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Modeling Auto-Mobility: Combining Cohort Analysis with Panel Data Econometrics

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Abstract: In this paper, we present an *ad hoc* model for car traffic generation, which is used to make projections in 2060, according to a number of scenarios based on various assumptions about fuel prices, fuel efficiency, income growth and travel behaviors of new generations. Two sets of scenarios are successively tested, corresponding either to the “business as usual” case, or to a declining appetite for car ownership in new generations. Projection results serve to discuss the “peak car” hypothesis of a decline to come in average car travel per adult. The modelling framework is based on a sequential and individual approach to car traffic generation where the age-cohort framework is combined with panel data econometrics. Projection results suggest that under stable behaviors, “peak car” is less likely to happen than a *plateau*. A decline in car travel could happen, nonetheless, in case of changing behaviors in new generations.

Keywords: Auto-mobility, Cohort Analysis, Panel Data, Econometrics, Traffic Forecasting

1. INTRODUCTION

In this paper, we display a disaggregated panel data model for auto-mobility - driving license, personal car availability, and vehicle mileage – which is used for the projection of average car travel per adult and total car traffic in France by 2060, according to various scenarios based on different assumptions about income growth, fuel prices, fuel efficiency of the future vehicle stock, and attitudes to car travel in new generations. Car traffic projections from these scenarios then serve as a basis to discuss the “peak car” hypothesis of a future decline of auto-mobility. This research falls within a context of international research to get a better understanding of travel behavior transition, more precisely the stagnation of average car traffic per adult in many developed countries from the beginning of the millennium (Millard-Ball and Lee-Schipper, 2010; OECD/ITF, 2011). In France, this break in trend was registered from 2003 through national traffic accounts (CGDD, 2012). This model was designed in order to be capable of describing this historical inflexion. More generally, it was also conceived to fit with long-term observation of car travel behaviors, in order to explain heterogeneity between households or individuals, travel change over time for a given economic agent, and car travel growth resulting from the changing structure of the population. Model design is explained and justified in section 2, both with theoretical arguments and through empirical findings. Section 3 briefly describes the dataset which was used for this research and the methodology of data analysis. In section 4, model specification is provided as well as estimation results. The assumption of a sequential choice process is further justified through the evaluation of a joint model for car ownership and car use. Section 5 displays projections of average car travel per adult and total car traffic in 2060, according to different scenarios. A comparison is made between “business-as-usual”

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scenarios and a different set of scenarios which is based on the alternative assumption of a perennial decline of auto-mobility in new generations. These projections serve as a basis to discuss the “peak car” hypothesis of a future decline to come in car travel. In the conclusion, we discuss additional uncertainties likely to influence future travel demand, related to car ownership diffusion, fuel prices, individual preferences, as well as a possible dissociation between car travel and car ownership.

2. MODEL DESIGN

In this section, we justify the choices which were retained to model auto-mobility, coming both from theoretical arguments and empirical findings. Model design is characterized by a triple specificity:

- The association of a long-run cohort analysis to capture generation and gender effects, with panel data econometrics in order to capture monetary-related period effects such as income or fuel prices.
- A sequential design in three levels: driving license, car ownership and travelled distances by vehicles. This design was implemented to account for heterogeneous dynamics and determinants between car ownership and vehicle use. We made the assumption that driving license, car ownership and car use choices are, *ceteris paribus*, independent, an assumption which is then discussed through both theoretical arguments and empirical findings.
- Most disaggregated models of auto-mobility in the literature are household-based, with a few exceptions where the individual was chosen as the relevant level of analysis (for instance Golounov *et al.*, 2002). Instead of this traditional household-based analysis, an individual-based approach was preferred here. Correlatively, the model was also segmented by gender.

2.1 Combining Age-Cohort Analysis with Panel Data Econometrics

A great diversity of models was used over time to describe auto-mobility in different contexts, either car ownership alone or joint models for car ownership and car use, depending on their purpose, available data, institutions, etc. In relation with these contextual factors, models for auto-mobility differ with respect to their level of aggregation, static or dynamic nature, theoretical foundations, segmentation, etc. For a glimpse of model diversity, one can see for instance De Jong *et al.* (2004). However, these models can basically be classified according to the type of data and the level of aggregation, a distinction being made between models based on time series (Dargay and Gately, 1999), cross-sections, time-series of cross-sections (Dargay and Vythoulkas, 1999) or panel data (Kitamura and Bunch, 1992). These two dimensions of variability in travel behaviors – change over time for a given group of individuals, and permanent heterogeneity between individuals – were found not to be equivalent. For instance, generation, gender and individual-specific effects accounting for permanent preferences and habits, only explain heterogeneity between agents, but can't explain changes in individual travel behaviors over time as they remain constant. Generation effects are also decisive in explaining growth in average auto-mobility (Gallez, 1994) through generational renewal, as older generations with a restrained access to driving license and car ownership, were replaced by new cohorts accustomed to auto-mobility. This process was nonetheless very slow and gradual, resulting in long-term change rather than short or medium-term variations. On the contrary, some variables, mostly influent in the longitudinal dimension, poorly contribute to explain heterogeneity between individuals, such as fuel prices. Finally, some factors are influent on both dimensions of variability: this is the case for instance of income, as it is changing over time along with professional careers, phases of unemployment and retirement, but permanent differences of income between individuals also traduce different levels of education and

individual career perspectives. However, even in this case, cross-sectional and longitudinal estimates of these effects – and derived elasticities – were found not to be equivalent (Kitamura, 1990; Gardes *et al.*, 1996) for different reasons, among which the existence of endogeneity and the gap between short-run variations and long-term equilibrium (Mundlak, 1978). In particular, endogeneity in panel data is caused by the existence of unobserved heterogeneity, which can be modeled through the introduction of individual-specific effects, standing for permanent attributes such as preferences, capacities, habits, etc. Moreover, cross-sectional estimates are themselves changing over time when relationships are non-linear, notably in the case of discrete choice models that may be used to model the diffusion of durables such as car ownership. Advantages of panel or pseudo-panel approaches on time-series or cross-sectional models include the capacity to describe separately and compare these two dimensions of variability, to account for unobserved heterogeneity, and for short-term variations related to economic conditions. However, they usually don't specify cohort effects as they are often based on econometrics rather than on a demographic approach. As a result, they are better suited to deal with short-run variations than long-term change.

On the other hand, models based on the follow-up of cohorts have proved the strength of generation effects in explaining both heterogeneity in behaviors and change in average auto-mobility over time. The implementation of generation effects usually gives good dynamic properties to car traffic models, allowing to overcome some limitations of traditional econometric models and to account for phenomena of saturation, as behaviors of successive generations have become ever-closer. In particular, these models allowed anticipating a slowdown in motorization and car travel growth during the 2000's (Madre *et al.*, 1996; Madre *et al.*, 2013). However, they were often reproached their lack of theoretical economic background, and to be descriptive statistical models. Reasons for generation effects may be complex but underline the persistence of habits and lifestyles all over the life course, giving an indication that social change is not ubiquitous but happens through the replacement of generations, given the decisive influence of youth in shaping attitudes and behaviors. They are usually appropriate to forecast long-term change resulting from structural socio-demographic factors (generational renewal, population ageing...), but they don't account for short to medium-run variations caused by temporary economic conditions (fuel prices, recession...), or by public policy measures. They don't allow either to capture unobserved heterogeneity in the distribution of travel behaviors. However, they can be adapted to take into consideration economic drivers within the age-cohort-period (ACP) framework (Gallez, 1994). In this paper, we combine age-cohort analysis with panel data econometrics, in order to account both for structural behavioral change related to demographic factors (generation, gender...), economic drivers, and unobserved heterogeneity.

2.2 A Sequential Framework

Reasons for a sequential approach to auto-mobility are both theoretical and empirical. As already mentioned, some models of auto-mobility – car travel per adult or household - are direct while others are sequential, explicitly controlling for car ownership as a decisive underlying factor of car travel. This is the case for joint models for car ownership and car use (Mannering and Winston, 1985; Hensher *et al.*, 1990). This sequential approach best fits the need for a comprehensive model of auto-mobility, as household car availability is usually required for an individual to travel by car. To some extent, classical car travel devices such as car rental, or more innovative such as car sharing and carpooling, allow a certain degree of dissociation between car ownership and car use. However, they still remain marginal with respect to the total amount of car travel, both in terms of number of trips and vehicle*miles travelled (VMT).

At least from a medium-term perspective, it seems possible to forecast car traffic from household's car fleet, without specifically modeling the traffic generated by travel services. Likewise, driving license is also part of this filtering process, as it is usually required for driving a vehicle, notably if one is willing to drive on a regular basis, rather than using the household's vehicle only occasionally and as a passenger. Of course, situations of unlicensed driving exist, and tend to increase with license withdrawals following road safety regulations, especially the combination of speed cameras with the system of driving license with penalty points (French Ministry of the Interior, 2011), but still remain marginal at this time. As a result, either at the household or individual level, auto-mobility can be seen as the result of successive filters.

The importance of this filtering process can be highlighted when repositioning the analysis into a longer-term perspective. In a previous paper (Grimal *et al.*, 2013), we formed time-series of average car traffic per adult and the average number of cars per adult over a long-term period, by concatenating the French Household Continuous Surveys (1974-94) and the French Car Fleet Surveys (1993-2010). We found that at the aggregate level and over several decades running from the 70's to the late 2000's, average car traffic per adult has been increasing proportionally to the average number of cars per adult, though with mid-term fluctuations, themselves related to fuel price volatility. Yet, the average number of cars per adult was characterized by steady growth over time, while average distance travelled per vehicle remained stationary, its fluctuations being related to income and fuel prices, with successive effects of the late 70's oil shock, the mid-80's counter-shock, and finally a long-term trend of rising fuel prices accompanied with strong volatility from the late 90's. Therefore, at the aggregate level, an easy way to model time-series of car traffic is to represent it as the product of the vehicle fleet by average car use per vehicle, and to design appropriate models respectively for car ownership and car use among motorized agents. When coming to the disaggregate level, these results can be extrapolated to design a sequential model of auto-mobility. Apart from the decisive influence of personal access to a car in shaping car traffic growth, a sequential approach should also be privileged for the following reasons:

- First, dynamics of motorization and car mileage per vehicle are very different, one being characterized by permanent growth over time, while the other is stationary;
- Determinants for the different components of auto-mobility are themselves heterogeneous. For instance, fuel prices were proven to be influent on car use but of weak effect on car ownership (Sweeney, 1978; Johansson and Schipper, 1997). By implementing a sequential approach, we also found that while generation effects are decisive on driving license and car ownership, they are negligible on car mileage among individuals with personal car availability (Grimal, 2015a,b). Furthermore, measures of income effects depend much on whether one does or doesn't control for motorization (Graham and Glaister, 2004) as an underlying driver for car travel.

At the disaggregate level, these results can be used to design separate models respectively for car ownership and car mileage allocated to autonomous drivers, and to articulate them into a sequential or joint model of auto-mobility. Instead of an average motorization rate, agent-based probabilities of being motorized can be simulated through the estimation of a discrete choice model, and instead of the average car traffic per individual, a linear panel data model of car mileage expectation will have to be implemented among autonomous drivers.

2.3 An Individual Approach

As already mentioned, many disaggregate models for auto-mobility are household-based, while individual-based approaches are only a few. One decisive limitation to the diffusion of individual-based models may be historical, in relation with available datasets which were

usually either household travel surveys or panel data, both being household-based. Nonetheless, an individual approach might present significant advantages to explain both heterogeneity and growth of auto-mobility, to deal with saturation phenomena, to forecast future car travel, and also for its facility of implementation. Reasons for such a shift are both theoretical and empirical.

2.3.1 Theoretical arguments

From a theoretical point of view, a decisive issue is to determine whether travel decisions are generated at the household or the individual level, and to determine whether car ownership should be considered as a household or an individual item. In order to discuss this issue, one can start from the analysis of travel needs, which are both individual and common to several household members, depending on trip purposes. For instance, commuting trips are often realized alone, while leisure and holiday trips are rather common to the family and imply several household members. However, many determinants of car travel are individual: driving license, personal car availability, generation and sex, job status. Moreover, trip generation, as well as mode and destination choices, are mostly individual and derive from personal schedules. Of course, household characteristics such as household income or the zone of residence may also play a role, as a low car ownership may generate intra-household trade-offs between its members. However, they can easily be specified as explanatory variables of individual car travel behaviors, while the reverse specification is more difficult: characteristics of household members cannot easily be accounted for in a household-based model, or only indirectly, through the characteristics of the household head, or through synthetic numeric variables such as the number of driving license holders, the number of working adults, the number of children, etc. Incidentally, these specifications implicitly postulate linear relationships between these variables and utility functions for given levels of auto-mobility at the household level, which may be questionable as the influence of these variables is strongly gender-related, explaining why multinomial discrete choice models of household car ownership better fit than ordered response models, given a different influence of some factors on utility functions for different levels of car ownership (Bhat and Pulugurta, 1998). Another advantage of an individual-based approach is that individuals are characterized by permanent characteristics - generation, sex, personal attributes. Their influence can be assessed within the framework of panel data models by separating the influence of these attributes from those of contingent characteristics such as income. In other words, individuals are consistent and permanent units, contrarily to households, whose size and composition are constantly changing, as they are not constituted from the same individuals over time. As a result, the influence of external factors is difficult to disentangle from the influence of internal change.

2.3.2 Empirical findings

The long-term proportionality between average car traffic per adult and the average number of cars per adult over several decades is a very significant result, which has to be taken into consideration in searching for a robust design of a traffic generation model. An obvious reason for this strong relationship is that as the number of vehicles per household is increasing, an increasing proportion of adults have access to a personal vehicle, and will now give priority to the car for their daily trips. In other words, more and more individuals are acquiring travel autonomy over time. To be more specific, car ownership growth was principally caused by the diffusion of the second vehicle, with several consequences: their principal users ceased to use transit, and moved from occasionally using the household's car as a driver and/or passenger to regularly driving their own personal car. These observations can serve to design an individual-based model where traffic generators are drivers rather than all adults, and long-term growth of

auto-mobility is caused by the increasing number of autonomous drivers. Reasons explaining the increasing proportion of autonomous drivers are fully appearing when implementing a sequential and gender-segmented analysis of auto-mobility, *a posteriori* justifying the legitimacy of such an approach. In particular, car travel growth in the most recent period was found to come principally from the continued diffusion of driving license and car availability among women, while being stable for men. Yet, most women are not household heads by convention. To be more specific, we found the important following results (Grimal, 2015a,b):

- For every step in a sequential description of auto-mobility – driving license, personal car availability among licensed adults, vehicle*miles traveled (VMT) per autonomous driver - auto-mobility is higher for men than for women.
- For every step by gender, growth is related to generation effects. Yet, cohort effects exist only for women, while being negligible for men. Moreover, they concern driving license diffusion and the rate of personal car availability among driving license holders, while being negligible for VMT generated by autonomous drivers.
- There is an interaction between generation and gender effects. While gender effects were found to be important in older generations, they are negligible in generations born after 1975.

Yet, this interaction cannot be fully captured by reasoning at the household head level – or only indirectly, if using generation of the household head as a *proxy* for the partner's generation - as gender-related differences between household heads are far less significant than the intra-household gender gap. We suggested the following interpretation for these results: in older generations, most households only had a single vehicle. First, a large proportion of women were unauthorized to pass driving license exams in their youth - or at least it was not conventional wisdom - and they remained unlicensed later. But even licensed, their travel needs were usually restrained by the lack of job participation. Also, households lived closer to dense urban areas on average, and were less car-dependent. Finally, gender roles privileged attribution of the single household vehicle to the household head, and the second vehicle didn't appear as a necessity yet. With a single income bearer, households also had less financial resources to afford a second vehicle. The single vehicle was then simultaneously the common household vehicle, used for family long-distance trips, and the personal daily vehicle of the household head. Within post-war generations, the gender gap gradually reduced until its complete disappearance. First of all, the rate of female driving license holding increased, making autonomous driving theoretically feasible. In addition, driving license holders became themselves increasingly motorized, in relation with several factors. Among them, an increasing proportion of women entered the job market, increasing the number of commuters. Yet, travel by car is more suitable for commuting trips as they are usually longer than for other purposes (Baccaini *et al.*, 2007; CERTU, 2010). Commuting distances have themselves been increasing along with changing land use patterns and the growing spatial mismatch between housing and employment areas, making successive generations more dependent on the car. Finally, with a second income bearer, purchasing a second car was made more affordable to many households.

An individual-based and gender-segmented analysis will therefore prove more efficient in explaining both heterogeneity in car travel behaviors and past traffic growth, both coming principally from gender-related differences between household members, rather than from differences between household heads. In correlation, it will also provide a more robust model to forecast future auto-mobility. Though car ownership was first considered as a household durable, the more recent research underlines that it has moved from a household to an individual good (Papon and Hivert, 2008). However, one could also sustain the more radical assumption that it was an individual good from the beginning, which is fully data-consistent. Indeed, increasing personal car availability among women can be seen as the result of changing personal attributes, with an increasing access to driving license, job participation, and personal income,

making personal car availability simultaneously more necessary and more feasible. Meanwhile, these characteristics remained rather stable for men, also accounting for stabilization in the proportion of motorized male adults. Decisions about car ownership can therefore be interpreted as the outcome of changing personal attributes, though personal vehicles may acquire *de facto* collective functions afterwards. Beyond the fact that this interpretation is data-consistent if reasoning over a long time period, it is also advantageous for its simplicity of implementation, as it doesn't imply assumptions about trade-offs between household members. Finally, it is also convenient for car traffic projections, as an individual-based model can be associated with demographic projections of individuals by age and sex by the French Institute of Statistics and Economic Studies to forecast future car traffic levels in 2060.

2.3.3 A convenient approach to deal with saturation

The notion of demand saturation is not new, either for car ownership or car travel, and different approaches to the idea of saturation have been implemented over time, either empirical (BITRE, 2012; Collet and al., 2013) or relying on theoretical assumptions (Marchetti, 1994; Aoki and Yoshikawa, 2002; Metz, 2010). Though these assumptions are usually based on economic theory, the estimation of saturation thresholds is rather empirical, and can be realized through functional forms, notably consisting in different kinds of sigmoid-type curves. However, establishing thresholds of saturation is made complex by the fact that, contrarily to other durables such as the mobile phone, the car was not considered as an individual item from the beginning, but was first implemented at the household level (Papon and Hivert, 2008). Given this uncertainty about the relevant level for car ownership decisions, the estimation of saturation thresholds through functional forms was frequently revised upwards over time (Ingram and Liu, 1999).

Theoretical arguments justifying ideas of saturation are at least of three kinds:

- The demand for car travel is limited by daily travel time and/or household travel budgets. Daily travel time and expenditures expressed as a percentage of income appear as remarkably stable over time (Zahavi, 1974). The main driver of car travel growth in these models is the increasing average travel speed and/or income, resulting in increasing car travel. It is assumed that as average travel speed is attaining its limits, average car travel will also tend to saturate;
- Another argument is based on the assumption of decreasing marginal returns of additional car travel in terms of accessibility and utility (Metz, 2010);
- Finally, there may also be limits to car ownership diffusion as a durable good, either at the household or individual level.

However, assumptions of saturation based on limited daily travel times are not necessarily fundamentally different in nature from those based on car ownership diffusion, which may also constitute the main explanation to increasing travel speeds. One can make the observation, for instance, from successive National Transport Surveys, that average travel distances and speeds increased directly in line with the increasing modal share for car in daily trips, itself related to increasing access to a personal vehicle. Therefore, one can also expect growth in average travel speed to come to an end when limits to personal car availability would be attained. Apart from National Transport Surveys, French Car Fleet Surveys also tend to corroborate the observation that car traffic growth - apart from the demographic factor - is principally caused by increasing personal car availability, as already noticed. A sequential and individual approach is therefore convenient to deal with saturation phenomena, as one can expect average car travel per adult to level off once every adult will be endowed with a personal car, or even before as limitations to the diffusion of personal car availability would persist, for instance related to a low income or

the lack of need for a car in some residential areas well-provided with efficient alternatives to the car. Indeed, additional cars beyond the requirement of autonomy can be used, for instance, according to a framework of vehicle specialization by purpose, with supplementary vehicles being dedicated to long-distance trips. However, we make the assumption that these additional vehicles will have little effect on household car travel, as they don't induce by themselves additional travel, but travel is only distributed over a greater number of vehicles, an assumption which is consistent with those retained in some other models (Whelan, 2001). In turn, there is no real explicit saturation threshold for the average VMT generated per autonomous driver, as they are increasing with income according to a given elasticity, and a (log)-linear relationship is assumed. The double-log relation only implies that mileages are slowing down from a given level of income, accounting for decreasing marginal returns of additional trips and/or accessibility.

Another advantage of this model design is that it consistently gives account for regular results of decreasing income elasticities over time coming from the literature (Goodwin *et al.*, 2004), as an output of discrete choice models for driving license and personal car availability. Indeed, as the proportion of autonomous drivers would tend to slow down over time when approaching saturation, it would result in decreasing income marginal effects and elasticities. This property contaminates car travel elasticities, given the property of additivity between elasticities for personal car availability and VMT per autonomous driver. Though motorization levels would tend to become less sensitive to income variations over time, one can nonetheless expect some heterogeneity to remain at saturation, related either to limited car travel needs or to low financial resources. The model therefore allows to account for an incomplete diffusion of car ownership.

2.3.4 Feasibility of an individual-based approach with French car fleet surveys

Finally, several arguments can be advanced to justify the choice of an individual approach to auto-mobility: the determinants of car travel are mainly individual; individuals are consistent and permanent units; household characteristics can easily be accounted for within the framework of an individual-based model, while the reverse is not true; car travel growth is caused by increasing personal car availability, itself related to an interaction between generation and gender; it is convenient to deal with saturation and decreasing income elasticities over time. An individual-based approach can be implemented through a three-step method, where the probability for driving license holding, the probability for personal car availability, if licensed, and the expectation for vehicle mileage, if motorized, are successively estimated. French Car Fleet Surveys, though household-designed, make such an approach feasible, as for every vehicle up to three per household, its annual mileage is declared along with the principal user of the vehicle. From this information, it is possible to determine whether an individual can be considered as “motorized”, if being the principal user of at least one household vehicle. Cross-analysis of personal car availability and driving license holding from French Car Fleet Surveys confirms that driving license is in the vast majority of cases a requirement for being motorized, according to the latter definition. Besides, by attributing vehicle mileages to their main users, VMT is by construction a censored variable, equal to zero if an individual is non-motorized, and strictly positive otherwise. This convention doesn't imply that an individual who is not considered as motorized will not travel by car at all. He will be able, of course, to use the car as a passenger or even occasionally as a driver, but he is not considered as a traffic generator, the corresponding mileage being attributed to the main vehicle user. This rule of allocation is consistent with the purpose of the current exercise which is to make robust traffic projections according to different scenarios. However, if one was willing to make projections of travel demand in terms of trip*miles rather than vehicle*miles, he would have to account for vehicle

occupancy rates. Even when dealing with car traffic projections, one obvious limit to this method is that it doesn't allow to estimate travel-related personal contributions to car traffic generation, as vehicle mileages also correspond for a part to car travel as a passenger. In order to do so, one would have to define a theoretical method to distribute car mileages between household members, as this distribution is unknown in French Car Fleet Surveys, only providing annual vehicle mileages. One possibility would be to estimate occupancy rates from French National Travel Surveys according to different purposes. In addition, vehicle mileages would have to be distributed by purposes. In order to do so, one could exploit data from the vehicle notebook in National Household Travel Surveys.

3. DATA AND METHODOLOGY

3.1 The French Car Fleet Surveys

The analysis relies on French Car Fleet Surveys, providing in-depth information about car ownership and car use among French households. This inquiry, led by the tolling institute TNS-SOFRES since 1976, consists in a panel of 6 000 to 7 000 respondent households, renewed by roughly a third every year, and is assumed to be representative of the French population. It is financed by a bunch of public and private stakeholders and exploited by the French Institute of Sciences and Technologies on Transports, Networks and Town Planning (IFSTTAR). The data contain three distinct files, respectively for vehicles, households and from 2004, individuals. Household vehicles are described up to three, including personal cars and light-duty vehicles. They contain information about the principal and occasional users of every vehicle, as well as the characteristics of household respondents and household adult members up to six. Identifiers for households combined with the rank of individuals allow following individuals over time.

3.2 Methodology of Data Analysis

Given the panel nature of the data, longitudinal age-cohort analysis can be performed altogether with panel data econometrics. Only behaviors of adults are studied as the legal age for driving is eighteen. For every adult, generation can be deducted from its age and the year of observation. A selection was proceeded to retain only observations where the number of declared adults in the household file matched the number of adults identifiable through the individual file. As the quality of data collection is decreasing with the number of adults, selection rates are heterogeneous, leading to apply corrective weightings to maintain the selected sample representative of the initial one. Only 185 000 observations over an initial 213 000 were retained at the individual level, an observation being defined as an individual for a given year. In addition, we kept into the analysis only individuals with at least five years of observation.

Missing values were completed through the "hot-deck" method, rather than eliminating the corresponding observations. The idea of the hot-deck method is to proceed in two steps: first, observations are classified according to the determinants of the dependent variable; then, missing values are replaced by the value in the immediate preceding or following observation. This method was used to complete values for income, qualification and annual mileage per vehicle.

In the French Car Fleet Surveys, household income is not filled in with precision but given only in brackets. In addition, income brackets have changed over time. Yet, in order to estimate income effects, it is more convenient to use numeric values, for instance to estimate elasticities. Therefore, numeric values were randomly drawn out within each bracket. This random draw results in estimates interpretable mostly in the cross-sectional dimension, while

longitudinal estimates for income effects are less precise as the random noise may prevail on real income variations over time.

Indicators of fuel prices for every engine type (gas, diesel, GPL...) are weighted by the structure of the fleet to obtain average fuel prices. Indicators of fuel costs are also estimated by taking into account energy efficiency. For years preceding the introduction of the euro, we used the conversion rate of the euro in francs at the moment of its introduction to obtain incomes and prices in €s. Moreover, in order to compare incomes for households of a different size and composition, a scale of equivalence is required. We used the OECD scale (Houriez and Olier, 1997), providing respective weightings of 1 for the household head, 0,5 for every other adult, and 0,3 for children aged less than 14, to calculate an income per consumption unit. By using the INSEE price consuming index (IPC), we also corrected monetary values – income, prices – from inflation to compare them at different periods in time, expressing them in constant €s rather than real €s.

4. MODEL SPECIFICATION AND ESTIMATION

4.1 Model Specification

The modeling framework for auto-mobility is sequential and consists of three components. For a given individual, the expected level of car use is assumed to result from:

- The probability of being licensed;
- The probability of being an autonomous driver, if licensed;
- The expectation for car mileage, if being an autonomous driver.

Driving license and personal car availability can then be modeled through discrete choice panel data models. In a similar way, the expectation for car mileage among autonomous drivers can be pictured through a linear model. In the context of panel data, the general specification for these models is the following:

$$z_{it}^* = \nu Z_i^1 + \gamma X_{it}^1 + \alpha_i + u_{it}, \quad z_{it} = 1 \text{ if } z_{it}^* > 0, \text{ otherwise } z_{it} = 0 \quad (1)$$

$$y_{it}^* = \delta Z_i^2 + \beta X_{it}^2 + \eta_i + \varepsilon_{it}, \text{ if } z_{it} = 1; \quad y_{it} = 1 \text{ if } y_{it}^* > 0, \text{ otherwise } y_{it} = 0 \quad (2)$$

$$w_{it} = \mu Z_i^3 + \theta X_{it}^3 + \xi_i + r_{it}, \text{ if } y_{it} = 1, \text{ otherwise } w_{it} = 0 \quad (3)$$

In this formulation, i and t are indexes for individual i at time t , z_{it}^* and y_{it}^* are latent variables respectively figuring out the utilities of driving license holding and personal car availability among driving license holders, z_{it} and y_{it} are the related choices, and w_{it} stands for mileages among autonomous drivers; α_i , η_i , ξ_i figure out individual-specific effects in every sub-model, while u_{it} , ε_{it} and r_{it} stand for normalized error terms; Z_i^1 , Z_i^2 and Z_i^3 are time-invariant variables such as generation and sex, varying only from an individual to another; X_{it}^1 , X_{it}^2 and X_{it}^3 are variables changing both over time and between individuals, such as income; finally, ν , γ , δ , β , μ , θ are parameters to estimate.

If we assume decisions of having a driving license, having a personal car if licensed and travelling a given mileage if being motorized to be independent, everything else being equal, or said otherwise, if the error terms u_{it} , ε_{it} and r_{it} , standing for unobserved heterogeneity, are independent, then there is no endogenous selection bias in the subsamples used for estimation of models (2) and (3). If in addition we assume that individual-specific effects α_i , η_i and ξ_i are known, the expectation for car mileage for a given individual i at time t , noted U_{it} , can be obtained as:

$$E(U_{it}|\alpha_i, \eta_i, \xi_i) = E(w_{it}|\xi_i, y_{it} = 1)P(y_{it} = 1|\eta_i, z_{it} = 1)P(z_{it} = 1|\alpha_i) \tag{4}$$

In practice, one first estimates separately models (1), (2), (3), before combining them to obtain individual probabilities of personal car availability, and expectations for car travel.

$$E(U_{it}|\alpha_i, \eta_i, \xi_i) = (\mu Z_i^3 + \theta X_{it}^3 + \xi_i)\Phi(\delta Z_i^2 + \beta X_{it}^2 + \eta_i)\Phi(v Z_i^1 + \gamma X_{it}^1 + \alpha_i) \tag{5}$$

If in addition the error terms u_{it} , ε_{it} and r_{it} are assumed to follow a standard normal distribution, we obtain formula (5).

In this last formulation, $\Phi(\cdot)$ designs the standard normal cumulative distribution function (c.d.f). However, knowledge of individual-specific effects is difficult to obtain in practice. Rather, one can specify them as random. In this case, one doesn't try to obtain estimates for individual-specific effects, but only to estimate the parameters of their distribution, which shape is assumed to be known *a priori*. Then, all values of interest can be calculated by integrating over this distribution.

4.2 Model Estimation

The model structure consists in three sub-models, models (1) and (2) being *probit* error component models, and model (3) being a generalized linear regression model. The best-fitting parameters for models (1) and (2) are calculated through maximum likelihood estimation. A quadrature procedure is used to obtain a numerical approximation to the integral, while the maximization problem is solved through the Fischer score method. In turn, model (3) is estimated through the quasi-generalized least squares estimator, which is the most efficient linear estimator. All parameters were estimated from French Car Fleet Surveys, including a parameter of variance for the distribution of individual specific effects. Estimation results for models (1), (2) and (3) are respectively given in tables 1.a, 1.b and 1.c, including parameter estimates with their confidence intervals and p-values.

Table 1.a: Parameter estimates with their confidence intervals and p-values – Driving license model

	Men				Women			
	Estimate	Pr > t	95% C.I		Estimate	Pr > t	95% C.I	
G ₀₋₁ (< 1920)	0.72	<.0001	0.57	0.87	-1.37	<.0001	-1.64	-1.10
G ₂₋₃ (1920-30)	1.22	<.0001	1.14	1.30	0.91	<.0001	0.82	1.00
G ₄₋₅ (1930-40)	1.68	<.0001	1.59	1.77	1.36	<.0001	1.28	1.43
G ₆₋₇ (1940-50)	2.17	<.0001	2.01	2.34	1.66	<.0001	1.57	1.74
G ₈₋₉ (1950-60)	1.97	<.0001	1.86	2.07	1.97	<.0001	1.87	2.07
G ₁₀₋₁₁ (1960-70)	2.40	<.0001	2.26	2.54	2.20	<.0001	2.03	2.36
G ₁₂₋₁₃ (1970-80)	2.17	<.0001	2.06	2.30	2.40	<.0001	2.28	2.53
G ₁₄₋₁₆ (> 1980)	1.18	<.0001	1.04	1.32	1.56	<.0001	1.41	1.70
18 - 20 years	-2.35	<.0001	-2.49	-2.21	-2.60	<.0001	-2.75	-2.45
20 - 25 years	-0.94	<.0001	-1.07	-0.81	-1.19	<.0001	-1.33	-1.06
Income	4 ^E -5	<.0001	3.6 ^E -5	4.3 ^E -5	2.7 ^E -5	<.0001	2.4 ^E -5	3 ^E -5
σ_{η}^2	2.90	<.0001	2.77	3.04	4.96	<.0001	4.80	5.12

Parameter estimates for model (1) are all significant and their signs are consistent with *a priori* expectations. Everything else being equal, the probability for being licensed is increasing from a generation to another among generations born in the 1960's among men, and in the 1970's among women. It is seemingly decreasing in the generation born in the 80's, which is sometimes referred to as the “millennials” or the “Y generation”, though we don't know for sure whether this is a generation effect or an age effect, given the fact that the period of

observation for this generation is limited at its younger age where it has not completed its access to driving license yet. Indeed, *ceteris paribus*, driving license diffusion is lower below 25. Income is also influent on the probability of being licensed, given the training cost of license exams which can be deterrent to lower-income adults. The parameter of variance for individual-specific effects is also higher for women than for men, pointing out a greater heterogeneity in driving license diffusion, which can be related to a higher proportion of housewives in older generations, not needing a car for their daily trips. In addition, households with a single income bearer cannot always afford a second car, given inadequate resources.

Table 1.b: Parameter estimates with their confidence intervals and p-values – Main user model

	Men			Women		
	Estimate	Pr > t	95% C.I	Estimate	Pr > t	95% C.I
G ₀₋₁ (< 1920)	-2.22	<.0001	-2.59 -1.84	-1.96	<.0001	-2.41 -1.51
G ₂₋₃ (1920-30)	-1.83	<.0001	-2.09 -1.57	-1.71	<.0001	-1.99 -1.44
G ₄₋₅ (1930-40)	-1.51	<.0001	-1.75 -1.27	-1.55	<.0001	-1.77 -1.32
G ₆₋₇ (1940-50)	-1.06	<.0001	-1.27 -0.84	-1.33	<.0001	-1.54 -1.12
G ₈₋₉ (1950-60)	-0.81	<.0001	-0.99 -0.62	-0.50	<.0001	-0.69 -0.32
G ₁₀₋₁₁ (1960-70)	-0.47	<.0001	-0.63 -0.32	-0.24	0.0024	-0.39 -0.08
G ₁₂₋₁₃ (1970-80)	-0.33	<.0001	-0.46 -0.19	-0.14	0.0490	-0.27 -0.00
18-20 ans	-0.53	<.0001	-0.71 -0.34	-0.93	<.0001	-1.14 -0.73
20-25 ans	0.43	<.0001	0.31 0.56	0.16	0.0190	0.03 0.28
25-30 ans	1.38	<.0001	1.24 1.52	0.84	<.0001	0.70 0.98
30-35 ans	1.86	<.0001	1.71 2.02	1.22	<.0001	1.07 1.37
35-40 ans	2.11	<.0001	1.95 2.28	1.36	<.0001	1.20 1.52
40-45 ans	2.30	<.0001	2.12 2.48	1.38	<.0001	1.20 1.55
45-50 ans	2.55	<.0001	2.36 2.74	1.43	<.0001	1.25 1.62
50-55 ans	2.74	<.0001	2.53 2.94	1.36	<.0001	1.16 1.57
55-60 ans	3.08	<.0001	2.86 3.31	1.14	<.0001	0.93 1.35
60-65 ans	3.52	<.0001	3.28 3.75	0.98	<.0001	0.76 1.20
65-70 ans	3.65	<.0001	3.40 3.90	0.89	<.0001	0.67 1.12
70-75 ans	3.76	<.0001	3.50 4.02	0.78	<.0001	0.54 1.02
75-80 ans	3.58	<.0001	3.31 3.85	0.66	<.0001	0.40 0.92
80-85 ans	3.12	<.0001	2.82 3.42	0.19(NS)	0.2200	-0.11 0.49
85-90 ans	2.18	<.0001	1.80 2.56	-0.65	0.0036	-1.08 -0.21
90-95 ans	1.84	<.0001	1.21 2.47	-2.19	0.0003	-3.38 -0.99
> 95 ans	0.54(NS)	0.360	-0.62 1.71	-0.46(NS)	0.6911	-2.72 1.80
Income	1.2 ^E -5	<.0001	9.7 ^E -6 1.4 ^E -5	1.1 ^E -5	<.0001	8.5E-6 1.3 ^E -5
σ_{η}^2	3.21	<.0001	3.04 3.37	4.47	<.0001	4.25 4.69

Parameters for model (2) are equally significant, except some of those related to the older age groups, because of small sub-samples. *Ceteris paribus*, the probability of being motorized if licensed increases from a generation to the following, either for men or for women. However, age effects are different between men and women. Among men, the probability of being motorized is continuously increasing until the age of 75, before decreasing. Among women, a peak is attained by 45-50, before decline. This peak corresponds to a period of maximal travel needs resulting in a large number of professional and family-related trips among women, notably because of higher activity rates at this period and the necessity to escort children at school. It is also a period where households more frequently live in outer suburbs of metropolitan areas where they are dependent on the car, further justifying the need for a second vehicle. The decreasing motorization rate above 45 among women is also caused by a declining job participation, with more frequent career interruptions making it difficult to return to work afterwards, separations leading to lower financial resources, and children departure from the

parental home. The effect of income on the probability of being motorized, if licensed, is significant and similar between men and women. Finally, as for driving license, the variance of individual-specific effects is higher among women, pointing out the fact that personal car availability is less systematic than for men. Generally speaking, access to auto-mobility is thus more heterogeneous among women than for men. This result may receive an economic interpretation by considering that the second car, of which the main user is usually the wife within couples, still remains an intermediary good, of which the opportunity is evaluated upon circumstances, notably depending on the wife’s job participation, the household income and the place of residence.

Table 1.c: Parameter estimates with their confidence intervals and p-values – Car mileage model

	Men			Women		
	Estimate	Pr > t	95% C.I	Estimate	Pr > t	95% C.I
18-20 ans	5.56	<.0001	5.16 5.97	5.92	<.0001	5.37 6.47
20-25 ans	6.03	<.0001	5.65 6.40	6.44	<.0001	5.92 6.96
25-30 ans	6.25	<.0001	5.88 6.62	6.64	<.0001	6.13 7.16
30-35 ans	6.24	<.0001	5.88 6.61	6.60	<.0001	6.08 7.11
35-40 ans	6.16	<.0001	5.79 6.53	6.56	<.0001	6.05 7.08
40-45 ans	6.19	<.0001	5.82 6.55	6.52	<.0001	6.01 7.04
45-50 ans	6.19	<.0001	5.83 6.56	6.52	<.0001	6.00 7.03
50-55 ans	6.12	<.0001	5.75 6.48	6.43	<.0001	5.91 6.95
55-60 ans	6.09	<.0001	5.72 6.46	6.27	<.0001	5.75 6.79
60-65 ans	6.06	<.0001	5.69 6.43	6.14	<.0001	5.62 6.66
65-70 ans	5.98	<.0001	5.61 6.35	5.98	<.0001	5.47 6.50
70-75 ans	5.82	<.0001	5.45 6.18	5.77	<.0001	5.25 6.29
75-80 ans	5.58	<.0001	5.22 5.95	5.50	<.0001	4.98 6.02
80-85 ans	5.22	<.0001	4.85 5.58	5.15	<.0001	4.62 5.68
85-90 ans	4.81	<.0001	4.43 5.20	4.94	<.0001	4.35 5.53
90-95 ans	4.09	<.0001	3.56 4.61	5.33	<.0001	4.29 6.36
Income	0.11	<.0001	0.09 0.14	0.068	<.0001	0.043 0.093
Fuel cost (€/km)	-0.53	<.0001	-0.65 -0.40	-0.58	<.0001	-0.76 -0.40

Generation effects have been excluded from model (3) as they appear to be non-significant. Indeed, the profile for car mileage over the life course was shown to be similar across all generations of motorized adults in prior descriptive analysis (Grimal 2015a,b). Age effects consist of an increasing car mileage among motorized adults until 25-35, before declining thereafter all life long, either for men or for women. The influence of fuel cost on car mileage is quite independent from gender, with an elasticity estimated at respectively – 0,53 for men and – 0,58 for women. Car mileage is slightly more dependent on income among men, with an elasticity estimated at + 0,11, vs. + 0,07 for women. This subtle difference may be attributed to the collective function of the first household vehicle, of which the main user is usually the man within couples (Papon and Hivert, 2008), which is also used for long-distance and leisure trips, more dependent on household income.

4.3 Discussion of the Assumption of Independent Decisions and A Posteriori Evaluation

A sequential rather than joint specification for driving license, personal car availability and car mileage relies on the assumption that the corresponding choices are independent, after controlling for variables that are simultaneously included into the different level-specific models. The assumption that the acquisition of driving license is independent from desired levels for motorization and car use looks quite reasonable, as driving license is usually considered as an essential and some kind of “mobility insurance” for a lifetime, which is

required for social life and professional insertion (Claisse *et al.*, 2003), independently from preferences towards a more or less car-oriented mobility, and from future levels of motorization and car use which may depend much on circumstantial change over a life course. However, the assumption of independence between personal car availability and expected car mileage may look more questionable as one can expect personal car availability to be correlated with preferences towards a more or less car-oriented mobility. This assumption can be released within the framework of a *Tobit II* model, where car ownership decisions are *a priori* supposed to be correlated with future desired car mileages, allowing to perform a statistical test in order to assess this assumption. It is constituted from two sub-models, respectively for personal car availability and car mileage, corresponding to equations (6) and (7), where u_{it} and v_{it} are assumed to follow a normal distribution and are this time allowed to be correlated. The meaning of the other symbols is similar to equations (2) and (3). The model is estimated through the two-step method of Heckman (1979).

$$y_{it}^* = \delta Z_i^2 + \beta X_{it}^2 + u_{it}; y_{it} = 1 \text{ if } y_{it}^* > 0, \text{ otherwise } y_{it} = 0 \tag{6}$$

$$w_{it} = \mu Z_i^3 + \theta X_{it}^3 + v_{it}, \text{ if } y_{it} = 1, \text{ otherwise } w_{it} = 0 \tag{7}$$

In the first step, model (6) for personal car availability is estimated by maximum likelihood. Then, additional regressors, noted as the λ_i , are introduced into equation (7), in order to obtain consistent estimates of (μ, θ) . They are defined as:

$$\lambda_i = \frac{\varphi(\hat{\delta}Z_i^2 + \hat{\beta}X_{it}^2)}{\Phi(\hat{\delta}Z_i^2 + \hat{\beta}X_{it}^2)} \tag{8}$$

In this equation, $\varphi(\cdot)$ represents the standard normal probability density function (p.d.f), while $\Phi(\cdot)$ has the same signification than above and stands for the standard normal c.d.f. The λ_i correspond to $E(u_{it} | u_{it} > -\hat{\delta}Z_i^2 - \hat{\beta}X_{it}^2)$ and their coefficient is the covariance σ_{uv} between u_{it} and v_{it} , the variance of u_{it} being normalized to one. In order to allow model evaluation, generations are used as instruments: indeed, generation effects are significant on car ownership but do not influence car mileage, as was already noticed.

Table 2: Parameter estimates for a model of car use with additional regressors in the framework of a Tobit II model estimated through the two step approach of Heckman (1979)

	Men				Women			
	Estimate	Pr > t	95% C.I		Estimate	Pr > t	95% C.I	
Income	+0,204	<,0001	+0,175	+0,232	+0,145	<,0001	+0,111	<,0001
Fuel cost (€/km)	- 0,399	0,0001	-0,600	-0,197	-0,477	+0,003	-0,788	+0,003
Log-density	-0,051	<,0001	-0,063	-0,039	-0,048	<,0001	-0,067	<,0001
Temporal trend	-0,027	<,0001	-0,032	-0,023	-0,025	<,0001	-0,031	<,0001
λ_i	+0,022	+0,086	-0,003	0,046	-0,036	+0,283	-0,102	+0,283

Either for men or for women, parameter estimates for λ_i are non-significantly different from zero at the 5 % level of significance. Therefore, one cannot reject the assumption of independent disturbance terms for the respective models for car ownership and car mileage, which tends to validate *a posteriori* our choice of a sequential model of auto-mobility as a satisfying approximation. This result may receive different interpretations. Among them,

empirical findings from the literature suggest that the link between individual preferences, opinions and attitudes and travel behaviors may be weak, or is at least questionable, as behaviors would be strongly shaped by daily travel needs and constraints (Kaufmann and al., 2010; Delbosc and Currie, 2012). As a result, one can expect decisions of auto-mobility to be partly independent from individual preferences and attitudes. Besides, car ownership also constitutes some kind of mobility insurance, which tends to be largely independent from the anticipated level of car use. Even in the case of an individual only making occasional trips, the lack of a car can be penalizing in daily life despite a low level of utilization, in the lack of valuable alternatives to secure these trips. It can also be explained by the fact that car diffusion does not only satisfy daily travel needs, but also responds to a desire for autonomy and comfort that still remains hardly attainable through the other modes. This is also consistent with the fact that in a context of harder economic conditions, individuals tend to keep their cars as long as possible by first trying to rationalize car travel before giving up their cars (Dargay, 2001).

5. PROJECTIONS OF AVERAGE CAR TRAFFIC PER ADULT IN 2060

5.1 Methodology of Projection

At this stage, the model solely accounts for age, generation, income and fuel cost effects. However, all variables are not included in all sub-models. In particular, fuel cost is being accounted for only in the upper sub-model (3), given its weak influence on the number of cars per household according to the literature (Sweeney, 1978; Johansson and Schipper, 1997). On the other hand, generation effects were not included in model (3) as they were shown not to be significant in previous analysis (Grimal, 2015a,b). Though the literature usually points out the need to control for a large number of variables, in this case the model structure was deliberately simplified to include only a few variables for the purpose of forecasting car traffic according to different scenarios which are described in section 5.2, by combination with the demographic projections of individuals by sex and age group in 2060 obtained through the model OMPHALE, which can be uploaded on the website of the French National Institute of Statistics and Economic Studies (INSEE). However, these few variables allow to account for the changing demographic structure of the French population and various assumptions about economic conditions and technological progress in 2060. Therefore, the modeling structure retained is some kind of ACP model, its originality lying in the individual approach with a segmentation by gender, the full decomposition of car traffic generation through a sequential process, and the hybrid specification associating discrete choice models with linear regression. This kind of model is also particularly interesting because of its capacity to explain past growth in car ownership and car traffic, and its remarkable predictive power that were both mentioned in section 2.

Estimations are aggregated by sex and age groups in 2060, before averaging them over the whole population, after accounting for preference heterogeneity through the simulation of individual-specific effects according to a distribution estimated from the sample. Average probabilities for driving license holding and car ownership conditional on driving license holding, respectively noted as $P(z_{j2060} = 1)$ and $P(y_{j2060} = 1 | z_{j2060} = 1)$ were first estimated for every sex and age group j in 2060. In order to estimate these values, one first has to integrate over the distribution of individual-specific effects. For instance, $P(z_{j2060} = 1)$ is estimated through formula (9), where $g(\alpha_i)$ stands for the distribution of α_i , which is normal of variance σ_α^2 :

$$P(z_{j2060} = 1) = \int_{-\infty}^{+\infty} \Phi(vZ_i^1 + \gamma X_{it}^1 + \alpha_i) g(\alpha_i) d\alpha_i \quad (9)$$

However, in practice, a numerical approximation of the integral is calculated by drawing out a hundred individual-specific effects from their estimated distribution, before averaging individual probabilities. Then, the expectation for car mileage per autonomous driver in 2060 is calculated by applying income and fuel cost elasticities to the average car mileage in 2010 through the formula:

$$w_{j2060} = w_{j2010} \left(\frac{R_{j2060}}{R_{j2010}} \right)^{\theta_R} \left(\frac{C_{j2060}}{C_{j2010}} \right)^{\theta_C} \quad (10)$$

In this expression, w_{j2060} , X_{j2060} , Y_{j2060} , Z_{j2060} stand for the average values of these variables for group j in 2060, while θ_R and θ_C respectively stand for income and fuel cost elasticities. Their values are given in table 3:

$$E(U_{j2060} | X_{j2060}, Z_j) = w_{j2060} P(y_{j2060} = 1 | z_{j2060} = 1) P(z_{j2060} = 1) \quad (11)$$

Finally, average probabilities for being licensed and being motorized if licensed, and car mileage expectations if motorized are combined according to formula (11).

However, additional assumptions have to be made in order to make projections in 2060, for instance on behaviors of generations to come as they are still unknown and cannot be deduced from the sample (see section 5.2). Apart from age and generation effects, model implementation also implies projections of income and fuel cost in 2060. Fuel cost was estimated by accounting both for assumptions about fuel price and fuel efficiency, depending on the scenarios.

5.2 Scenarios

Two different sets of scenarios were tested. In the first set, which is qualified from “business-as-usual”, the distribution of individual preferences is assumed to be unchanged by 2060, as well as age and generation parameters, as there is no assumption of changing travel behaviors in generations to come. For every gender*age group in 2060, average probabilities for driving license holding and personal car availability are estimated according to the following rules. Generation parameters were reported in 2060 for generations born before 1980, which had already attained the age of 30 in 2010. Generations born after 1980 were assumed to have the same travel behaviors than generations born between 1975 and 1980, as respective driving license levels for generations born between 1970 and 1975 and for generations born between 1975 and 1980 were very close. Besides, the apparent decline in auto-mobility in generations born after 1980 was attributed to age effects, given a still incomplete diffusion of driving license in these generations. Indeed, empirical evidence was found from French Car Fleet Surveys that in new generations, auto-mobility was catching up levels from previous generations by the age of 30 to 35, suggesting a delayed access to auto-mobility rather than a durable disinterest for the car (Grimal, 2015a,b), an interpretation which is consistent with other empirical findings from the literature (Kim, 2014). This result could come from a delayed entrance into adult life, resulting either from longer studies, or a later entrance into the job market and household foundation. These different stages have themselves become more uncertain with social and economic change. In addition, a higher proportion of young adults are living in metropolitan areas, where the car is neither really needed, nor always practical. New mobility devices (car

sharing, carpooling...) could also represent a convenient and cheap substitute to car ownership to some of them. However, the car remains necessary at later stages of the life course when professional, family and spatial constraints are at their peak, explaining why new generations also give priority to the car at this stage, though their preferences and attitudes may have changed with respect to their predecessors.

However, an alternative set of scenarios were implemented, corresponding to a break-in-trend in behaviors of generations to come, taking the form of a declining car ownership. Such an evolution might result from several factors, among which changing attitudes towards the car, which may be characterized either by a greater rationality or increasing environmental awareness, technological evolutions and economic constraints. Increasing rationality may result in a greater multimodality, with the car losing its privilege to be only considered as one transportation mean among others, but may also generate an increasing dissociation between car ownership and car use, with the expansion of new travel devices such as car-sharing and carpooling, challenging the traditional scheme relying on private car ownership. Mentalities might also change with increasing environmental awareness and sensitivity to climate change issues in new generations. Technological factors might influence travel organization, though with ambivalent effects. A regular assumption is of a possible dissociation between activity programs and travel, though empirical evidence for this hypothesis was hardly ever found. One may also argue that as new generations are perpetually connected, driving a car will seem unattractive to them as it requires constant attention, while transit attendance provides greater intrinsic utility (Papon *et al.*, 2008), though this argument may vanish if autonomous cars were to become mainstream. Carbon-free cars may also generate rebound effects with reduced environmental pressure and oil dependency. Finally, increasing income inequalities may also hinder out the ability to pass driving license exams and acquire personal cars in new generations. Overall, behavioral and economic factors may contribute to a declining auto-mobility, while the net output of technological factors appears to be far more uncertain.

A central issue is also to determine whether the assumption of a declining auto-mobility may apply in the same manner to the first and second household vehicle. We made the assumption that more sensible attitudes would result in a greater sharing of the main household vehicle between household members, and in a lesser necessity for a second car, a phenomenon which could be reinforced by increasing financial constraints. This new paradigm for travel behaviors would result in delaying driving license exams, either for men or for women, while personal car availability among licensed adults would decrease only for women, corresponding to the lesser need for a second car. Practically, age parameters for driving license utility functions were extended to all adults aged less than 35 and their values doubled, while parameters for personal car availability if licensed were assumed to decrease symmetrically to their previous increase in generations born after 1980 – the so-called “millennials” - to finally attain the same level they had in generations born before WWII.

Every set is made out of six scenarios resulting from different assumptions about fuel prices, fuel efficiency and income growth. Four of these include economic growth resulting in a yearly 1 % average income growth over the period 2010-60, while two of them assume zero income growth corresponding to a long-lasting recession. These growth rates are applied to all sex*age groups in the panel in 2010. Growth scenarios differ by assumptions about fuel prices and fuel efficiency. In the first one, fuel prices are assumed to double by 2060, while fuel efficiency remains at its level of 2010. As a result, the mileage cost of travel also doubles. This scenario therefore corresponds to a situation of increasing tensions on fuel prices combined with the lack of technical progress. In the second scenario, fuel prices also double, but this time fuel efficiency is multiplied by two. As a result, fuel cost remains stable, the energetic crisis being balanced by the benefits of technical progress. In the third scenario, fuel prices remain at

their 2010 levels, while fuel efficiency is multiplied by two. This situation, characterized by a cheap resource, is the most favorable to car traffic growth. Finally, the last of these corresponds to the *statu quo* where fuel prices and fuel efficiency remain at their 2010 level. As in the second scenario, fuel cost remains stable, though for a different evolution of fuel prices and fuel efficiency. These four scenarios were named respectively as *High price – Low efficiency*, *High price – High efficiency*, *Low price – High efficiency*, and *Low price – low efficiency*. In addition, two scenarios of simultaneous economic and energetic crisis were tested, corresponding to the more pessimistic assumption of societies without growth and higher fuel prices. However, one of them is characterized by the lack of technical progress, while the other displays increasing fuel efficiency.

5.3 Projection Results

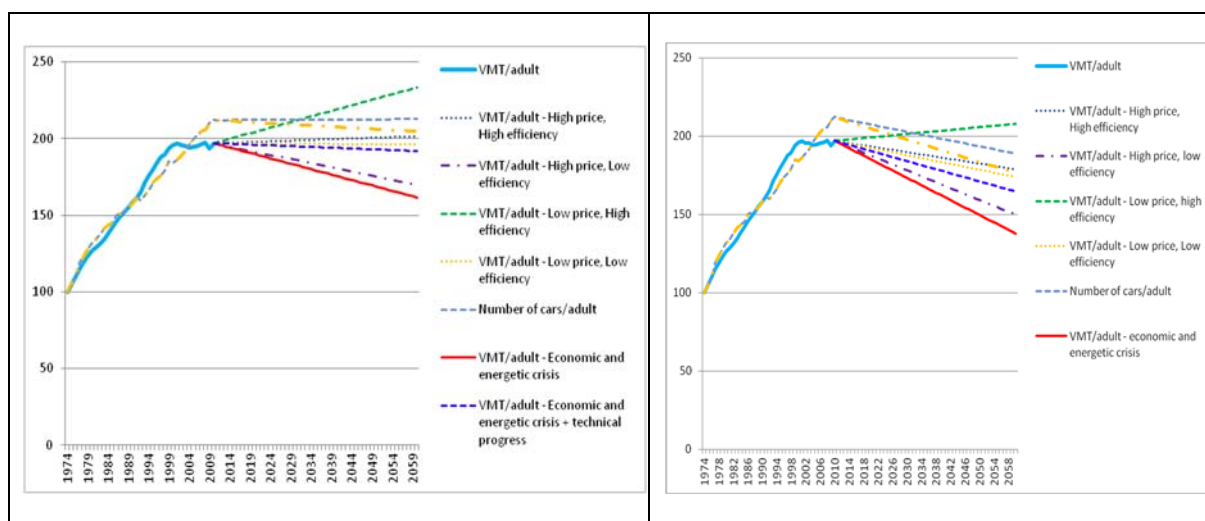


Figure 1.a,b: Projections of average car traffic per adult in 2060 according to different sets of scenarios, basis 100 in 1974

1.a. “Business-as-usual” scenarios; 1.b. Scenarios with behavioral change

Projection results are synthesized in figures 1.a and 1.b, respectively for “business-as-usual” scenarios and scenarios with behavioral change corresponding to a declining auto-mobility in new generations. In all scenarios, growth remains moderate by comparison with the previous phase in the development of auto-mobility between the mid 70’s and the early 2000’s, where average car travel per adult doubled. It can be explained by the low income sensitivity of car mileage among motorized adults, while car ownership growth is slowing down as it is approaching saturation and becoming insensitive to income growth. To illustrate this point, we also figured out the projected number of cars per adult in 2060, both in scenarios of moderate growth and of recession.

In both sets of scenarios, projections are quite contrasted depending on assumptions about fuel prices, fuel efficiency and income growth. In the “business-as-usual” set, only the scenario with low prices and high fuel efficiency leads to continuous growth in average car travel per adult, around + 18,5 %. Other scenarios are resulting either in stability, or in decline. Three scenarios lead to a stabilization of average car traffic per adult: low price and low efficiency, corresponding to the *statu quo*, high price and high efficiency, and the scenario of double crisis balanced by technical progress. All these scenarios are characterized by fuel cost stability, resulting either from the *statu quo*, or from compensation between higher fuel prices and reduced fuel consumption. Two scenarios lead to a strong decline in average car traffic per adult, respectively of – 18 % and – 13,9 %, corresponding either to a situation of simultaneous

economic and energetic crisis without technical progress, or to the combination between higher fuel prices and the persistence of a low fuel efficiency in a context of moderate economic growth. Both are characterized by a doubled fuel cost, which happens to be the main factor of variation between scenarios, while projections are rather insensitive to assumptions about income growth, given higher fuel cost elasticities than income elasticities of car mileage. In “business-as-usual” scenarios, projections of average car traffic per adult depend almost exclusively on the evolution of average car mileage among motorized adults, as the proportion of autonomous drivers is now close to saturation and its evolution quite independent from the choice of a scenario, with an expected increase from 65,1 to 65,4 % in scenarios with economic growth, and an expected decrease from 65,1 to 62,9 % in case of a durable recession.

In scenarios with behavioral change, only the scenario with unchanged fuel prices and higher fuel efficiency, where the average fuel cost of the household vehicle fleet is divided by two, still leads to traffic growth, which is nonetheless reevaluated downwards by comparison with “business-as-usual” scenarios, around + 5,5 %. All other scenarios are leading to a decline of average car travel per adult, which is more or less pronounced according to the chosen assumptions about income growth, fuel prices and fuel efficiency. The most important decline corresponds to the scenario of a “double crisis” without technical progress, with a – 30 % shortfall in average car traffic per adult. Decline is also particularly strong in the equivalent scenario apart from economic growth, where it is evaluated at – 24 %, against – 16,5 % in the scenario of “double crisis” compensated by technical progress. Finally, scenarios with economic growth and a stable fuel cost are leading to a moderate decline of average car travel per adult, of about – 10 to – 11 %. Here again, assumptions about fuel costs happen to be the main cause of variation between projections within a same set of scenarios, with a – 20 % shortfall caused by doubled fuel costs, *ceteris paribus*, while the shortfall caused by the absence of economic growth is only of – 6 %. The general reason for decline in scenarios with behavioral change comes from decreasing personal car availability, falling down from 65,1 to 58,1 % in scenarios with economic growth, and from 65,1 to 54,3 % in scenarios of recession, while the average car mileage among autonomous drivers depends much on fuel costs. When comparing different sets of scenarios, behavioral change is responsible, everything else being equal, for a strong decline of average car traffic per adult, which can be evaluated from – 11 to – 14 % across scenarios. The consequences of a potential break-in-trend in car travel behaviors in new generations would therefore be far from being negligible.

The notion of “peak car” is usually understood as a decline to come in average car traffic per adult. However, despite the current downturn in travel behaviors, traffic growth might continue in relation with future demographic growth. Therefore, one might be willing to complete this analysis by forecasting total car traffic, leading to significantly different results. Indeed, when accounting for demographic growth, none of the “business-as-usual” scenarios leads to a declining car traffic, with growth varying from + 5,4 to + 59,1 % across scenarios. Among scenarios with behavioral change, only two are leading to a decreasing car traffic, corresponding to the assumption of a doubled fuel cost, while others lead to car traffic growth, varying between + 2,5 % to + 29,4 % across scenarios.

These results can be used as a basis to discuss the assumption of “peak car”, i.e the possibility of a structural decline to come in auto-mobility. If understanding “peak car” as declining average car traffic per adult, the structural trend would rather be of a “plateau” in the absence of behavioral change, corresponding to a threshold of saturation in the diffusion of personal car availability. In this first set of scenarios, decline would only be possible if fuel costs were to remain structurally high over a long-time period, a scenario which would correspond to the combination of higher fuel prices with the lack of technical progress. However, this scenario looks quite unlikely to come true as the natural fleet renewal should

rapidly improve average vehicle efficiency by one or two decades, given already available technologies. Therefore, average car traffic per adult is only likely to decline in the case of structural behavioral change in generations to come. In this case, almost all scenarios would be leading to a shortfall in average car travel per adult. Peak car can therefore be reinterpreted *a posteriori* as the output of a willful political scenario aiming at changing travel behaviors in new generations. However, even in this case, total traffic would continue to increase in relation with demographic growth, apart from two scenarios where behavioral change is combined with higher fuel costs. Yet again, these scenarios are unlikely to become reality, given expected progress in fuel efficiency. Therefore, traffic growth is almost unavoidable, only the intensity of growth varying across scenarios. Given reasonable expectations of higher fuel efficiency, the most probable range for total traffic growth varies between + 25,2 % and + 59,1 % in “business-as-usual” scenarios, and between + 2,5 % and + 29,4 % in case of behavioral change.

6. CONCLUSION

As a conclusion, “peak car” looks less likely to happen than saturation coming from car ownership diffusion, the intensity of growth varying across scenarios according to the evolution of fuel prices. At least, a break-in-trend would be required in behaviors of generations to come, which has not been confirmed yet according to the corresponding literature. Even in this case, total traffic should continue to increase because of demographic growth. However, traffic growth will considerably slow down, given car ownership saturation, and possibly because of further increases in fuel prices and changing travel behaviors of new generations. However, we should also mention some uncertainties likely to affect projection results. For instance, we don’t know for sure what limits should be given to the diffusion of the car. It could either come into a new phase of growth, moving towards its complete individualization, or even enter into a logic of vehicle specialization, with some vehicles being used only for long-distance trips, or remain at its current stage of diffusion, intermediary between a household and individual-based item. We don’t know either what will be the penetration of new technologies (hybrid/electric/other), which could reduce environmental pressure and release financial constraints on vehicle mileage, given reduced oil dependency. Indeed, in our scenarios, fuel prices have been assumed to remain stationary or to increase by 2060, as until a few years, external trends – geopolitics, taxation, environmental regulations, increasing world demand, perspective of the “peak oil” – were favorable to the preservation of high levels of fuel prices. However, some signs are now pointing out in the opposite direction. Apart from the recent decrease in fuel prices noticed from 2012, some structural factors could contribute to a lesser demand over time, in particular the rapid renewal of the fleet towards more efficient vehicles - a trend that will probably accelerate with the diffusion of hybrid and electric technologies – and perspectives of car ownership saturation. As a result, fuel demand could slow down, putting downward pressure on fuel prices. Future levels of car use could also depend on changing housing and transportation preferences, as policies designed to limit car travel in conurbations, or reduce its efficiency through reduced travel speeds, certainly contribute to redirect residential choices towards dense urban areas. Finally, some important assumptions of our model might also be challenged in a long-run perspective. In particular, there might be an increasing dissociation between car ownership and car use with the development of new travel devices. But also, fuel prices will lose of their importance if carbon-free technologies make households less dependent on fuel to fulfil their travel needs. Prospective about emerging trends would therefore be the necessary complement to test at regular intervals the validity of our model assumptions.

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