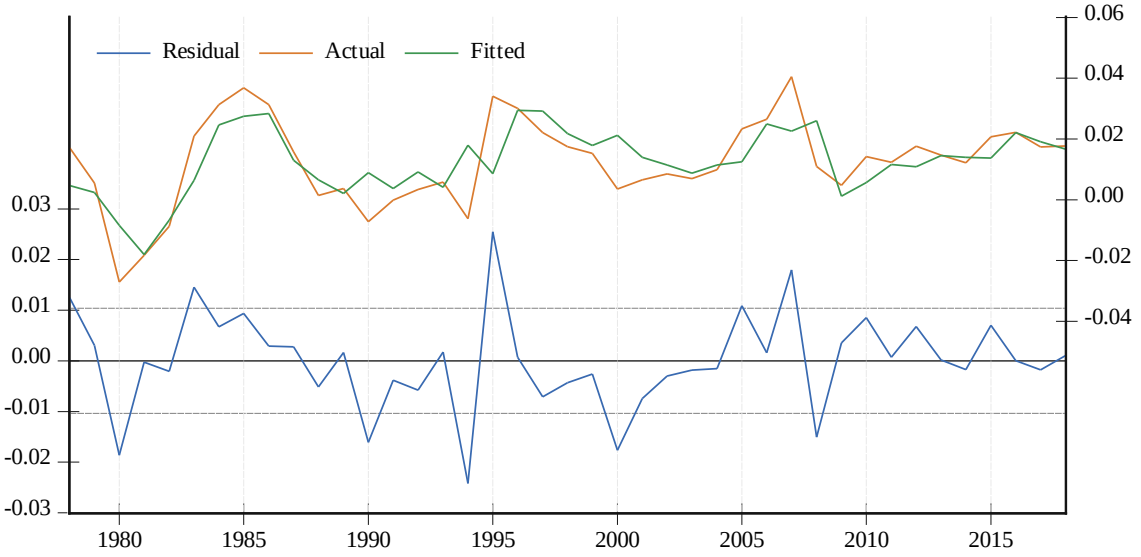


Figure 8: Actual fleet size per capita and prediction based on FM3

When we compare our results with the results from the 2004 ART model (Table 5), we see that the long run income elasticity and purchase price elasticity are now larger in absolute value while the absolute value of the operating cost elasticities are lower (though not significantly smaller due to the large standard error).

Table 5: Elasticities from our preferred model (FM3) and the 2004 ART model

	FM3		2004 ART FLEET model	
	Short run	**Long run**	**Short run**	**Long run**[††]
GDP per capita	0.23***	0.83***	0.27***	0.67
Purchase price index	-0.16***	-0.57***	-0.19***	-0.48
Operating cost index	-0.09	-0.34[†]	-0.22***	-0.55

- ***, **, * indicate significance at the 1%, 5% and 10% levels.
- [††] Significance levels are not provided for the 2004 ART model.
- [†] The p-value of the estimate is 0.29.

5.2 Mileage model

In this section, we present and discuss estimation results from the model for car use – the mileage model. As stated earlier, this model analyses the extent of car use as a function of its past values and contemporaneous and lagged values of GDP, operating cost and purchase price.

In this report, the extent of car use is measured in terms of mileage per capita while the 2004 study (Fosgerau, Holmblad & Pilegaard, 2004) used mileage per car. Both are good indicators of travel demand, and given fleet size, either one can be predicted from the other. As described earlier, mileage per car showed a complex pattern over time, changing from an increasing trend up until the mid-1990s to a decreasing trend after, which is likely due to the rise in the share of multicar households. With GDP and operating cost showing an overall upward or downward trend,

it turned out to be difficult to model the changing pattern of mileage per car, even when we attempted to include the share of multicar households as an explanatory variable. This variable was only available for 1996-2018, which considerably reduced the number of observations. In fact, all attempts to estimate a model for mileage per car were unsuccessful as most coefficient estimates appeared insignificant and/or had unexpected sign. Hence, our analysis of car use is based on mileage per capita.

We modelled mileage per capita as a function of GDP, operating cost and purchase price. We estimated two Error-Correction models: One with 2 lags of both the dependent and independent variables (p=2, q=2), and one with 2 lags of the dependent variable and 1 lag of each explanatory variable (p=2, q=1). These two specifications yield comparable estimates. We tested for the reduction from the specification involving 2 lags to the one that includes just 1 lag, and the resulting test statistic indicates that the two specifications are similar (LR=2.00, 3 degrees of freedom, p-value=0.57). Consequently, we use the more parsimonious model with $p = 2$ and $q = 1$. Estimation results from this model are shown in Table 6.

Results indicate that the estimated long run elasticities of all the three explanatory variables are significant and have the expected signs. The estimated short run elasticities of GDP and purchase price are insignificant while the short run elasticity of operating cost is significant and positive as expected.

Table 6: Estimation results from the EC form of the mileage model

Dependent variable: change in log mileage per capita					
Variable		Estimate	Standard error	t-statistic	Prob.
Log mileage per capita [t-1]	$-\alpha$	-0.256	0.08	-3.33	0.00
Change in log mileage per capita [t-1]	$\psi_{\Delta y_1}$	0.438	0.12	3.65	0.00
Change in log GDP per capita	$\psi_{x_{1_0}}$	0.219	0.14	1.59	0.12
Change in log purchase price	$\psi_{x_{2_0}}$	-0.111	0.18	-0.63	0.53
Change in log operating cost	$\psi_{x_{3_0}}$	-0.289	0.11	-2.63	0.01
Constant	δ	2.460	0.75	3.30	0.00
Long run elasticities					
Log GDP per capita	θ_1	0.805	0.09	8.79	0.00
Log purchase price	θ_2	-0.637	0.119	-5.354	0.000
Log operating cost	θ_3	-0.607	0.21	-2.84	0.01
R-squared		0.69			
Number of observations		41			

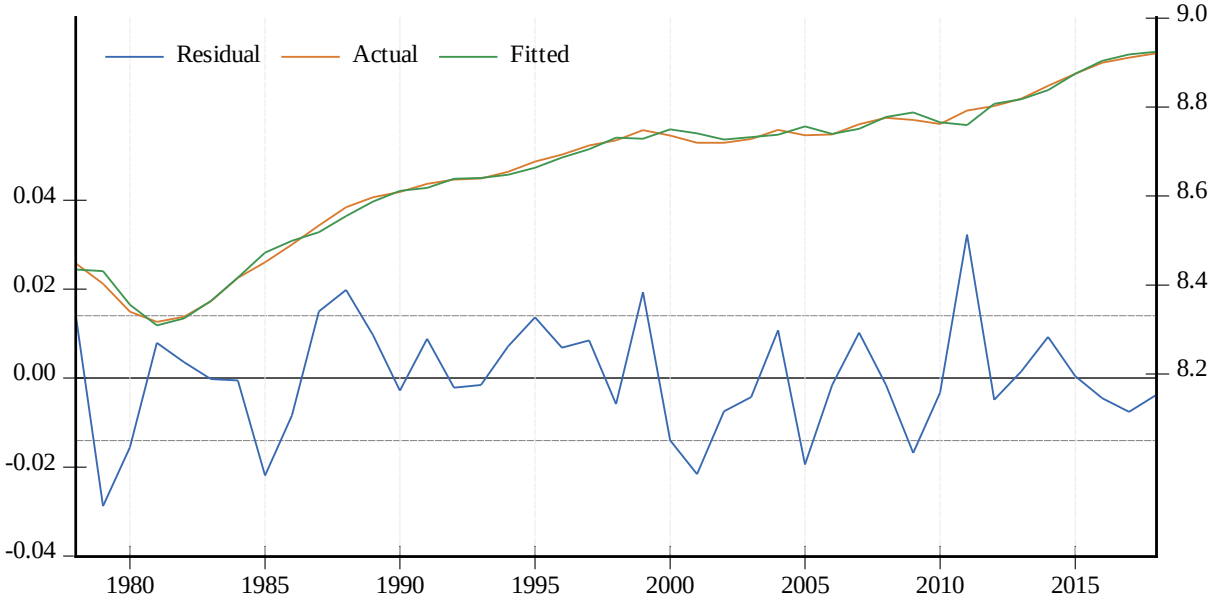


Figure 9: Observed versus fitted values as well as residuals from the mileage model

Residuals from the model have been tested for and found to be homoscedastic, serially uncorrelated and normally distributed. The hypothesis of a unit root in the residuals is rejected.

Table 7: Elasticities from the mileage model

	Short run	Long run
GDP per capita	0.22	0.80***
Purchase price	-0.11	-0.64***
Operating cost	-0.29**	-0.61**

- ***, ** indicate significance at the 1% and 5% levels.

The estimation results show that the long run effects of GDP and purchase price are almost the same on mileage per capita as on fleet size per capita. This indicates that changes in income or in the purchase price make people change their transport behaviour by adjusting the number of cars whereas the use of each car (mileage per car) is only marginally affected. For the operating cost, however, there is a larger difference where only about half of the long run effect on mileage comes from adjustment in fleet size while the other half comes from adjustment of mileage per car.

As mentioned earlier, this model is different than the mileage model in Fosgerau, Holmblad & Pilegaard (2004) and the elasticities therefore cannot be compared directly with one another. However, it is possible to infer the effect on mileage per capita from estimates of the 2004 ART mileage and fleet size models by adding the effects from the fleet size and the mileage per car models. Our finding for the long run effect of GDP on mileage per capita, which is 0.80, is very close to the effect derived from the 2004 ART estimation (0.67+0.16=0.83). There is however a difference indicating that the effect is now primarily driven by adjustment in the fleet size whereas mileage per car changes less. The long run effect of purchase price is also close to the 2004 ART estimate but it is slightly larger (-0.64 compared to -0.48). For operating costs, the long run effect is now lower than in the ART (2004) estimation (-0.61 compared to (-0.55-0.37=-0.92). It seems

that it is primarily the effect from fleet size that is lower (-0.34 compared to -0.55) whereas the implied effect from adjustment of mileage per car is only slightly lower than the 2004 ART estimates (-0.61-(-0.34)=-0.27 compared to -0.37). However, as the elasticity of -0.34 in our fleet size model is not significant at conventional levels, this is to be interpreted with caution.

Table 8: Elasticities from the 2004 ART model for mileage per car

	Short run	Long run
GDP per capita	0.13	0.16
Operating cost	-0.30	-0.37

5.3 Sensitivity analysis

We now present some other model specifications that we have tested to address several issues. One of such issues is the statistically insignificant elasticity of operating cost in the car ownership model. As this is contrary to our expectation, we conducted a further analysis to see if this can change with the inclusion of relevant other factors in the model or the use of a proxy for operating cost.

- Firstly, we re-estimated FM3 using real petrol prices instead of operating cost since petrol price is the most important component of operating costs and it is widely used in the literature. Doing this however brought little change in the short run and long run elasticities of GDP and purchase price, though the short run elasticity estimates are now less precise. The estimated short run and long run elasticities associated with petrol price are found to be statistically insignificant and very small (it is only one-third of the corresponding operating cost elasticity). Therefore, using petrol price as a proxy for operating cost improved neither the overall model fit nor precision of the cost elasticity estimate. In light of the expected increase in non-fossil fuelled cars in the coming years, the importance of petrol price is likely to be reduced in the future and projections based on petrol prices could be problematic.

- Secondly, we re-estimated the fleet size model, FM3, by including the share of households with two or more vehicles. Estimation is carried out using data from 1996 to 2018 since data on the share of multicar households is unavailable for earlier years. Not only was the estimated elasticities of the share of multicar households insignificant, but also the inclusion of the variable worsened the statistical significance of other estimates of the model. The fact that model is estimated using a smaller sample has also contributed to the loss in precision of the estimates.

- We also re-estimated FM3 including a set of additional dummy indicators for periods with economic or oil crises or relevant policy interventions. In particular, we defined four dummy variables that indicate the 1994-95 policy on scrap premium, the 1980-82 economic crisis, the 1990-91 oil crisis, and the 2008-10 economic crisis. We re-estimated the model by including each dummy variable separately, a pair of the dummy variables at a time and all the dummy variables at once. While there was some variation in the implied elasticities across these specifications, the estimated long run elasticities of GDP and purchase price were significant and roughly similar to those estimated under FM3. In particular, the long run elasticities of GDP were found to be in the range from 0.55 to 0.90 while that of purchase price were in the range from -0.61 to -0.50. We found a more

pronounced variation in the long run elasticity of operating cost from one to another specification; however, the estimate was always insignificant. Besides, nearly all estimates associated with the dummy variables are found to be small and statistically insignificant. So, none of the above considerations provide a specification with a significant cost elasticity.

As was the case with the fleet size model, the mileage model was estimated including a set of dummy variables as additional covariates. Estimates of the long run income and price elasticities are similar to corresponding estimates that we discussed in the above section. While most of the estimated cost elasticities appeared significant, the estimates showed a slightly larger variation from one to another specification depending on which dummy variable(s) were included in the model. As was the case with the fleet size model, estimates associated with the dummy variables were neither significant nor economically meaningful.

In general, we conclude that the results presented in Sections 5.1 and 5.2 are preferred to those implied under the alternative specifications presented in this section.

5.4 Comparison with the literature

The literature on car ownership and use comprises a number of studies that differ based on data, method, target area, unit of analysis, sample period, etc. In this section, we present a few of them to compare with our results. A detailed review of the literature can be found in Goodwin, Dargay, & Hanly (2003), de Jong et al. (2004) and Graham & Glaister (2004). A review of more recent studies is given in Dunkerley, Rohr, & Daly (2014).

Earlier studies typically used aggregate data at national or regional levels and modelled car ownership in terms of income or GDP using specifications that allowed to capture the potential decreasing sensitivity of income or GDP. Recent studies tend to use disaggregate data observed at the household or individual level to estimate elasticities that reflect behavioural response at the individual level. Since our analysis is based on aggregate data, the implied elasticities can therefore differ from those reported in studies that are based on disaggregate data.

In the following, we discuss our results vis-à-vis results in previous studies that are based on aggregate data and results from reviews, including studies that are based on both aggregate and disaggregate data.

Dargay and Gately (1999)	Dargay and Gately (1999) analysed car ownership using cross-country panel data and a simple model in which car ownership levels are determined solely by per-capita income levels according to the Gompertz function. They found long run income elasticities for Denmark of 1.13 in 1992 and 0.27 in 2015 for cars and 1.29 to 0.40 for vehicles. The estimated elasticity declined over time due to the assumption of increasing income and the resulting saturation effect. In contrast to such a declining income effect, the present study finds an estimate that is at least as high as that found in Fosgerau, Holmblad & Pilegaard (2004).

While being well within the range of estimates in Dargay & Gately (1999), the income elasticity in the current study of 0.83 is three times higher than their estimate for 2015. The difference in elasticities between the two studies could be due to differences in data, model or both. However, the projected vehicle (resp. car) ownership per capita for Denmark of 0.52 (resp. 0.65) in 2015 is yet to be achieved pointing at a possible overestimation of the income effect in 1992 and underestimation in later years in the Dargay & Gately study.

Romilly, Song, and Liu (2001)

Using aggregate historical data and time series models similar to those used here, Romilly, Song, and Liu (2001) modelled car ownership and use in Britain as a function of income, bus fare and 'motoring cost', which is an aggregate index for purchase and running costs of private motor vehicles.

Romilly, Song, and Liu (2001) found the elasticity of car ownership with respect to income to be between 1.06 and 2.63 in the long run and 0.37 and 0.43 in the short run. The range of values for the short run elasticity are within the 95% confidence interval for our estimate, and while appearing lower, our finding for the long run income elasticity is well within the range of values recommended in Romilly, Song, and Liu (2001).

Their estimate for the elasticity of car ownership with respect to 'motoring cost' varied from -2.33 to -1.22 in the long run and from -0.30 to -0.20 in the short run. As their cost variable includes both purchase price and operating costs, direct comparison is not possible.

The elasticity estimates in Romilly, Song, and Liu (2001) from the car use model are also somehow comparable to those of ours. Our estimate for the income elasticities are lower than one-half of the corresponding estimates in Romilly, Song, and Liu (2001) (0.64 to 0.70 in the short run and 1.85 to 2.76 in the long run). We note that these differences are significant, and the difference could be due to differences in sample periods and peculiarities in target countries.

Medlock and Soligo (2002)

Medlock and Soligo (2002) analysed car ownership in 28 countries using panel data and a model similar to that used in the current study. In addition to income and operating cost, for which the price of motor fuel is used as proxy, their model includes income-squared to capture a potential saturation effect. The saturation effect is allowed to vary across sample countries. However, their prediction for Denmark of 0.41 vehicles per capita in 2015, was already achieved in 2007 with the per capita fleet size still rising.

The finding of Medlock and Soligo (2002) for the elasticity of car ownership with respect to operating cost was -0.12 in the short run and

-0.61 in the long run. While the short run elasticity is comparable to our finding, the long run elasticity is about twice as high despite not being statistically different. Their finding for the income elasticity varies with the level of income ranging from 3.61 at the lower level of income to 0 at the point of saturation. Our finding is well within this range.

Goodwin, Dargay, and Hanly (2003)

Goodwin, Dargay, and Hanly (2003) provides a summary of results from a review of empirical studies published since 1990. They include studies that are based both on aggregated and disaggregated data. Some of the main conclusions of their study are as follows:

- Reviewed evidence indicate that long run elasticities are larger than corresponding short run elasticities, mostly by factors of 2 to 3. This also applies to estimates in the present study.

- Their findings of the average from dynamic models of the elasticities of car stock with respect to fuel price of –0.08 in the short run and -0.25 in the long run are very similar to estimated cost elasticities in the present study. The average long run elasticity of mileage with respect to fuel price of -0.29 is slightly lower than our estimate for the elasticity of cost; however, the difference is not significant.

- The average long run elasticities of total fleet size with respect to income of 0.81 and mileage with respect to income of 0.73 obtained in their study are quite comparable to those found here (0.83 and 0.80).

Graham and Glaister (2004)

Graham and Glaister (2004) summarised elasticity estimates reported in the international literature.

- Graham and Glaister (2004) found estimates of the long run income elasticity of car ownership to be within the range from 0.3 to 1.1 with a mean value of 0.74. Our long run income elasticity is well within this range, and close to the mean value. Our finding for the short run income elasticity is not much different from their finding for the range of values in the literature (0.24 to 0.34). Estimates of the price/cost elasticity in the present study are also well within the range Graham and Glaister (2004) found (-0.24 to -2.65 in the long run and -0.35 to -0.09 in the short run).

- The finding by Graham and Glaister (2004) for an elasticity of mileage with respect to fuel price of -0.16 in the short run and -0.26 in the long run are about one-half of the estimated cost elasticity in the current study. However, neither of the differences is statistically significant. Our estimates for the elasticities of mileage with respect to income are also

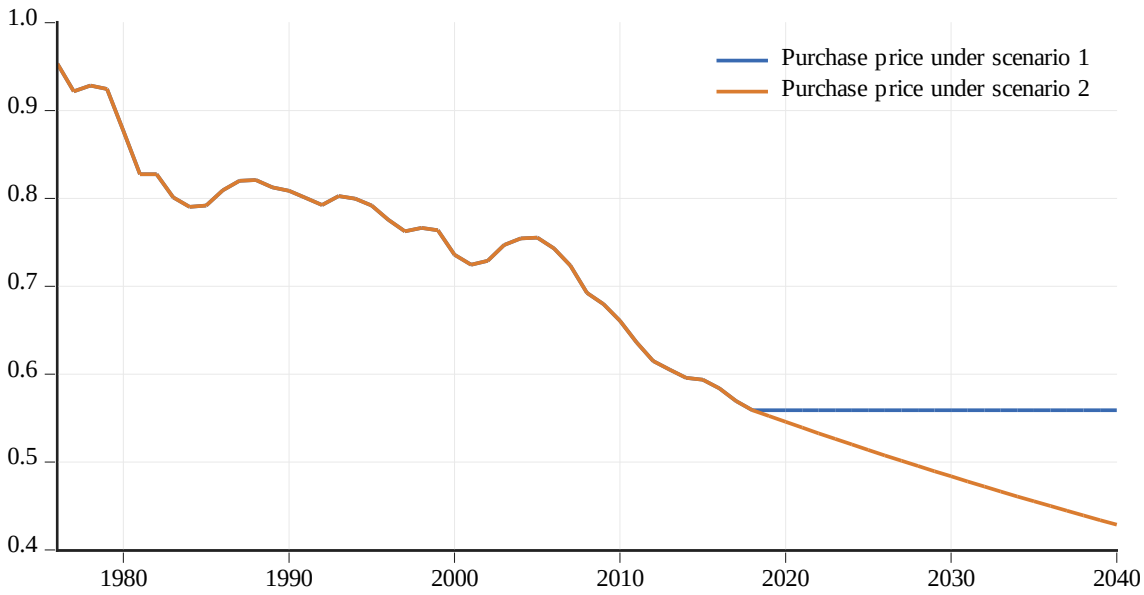
comparable to values that Graham and Glaister (2004) found in reviewed studies.

Based on the evidence reviewed, we can conclude that estimates of the elasticities of income, purchase price and operating cost that we find in the present study are largely comparable to those in the literature. A direct comparison of our estimates vis-à-vis those in the literature is hampered, however, by differences across studies in terms of elements included and/or excluded in operating cost or purchase price and how they are measured.

6. Forecast

In this section, we use our preferred models together with projections of GDP, purchase price and operating cost to predict future fleet size and car use. While GDP and operating cost projections can be found in the Transport Economic Unit Prices (Transportministeriet, 2019) where projections from several sources are collected (see Table 11 in the Appendix), we did not find similar projections for purchase price. Subsequently, forecasts are developed under the following scenarios regarding the growth rate of purchase price in the forecast period (2019-2040):

- Scenario 1: purchase price remains constant at the 2018 level
- Scenario 2: purchase price declines at the rate of 1.2% per annum starting from the 2018 level, where 1.2% is the average annual rate at which price declined between 1976 and 2018.



6.1 Fleet size model

Given the estimation results discussed in the previous section and projections of GDP, purchase price and operating cost, the level of car ownership per capita is predicted to increase from about 0.49 in 2018 to 0.62 (under scenario 1) – 0.71 (under scenario 2) in 2040. The estimated average annual growth rate is between 1.0% and 1.7% in the coming two decades.

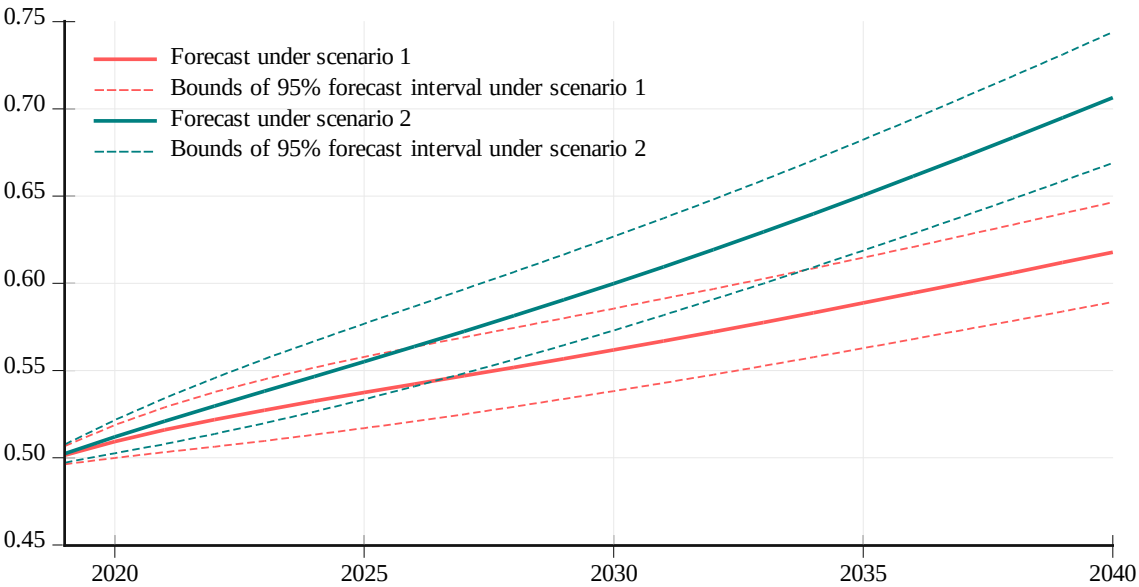


Figure 10: Fleet size per capita projected under alternative scenarios

Table 9: Fleet per capita projections for selected years in the forecast period

Year	Scenario 1	Scenario 2
2020	0.51	0.51
2025	0.54	0.56
2030	0.56	0.60
2035	0.59	0.65
2040	0.62	0.71

6.2 Mileage model

Our analysis suggests that the level of mileage per capita, which is about 7,500km in 2018, is predicted to reach between 9,900km and 11,600km in 2040 thereby registering an average annual growth rate of 1.3%-2.0% in the period depending on assumptions regarding the growth of purchase price in the forecast sample.

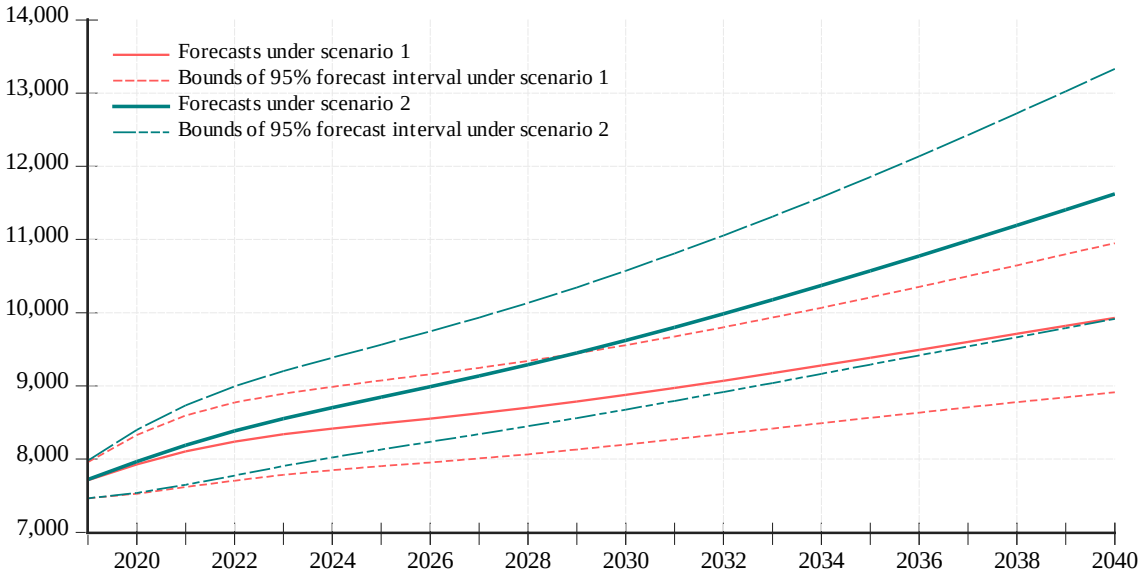


Figure 11: Mileage per capita projected under alternative scenarios

Table 10: Mileage per capita projections for selected years in the forecast period

Year	Scenario 1	Scenario 2
2020	7,900	7,970
2025	8,490	8,850
2030	8,880	9,620
2035	9,390	10,570
2040	9,930	11,620

7. Conclusion

This report documents the work carried out in relation to the estimation and forecast of private car ownership and use for Denmark. The work is carried out with a view to update forecasts based on the 2004 study (Fosgerau, Holmblad & Pilegaard, 2004) taking account of recent changes in travel behaviour and overall economic conditions.

The estimation of car ownership and use models is performed using annual data for the period 1976-2018 and a dynamic time series method that allow estimation of both short run and long run elasticities. In particular, the car ownership and use models are estimated using an Error Correction Model (ECM), a model that assumes the existence of an equilibrium relationship that determines both short and long run relationships. Fleet size and mileage levels are modelled as functions of GDP per capita and official indices for vehicle purchase price and vehicle operating costs.

The resulting models provides a good fit to the data and coefficient estimates that have the expected signs and are statistically significant. Our estimates show that a change in income or purchase price has a significant long run effect on the level of per capita fleet size and mileage. A change in operating costs is found to have a significant effect on the level of per capita mileage while its effect on fleet size is not significant at conventional levels.

We find that a percentage increase in GDP per capita is associated with a significant increase in the per capita fleet size by 0.83% and per capita mileage by 0.80% in the long run. Similarly, a percentage increase in purchase price leads to a fall in the per capita fleet size by 0.57% and the per capita mileage by 0.64%. The corresponding effects due to a percentage increase in operating costs are decreases of 0.34% and 0.61%, respectively, but the former effect is not statistically significant at conventional levels.

Our findings for the elasticities of purchase price, income and vehicle operating costs are quite comparable to the results from the 2004 study (Fosgerau, Holmblad & Pilegaard, 2004). The long run effect of income on mileage per capita is the same, while its effect on fleet size per capita is now higher. The long run effect of purchase price now higher on both mileage per capita and fleet size, although the difference is not large. For operating costs the long run effect on mileage per capita is now lower. These findings are not surprising considering the recent trend in data. The observed change in effects could be explained by the increase in the number of multicar households. When households buy an additional car, they are likely to increase their overall mileage but however not to double it. Therefore, purchase price becomes relatively more important while the importance of operating costs will be lower. Our results also indicate that reactions to income and purchase price changes in the long run will primarily be in the form of adjustments to the fleet size, while the adjustment in mileage per car will be smaller and less significant. We find our results to be comparable to findings in the international literature.

Forecasts of future fleet size and mileage levels are produced under alternative scenarios. Our projections show that both car ownership and mileage levels are predicted to increase in the next two decades. The level of car ownership is predicted to increase from 0.49 cars per capita in 2018 to 0.62-0.71 in 2040 depending on alternative assumptions about the growth rate of purchase

prices. Similarly, mileage per capita is predicted to increase from 7,500km in 2018 to 9,900km - 11,600km in 2040.

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Appendix

Table 11: Data sources

Variable	Description	Source
Fleet size	The number of motorcycles, personal cars and vans (<2 tons).	Statistics Denmark, www.statistikbanken.dk, table BIL6, "Bestand". Sum of three entries: "Personbiler i alt" (including taxies), "Varebiler, totalvægt 0-2.000 kg" and "Motorcykler i alt".
Mileage	The total distance in million kilometres driven by the vehicle fleet defined above	The Danish Road Directorate's statistics "NATIONALT TRAFIKARBEJDE (mio. kørte kilometer i DK med danske køretøjer)". Sum of four entries: "Personbiler", "Taxi", "Varebiler under 2 ton" and "Motorcykler". Alternatively, the data can be found in: Statistikbanken-table VEJ23.
Population: 1976-2018	The number of all persons in Denmark	Statistics Denmark, www.statistikbanken.dk, Statistikbanken-table FT, Population by January 1.
Population: 2019-2040	Population projection	Statistics Denmark, www.statistikbanken.dk, table FRDK119 (projection from May 2019).
GDP: 2017-2018	The Gross Domestic Product in Denmark using 2010 chained prices (in million Danish Kroners).	Statistics Denmark, www.statistikbanken.dk, Statistikbanken-table NAN1, entry "B.1*g", Bruttonationalprodukt, BNP, Label: "2010-priser, kædede værdier, (mio. kr.)"
GDP: 2019 – 2040	GDP projections	- Danish Ministry of Finance: "Økonomisk Redegørelse", Dec. 2018, Bilagstabel 1 og 4. (for the period 2019-2020) - Projections for 2021-2040 are based a 0.9% annual growth rate recommended by the Danish Ministry of Finance
Number of households by car ownership	The share of households owning no car, one car or multiple cars.	Statistics Denmark, www.statistikbanken.dk, tables BIL82 and BIL800.
Vehicle operating cost index: 1976-2018	Average vehicle operating cost relative to that in 1964. The index includes the cost of spare parts and accessories, tyres, propellants, lubricants, maintenance, repair, parking fees, toll, driving lessons and tests, car inspection and car hire.	Statistics Denmark, www.statistikbanken.dk, Statistikbanken-table PRIS111, entry 07.2 "Operation of personal means of transportation".

Vehicle operating cost index: 2019-2040	Projections of vehicle operating costs	Danish Energy Agency: "Basisfremskrivning 2019" (This is based on fuel prices and fuel efficiency while keeping other components of operating cost constant in the projection period.)
Vehicle purchase price index	Average vehicle purchase price relative to that in 1964. The index includes the price of passenger cars and passenger vans, motorcycles and bicycles.	Statistics Denmark, www.statistikbanken.dk, Statistikbanken-table PRIS111, item 07.1.1 "Acquisition of passenger cars".
Petrol price	Average annual petrol price in chained 2010 Danish kroners	"DrivkraftDanmark" (Danish Energy Retailers) https://www.drivkraftdanmark.dk/priser/benzin/
General consumer price index	The general price index based on which chained indices are determined.	Statistics Denmark, www.statistikbanken.dk, Statistikbanken-table PRIS112

Table 12: Test statistic from alternative approaches for testing stationarity

	Series in levels				**Series in first difference**			
Test	ADF	DF-GLS	PP	KPSS	ADF	DF-GLS	PP	KPSS
Fleet per capita	0.53	0.77	0.96	2.18***	-3.34**	-2.75***	-3.59***	0.17
Mileage per car	-1.55	-1.58	-1.13	0.43*	-3.72***	-2.87***	-4.64***	0.16
Mileage per capita	-0.54	-0.06	-0.29	2.04***	-3.55***	-3.52***	-3.89***	0.17
GDP per capita	-1.60	0.35	-1.73	2.14***	-2.79*	-2.85***	-3.79***	0.26
Purchase price index	0.24	0.98	0.18	1.95***	-2.99**	-3.05***	-2.84*	0.34
Operating cost index	-1.59	-0.63	-1.27	1.83***	-4.19***	-3.83***	-4.15***	0.09

- *, ** and *** respectively indicate statistical significance at the 10%, 5% and 1% levels.
- All tests have a null hypothesis of a unit-root except KPSS which has a null of stationary.

Table 13: Definition and measurement units for variables used in econometric analysis

Variable	**Description**
y_t	The logarithm of fleet size per capita, measured in number of vehicles per person.
m_t	The logarithm of mileage per capita, measured in km per person.
x_{1t}	The logarithm of GDP per capita, measured in millions DKK per person.
x_{2t}	The logarithm of purchase price index
x_{3t}	The logarithm of operating cost index