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Powertrain Technology Transition Market Agent Model (PTTMAM)

An introduction

Gillian Harrison[1]
Christian Thiel[1]
Lee Jones[2]

[1]JRC [2]Ventana Systems UK

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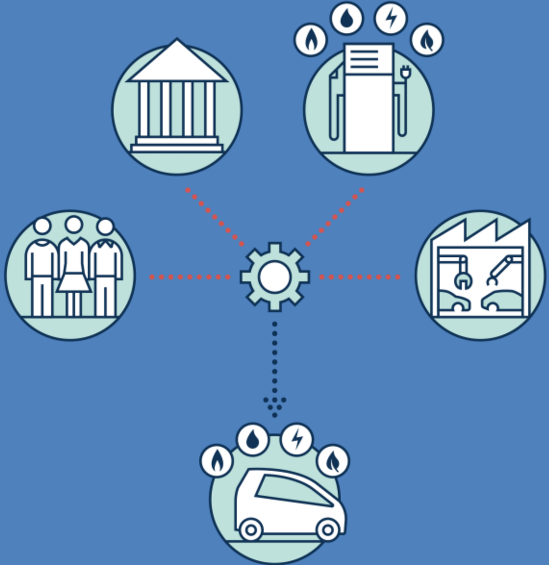

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Joint Research Centre

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Contact information
Name: Christian Thiel
Address: Joint Research Centre, Institute for Energy and Transport, Via Enrico Fermi 2749, I-21027 Ispra (VA), Italy
E-mail: Christian.Thiel@ec.europa.eu
Tel.: +39 0332 78 9207

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Table of Contents

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Abstract

This JRC Technical Report provides an introduction to the JRC system dynamics based Powertrain Technology Transition Market Agent Model (PTTMAM). This comprehensive system dynamics model, covering the period 1995 to 2050, was designed to capture the key feedbacks and interactions between manufacturers, authorities, infrastructure providers and users across the 28 EU member states and 16 powertrain options available in the light duty vehicle market. The purpose of this report is to serve as a source of reference for future publications based on the PTTMAM and for those engaged in the interpretation of PTTMAM output. In addition to describing the general PTTMAM structure and main interactions, this report sets out a baseline scenario to demonstrate the flexibility of the model. Only brief mention is made to model validation, in order to assure the robustness to the reader, with more detail provided as Annexes to the report. Due to the high degree of complexity within the model the report remains a high level overview and should the reader be interested in learning more detail on the structure, development or specific parameters they should refer to the authors directly. We welcome any suggestions for adaption or improvement.

1 Introduction

This technical report contains an introduction to the EC JRC-IET Powertrain Technology Transition Market Agent Model (PTTMAM). The system dynamics model is wholly owned by the JRC-IET, and was initially developed in-house in conjunction with Ventana UK between 2010 and 2012. Due to the nature of the model, it is subject to continual improvement and regular updates by our in-house experts.

This report has been produced to provide background to any researchers or policy makers who are interested in publications or data output from the PTTMAM and require more context and detailed information to aid their understanding and application of model output. As with any model, this understanding is key to the integrity of any professional when interpreting modelled data. We assume that the reader may have some basic knowledge of system dynamic modelling and Vensim software but try to provide background to these for novices.

The report is set out as follows. Following a high level overview of the background of the model including motivation for initial development, literature review and an overview of system dynamic modelling, we describe the model in detail. In these sections (Chapters 2 - 5) we present the model in terms of conceptual market agent groups within the automobile system. Although a complete description of every single parameter or relationship, or the rationale behind the development is not discussed, some particularly important aspects are highlighted. In the next section, we present the baseline scenario that was developed in the model to demonstrate the capability and the associated impacts on key performance indicators. Chapter 7 focuses on the validation of the model, including the calibration, testing and sensitivity analysis of the model which was carried out to ensure model robustness, though most detail on these is provided in the Report Annexes. Finally, in the Conclusion, model limitations and future improvements are highlighted.

1.1 Background

The goal of the European Union's (EU) sustainable transport policy is to ensure that the transport system meets the economic, social and environmental needs of society [1]. Effective transport systems are essential for Europe's prosperity and of the competitiveness of European industry and services. Mobility is also an essential right for EU citizens. Road transport plays an important role in this context and it covers a significant proportion of the European transport needs as described in detail in Pasaoglu et al (2012). Due to factors such as globalization, changing customer needs and economic and environmental pressures, the European road transport sector is continually undergoing transformations, including technology transitions. Within wider carbon reduction targets, the EC set out in the White Paper on Transport a target of reducing transport GHG emissions by 60% of 1990 level by 2050 [1]. Recent European policy initiatives targeting the decarbonisation of road transport, which contributes about a fifth of total EU emissions [2], are directed towards (i) enforcing CO_2 reductions on a fleet level for all vehicles [3-6], (ii) reducing the carbon intensity of the fuel mix and energy supply [7, 8], (iii) supporting research, development and demonstration (R, D & D) [9, 10] and promotion [8] of alternative technologies, (iv) the provision of consumer information on fuel efficiency and CO_2 emissions [11] and (v) fostering the deployment of the infrastructure necessary for alternatively fuelled vehicles [12].

These actions are supplemented by demand-side measures in the Member States, such as scrappage schemes and financial incentives tailored towards lower CO_2 cars to stimulate alternative vehicle purchases by customers. Many EU countries have already taken individual initiatives to introduce electric vehicle (EV) technologies, and have launched pilot projects to show their technical feasibility, as well as incentive schemes to promote the deployment of an electrical driven fleet and associated infrastructure. Due to these initiatives, the expectation is that the adoption of alternative fuels and powertrains will accelerate in the EU road transport sector and that consequently CO_2 emissions and fuel dependency will be reduced [13]. However, there is no common agreed penetration rate projection for alternative vehicles in Europe [14]. Although the market penetration rate of new propulsion technologies (alternative fuels and powertrains) will mainly depend on their cost competitiveness vis-à-vis conventional vehicles, there are other factors which may influence the deployment of alternative vehicles, such as infrastructure availability, consumer awareness, technological features (range, speed, safety, fuel consumption, emissions, technology maturity etc.), after-sale service availability and government support. Consequently, although early indications of the electric vehicle market are positive [15] the market viability and the future market penetration of these technologies remain highly uncertain. Therefore, it is of critical importance to base technology transition expectations on a solid foundation, taking into account the main drivers and parameters influencing the transition.

In the light duty road transport sector, combined forces of supply and demand conditions, rather than the historic costs, demand and trends of the market, will determine the deployment of new powertrain types, infrastructural investments and customer preferences. In such an environment, future developments are difficult to predict as all of the relevant factors highly interact and directly influence each other. Manufacturer and infrastructure provider investment decisions mainly depend on their cash flow expectations while user powertrain preferences and authorities' policies (incentives, penalties, and taxes) greatly influence these expectations.

To aid the understanding of these transitions and relationships, in this report we present an extensive system dynamics (SD) model of powertrain technology transitions across the EU over the period 1995 to 2050, incorporating the major market agents' decisions, activities and their feedback and interaction with each other. The model is designed to assist in analysing likely trends under various conditions involving future technologies in the EU light duty road transport sector. In the current environment, where private firms, powertrains and fuel types are competing amongst each other and authorities define regulations and policies in order to reduce greenhouse gas emissions and ensure sustainable transport, traditional modelling and analytical tools for long-term planning need to be complemented with tools or features investigating market agent interaction. In particular, models need to take into account the fact that market trends do not depend on any single decision makers' actions, but rather on actions, interactions and feedback mechanisms involving multiple decision makers, including consumers, manufacturers, infrastructure providers and authorities. As alternative vehicles have different infrastructural needs, drawbacks and advantages, time series based approaches, which are typically used for sales forecasting and infrastructural planning of conventional vehicles, may be less relevant to analyse the transition to new powertrains in the road transport sector. The limitations of traditional optimization and forecasting approaches are that they are inherently prescriptive, linear, and mechanistic, while ignoring important feedbacks and overly relying on non-behavioural mechanisms [16]. In markets where private agents, technologies and products are competing with each other, the need is shifted from planning to designing strategy, requiring complementary modelling approaches such as SD, agent-based models and game theory.

1.2 Model Development

The model development, which was carried out by Ventana (UK) alongside JRC in-house experts, comprised three project phases: (i) Qualitative representation of the market mechanisms leading to new technology market penetration; (ii) Development of a quantitative simulation model and interface; and (iii) Establishment of a calibrated baseline model scenario and conduct scenario analyses. The study team proposed to bring together the latest research in the fields of road transport technology and system dynamics modelling. In the chosen modelling approach, the number of technology adopters, and hence market penetration, is a key output for any technology transition study. Although the number of adopters will have feedback influences on the number of future adopters, it is likely only one of many influencing factors. The main area of focus was, therefore, on the leverage factors on adoption rate, which ultimately determine success or failure of the technology.

The model is a comprehensive representation of light duty (Passenger Cars (PC) and Light Commercial Vehicles (LCV)) vehicle fleet evolution in Europe and includes feedback between major stakeholders influencing the evolution of the market shares of 16 powertrain options in each of the 28 member states of the European Union. Through the use of this simulation tool, users will be able to evaluate the possible impacts of policies on the behaviour of the system and ultimately support the design of the best policy options to reduce the environmental impact of transportation. Using the power of the System Dynamics methodology and the SD software, Vensim (VENtana SIMulation), a scenario run can be completed in a matter of a few seconds enabling the multiple iterations and sensitivity analysis necessary to form a robust understanding of the policy implications.

1.3 System Dynamics

Modelling takes place in the context of real world problem solving. The purpose of modelling not only is to gain insight but to solve a problem. System Dynamics (SD) is simple, open and intuitive. It does not depend on advanced mathematics, it is more powerful than the ubiquitous spread sheet and it is more capable of addressing problems at the highest level of strategic impact. SD is a method for studying and managing complex feedback systems in the world around us, such as one finds in business and other social systems [17]. Unlike other scientists, who study systems by breaking them up into smaller and smaller pieces, SD practitioners look at things as a whole.

The central concept to SD is the understanding of how all objects in a system interact with one another. This is in contrast to agent based modelling, which focuses on individual actions. The objects and agents in a system interact through "feedback" loops, where a change in one variable affects other variables over time, which in turn affects the original variable, and so on. One cannot study the link between two variables X and Y and, independently, the link between Y and X and predict how the system will behave. System components (agents) in isolation may have detailed complexity but are relatively straight forward to investigate. However, the dynamic complexity of component interactions and dependencies upon each other can only be observed by assessing the overall system behaviour using an approach such as SD. SD models can help identify the policy leverage points likely to have the greatest overall influence, taking into account policy resistance feedback loops which may be present with the system, such as side effects, delayed reactions, changing goals, interventions and tipping points. Today, there's a widely held belief that SD is a better way for challenging the increasing complexity of decision making in general and the best solution to avoid unintended consequences [18].

The SD process can be described by various steps which are usually iterated many times in any possible order. Modelling is embedded in the larger cycle of learning and action which constantly take place in organisations. Simulation models are informed by our mental models and by information obtained from the real world. Strategies, structures and decision rules used in reality can be represented and tested in the virtual world of the model. The experiments and tests conducted in the model feedback to alter our mental models and lead to the design of new strategies, structures and decision rules. Then these new policies are implemented in the real world while feedback about their effects leads to new insights and further improvements in both our mental and formal models. In general, the SD approach is more than just the creation of a mathematical simulation model. SD is used to understand the basic structure of a system, and thus understand the behaviour it can produce. Many of these systems and problems which are analysed can be built as models on a computer. SD takes advantage of the fact that a computer model can be of much greater complexity and carry out more simultaneous calculations than can the mental model of the human mind.

The essential tools for the modelling process of system dynamics are causal loop diagrams (CLD) and stock and flow diagrams (SFD) which are applied in qualitative and quantitative system dynamics modelling. These two tools are the central concept of SD theory. Further unique to SD is the incorporation of subscription and non-linearity. Overviews of these are given here, but for more in-depth explanations the reader should refer to more comprehensive introductions to SD, such as [17].

1.3.1 Causal Loop Diagrams (CLD)

Causal or feedback loops exist in every system imaginable and determine the behaviour of the system over time. Feedback is a central feature of system dynamics (SD) models and any one CLD will contain one or more feedback loops. A CLD consists of variables that are connected by arrows representing causal links between said variables, representing either positive (self-reinforcing) or negative (self-correcting or balancing) feedback dependency. Reinforcing loops amplify what is happening in the system, i.e. where an increase in one parameter leads to an increase in another, and without any other interacting parameters, this increase will continue exponentially. Balancing loops are relationships that oppose change, so in such a loop an increase in one parameter leads to a decrease in another, until a dynamic equilibrium is reached. The interaction of multiple causal loops makes up the wider dynamic system. Causal loop diagrams are a powerful tool to qualitatively map the feedback processes of complex systems. They provide a high level means of conceptualising models in terms of their feedback loop structure [19].

An example of a simple reinforcing and balancing loop in a system relevant to our model is shown in Figure 1, the causal loops which represent the theoretical early years interaction between Charging Infrastructure, Plug-in Vehicles and Fiscal Incentives. The 'infrastructure and vehicles' loop is reinforcing (denoted R) (hence the "+" of the arrow heads) as more infrastructure could lead to more vehicles, which in turn leads to more infrastructure. If this loop was operating on its own, both vehicles and infrastructure would increase exponentially. On the other hand, the 'vehicles and incentives' loop is balancing (denoted B) – although more vehicles may reduce fiscal incentives (as they are no longer needed - denoted by "-"), the lower fiscal incentives may also reduce sales of plug-in vehicles (if the market is not self-sustaining before they are reduced). If this loop were operating alone, the vehicles (and fiscal incentives) would gradually decline to zero. In reality, as the loops interact, the path of infrastructure, vehicles and incentives over time are dependent on the relative rates but will eventually reach a dynamic equilibrium, and ensures that the number of vehicles do not increase exponentially.

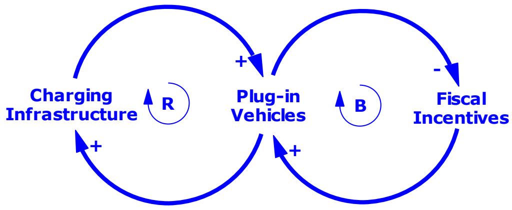

Figure 1: Example simple causal loop diagram (CLD)

1.3.2 Stock and Flow Diagrams (SFD)

The process of quantifying the qualitative design necessitates adjustment to the design as new evidence and research emerges in conjunction with simulation results. Good practice dictates the use of stock-and-flow diagrams (SFD) in the development of a quantitative system dynamics model. Stocks and flows are required in system dynamic models as in certain processes the parameters may accumulate as a stock from an inflow that declines once an outflow is permitted, similar to a bath before the plug is removed. These stocks represent the current state of that system. The in and out flows may be non-linear and operate at different rates that are independently dependent on other parameters. For example, in the developed model, the Vehicle Stock indicates how many vehicles are on the road at any point in time. Flows, on the other hand, determine the change in the stocks as time goes by. In this simple example, the stock of vehicles currently on the road is increased by the flow of new vehicle registrations each year and decreased by the flow of de-registration of vehicles at the end of their life, and determined by Equation 1. In this simple example, shown in Figure 2, the stock is shown as a box with arrows flowing into and out of it, representing the flows having influence on the stocks. Thus, the stock evolution follows a simple S-shaped curve. They link into the rest of the model using causal loops. This expansion of the influences into their components parts is critical to support understanding and validation of the model.

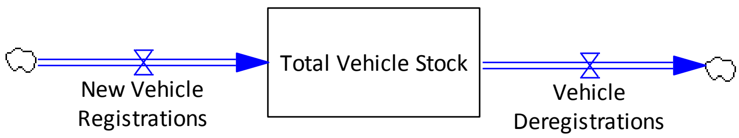

Figure 2: Example stocks and flow diagram (SFD)
Adapted from PTTMAM

$$Total\ Vehicle\ Stock = Initial\ Vehicle\ Stock + \int_0^t New\ Vehicle\ Registrations - Vehicle\ Deregistrations\ \ dt$$

Equation 1: Underlying equation for *Total Vehicle Stock*

1.3.3 Non-Linearity

The relationship between variables in the model is normally determined by a simple mathematical equation, but a non-linear relationship requires a different approach, for example through the use of look-up tables or non-linear sensitivity equations.

1.4 Previous SD-based Technology Transition Studies

The SD approach, which was developed in the 1950s [20], has been regularly applied to study the diffusion of innovations and new technologies [17, 21-23], in particular to analyse possible future scenarios of technology transition in the automotive sector [24-36]. An overview of such studies can be seen in [22, 26].

An important example is [34], who developed a behavioural dynamics model that explores the transition from conventional vehicles to generic alternative fuel vehicles (AFVs), utilising basic technology diffusion concepts. Many of the mentioned studies focus only on one specific interaction, AFV or country. Conversely, the Astra model considers many factors in the EU transport sector and the influence of European transport policy [37, 38]. However, the Astra model lacks the agent approach.

Filling the abovementioned gaps in the literature, we developed an extensive SD simulation model, employing an agent approach and incorporating many factors from the above studies that influence the technology transition in the EU light duty road transport sector, in order to better understand and analyse the market trends in the future vehicle market. To our knowledge, the model seeks to integrate a wider range of market, industry and technology dynamics compared to other modelling exercises that have been attempted to date. Furthermore, the model not only addresses the competition between the incumbent technology and new technologies, but also the competition among specific alternative vehicle types. This approach is aligned with the actual complexity of the automotive sector, which is characterised by multiple players with often conflicting incentives.

1.5 Model Description

This section presents some general features of the PTTMAM. Although it is not the intention to provide detail of every single element within this report, which would make it unmanageable, it is hoped that it will give the reader a thorough understanding behind the rationale of the model suitable for interpretation of results. A basic level of knowledge regarding system dynamics models and Vensim software is assumed. We aim to provide enough information on the design and rationale of the model, including both exogenous inputs and endogenous relationships, in order to support in the confidence of an external party in the suitability of our model when interpreting our results.

Following the description of some major elements of the model in this section, the model will be described in relation to its four major conceptual market agents. The most relevant sections of the model and key equations are presented, as are the more important sources of exogenous inputs. In our diagrams, all endogenous variables are in black or grey[1] text, exogenous inputs are dark red underlined text[2] and calibrated inputs are pink underlined text. In this report we have also included many model equations, presented in a conventional format [39]. If no unit is indicated, the parameter is dimensionless. Most parameters within these equations are highly subscripted (see Table 1) and as such it is impractical to include all input data. We have however, attempted to reference all sources where possible. If no citation is made, the value has been assumed by the authors using expert judgment. Some formula and parameter names have been simplified from the model.

[1] When endogenous variables are part of a wider causal loop not relevant to the discussion.
[2] Inputs in bright red are historical time-series inputs used in calibration.

1.5.1 Scope and Boundaries

The model is primarily concerned with the interactions between representative market agents as they influence possible technology and fuel transitions in the European light-duty vehicle market. Figure 3 illustrates the scope and boundary of the key elements of the model. In the initial development phase, following identification of scope and boundary, a series of Causal Loop Diagrams (CLD) for each conceptual market agent was created from research and expert input and the interactions between agents were identified and described. Once these CLDs were agreed, the quantitative model was developed and data gathered to support model execution and calibration. The developed model is a comprehensive representation of the light duty vehicle fleet evolution in Europe, at EU28 member state level, and includes major interactions and feedbacks between the four identified relevant representative market agents (Users, Manufacturers, Infrastructure Providers and Authorities) influencing the evolution of the powertrain market shares. Simple assumptions are made regarding regions outside the EU, and treated together as the rest of the world (RoW) in order to decrease model complexity. Input data was obtained from various sources alongside expert judgement when specific data was not available. Some key sources were Eurostat (2014), Tremove (2010), the EU 2050 Reference Scenario (2013) (which is based on PRIMES) and the TRACCs project [40]. The model can make simulations between 1995 and 2050, incremented into annual periods. Naturally, it is worth stating that the model remains a simplified representation of reality and should therefore be used with caution; mainly as a means of exploring "what if" scenarios under various conditions.

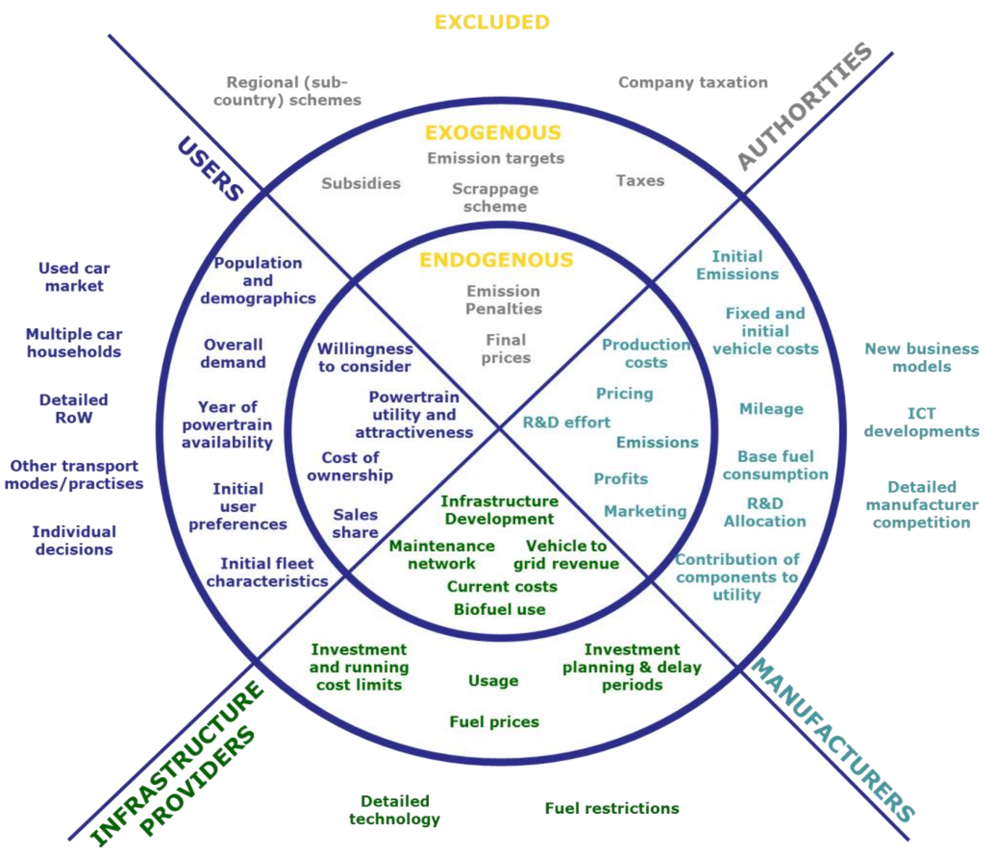

Figure 3: Model scope and boundaries

Colours represent key market agent. Grey: Authorities; Green: Infrastructure Providers; Blue: Users; Turquoise: Automobile Manufacturers.

1.5.2 Market Agents

As already alluded to, this model is built up around the idea of the interaction between the relevant market agents within the automobile sector, identified as being Authorities, Users, Manufacturers and Infrastructure/Maintenance Providers. It is important for those interpreting model outputs to understand that these agents are represented in the model as conceptual groupings, and in no way should this model assumed to be agent based, which may be more relevant for studies more deeply considering the detailed spatial use of vehicles that is outside the current boundaries of the PTTMAM. Despite this, some degree of heterogeneity can be represented within each market agent, even though the groups are characterised by certain decision rules. This heterogeneity may come about for Users by the use of subscripts for certain elements (eg geography, user type) and the build in of competition dynamics for manufacturers and infrastructure. Authorities in our model are distinguished by individual member state but not by individual region or municipality. Figure 4 illustrates the main behaviours attributed to each of the market agents and their interactions. These decision rules were developed in the original conceptualisation of the model and formed the basis of initial CLDs which make up the model structure. In addition, they are used in the following sections to describe the model behaviour.

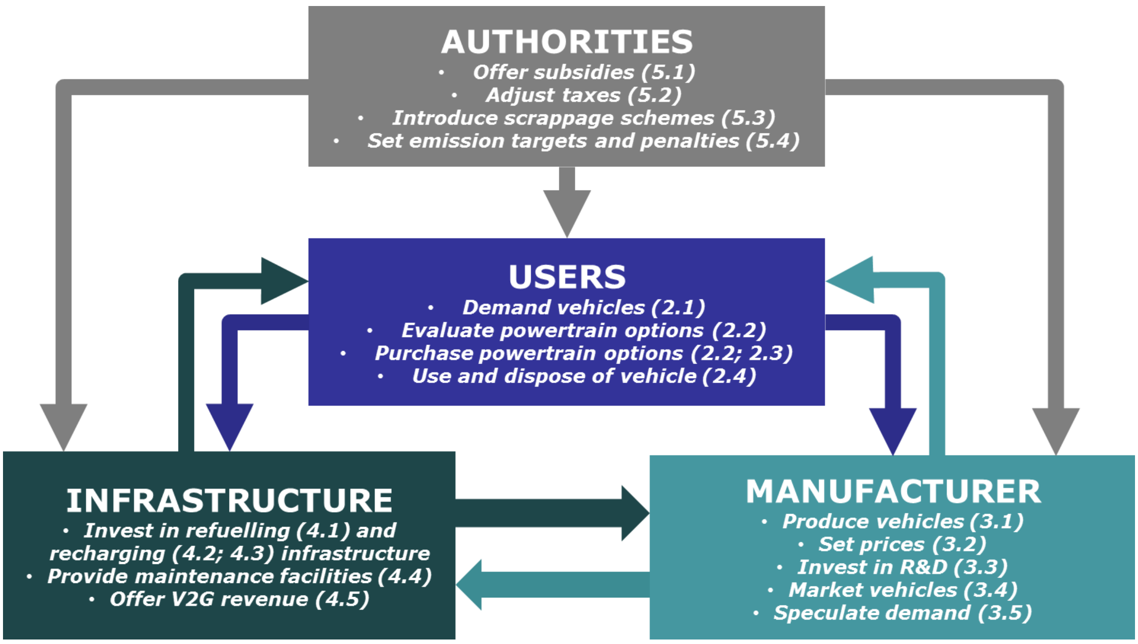

Figure 4: Market agent behaviour

Described in report section given in brackets

Colours represent key market agent. Grey: Authorities; Green: Infrastructure Providers; Blue: Users; Turquoise: Automobile Manufacturers.

1.5.3 Overview Diagram

The high level diagram in Figure 5 shows the main elements of the model grouped by market agent, though the reader should note that this is NOT the full model, which in fact expands over nearly 50 separate Vensim "views" (or modules) and contains over 1500 separate parameters. This leads to around 700,000 once subscripts are accounted for, with over 1000 data input points.

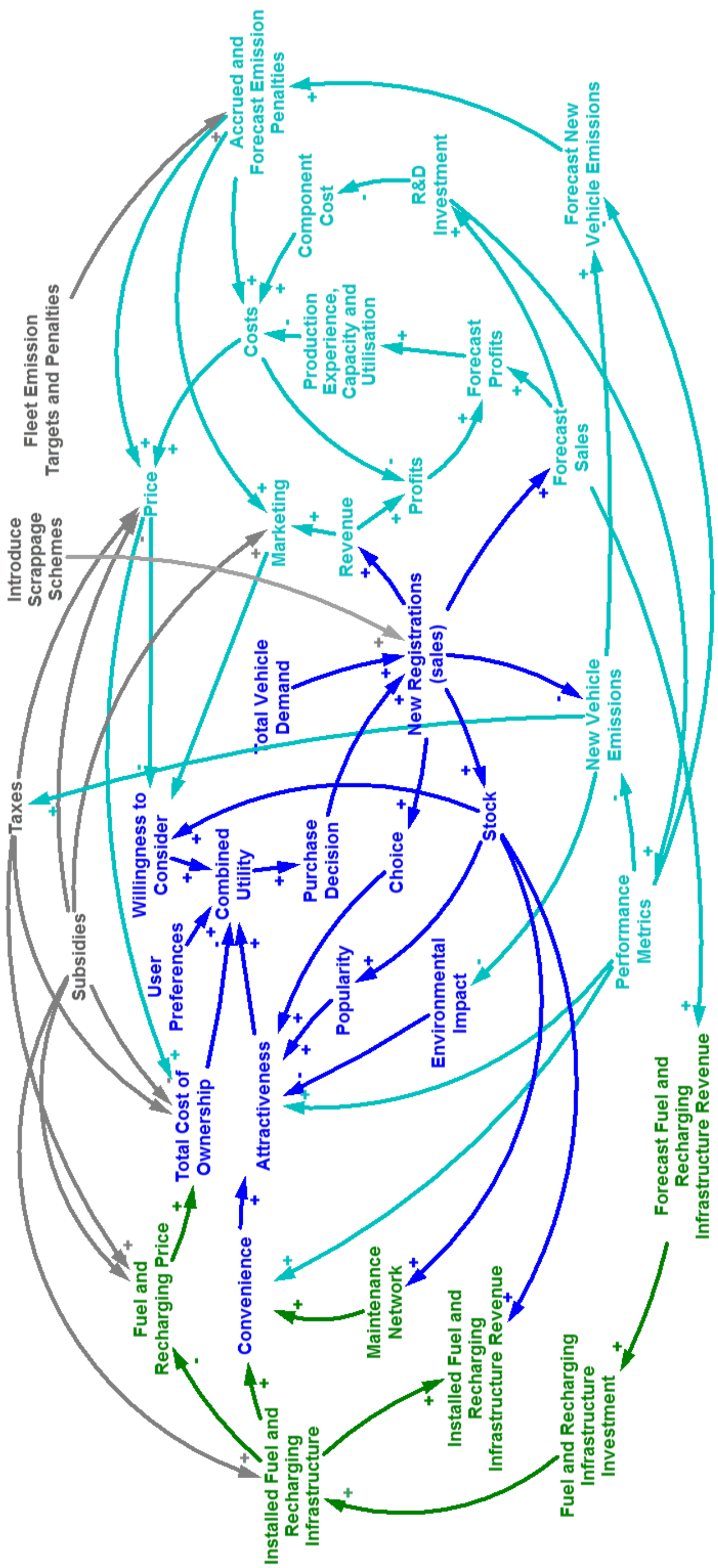

Figure 5: Overview causal loop diagram

Colours represent key market agent. Grey: Authorities; Green: Infrastructure Providers; Blue: Users; Turquoise: Automobile Manufacturers

1.5.4 Subscripts

Subscripts are a particular feature of the Vensim simulation tool enabling repetition of structure. In our simple example from 1.3.2, subscripts could be used to further elaborate on the vehicle types within the stock eg ICEV, HEV, PHEV, BEV and FCV. To accomplish this in Vensim, a subscript range is created, called "Powertrain", and the subscript elements listed above added. If vehicle stock is then subscripted by this subscript range then it will allow for the allocation of each and every category in the range. It follows that categories can be changed, added or removed without changing the structure of the model, simply by changing the list of subscript elements. There are thirteen subscript ranges represented in the model and presented in Table 1. Some are specific to particular parameters or agents while others span multiple parameters or agent types. The ranges can be further grouped into subranges where necessary e.g. "Zero Emission Powertrains". As such, parameters may have up to 10,000 subscripts.

Name	Description	Elements
Powertrain (P)	Each potential powertrain option available in Europe	Petrol ICEV; Diesel ICEV; LPG ICEV; CNG ICEV; Biodiesel ICEV; Bioethanol ICEV; Petrol HEV; Diesel HEV; Biodiesel HEV; Bioethanol HEV; Petrol PHEV; Diesel PHEV; Biodiesel PHEV; Bioethanol PHEV; BEV; FCV
Vehicle Class (V)	Distinguishes light duty vehicle class	Passenger car (PC); Light commercial vehicle (LCV)
Vehicle Size (S)	Size categories of vehicles	Small; Medium; Large
Vehicle Age (A)	Age categories of vehicles	< 2 Years; 2 - 5 Years; 5 - 10 Years; > 10 Years
Country (C)	Each member state	Austria; Belgium; Bulgaria; Cyprus; Croatia; Czech Republic; Denmark; Estonia; Finland; France; Germany; Greece; Hungary; Ireland; Italy; Latvia; Lithuania; Luxembourg; Malta; Netherlands; Poland; Portugal; Romania; Slovakia; Slovenia; Spain; Sweden; UK
Powertrain Class (Cl)	Type of powertrain	BEV Class; FCV Class; HEV Class; ICEV Class; PHEV Class
Fuel (F)	All fuels used by the powertrain types	Biodiesel Fuel; Bioethanol Fuel; CNG Fuel; Diesel Fuel; Electric Fuel; Hydrogen Fuel; LPG Fuel; Petrol Fuel
Users (U)	Groups of user types	Private; Fleet; Public
Geography (G)	Sub-group for users	Urban; Non-Urban
Utility Criteria (Cr)	Criteria under which users make purchase decisions on powertrain	Environment; Performance; Reliability; Safety; Convenience; Popularity; Choice;
Component (Ct)	Major components of vehicle types	Electric drive system; BEV battery; HEV battery; PHEV battery; IC engine; Hydrogen storage tank; Body materials; Fuel cell system
Primary Energy Source (E)	Used in calculation of CO_2 from electricity generation	Renewables; Oil; Gas; Solids; Nuclear
Emissions Option (Em)	Accounting of associated emissions	Well to Wheel; Tank to Wheel

Table 1: Subscripts

2 The Users Agent Group

As with all market agents within the PTTMAM, the user agent group is a conceptual representation of all users within the automobile system. The decision rules which characterise the user agent group are related to the evaluation and purchase of powertrain options, which are influenced by the actions of the other market agents (eg policies and subsidies from authorities, infrastructure and maintenance services provided and development of powertrain characteristics) and result in the market shares and stocks of powertrains that in turn drive investment decisions of manufacturers and infrastructure providers. Users can be represented as urban and non-urban populations in each of the EU28 member states. They are further categorised by their type of vehicle use; private, public or fleet. As a primary market agent, the users have a central role in determining the evolution of the powertrains through the vehicle purchase decision process. Under a number of defined criteria, users evaluate the performance of each powertrain option when making purchasing decisions. There are four main decision rules of the user:

- ***Demand vehicles*** (2.1)
  Underlying vehicle demand determined by regression analysis of past purchases and future stock projections, scrappage replacements and vehicles decommissioned due to unaffordability.

- ***Evaluate powertrain options*** (2.2)
  New powertrains may take some time to fully enter the users consideration set, and increase with social exposure.

- ***Select powertrain type to purchase*** (2.2, 2.3)
  Sales market shares are determined using a choice model and influences of subsidies.

- ***Use and dispose of vehicle*** (2.4)
  Disposal patterns are calibrated to survival rates, and the influence of scrappage schemes or unaffordability.

2.1 Vehicle Demand

The determination of demand for new registrations of vehicles in each member state is illustrated in Figure 6 and Equation 2. The optimisation routines used to determine the calibrated values of the required coefficients for each member state are described in more detail later in this report (7.1). For now the reader should note that the payoffs which determine the calibration are vehicle stock, a projected dataset based on PRIMES modelling [41] and vehicle demand, a historical dataset of 1995-2012 [9, 42-47]. For those countries where data for the initial year of 1995 could not be obtained, which is required for initial demand, this is also calibrated. The model also allows the modeller to choose if the historic demand data is used where available or to use the endogenous data.

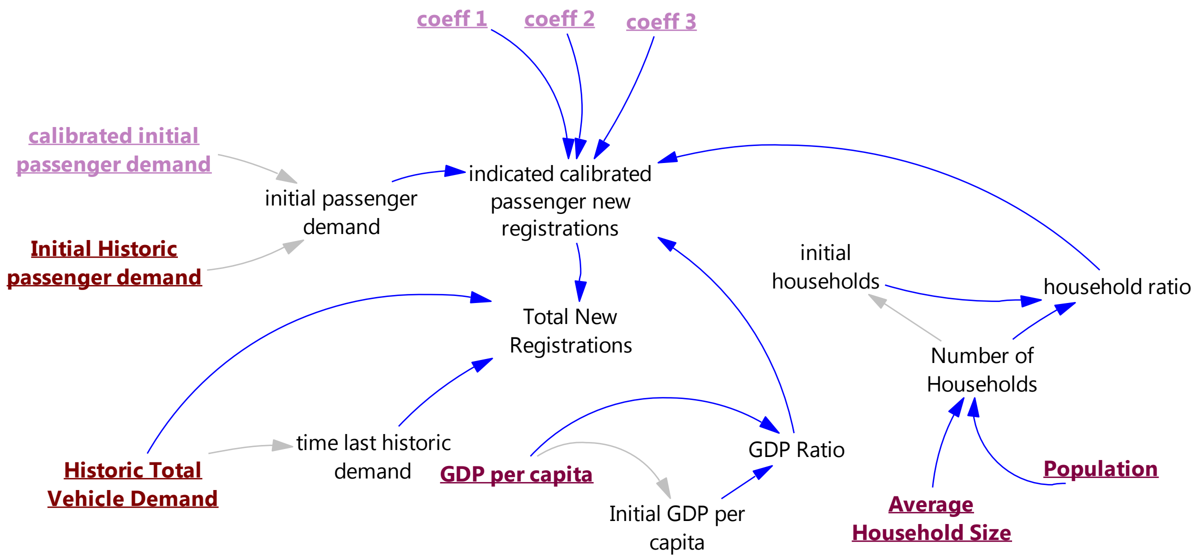

Figure 6: Passenger car (PC) vehicle demand
LCV same as PC

$$Total\ new\ registrations = Initial\ demand \times Coeff\ 1 \times GDP\ ratio^{Coeff\ 2} \times Household\ ratio^{Coeff\ 3}$$

Equation 2: Vehicle demand in each member state *(vehicle/year)*
Initial demand = [9, 42-47]
Coefficients = Internally calibrated (See 7.1)
GDP ratio = Derived from [41, 48]
Household ratio = [41]

2.2 Vehicle Purchase Evaluation and Decision

The previous section has described how the underlying vehicle demand by the user agent group is determined within the model. Here we explain how market shares of those powertrains are calculated within the model, using a choice model that assesses the relative utility of the powertrains, represented in Figure 7. Choice models have been widely employed for the determination of user choices regarding car ownership, and more recently, specific powertrain types [49-57]. This utility comprises of several dynamic attributes relating to the technology, and the strength of consumer preference for these criteria in their purchase decision. For every year during the simulation period, the purchase likelihood of a powertrain in each member state, user segment and size segment is then calculated by the ratio between the utility of a specific powertrain in a specific condition (country/user/size) and the sum of all powertrains in that condition. The choice model employed currently is a simple standard Multinomial Logit (NML) as in Equation 3, though it is noted that this is clearly not as sophisticated as the majority of the choice models in the literature.

$$Indicated\ market\ share_{C,U,P,S} = \frac{e^{Combined\ utility_{C,U,P,S}} - 1}{\sum_P e^{Combined\ utility_{C,U,P,S}} - 1}$$

Equation 3: Indicated market share
Combined utility = See 2.2.1

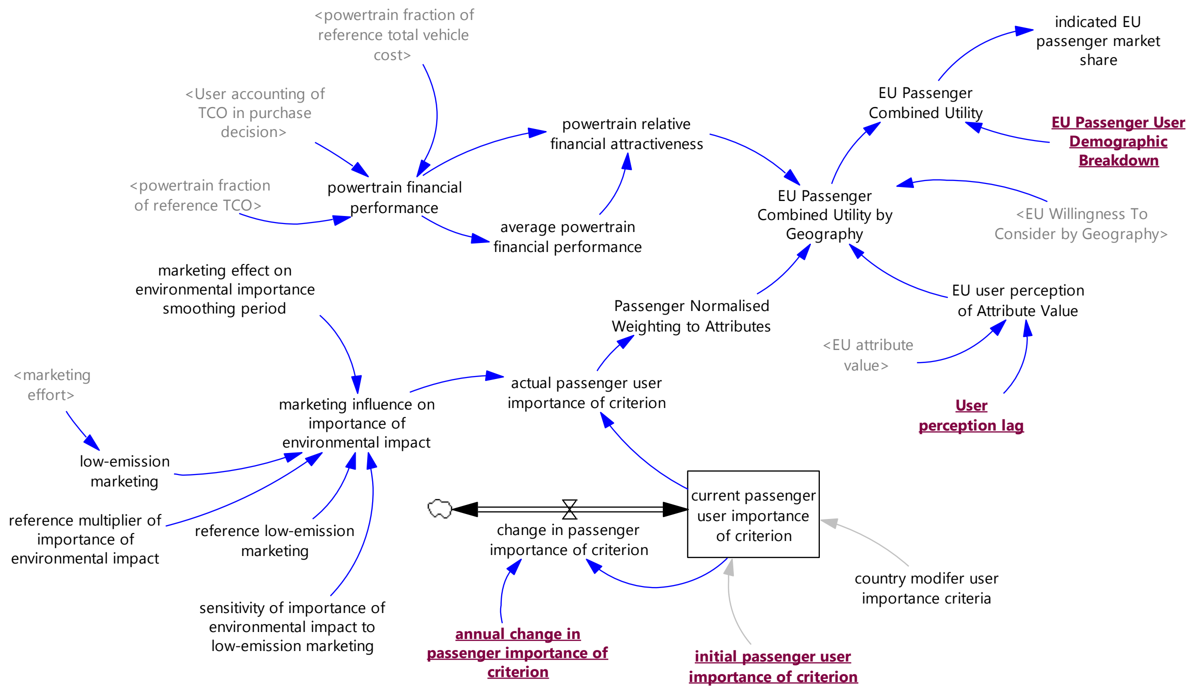

Figure 7: PC new registrations market share
(LCV same as PC)

2.2.1 Combined Utility

Equation 3 showed how the market share of powertrains is indicated from a combined utility which characterises each powertrain. This combined utility (Equation 4) incorporates a number of aspects, including the willingness to consider (2.2.2), a financial attractiveness (2.2.5), values of a number of attributes (*Environment, Performance, Reliability, Safety, Convenience, Popularity, Choice*) of the individual powertrains (2.2.4) and the preferences of users towards the importance of these attributes (2.2.3). The chosen attributes were determined by the availability of the preferences. The combined utility of vehicles evolves over time due to the evolution of these parameters.

$$\begin{aligned} \mathit{Combined\ utility}_{C,U,P,S} &= \sum\nolimits_G \Bigg(\Big(\sum\nolimits_A \big(\mathit{Attribute\ value}_{C,P,S,A} \times \mathit{Attribute\ importance}_{C,A,G,U} \big) \\ &\times \mathit{Willingness\ to\ consider}_{\ C,G,P} \times \mathit{Financial\ attractiveness}_{C,U,P,S} \Big) \\ &\times \mathit{Demographic\ breakdown}_{C,G} \Bigg) \end{aligned}$$

Equation 4: Combined utility of powertrain[3]

Attribute value = See 2.2.4
Attribute importance = See 2.2.3
Willingness to consider = See 2.2.2
Financial attractiveness = See 2.2.5
Demographic breakdown = (Proportion of population residing in urban/rural areas) [58]

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[3] As a reminder to the user, subscripts are explained in 1.5.4 and Table 1. As way of further explanation of the equation, the summations over age (A) and geography (G) bring together all subscripted groups within each category.

2.2.2 Vehicle Willingness to Consider

Before users may chose a particular powertrain it must exist in the user's "consideration set". Struben and Sterman (2008) introduced this concept of a "willingness to consider" (WtC), which "*captures the cognitive, emotional and social processes through which drivers gain enough information about, understanding of and emotional attachment to a platform for it to enter their consideration set*". They propose that drivers learn about a particular platform through three channels of social exposure, being marketing and word of mouth from both users and non-users of the powertrain. All three combine to increase the exposure of a powertrain to potential users. However, knowledge and information about a powertrain also decays over time as users may forget about them. If interaction with users and others having knowledge of the powertrain plus marketing information about the powertrain is lower than the decay rate, then the WtC the powertrain would fall and market share would be affected. The Struben & Sterman formulation has been modified in the PTTMAM to include the effect of difference in price between the powertrain types, as presented in Figure 8. WtC powertrain i, by a user of powertrain j in each member state (Equation 5) is a stock that increases over time relative to the increase (from social exposure) and a fractional decay rate (Equation 6).

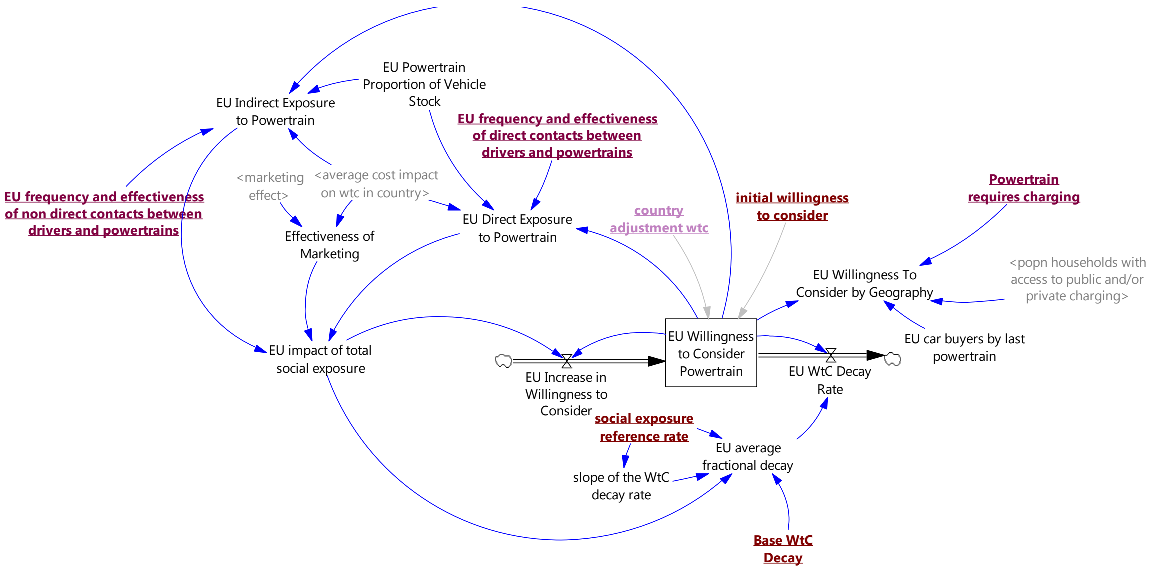

Figure 8: Willingness to consider powertrains

$$WtC_{i,j} = Initial\ WtC_{i,j} \times Country\ adjustment\ WtC_i + \int_o^t Impact\ of\ social\ exposure_{i,j}(1 - WtC_{i,j}) - Fractional\ decay_{i,j} \times WtC_{i,j}\ dt$$

Equation 5: Willingness to consider powertrain i by users of powertrain j in each country

Initial WtC = 1 (for all ICEV and Petrol HEV), 0 (all other powertrains)
Country adjustment WtC = Internally calibrated (See 7.1)
Impact of social exposure = Marketing effectiveness (2.2.2.1) + Word-of-Mouth (2.2.2.2)
Fractional decay = See Equation 6

$$Fractional\ decay_{i,j} = Base\ WtC\ decay \times \frac{e^{-4 \times WtC\ decay\ rate\ slope\ \times\ (Impact\ of\ social\ exposure - Social\ exposure\ reference\ rate)}}{1 + e^{-4 \times WtC\ decay\ rate\ slope\ \times\ (Impact\ of\ social\ exposure - Social\ exposure\ reference\ rate)}}$$

Equation 6: Fractional decay of WtC in each country

Base WtC Decay = 0.15 [34]
WtC decay rate slope = 1 / (2 x Social exposure reference rate) [34]
Impact of social exposure = Marketing effectiveness (2.2.2.1) + Word-of-Mouth (2.2.2.2)
Social exposure reference rate = 0.05 [34]

The resultant WtC a powertrain in each member state by geography (rural/urban), which is limited by the proportion of households with access to charging for plug-in vehicles, is then determined using Equation 7 by the disposal of other powertrain types at the time of the new purchase decision.

$$WtC_i = \sum_{powertrain\,j} WtC_{i,j} \times Car\ buyers\ by\ last\ powertrain_j$$

Equation 7: Willingness to consider powertrain i in each country

Car buyers by last powertrain = See 2.4

2.2.2.1 Marketing

The effectiveness of the marketing (by manufacturers) influences knowledge and acceptance of a powertrain option. Marketing effort is also determined within the model, according to forecast/speculative sales, expected emission penalties, the impact from subsidies and initial launch of a new powertrain (3.4).

2.2.2.2 Word-of-Mouth

Exposure to knowledge about a powertrain through interaction with users of that powertrain is determined by the frequency and effectiveness of contacts between users and non-users of the powertrain type, as determined by Equation 8.

$$Direct\ exposure\ to\ powertrains_{i,j} = Frequency\ and\ effectiveness\ of\ direct\ contacts\ between\ drivers\ and\ powertrains_C \times WtC_{i,j} \times Powertrain\ proportion\ of\ vehicle\ stock_j \times Average\ cost\ impact\ on\ WtC_i$$

Equation 8: Direct exposure to powertrain i in each country

Frequency and effectiveness of direct contacts = 0.25 [34]
WtCij = See Equation 5
Powertrain proportion of vehicle stock = See 2.4
Average cost impact on WtC = See 2.2.2.3

Exposure to a powertrain through interaction with others having knowledge of that powertrain also contributes to social exposure. This effect is assumed to be weaker than the direct interaction, as in Equation 9.

$$Indirect\ exposure\ to\ powertrains_{i,j} = \sum_{Pj} Frequency\ and\ effectiveness\ of\ non\ direct\ contacts\ between\ drivers\ and\ powertrains \times WtC\ Powertrain_{i,j} \times Powertrain\ proportion\ of\ vehicle\ stock_j \times Average\ cost\ impact\ on\ WtC\ in\ country_i$$

Equation 9: Indirect exposure to powertrain i in each country

Frequency and effectiveness of non-direct contacts = 0.15 [34]
WtCij = See Equation 5
Powertrain proportion of vehicle stock = See 2.4
Average cost impact on WtC = See 2.2.2.3

2.2.2.3 Cost Influence on WtC

The relative cost between powertrains has an influence on the WtC. The average cost impact on WtC in a certain country influences the growth in WtC as a modifier of the exposure to the powertrain. Powertrains markedly more expensive than the norm within the country can only be considered by a proportion of the population. An exogenous lookup table, cost multiple of average / WtC, relates the impact of the cost differential within a country to the modifier of WtC with reference to a maximum cost differential for WtC and a minimum cost differential for WtC (both expert assumed exogenous data inputs) compared to the fraction of average total cost of ownership (TCO) (see 2.2.5.1); the greater the cost differential for a powertrain the smaller the potential population of purchasers. The maximum and minimum differential is determined by comparing the current GDP per capita [41] for the country with the EU average GDP per capita. Differences between the two are translated into higher or lower tolerance of price differentials through an exogenous sensitivity parameter. Thus, countries with lower GDP are less likely to be early adopters of new, potentially more expensive, powertrains. A similar method is used on the determination of cost impact on affordability as described later in section 2.3.2.

2.2.3 Importance of Attributes to Users

In Equation 4 the attribute importance term represents the importance of each vehicle attribute to users. They are based on the percentage of respondents in a survey saying that these criteria are "important" or "very important" in car choice in "mature markets", i.e. including North America [59], except for *Convenience*, which is from a 2011 global electric vehicle survey [60]. These values are used for private users, with our own assumptions for non-private users, as shown in Table 2. It should be noted that we have taken our own interpretation of the meaning of these criteria, as described in the following sections on the attributes. Furthermore, these preferences are the same for the subscripts country and geography. Currently the preferences are equal for PCs and LCVs as there is no data available for LCVs. The weights are dynamic in that they have an initial value (Table 2) and can change over time, determined by an exogenous data input of annual percentage, currently set at 0. Country specific modifier values could also be calibrated if relevant data became available. It is recognised that this preference approach is simplistic compared to other choice models that have been developed, which incorporate detailed stated preference surveys and consider socio-demographics to household or individual levels.

	Private	Fleet	Public
Environment	0.67	0.67	0.90
Performance	0.94	0.80	0.80
Reliability	0.94	1.00	1.00
Safety	0.91	0.91	0.91
Convenience	0.80	0.90	0.90
Popularity	0.70	0.50	0.50
Choice	0.68	0.50	0.50

Table 2: Importance of attributes to users

As the model is currently set up, the current importance of the utility criteria (or attributes) is equal to the initial importance for all except *Environment*, which is influenced over time by a low emission marketing effort, as described in Equation 10. This study was unable to unearth hard evidence of this phenomenon other than the authors' common-sense assessment of the likely link; the inclusion of a marketing effect on environmental awareness resulted from an assessment of the likely response of users to manufacturers' marketing of the environmental 'friendliness' of lower-emission powertrains. Given the considerable sums spent by automotive manufacturers on such marketing, it is assumed that the latter have observed an effect on user behaviour Following this adjustment of the importance of *Environment*, the weighting of all importance criteria are normalised. There is however, within the PTTMAM a user input of annual change of importance of criterion, which would allow scenarios where each attribute becomes more or less important to the user over the simulation period.

$$Importance\ of\ Environment\ attribute = Initial\ importance\ of\ Environment\ attribute \times Reference\ multiplier\ of\ environmental\ impact \times \frac{Average\ marketing\ effort\ across\ alterantive\ powertrains}{Reference\ level\ of\ marketing\ that\ reference\ multiplier\ is\ observed}^{Sensitivity\ of\ Environment\ importance\ to\ marketing}$$

Equation 10: Importance of *Environment* attribute

Initial importance of *Environment* attribute = 6.7
Reference multiplier of environmental impact = 0.5
Average marketing effort across alternative powertrains = See 3.4.1 (smoothed over 3 years)
Reference level of marketing that reference multiplier is observed= 0.75
Sensitivity of *Environment* importance to marketing = 1

2.2.4 Attributes that Characterise Vehicles

As previously detailed, there are seven attributes which characterise the utility of a powertrain, (Equation 4). The attributes were chosen to reflect the available information in the literature on vehicle consumer choice but also to help simplify the model in that many of the future attribute values of yet-to-be-commercialised powertrains are difficult to acquire. Some studies use speed, acceleration etc as distinct choice attributes; this project combines these into a single *Performance* value together with other attributes such as interior space and comfort etc. In fact, it is the relative values for each attribute that determine market share. Each attribute score, which is between 0 and 1, is specific to member state, powertrain, user group and vehicle size. In the developed model, these criteria evolve over time, driven by the changing market share and performance of the powertrain component parts, which are in turn influenced by the level of investment in R&D by industry. Each powertrain attribute is smoothed to represent the delay in changing user perception of the attributes. If, for example, a new technology is introduced to reduce the environmental impact of ICE powertrains, this would not be immediately reflected as an improvement in that attribute to the user. In other words, it would take some time for the improvement to register in the purchase-decision process.

From Equation 11, the primary influence on all attributes apart from *Popularity* and *Choice* is the impact of R&D investment by the manufacturer on the maturity of components which characterise the powertrain and contribute to the attribute improvement (3.3.3). The initial value of the attribute, which is an exogenous data input based on expert judgement,[4] is shown in Table 3.

$$\begin{aligned} &Base\ attribute\ value_{P,S} \\ &= \Big(Initial\ attribute\ value_{P,S} \\ &+ \Big[(1 - Initial\ attribute\ value_{P,S}) \\ &\times \sum Contribution\ from\ current\ maturity\ of\ component_{P,Ct}\Big]\Big) \end{aligned}$$

Equation 11: Basis of attribute value for attributes affected by R&D

Initial attribute value = See Table 3

Contribution from component = See 3.3.3

Powertrain	Attribute				
	Environment	***Performance***	***Reliability***	***Safety***	***Convenience***
Petrol ICEV	0.73	0.85	0.95	0.95	1.0
Diesel ICEV	0.67	0.85	0.95	0.95	1.0
LPG ICEV	0.7	0.85	0.95	0.95	1.0
CNG ICEV	0.7	0.85	0.95	0.95	1.0
Biodiesel ICEV	0.7	0.85	0.95	0.95	1.0
Bioethanol ICEV	0.7	0.85	0.95	0.95	1.0
Petrol HEV	0.7	0.83	0.90	0.85	0.95
Diesel HEV	0.7	0.83	0.90	0.85	0.95
Biodiesel HEV	0.7	0.83	0.90	0.85	0.95
Bioethanol HEV	0.7	0.83	0.90	0.85	0.95
Petrol PHEV	0.7	0.77	0.80	0.85	0.60
Diesel PHEV	0.7	0.77	0.80	0.85	0.60
Biodiesel PHEV	0.7	0.77	0.80	0.85	0.60
Bioethanol PHEV	0.7	0.77	0.80	0.85	0.60
BEV	0.96	0.72	0.83	0.60	0.05
FCV	0.89	0.50	0.72	0.15	0.15

Table 3: Initial attribute value of variables affected by manufacturer R&D

(Medium segment vehicles for illustration; full maturity equals 1; based on expert judgement)

2.2.4.1 Performance, Reliability and Safety Attributes

The attributes of *Reliability* and *Safety* are self-explanatory. *Performance* is considered as a combination of undefined performance attributes such as interior (seat) space and comfort, trunk volume, handling, top speed and acceleration that may be influenced by the alternative powertrain configuration. These three attributes are only determined via R&D investment as in Equation 11.

2.2.4.2 Convenience

Convenience refers to "*convenience to charge* (or fuel)*, range, and the cost to charge* (or fuel)*".* Thus, this attribute was designed to capture the influence of suitable infrastructure that affects the range of the vehicle and the convenience of fuelling/charging. It is also influenced by the performance characteristics of the components of the powertrain and access to maintenance services for the vehicle, as shown in Equation 12 and Figure 9. As with all such cases where a non-linear relationship between two concepts (here, infrastructure influence on charging

[4] Though *Environment* was based around vehicle current and potential emissions at the time of development.

convenience) is modelled without the use of lookup tables, the marginal change in the influenced variable (from a baseline) as the influencing variable changes (from a reference value) is determined by sensitivity. This analytical approach has a number of advantages over the use of lookup tables in determining non-linear relationships in the instances where data availability is scarce. In such cases, the internal calibration routines can select sensible values for the reference dependant and independent variables in addition to the sensitivity index.

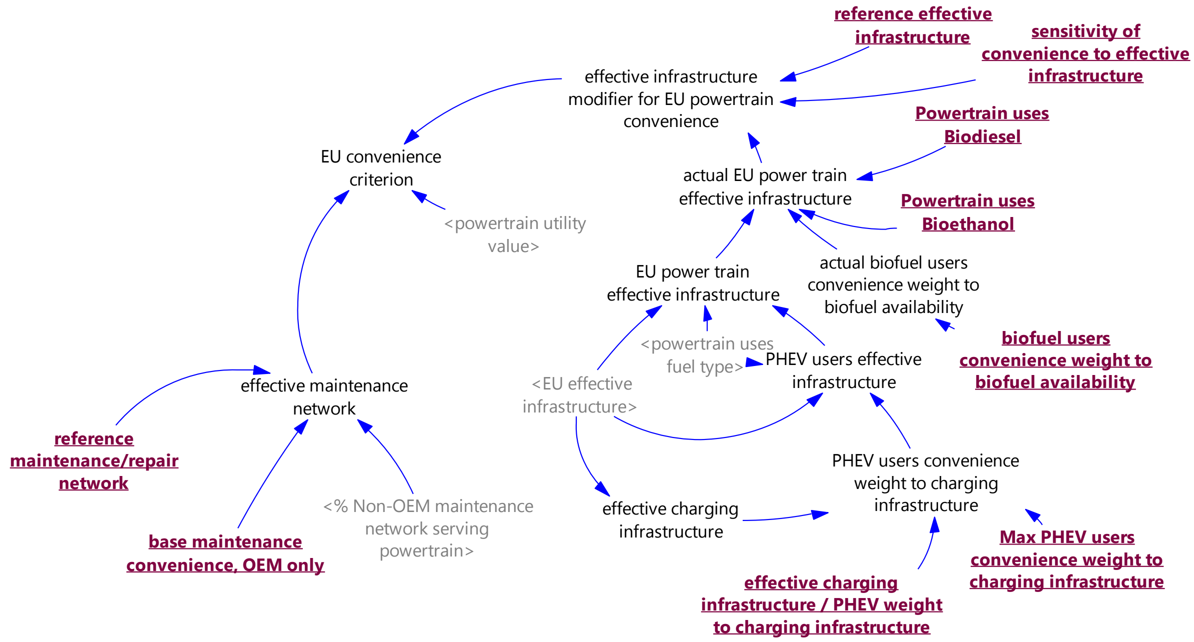

Figure 9: *Convenience* attribute

$$Convenience\ value_{C,P,S} = Base\ Convenience\ value_{P,S} \times \left(\frac{Actual\ effective\ infrastructure_{C,p}}{Reference\ effective\ infrastructure}\right)^{Sensitivity\ of\ convenience\ to\ effective\ infrastructure_C} \times Effective\ maintenance\ network_{C,P}$$

Equation 12: *Convenience* attribute value

Base *Convenience* value = (powertrain utility value) See Equation 11
Actual effective infrastructure = See Equation 13 - Equation 16
Reference effective infrastructure = 0.75
Sensitivity of convenience to effective infrastructure = 1.2
Effective maintenance network = See text

The effective infrastructure for each powertrain is shown in Equation 13 - Equation 16, and detail is found in the *Infrastructure Providers* section (4.1 and 4.2). For BEV this is the average population with installed access to charging for electric powertrains, taking account of both private/workplace charging and public standard (slow) charging and rapid charging. It is recognised that this does not explicitly encompass range or refuel/charge time, which are found by most choice modelling studies to be important attributes. PHEV also relies on this measure and a look-up table of effective charging infrastructure / convenience weight, bound by a maximum of 0.8. For all other powertrains, which are fuel based, it is the proportion of refuelling stations carrying the relevant fuel for the powertrain option. In the case of bioethanol and biodiesel-powered options, it is assumed that these vehicles may also be refuelled using conventional petrol and diesel, and so an adjustment is made to account for this additional convenience. When considering the availability of suitable infrastructure for biofuel, users will weigh the availability of biofuel stations as well as conventional fuel stations (assuming flex-fuel vehicles, FFV); this factor describes the relative weight. A value of 1 would mean that the conventional fuel infrastructure would not enter into the purchase choice.

$$\begin{aligned} Effective\ infrastructure_{Electricity} &= Convenience\ weight\ to\ standard\ charging \\ &\times\ Proportion\ of\ households\ with\ access\ to\ charging \\ &+ (1 - Convenience\ weight\ to\ standard\ charging) \\ &\times Proportional\ achievement\ of\ rapid\ charging\ locations \end{aligned}$$

Equation 13: BEV effective infrastructure in each country

Convenience weight to standard charging = 0.95
Proportion of households with access to (installed) charging = See 4.2 (Equation 70)
Proportional achievement of rapid charging locations = See 4.3

$$Effective\ infrastructure_{Other\ fuels} = \frac{Stations\ carrying\ fuel}{Total\ fuelling\ stations}$$

Equation 14: ICEV, HEV and FCV effective infrastructure in each country

Stations carrying fuel = See 4.1 (Equation 61)
Total fuelling stations = [61, 62] and various national oil industry associations

$$\begin{aligned} Actual\ effective\ infrastructure_{PHEV} &= Effective\ infrastructure_{Electricity} \\ &\times (1 - PHEV\ users\ convenience\ weight\ to\ charging\ infrastructure) \\ &+ Effective\ infrastructure_{Other\ fuels} \\ &\times\ PHEV\ users\ convenience\ weight\ to\ charging\ infrastructure \end{aligned}$$

Equation 15: PHEV effective infrastructure in each country

Effective infrastructure = See Equation 13 and Equation 14
PHEV users convenience weight to charging infrastructure = see text

$$\begin{aligned} Actual\ effective\ infrastructure_{FFV} &= Effective\ infrastructure_{Other\ fuel} \\ &\times (1 - FFV\ users\ convenience\ weight\ to\ biofuel\ availability) \\ &+ Effective\ infrastructure_{Biofuel} \\ &\times FFV\ users\ convenience\ weight\ to\ biofuel\ availability \end{aligned}$$

Equation 16: FFV effective infrastructure in each country

Effective infrastructure = See Equation 13 and Equation 14
FFV users convenience weight to biofuel availability = 1

Powertrains are assumed to be fully supported by Original Equipment Manufacturers (OEM) in terms of maintenance. Those also supported by independent garages can provide a higher perceived convenience (and lower cost) to the user. It is assumed that, in the early years, new powertrains will only be supported by OEMs. Here, the percentage of independent garages supporting a powertrain (see 4.4) is compared to a look-up table to arrive at an additional convenience over and above that provided by OEM support only (assumed to be 0.7). Sensitivity tests indicate that variation in these estimates has little/no impact on key model outputs.

2.2.4.3 Environment

The *Environment* attribute (Equation 17), is determined from CO_2 emissions performance which is itself calculated endogenously (Equation 18 and Equation 19). Future emission reduction is determined by the change in the environmental utility of the powertrain (itself affected by the R&D activities of the *Manufacturer* (See 3.3)), though this is not used directly in the attribute value employed here in the choice model. Emissions are calculated in a similar approach as to those required for the calculation of penalties in relation to fleet emissions regulations (see 5.4), with the difference being that users are assumed to consider Well to Wheel (WTW) emissions rather than Tank to Wheel (TTW). This is because *Users* are assumed to consider the full environmental impact, beyond the tail-pipe only emissions. Equation 18 and Equation 19 are also used in the calculation of emissions for tax, which also includes a real-world adjustment (see 5.2).

$$Environment\ value_{C,P,S} = \frac{Average\ emissions_{P,S} - Worst\ emissions_S}{Best\ emissions_S - Worst\ emissions_S}$$

Equation 17: *Environment* attribute value

Average emissions = See 5.4
Best/worst emissions = Maximum and minimum of average emissions

$$Powertrain\ WTW\ emissions_{C,P,S} = \frac{Initial\ TTW\ emissions_P \times Size\ relative\ emissions_S \times Country\ modifier_C}{Environmental\ utility\ relative\ to\ initial_{P,S}} + Initial\ WTT\ emissions_P \times Size\ relative\ emissions_S \times Country\ modifier_C$$

Equation 18: Powertrain WTW emissions (non-zero emission powertrains) (*g/km/vehicle*)

Initial emissions = Medium segment derived from various sources [13, 63-65]
Size relative emissions = Internally calibrated (See 7.1)
Country modifier = Internally calibrated (See 7.1)
Environmental utility relative to initial = See 3.3.3.4 and Table 3

$$Powertrain\ WTW\ Emissions_{C,P,S} = \frac{Fuel\ consumption_{P,S} \times Fuel\ CO_2\ Intensity_C}{Environmental\ utility\ relative\ to\ initial_{P,S}}$$

Equation 19: Powertrain WTW emissions (zero emission powertrains) (*g/km/vehicle*)

Fuel consumption = Base derived from [66] and expert judgement
Fuel CO_2 intensity = CO_2 arising from fuel production: Hydrogen [13]; Electricity [65]
Environmental utility relative to initial = See 3.3.3.4 and Table 3

It is assumed that information regarding the environmental impact of each powertrain or fuel option is available to consumers (e.g. through mandatory CO_2 band labelling), and that at least some consumers use this information to compare options. Consumers are also likely to be influenced by media coverage of new powertrain and fuel options, e.g. regarding their relative environmental and energy security benefits. The emissions output by each powertrain are converted into an emissions performance by comparing all emissions and normalising to a 0-1 scale with '0' representing the worse performing powertrain and '1', the best performing. EU emissions performance, therefore, ranks the relative performance of each available powertrain.

2.2.4.4 Popularity

One influence on the consumer buying habits is the popularity of a particular technology choice, over and above the willingness to consider. It should though be noted that the original survey used for user importance considers popularity as brand rather than technology. The relative occurrence of a particular vehicle option on the road will determine the popularity of that option. Popularity of a powertrain can have an influence on its attractiveness to potential adopters. *Popularity* here is taken to be related to the prevalence of the powertrain in the country; simply the proportion of the total fleet taken up by each powertrain.

$$Popularity\ value_{C,P,S} = \left(\frac{Stock\ share_{C,P}}{Base\ prevalence\ for\ popularity}\right)^{Sensitivity\ of\ popularity\ to\ prevalence_C}$$

Equation 20: *Popularity* attribute value
Stock share = See 2.4
Base prevalence for popularity= 0.5
Sensitivity of popularity to prevalence= Internally calibrated (see 7.1)

2.2.4.5 Choice

The choice of models offered to consumers is influenced by the availability of each powertrain option; in turn driven by overall demand for this option. The assumption here is that manufacturers initially restrict the number of models with new powertrain/fuel configurations in order to reduce risk (e.g. Toyota initially introduced only one hybrid model, the Prius). If the first models are successful, manufacturers introduce new models, thus offering more choice to consumers. The new registrations market share for the powertrain is taken as a good indicator for the availability of models.

$$Choice\ value_{C,P,S} = \left(\frac{Market\ share_{P,S}}{Market\ share\ for\ base\ choice\ availability}\right)^{Sensitivity\ of\ availability\ to\ sales}$$

Equation 21: *Choice* attribute value
Market share = See Equation 3
Market share for base choice availability = 0.1
Sensitivity of availability to sales = 0.6

2.2.5 Financial Attractiveness

Cost is an important element when it comes to the decision of purchasing a new vehicle. Financial attractiveness is the final component of the combined utility (Equation 4). This accounts for the financial performance of each powertrain relative to the average financial performance of all powertrains. Within this, the financial 'performance' of each powertrain is determined from a weighting of variable running costs and total cost of ownership (TCO – purchase price, variable and fixed running costs) as determined by Equation 22. When making a purchase decisions, it is assumed users look at initial purchase price and a proportion of the variable running costs for the vehicle. This is a proportion because a) not all cost elements taken into account and b) any relative savings, for example with an EV, may not be taken into account for the whole life of the vehicle. It is noted that there is no *User* importance of financial attractiveness, as is often employed in choice models, but instead it is applied as a modifier of the combined utility.

$$Financial\ performance_{C,U,P,S} = \left(\left(\frac{Variable\ running\ cost_{C,P,S}}{Average\ variable\ running\ cost_{C,S}} \times Accounting\ of\ running\ costs_U \right) + \left(\frac{Perceived\ TCO_{C,U,P,S}}{Average\ perceived\ \ TCO_{C,U,S} \times (1 + Value\ of\ enviroment_{C,P})} \times (1 - Accounting\ of\ running\ costs_U) \right) \right)^{-1}$$

Equation 22: Financial attractiveness

Variable running cost = See 2.2.5.3
Average variable running cost = Average of variable running costs across all powertrains
Accounting of running costs = Private 0.2; Fleet/Public 0.9
Perceived TCO = See Equation 23
Average perceived TCO = Average of perceived TCO across all powertrains
Value of environment = See Table 4

Powertrain	Environmental Value
Diesel ICEV	5%
Alternative ICEV	10%
HEV	20%
PHEV	30%
BEV / FCV	40%

Table 4: Environmental value of powertrains
Relative to Petrol ICEV

2.2.5.1 Total Cost of Ownership

The perceived TCO combines two cost elements, purchase price and the on-going average total running cost from both variable and fixed costs, as described by Equation 23.

$$Perceived\ TCO_{C,U,S} = Vehicle\ price_{C,P,S} + (Average\ total\ running\ cost_{C,P,S} \times Average\ years\ kept_C \times Accounting\ of\ running\ costs_U)$$

Equation 23: Perception of TCO

Vehicle price = See 2.2.5.2
Average total running cost = See 2.2.5.3
Average years kept = 5 years
Accounting of running costs = Private 0.2; Fleet/Public 0.9

2.2.5.2 Purchase Price

The vehicle price paid by the user is determined endogenously by the *Manufacturer* (3.2) and is influenced by the *Authorities* (5.1.1). In the case of plug-in electric vehicles requiring home charging (BEV, PHEV), an additional private charging installation cost is added to the vehicle price (Figure 10). The cost to install specialist charging facilities in the home is assumed to reduce with the sales volume of electric vehicles, between a maximum and a minimum private charging infrastructure cost. The rate of cost reduction is governed by the lookup table EV Sales/private infrastructure cost.

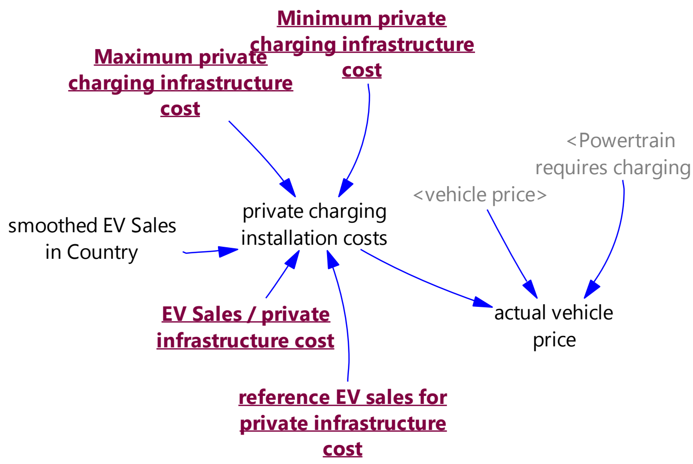

Figure 10: Vehicle price

2.2.5.3 Running Costs

Besides purchase price, the second financial element to the vehicle purchase decision is the on-going total running cost of ownership, as shown in Figure 11, which is composed of a fixed and a variable element.

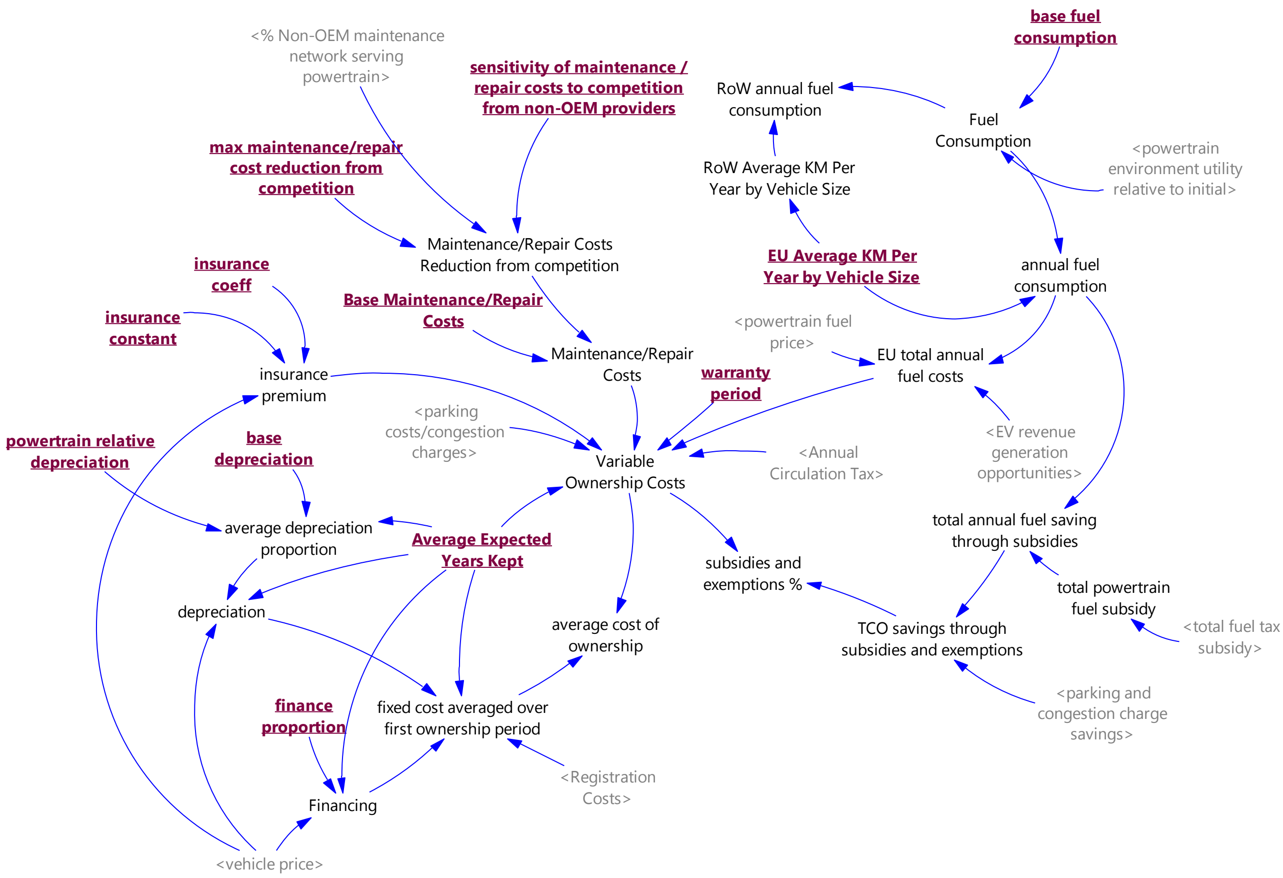

Figure 11: Ownership costs

Fixed running costs relate to unavoidable costs when the vehicle is purchased and are assumed to be accounted for over a period of ownership of 5 years:

- ***Depreciation***
  As a vehicle ages it loses value and will return less when it comes to sell on. The depreciation of each powertrain type is entered as a value relative to a base assumption for Petrol ICEV. These are exogenous data inputs based on expert judgement and currently all powertrains are assumed equal. An assumption is made that depreciation is t 20% for the first year and 90% by year 10, therefore 56% by year 5.

- ***Financing***
  The cost of financing the purchase is included as an average additional "vehicle cost" as a result of financing (as a proportion of vehicle price). It is an exogenous input applied to all vehicles and is assumed to be 25% of the vehicle price.

- ***Registration costs***
  Registration costs are the taxes for first year registration of the vehicle and are calculated endogenously in the authorities section of the model, relative to the emissions of the powertrain and exogenous input of previous registration costs in each country [40].

Variable running costs are related to the ongoing operation of a vehicle:

- ***Fuel costs***
  The average fuel consumption for a powertrain is based on a reference value of base fuel consumption [63] and modified by any improvements to the environmental utility of the powertrain as a result of R&D activity. It is implicitly assumed that the relationship between improvements in the environmental impact of the powertrain and the average powertrain fuel efficiency are linear. Combining consumption with annual mileage [40] and the specific energy costs for a given country yields the annual fuel costs.

- ***Maintenance / repair costs***
  The average cost of maintaining the powertrain is arrived at by taking a reference value [40] and adjusting for any savings to be made through competition enabled by independent garages supporting the powertrain. This cost reduction is controlled by a maximum possible reduction if 100% of garages can support the powertrain type using the look up table max maintenance/repair cost reduction from competition, with any cost improvement curve controlled by the sensitivity of maintenance/repair costs to competition from non-OEM providers. The maintenance charges are adjusted for the period the powertrain is likely to be under warranty, assumed to be 3 years for all powertrains.

- ***Parking and congestion charges***
  Parking and congestion charges are calculated endogenously from three exogenous data inputs, the separate average parking and toll costs [67] and congestion charges (assumed from current charges in operation), and average annual vehicle mileage in each country [40]. These are included particularly so that any subsidies offered by the authorities can be accounted for.

- ***Annual circulation tax***
  Similar to the registration taxes included in fixed costs, circulation tax is calculated from exogenous historical circulation tax in each country [40] and relative emissions of powertrains calculated endogenously. As with the parking and congestion charges, circulation tax has been included in order to reflect subsidies offered by authorities for particular powertrain types.

- ***Insurance premium***
  The average insurance premium is related to vehicle purchase price, as shown in Equation 24. The coefficient and constant were determined using regression analysis.

$$Insurance\ premium_{C,P,S} = Insurance\ coefficient \times Vehicle\ price_{C,P,S} + Insurance\ constant$$

Equation 24: Insurance premium
Insurance coefficient = 0.0238
Vehicle price = See 2.2.5.2
Insurance constant = 412.9

2.2.6 Rest of World (RoW) Utility

RoW utility is determined using the same equation as for EU, though makes use of a number of simplifications. Firstly, the attribute values (except Popularity), willingness to consider, weighting of attribute importance and user demand proportion are all taken as the average value from across Europe. There is no evidence to support this assumption but it is seen as a reasonable starting point while avoiding the need to model the whole world in the same level of detail. One suggestion may be to add a bias for the rest of the world towards one or more of the powertrains. The RoW demographic breakdown is also based on average EU demographics but with a relative modifier for RoW, in that urban population is assumed to be slightly higher. Finally, the RoW attribute value for popularity is calculated in the same way as for EU, but using RoW fleet size (also based on EU average but described in more detail in the *Manufacturer* section).

2.3 New Registrations

Once the indicated market shares of powertrains have been determined as described above, the actual number of new registrations can be calculated from the overall vehicle demand (see 2.1), requiring various modifications of the market share (Equation 25 and Figure 12). These include the influence of subsidies, the effect of de-registrations and scrappage, and the determination of demand by vehicle size [40, 68] and user type [69] which are exogenous data inputs that currently do not change over the time period. The first step is a smoothing from the exogenous data input of initial market share over a response delay of 2 years to capture the time taken for changes in user preferences to filter through to actual decision making.

$$\begin{aligned} New\ Registrations_{C,U,P,S} \\ &= \big(Total\ new\ registrations_{C} \times Demand\ proportion\ by\ user_{C,U} \\ &\times Market\ share\ adjusted\ for\ subsidies_{C,U,P,S} \\ &+ Additional\ demand\ from\ deregistrations_{C,P} \\ &\times Market\ share\ of\ additional\ registrations\ _{C,U,P,S}\big) \times Demand\ proportion\ by\ size_{C,S} \\ &+ Scrappage\ replacements_{C,U,P,S} \end{aligned}$$

Equation 25: New registrations *(vehicle/year)*
Total new registrations = See Equation 2
Demand proportion by User = (vehicle class registrations) [40, 69]
Market share adjusted for subsidies = See Equation 3 and 2.3.1
Additional demand from de-registrations = (additional de-registrations by user) See 2.3.2
Market share of additional registrations = See 2.3.2
Demand proportion by size = [40, 43]
Scrappage replacements = See 2.3.3

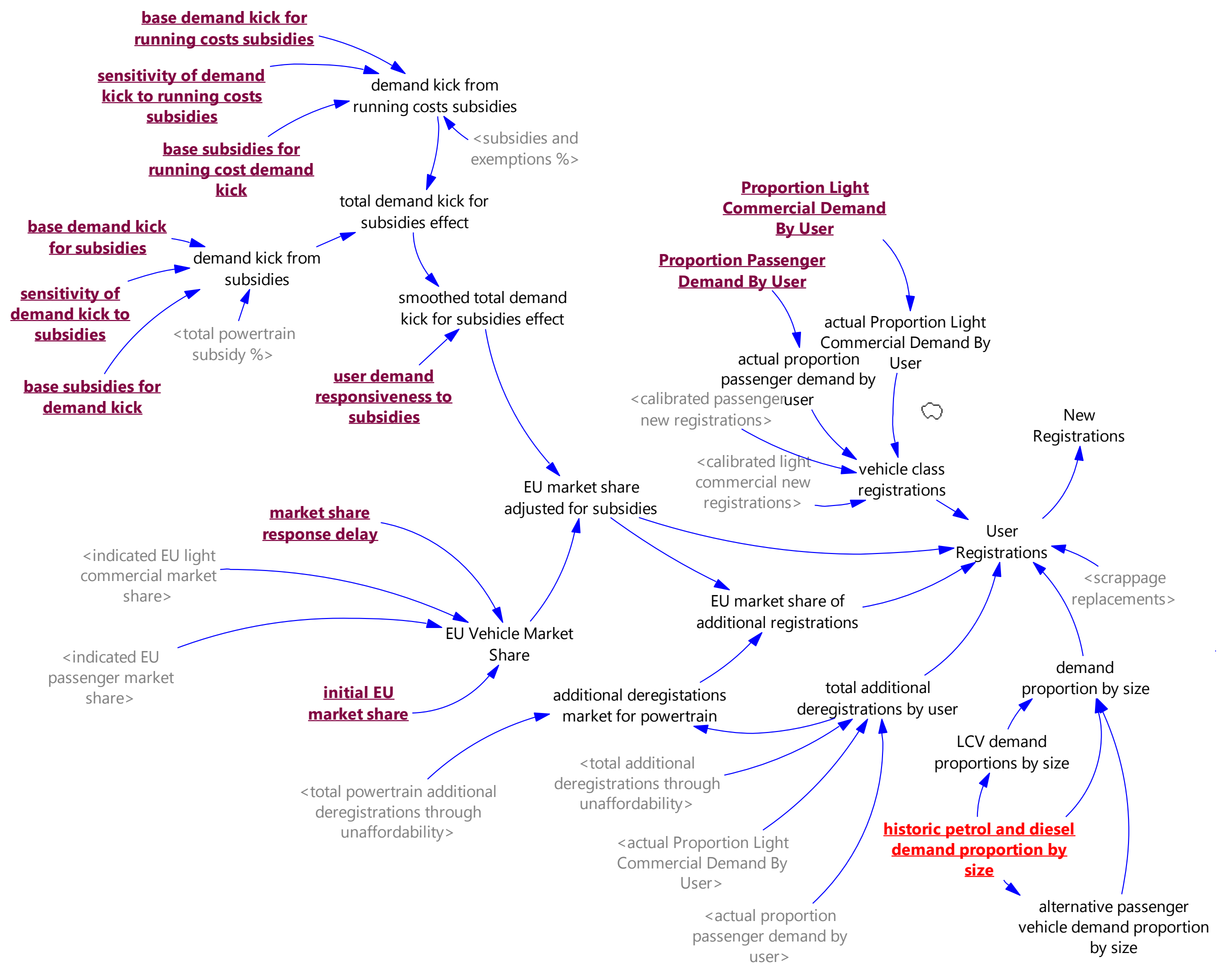

Figure 12: Determination of new registrations.

2.3.1 Influence of Subsidies on Market Share

The underlying market share is influenced by temporary "kicks" as a result of incentives offered by authorities and/or manufacturers. The available data suggests this influence is rapid (very little delay between incentive and resulting increase in demand) and short-lived (ending soon after the incentives are removed). The relationship between both purchase and running cost subsidy levels and resulting demand kicks is represented by a non-linear analytical function (Equation 26). This latter influence has been added as a result of observations made of the impact of incentives on clean-vehicle market share in a number of European countries, most notably Sweden [70], indicating a greater influence on user decision-making of running costs then had previously been thought. Parameter estimation was possible for the case of Sweden where good information on alternative powertrain subsidies and resulting demand were observed, through the calibration process. The two demand kicks are smoothed over a period of 0.5 years to account for user response time.

$$Demand\ kick\ from\ subsidies_{C,P,S} = 1 + Base\ demand\ kick\ for\ subsidies_{\ C} \times \left(\frac{Total\ powertrain\ subsidy_{C,P,S}}{Base\ subsidies\ for\ demand\ kick_{C}}\right)^{Sensitivity\ of\ demand\ kick\ to\ subsidies_{C}}$$

Equation 26: Subsidies demand kick

Base demand kick for subsidies = Purchase 0.7; Running 0.8
Total powertrain subsidy = Scenario input
Base subsidies for demand kick = Internally calibrated (see 7.1): Purchase 3%; Running 6.2%[5]
Sensitivity of demand kick to subsidies = Purchase 1; Running 0.95

2.3.2 De-registrations Due to Unaffordability

A further additional demand can result from the need to replace powertrains no longer affordable in a specific country, so specific vehicles are deregistered and the user effectively re-enters the market. This may come about from the impact of escalating running costs on the continued ownership of the type of powertrain. The cost impact is determined in a similar process as that on willingness to consider (see 2.2.2.3), based on GDP ratios, exogenous maximum and minimal cost differentials and a look-up table, but in relation to running costs rather than TCO. Comparing the running costs of the powertrain to a reference value determines a fraction that is used to determine the impact of "unaffordability" of the powertrain by comparing it to the minimum and maximum differential for affordability. A look-up table (cost multiple of average / WtC) is used to determine the relationship between cost ratio and unaffordability. After an assumed delay of 0.5 years, the number of de-registrations is calculated using Equation 27, which feeds into Equation 25 as the additional demand from de-registrations. The market share of this demand is adjusted so that powertrains that were de-registered in a country cannot receive a new share in that country.

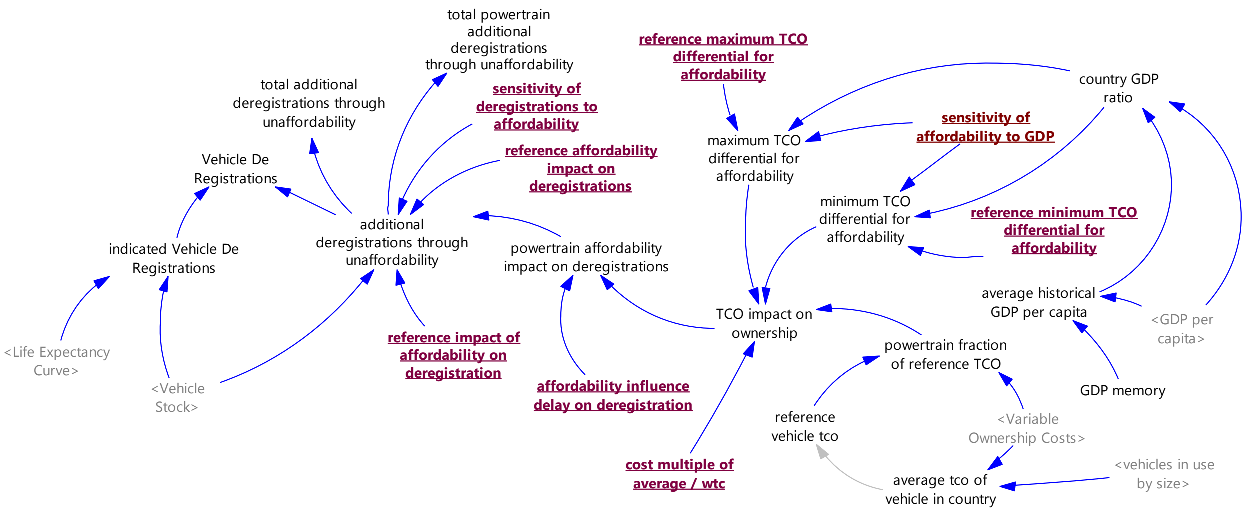

Figure 13: De-registrations due to unaffordability

[5] Subsidies are entered in the PTTMAM as proportion of full price (See 5.1)

$$Deregistrations\ from\ unaffordability_{C,P,S,A}$$
$$= Vehicle\ stock_{C,P,S,A} \times Reference\ impact\ of\ affordability\ on\ deregistration$$
$$\times \left(\frac{Actual\ affordability\ impact_{C,P,S}}{Reference\ affordability\ impact\ on\ deregistration}\right)^{Sensitivity\ of\ deregistrations\ to\ affordability}$$

Equation 27: De-registrations *(vehicle/year)*

Vehicle stock = See 2.4
Reference impact of affordability on de-registration = 0.05
Actual affordability impact = (powertrain affordability impact on de-registrations): See text
Reference affordability impact on de-registration = 0.5
Sensitivity of de-registrations to affordability = 1

2.3.3 Scrappage

Additional demand over and above the calibrated input demand, can also arise from scrappage schemes. The actual process and number of scrapped vehicles is described in the *Authorities* section. These vehicles are replaced, becoming additional sales for the powertrain type according to the incentives in place at the time. The model reflects an insight from [71] that straight swaps (eg diesel for diesels) or prevailing market shares do not govern user choice in scrappage schemes by skewing the market share for replacements away from the prevailing market share driven by user choice. This skew is determined by first assessing the contribution of the scrappage incentive to vehicle price and expressing this relative to the maximum. A calibrated sensitivity determines the strength of the skew from prevailing market share. Actual scrappage replacement market share is used, together with the relative proportion of scrappage replacements by user type to allocate scrappage replacements between powertrains.

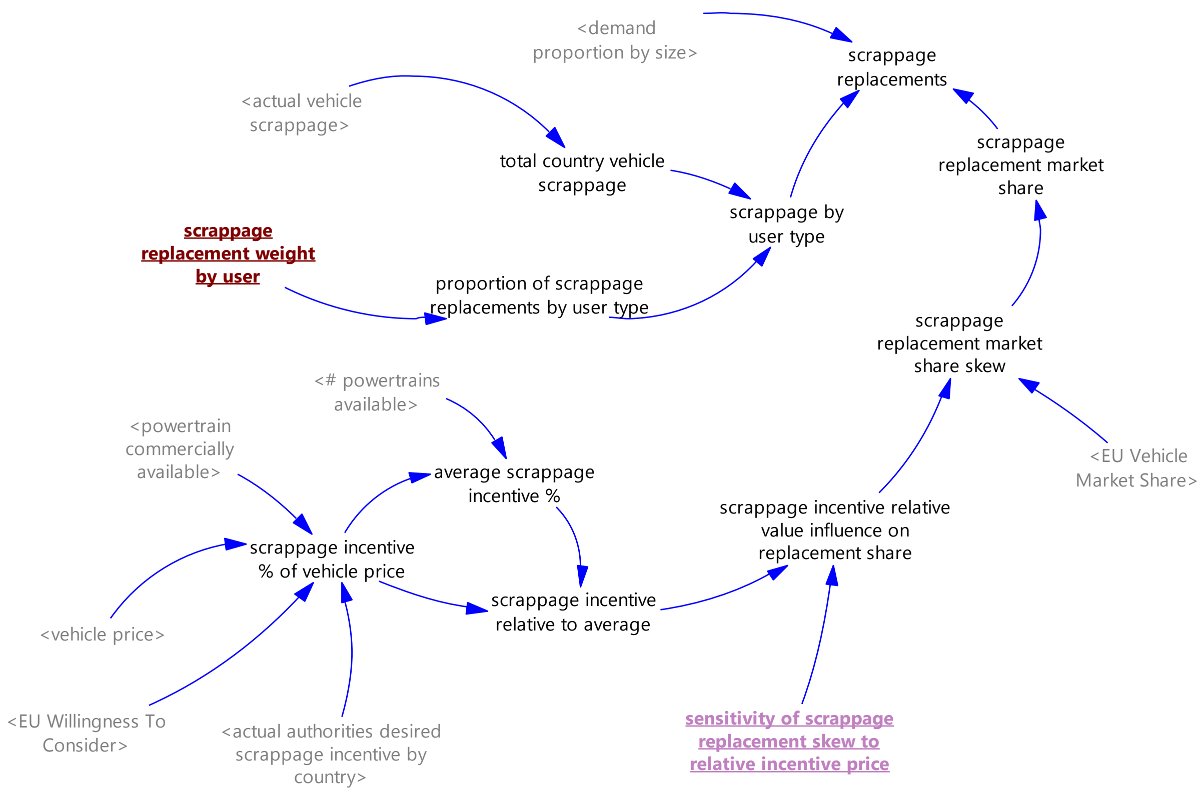

Figure 14: Scrappage

2.4 Vehicle Stock

The final aspect of the *User* group captured within the model is that of vehicle stock, i.e. the actual fleet of vehicles which exist in each country, as shown in Figure 15, Equation 28 and Equation 31. Stock is increased by new registrations and decreases over time as vehicles are de-registered (i.e. taken from the vehicle stock), either by natural end of life (wastage), early retirement (eg due to accidents), scrappage schemes or due to unaffordability (2.3.2). Within the stock, vehicles exist within four age cohorts as model subscripts: <2 years, 2-5 years, 5-10 years and >10 years.[6] Thus the stock ages throughout the simulation period. In the model, very few vehicles exist over 10 years. Vehicles move to the next age cohort through the vehicle aging process (Equation 30) with removals from the last cohort entering natural wastage. Other losses from the vehicle age cohorts are determined by vehicle de-registrations (Equation 29 and Equation 32) and actual vehicle scrappage (see 2.3.3). De-registration is determined through calibrated values enabling the model to generate a life expectancy curve commensurate with historical data on vehicle stock age distribution. As described in section 2.3.2, additional de-registrations can occur for those powertrains for which cost of ownership has become prohibitively expensive. A mass balance check within the model ensures that cumulative new registrations are equal to the fleet minus cumulative de-registrations and natural wastage at any time.

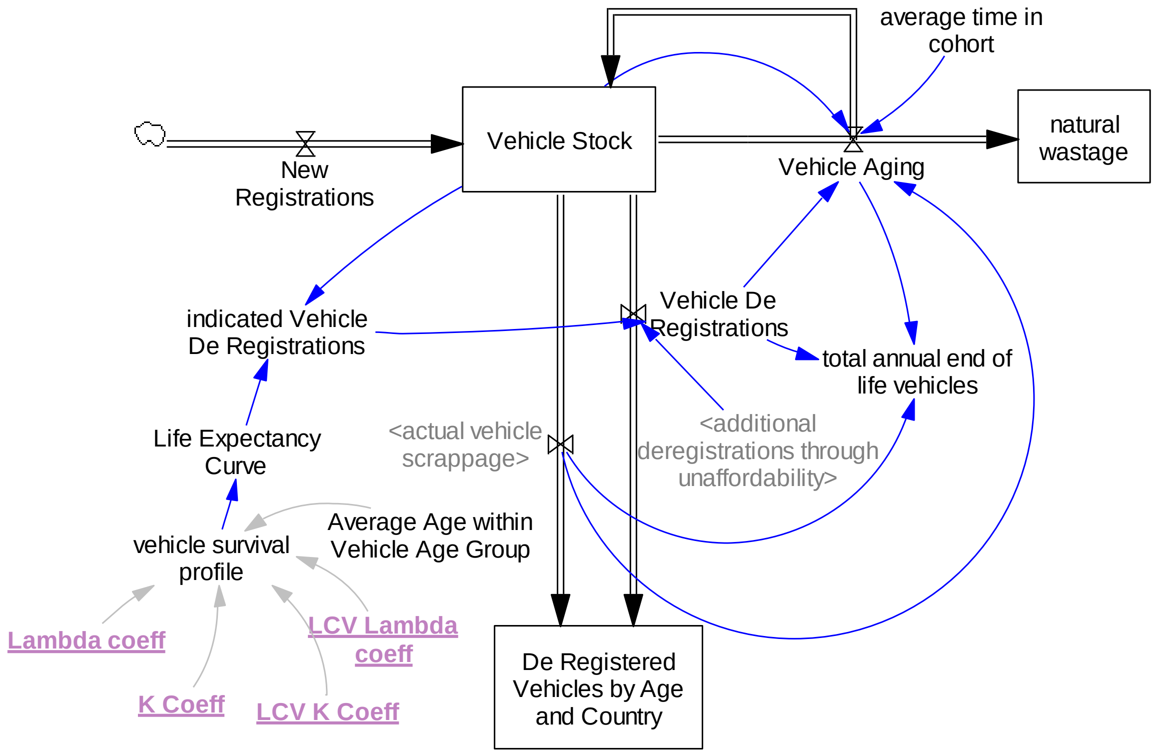

Figure 15: Vehicle stock

[6] Denoted with subscript A in equations

$$\begin{aligned} &New\ vehicle\ stock_{C,P,Cl,S} \\ &= Initial\ new\ vehicle\ stock_{C,P,Cl,S} \\ &+ \int_0^t \big(New\ registrations_{C,P,Cl,S} - New\ vehicle\ deregistrations_{C,P,Cl,S} \\ &- New\ vehicle\ aging_{C,P,Cl,S} - New\ vehicle\ scrappage_{C,P,Cl,S}\big)\, dt \end{aligned}$$

Equation 28: New (<2 years) vehicle stock (vehicles)

Initial new vehicle stock = Derived from [40, 64, 68, 72-75]
New registrations = See Equation 25
New vehicle de-registrations = See Equation 29
New vehicle aging = See Equation 30
New vehicle scrappage = See 2.3.3

$$New\ vehicle\ deregistrations_{C,P,S} = New\ vehicle\ stock_{C,P,S} \times \left(1 - e^{-\left(\frac{1}{Lambda_C}\right)^{K_C}}\right)$$

Equation 29: Deregistration of new (<2 years) vehicles (vehicles/year)

New vehicle stock = See Equation 28 and Equation 31
Lambda = Internally calibrated (See 7.1)
K = Internally calibrated (See 7.1)

$$Vehicle\ aging_{C,P,S,A} = \frac{Vehicle\ stock_{C,P,S,A}}{Average\ time\ in\ age\ cohort_A}$$

Equation 30: Vehicle aging (vehicles/year)

Vehicle stock = See Equation 28 and Equation 31
Average time in cohort = <2: 2; 2-5: 3; 5-10: 5; >10: 100M years[7]

$$\begin{aligned} &Old\ vehicle\ stock_{C,P,Cl,S,A} \\ &= Initial\ old\ vehicle\ stock_{C,P,Cl,S,A} \\ &+ \left(\int_0^t Old\ vehicle\ aging_{C,P,Cl,(A-1)} - Old\ vehicle\ deregistrations_{C,P,Cl,S,A} \right. \\ &\left. - Old\ vehicle\ aging_{C,P,Cl,S,A} - Old\ vehicle\ scrappage_{C,P,Cl,S,A}\right) dt \end{aligned}$$

Equation 31: Old (all-but-new) vehicle stock (vehicles)

Initial old vehicle stock = Derived from [40, 64, 68, 72-75]
Old vehicle aging = See Equation 30
Old vehicle de-registrations = See Equation 32
Old vehicle scrappage = See 2.3.3

$$\begin{aligned} &Old\ vehicle\ deregistrations_{C,P,S,A} \\ &= Old\ vehicle\ stock_{C,P,S,A} \\ &\times \left(e^{-\left(\frac{average\ age\ in\ previous\ cohort}{Lambda_C}\right)^{K_C}} - e^{-\left(\frac{average\ age\ in\ cohort}{Lambda_C}\right)^{K_C}}\right) \end{aligned}$$

Equation 32: Deregistration of old (all-but-new) vehicles (vehicles/year)

Old vehicle stock = See Equation 28 and Equation 31
Average age in cohort = <2: 1; 2-5: 3; 5-10: 7.5; >10: 15 years
Lambda = Internally calibrated (See 7.1)
K = Internally calibrated (See 7.1)

---

[7] As the last age category for vehicle of age is >10, you don't want the vehicles to age out of that stock. Hence the 100m years as the age cohort width. Deregistration probabilities will eventually claim vehicles from that stock rather than aging.

3 The Manufacturers Agent Group

The powertrain *Manufacturers* group (which are considered as a whole sector rather than individual OEMs) interact with all other market agent groups and decide on powertrain improvements, production capacity, marketing, pricing etc., influenced by market signals. This is the most comprehensive market agent group considered within the model, which reflects the actual complexity of European automobile manufacturers. Manufacturers are driven by financials, which operate within small margins, and are reluctant to invest in the development of new technologies without the external influence of user demand preferences and regulations applied by authorities. As the most comprehensive agent, manufacturers are defined by the following decision rules of all market agent groups:

- ***Produce, import and export vehicles*** (3.1)
  To satisfy demand within production capacity limitations.

- ***Set vehicle price*** (3.2)
  Based on fixed and variable production costs and to influence desired sales and include a mark-up.

- ***Invest in R&D*** (3.3)
  Allocation of proportion of profits into the R&D of powertrain components in order to satisfy the achievement of desired characteristics and avoidance of penalties.

- ***Market powertrain*** (3.4)
  Publicise powertrain in order to influence user purchase decisions.

- ***Speculate and forecast demand*** (3.5)
  Use current sales figures to forecast demand and make similar judgments for new powertrains.

3.1 Vehicle Production

Vehicle production in the EU responds to both domestic and international demand, while production capacity responds to the profitability of expected future growth in demand for a powertrain. The capacity to produce each powertrain type (in each vehicle size category) reacts to two main influences; capacity can be increased if the return on additional investment warrants it and capacity can be decreased if there is over-capacity in the system. Imports and exports are integral to domestic sales and EU revenue.

Total vehicle production in the EU, Figure 16, is governed by sales, including imports and exports, and limited by the production capacity described in 3.1.1. Imports into the EU are assumed to be a calibrated percentage of the total demand for vehicles. The model assumes any domestic demand unsatisfied by domestic production capacity is satisfied through imports from the rest of the world. Imports reduce the domestic demand for EU manufacturing. Similarly, an estimate of the export potential as a proportion of global demand of EU automobile manufacturers (also calibrated) is used to generate revenue from exports. Exports increase the demand for EU manufacturers.

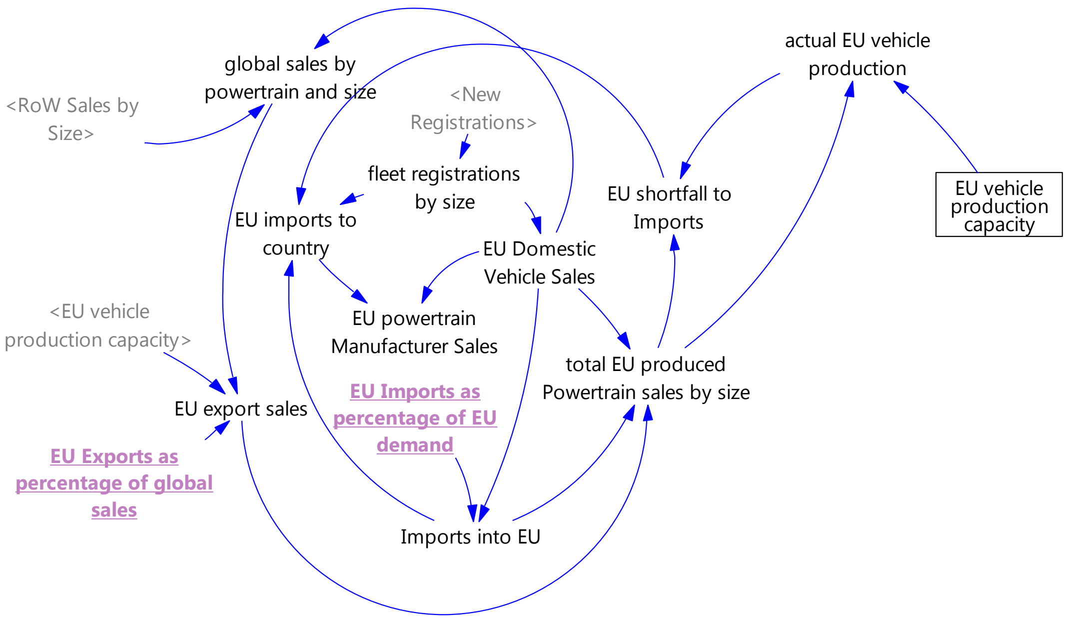

Figure 16: Vehicle Production

3.1.1 Production Capacity

The production capacity of the EU automobile manufacturers at any one time is defined as a stock in the PTTMAM, governed through an increase and decrease rate, as shown in Figure 17. Planned capacity (ie which is currently under construction) is also a stock.

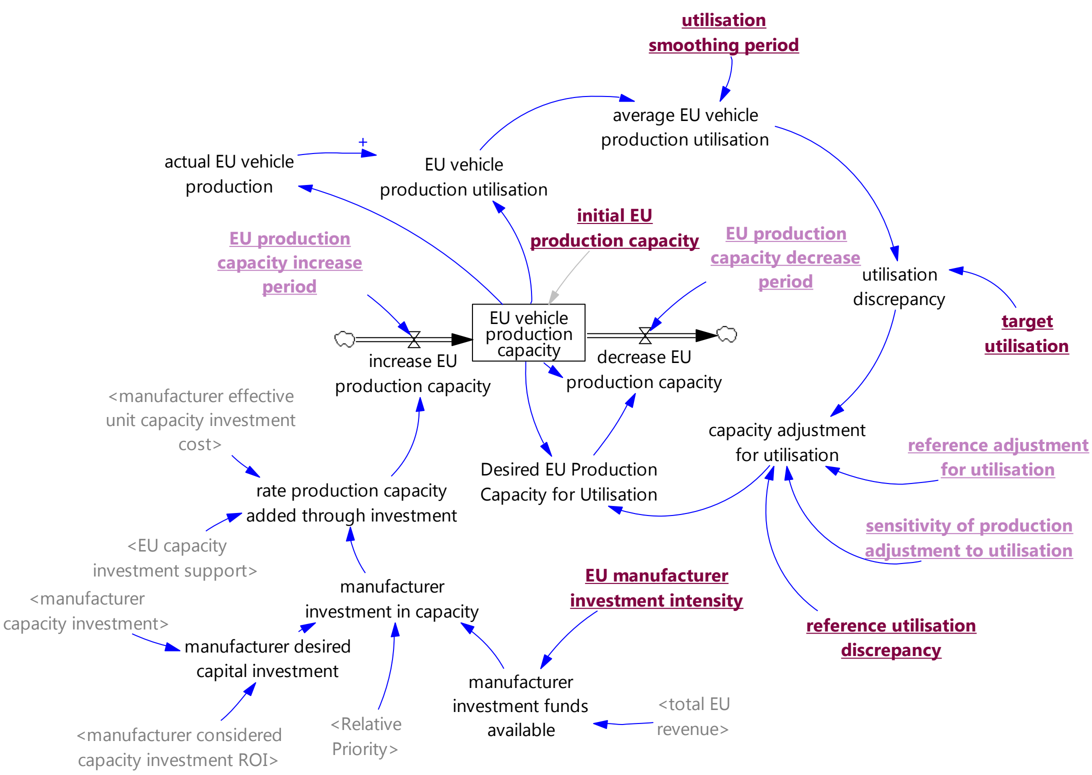

Figure 17: Production capacity

$$EU\ vehicle\ production\ capacity = Initial\ production\ capacity + \int_0^t (Production\ capacity\ increase\ rate - production\ capacity\ decrease\ rate)\ dt$$

Equation 33: Production capacity for each powertrain/size (vehicles/year)
Initial production capacity = Petrol ICEV S: 6,319; M: 8,129; L: 1,513; Diesel ICEV S: 250; M: 2,720; L: 674 (vehicle/year x10^3)
Production capacity increase rate= See 3.1.1.1
Production capacity decrease rate= See 3.1.1.2

3.1.1.1 Production Capacity Increase

The increase has an initial rate as of Equation 34. The growth in production capacity (which is influenced, but not determined, by vehicle sales) is calculated endogenously from vehicles produced and in use, limited to a maximum annual doubling of growth. Initial production capacity is an assumed exogenous input for Petrol and Diesel ICEV (the only powertrains produced at the start of the simulation). Following this, the rate is governed by Equation 35. The authorities proportional support is represented here at the highest level of aggregation, and is taken to be the net financial impact of various policies such as loan guarantees, monetary support etc. The investment in capacity for each powertrain is a minimum between the desired investment (a calibrated Return on Investment (ROI) of capacity investment (3.1.2), and the available investment funds (0.8% [76-78] of total revenue). The latter is prioritised between powertrains by the relative forecast profits from the investment (3.1.2), when available funds are insufficient.

$$Initialproduction\ capacity\ increase\ rate_{P,S} = \frac{New\ vehicle\ registrations_{P,S}}{Vehicle\ stock_{P,S}} \times Initial\ production\ capacity_{P,S} \times Increase\ period$$

Equation 34: Initial production capacity increase rate *(vehicle/year.year)*
New vehicle registrations = See Equation 25
Vehicle stock = See Equation 28 + Equation 31
Initial production capacity = Petrol ICEV S: 6,319; M: 8,129; L: 1,513; Diesel ICEV S: 250; M: 2,720; L: 674 (vehicle/yearx10^3)
Increase period = 1.875 years (Internally calibrated – see 7.1)

$$Production\ capacity\ increase\ rate_{P,S} = \frac{\frac{Investment\ in\ capacity_{P,S}}{1 - Authorities\ support_P}}{Unit\ capacity\ investment\ cost_P \times (1 - Authorities\ support_P)}$$

Equation 35: Production capacity increase rate *(vehicle/year.year)*
Investment in capacity = See text
Authorities support = Scenario input
Unit capacity investment cost = See Equation 37

3.1.1.2 Production Capacity Decrease

If demand for a powertrain were to reduce, this may lead to the utilisation of the available production capacity to fall below a target utilisation of 70% (an average across the industry) resulting in a utilisation discrepancy that can be costly for manufacturers.

An adjustment would need to be made in order to reduce the discrepancy, as determined by Equation 36. Finally, the adjustment filters through to change in capacity over a period of time shown by the calibrated production capacity decrease period.

$$\begin{aligned} &\mathit{Capacity\ adjustment\ for\ utilisation} \\ &\quad = \mathit{Reference\ adjustment\ for\ utilisation} \\ &\quad \times \left(\frac{\mathit{Utilisation\ discrepancy}_{P,S}}{\mathit{Reference\ utilisation\ discrepancy}}\right)^{\mathit{Sensitivity\ of\ adjustment\ to\ utilisation}} \end{aligned}$$

Equation 36: Capacity adjustment for utilisation

Reference adjustment for utilisation= 0.1989 (Internally calibrated – see 7.1)
Utilisation discrepancy = See text
Reference utilisation discrepancy = 0.1
Sensitivity of adjustment to utilisation= 0.7502 (Internally calibrated – see 7.1)

3.1.2 Capacity Investment

Investment in new production capacity, used in Equation 35, is influenced by an assessment of the potential ROI. This capacity investment, Figure 18, is a desired investment to support future demand and is a product of the capacity for investment and an effective unit investment cost. The capacity for investment accounts for an estimate of future capacity as well as both current and planned capacity, over a 3 year forecast horizon. Future capacity is influenced by the speculation made by manufacturers (3.5) combined with straight forecasting of existing sales trends subject to a minimum production capacity. It only applies when a powertrain is deemed commercially viable (2.2.4). The effective unit investment cost is the unit investment cost adjusted for an authorities support to manufacturers. The unit cost itself is arrived at via Equation 37, which a look-up table to determine the current cost of manufacturing capacity investment at the current production capacity.

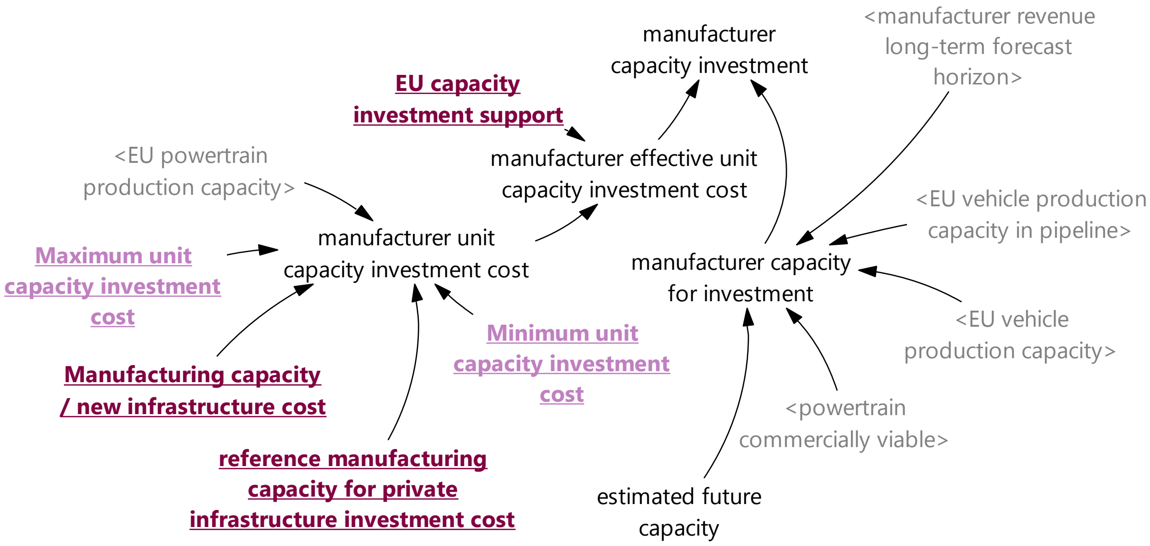

Figure 18: Capacity investment

$$
\begin{aligned}
&Unit\ capacity\ investment\ cost_P \\
&\quad = Minimum\ unit\ capacity\ investment\ cost_P \\
&\quad + \frac{Current\ production\ capacity\ investment\ \ cost_P}{Reference\ capacity\ for\ infrastructure\ investment\ cost} \\
&\quad \times (Maximum\ unit\ capacity\ investment\ cost_P \\
&\quad - Minimum\ unit\ capacity\ investment\ cost_P)
\end{aligned}
$$

Equation 37: Unit capacity investment cost (euro.year/vehicle)
Minimum unit capacity investment cost = €357.8(vehicle/year)$^{-1}$ (Internally calibrated – see 7.1)
Current production capacity investment cost =Look-up table
Maximum unit capacity investment cost = €2451(vehicle/year)$^{-1}$ (Internally calibrated – see 7.1)
Reference capacity for infrastructure investment cost = 100,000 vehicle/year

The net present value (NPV) of future revenue streams (Figure 19) is calculated from an assessment of the additional revenue with new investment less the additional cost with investment and the capacity investment required in order to capture the additional sales, using an exogenous input discount rate assumed to be 10%. Additional revenue is the difference between current and expected future revenue with the future revenue depending on an industry assessment of estimated future capacity. This estimation is also used to determine expectations on future additional costs and the capacity for investment. Current revenue is calculated endogenously from the number of sales (2.3) after imports are removed and the revenue per vehicle (the vehicle pre-tax price (3.2) and authorities subsidies (5.1.1), whereas expected revenue is based on the expected capacity. Costs include both fixed and variable costs (3.2.1), with expected future costs depending on the estimated capacity and forecast horizons of 3 years. Once determined, the NPV of future revenue is used to calculate the ROI required for the desired capital investment.

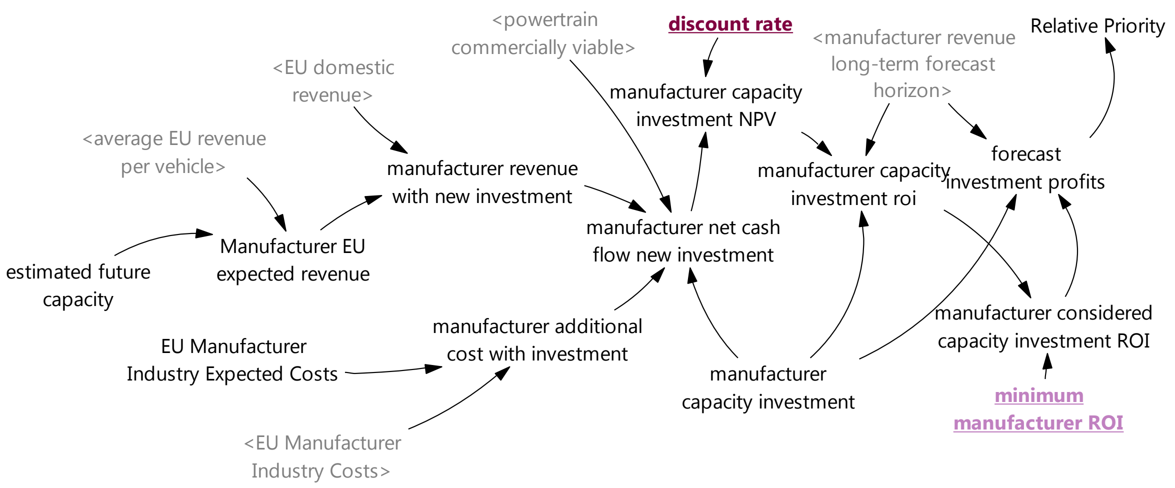

Figure 19: Capacity investment NPV

3.1.3 Rest of World (RoW) Production

Early in model development it was realised that the behaviour of the markets outside the EU member states could have a profound effect on the adoption of powertrain types within Europe. Throughout the model there are high-level assumptions regarding behaviour of the RoW region, some are endogenous but not modelled to the same level of detail as for the individual EU states. Good data could be obtained on the sales of passenger and light commercial vehicles in the EU states, so for ease of data collection and modelling, the demand for vehicles in the RoW was taken to be relative to a calibrated EU average share of global sales. The RoW market share determines the overall demand to each powertrain. Thus RoW production is the RoW Sales shared by an exogenous input of RoW production capacity utilisation of 94%, the estimated global capacity utilisation at the time of model development.

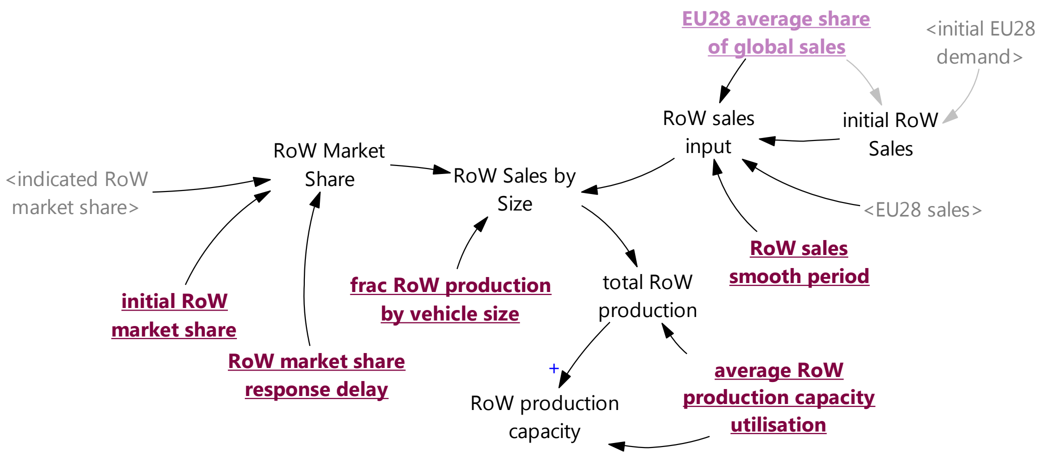

Figure 20: RoW production

3.2 Vehicle Pricing

Vehicle pricing by the *Manufacturers* group in the PTTMAM is calculated endogenously PTTMAM and is dependent on the cost of producing vehicles, powertrain tax rate (see 5.1.4), the desire to avoid future emission penalties, additional costs from accrued emission penalties and modified by a mark-up to account for production utilisation and a required profit margin. There is no competition directly built into the pricing strategy. Nominal price is shown in Equation 38. Powertrain average price to the *User* is then determined by subsidies from *Authorities* (5.1.1).

$$\begin{aligned} &Vehicle\ nominal\ price_{C,P,S} \\ &\quad = \frac{Unit\ production\ cost_{P,S} \times (1 + Markup_{C,P,S})}{(1 - Tax\ rate_{C,P})} \\ &\quad \times \left(1 + Emission\ penalties\ adjustment_{P,S}\right) \\ &\quad + Additional\ costs\ from\ emission\ penalties_{P} \end{aligned}$$

Equation 38: Vehicle nominal price *(euro/year)*

Unit production cost = See 3.2.1
Mark-up = See 3.2.4
Tax-rate = Derived from [40]
Emission penalties adjustment = See 3.2.3
Additional costs from emission penalties = See 3.2.2

3.2.1 Unit Production Costs

The unit production costs (Figure 21) comprises fixed and variable costs for the production of a vehicle. Fixed costs (3.2.1.1) are related to the production capacity while variable (3.2.1.2) are attributed to production.

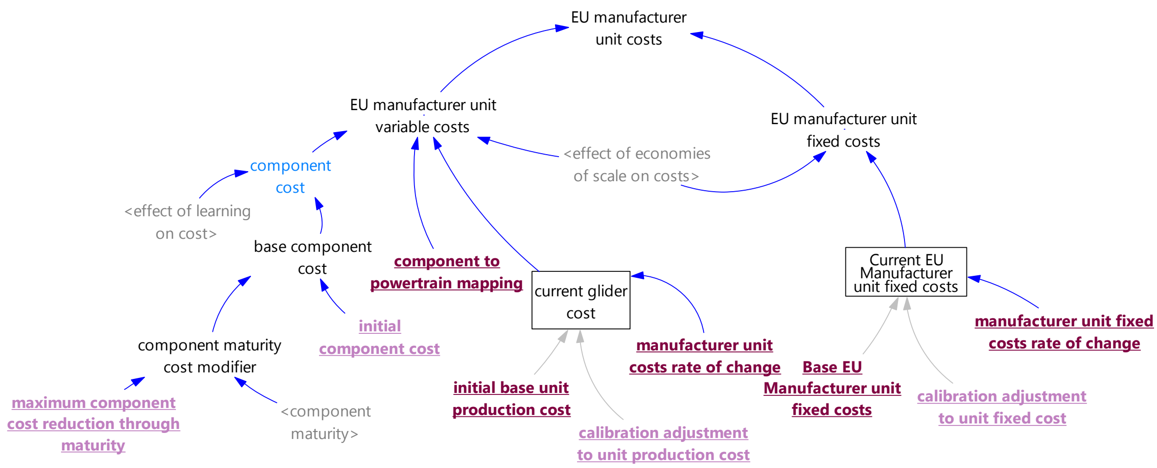

Figure 21: Costs

3.2.1.1 Fixed Costs

Initial unit fixed costs are an exogenous input for each powertrain type. As no specific costs could be found in the literature, an expert judgment was made, which is then adjusted for each powertrain by a calibration to vehicle price. The resultant fixed cost (Equation 39) is a stock that can change over time at an exogenous input rate of change, but this is currently set to zero in the baseline, and is subject to any cost reductions resulting from economies of scale (3.2.1.3).

$$Unit\ fixed\ cost_{P,S} = Base\ fixed\ cost_{P,S} \times Calibration\ adjustment\ _{P} \times Economy\ of\ scale_{P}$$

Equation 39: Unit fixed cost (euro/vehicle)

Base fixed cost = S: €1000; M: €1200; L: €1500
Calibration adjustment = Internally calibrated (See 7.1)
Economy of scale = See 3.2.1.3

3.2.1.2 Variable Costs

For each powertrain, variable costs comprise of the individual costs of the relevant components (Table 5) represented in the model plus the cost of the glider, as shown in Equation 40. Automotive manufacturers often benefit from extra-industry spillovers, i.e. development efforts outside the automotive industry, for example battery technology [79-81]. Component costs are determined by a calibrated initial component cost [82, 83] and are subject to cost reduction as the component matures (based on a calibrated maximum cost reduction and the current maturity – see 3.3.3.3) and to on-going cost reduction through the learning process (see 3.2.1.4). The glider cost is determined similarly to fixed costs, and can be reduced over time as technology is developed for both the automotive and non-automotive sectors.

Component	ICEV	HEV	PHEV	BEV	FCV
Electric Drive System			X	X	X
BEV Battery				X	
HEV Battery		X			
PHEV Battery			X		
IC Engine	X	X	X		
Hydrogen Storage Tank					X
Body Materials	X	X	X	X	X
Fuel Cell System					X

Table 5: Powertrain components

$$\begin{aligned} &\mathit{Unit\ variable\ cost}_{P,S} \\ &\quad = \left(\sum\nolimits_{Ct} \mathit{Learning\ effect}_{Ct} \times \mathit{Initial\ component\ cost}_{Ct} \times \mathit{Maturity\ modifier}_{Ct}\right) \\ &\quad \times \mathit{Economy\ of\ scale}_{P} + \left(\mathit{Initial\ glider\ cost}_{P,S} \times \mathit{Calibration\ adjustment}\right) \end{aligned}$$

Equation 40: Unit variable cost *(euro/vehicle)*

Learning effect = See 3.2.1.4
Initial component cost = Internally calibrated (See 7.1)
Maturity modifier = Internally calibrated (See 7.1)
Economy of scale = See 3.2.1.3
Initial glider cost: S:€8000; M: €9000; L: €10000 except CNG/LPG ICEV S: €9500; M: €10500; L: €11500
Calibration adjustment = 1.385 (Internally calibrated - see 7.1)

3.2.1.3 Economies of Scale

The cost of producing individual vehicles is a key driver of the price offered to users. As manufacturers produce vehicles of a particular type, the cost of producing each unit can be reduced through economies of scale (increasing production) and also through developing and learning new production methods (see 3.2.1.4). A simple process reflects real-world economies of scale in Equation 41 by relating the production capacity (3.1.1) to a scale of economy to define a multiplier of the cost of production.

$$\mathit{Economy\ of\ scale}_{P} = \frac{\mathit{Economy\ of\ scale\ at\ current\ capacity}_{P}}{\mathit{Reference\ production\ capacity}} \times \mathit{Maximum\ effect}$$

Equation 41: Economy of scale

Economy of scale at current capacity =Look-up table
Reference production capacity = 100,000 vehicle/year [84]
Maximum effect = 0.5 (Internally calibrated - see 7.1)

3.2.1.4 Learning by Doing

In addition to economies of scale (3.2.1.3), increased experience helps to drive down costs over time [85]. As the global production of a powertrain type increases there is an increased likelihood that experience gained during production of the components will lead to improvements in the performance of the process which will be reflected by reduced production costs. The relationship between accumulated production and component costs is captured by learning rates, which vary over time [86]. Generally speaking, the learning rate declines from 20-40% during the initial market introduction stage to 10-20% during the mass production stage and even less as the technology enters the saturation stage [87, 88].[8] This "learning by doing" is represented by a learning curve for each component to generate a multiplier of component cost as in Equation 42. The strength of the learning curve is derived from an exogenous input fractional reduction from learning for each doubling of cumulative production [17].

[8] One of the reasons for this is that raw material costs are not so affected by production volumes. These costs may even increase in time in the presence of resource scarcity. However, R&D on material substitution can open new trajectories and associated learning paths.

$$Learning\ effect_{Ct} = \left(\frac{Cumulative\ manufacture_{Ct}}{Minimum\ production}\right)^{LOG_2(1-Fractional\ reduction)}$$

Equation 42: Component learning effect

Cumulative production = see 3.1
Minimum production = 29,290 vehicle/year (Internally calibrated - see 7.1)
Fractional reduction = 0.1 (0.01 for ICE) [13]

3.2.2 Additional Costs from Emission Penalties

In addition to adjusting prices to avoid emission penalties, within the model *Manufacturers* also allow costs from emission penalties already received to filter through to users, based on the relative excess emissions of each powertrain, as determined by Equation 43.

$$Additional\ cost\ from\ penalities_P = \frac{Penalties \times Relative\ excess\ emissions_P}{Sales_P}$$

Equation 43: Additional Costs from penalties *(euro/vehicle)*

Penalties = See 5.4.3
Relative excess emissions = Derived from 5.4.2
Sales = See 2.3

3.2.3 Price Adjustment from Emissions Penalties

As depicted in Figure 22, another influence on vehicle price is the desire to avoid emissions penalties from Authorities (5.4). *Manufacturers'* forecast of likely emissions penalties lead them to adjust vehicle prices (Equation 44) in order to encourage the sale of the lower-emission powertrains (in addition to encouraging R&D into lower-emission technology (3.3) and marketing lower-emission technologies (3.4). The adjustment to a particular powertrain price is scaled to its emissions over and above the target emissions set by the authorities. For every g/km over the emissions target, the *Manufacturers* increase prices by the base price increase if the emissions penalty payments forecast are equal to the reference value base emissions penalties for price adjustment. If forecast emissions penalties are higher or lower, then the magnitude of these price increases will vary from this value. In the current model set-up the sensitivity is set at 1, so the relationship with linear. This is then subjected to a calibrated response delay.

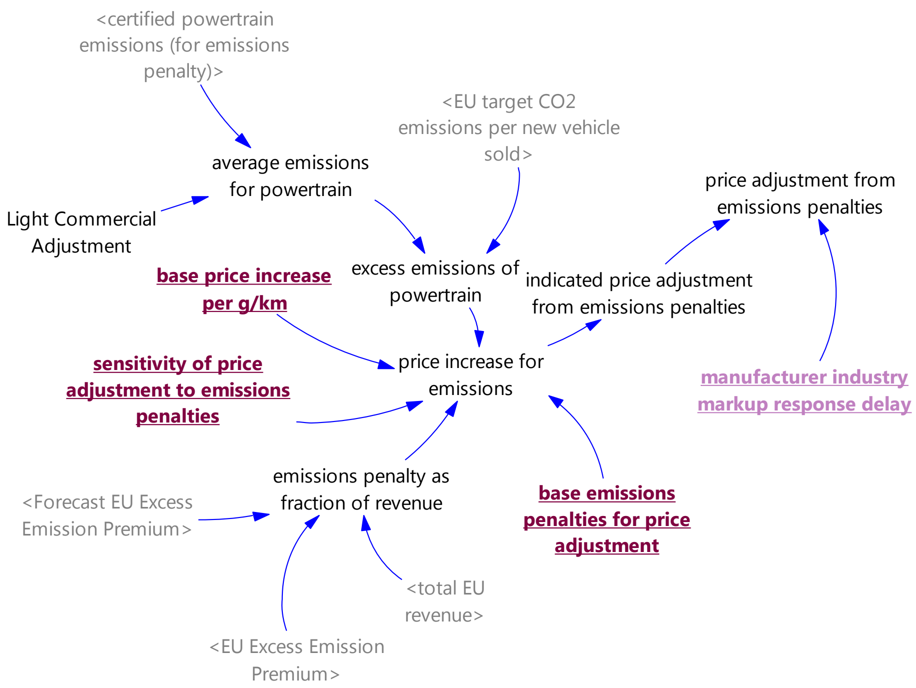

Figure 22: Price adjustment from emission penalties

$$Penalties\ price\ increase_{P,S,V} = Base\ price\ increase \times Excess\ emissions_{P,S,V} \times \left(\frac{Penalty\ as\ fraction\ of\ revenue}{Base\ penalties\ for\ adjustment}\right)^{Sensitivity\ of\ adjustment\ to\ penalties}$$

Equation 44: Price increase from penalties

Base price increase = 1%(g/km)$^{-1}$
Excess emissions = See 5.4.2
Penalty as fraction of revenue = See 5.4.3 and Equation 47
Base penalties for adjustment = (fraction of revenue) 0.2
Sensitivity of adjustment to penalties= 1

3.2.4 Mark-up

Although the cost of producing vehicles provides the basis for the powertrain pricing as described, a desired mark-up (Equation 45 and Figure 23), is added to the unit cost to arrive at a nominal powertrain price before external price subsidies. This mark-up is dynamic and reflects the manufacturers' attempts to encourage or discourage sale of particular powertrains. A calibrated reference value for the mark-up is influenced by the utilisation of the EU production capacity (see 3.1.1); should production capacity utilisation fall below a reference value, then the actual price mark-up would be adjusted downwards to encourage sales and raise utilisation. If, on the other hand, utilisation were above the reference value, then prices would start to rise as the supply/demand ratio increased. The final mark-up is further influenced by the relative buying power of users in the member state. The GDP ratio of a member-state GDP per capita to the average across all member states represents this relative wealth (GDP itself is an exogenous input from [65]). Finally, there is a calibrated response delay of 0.25 years.

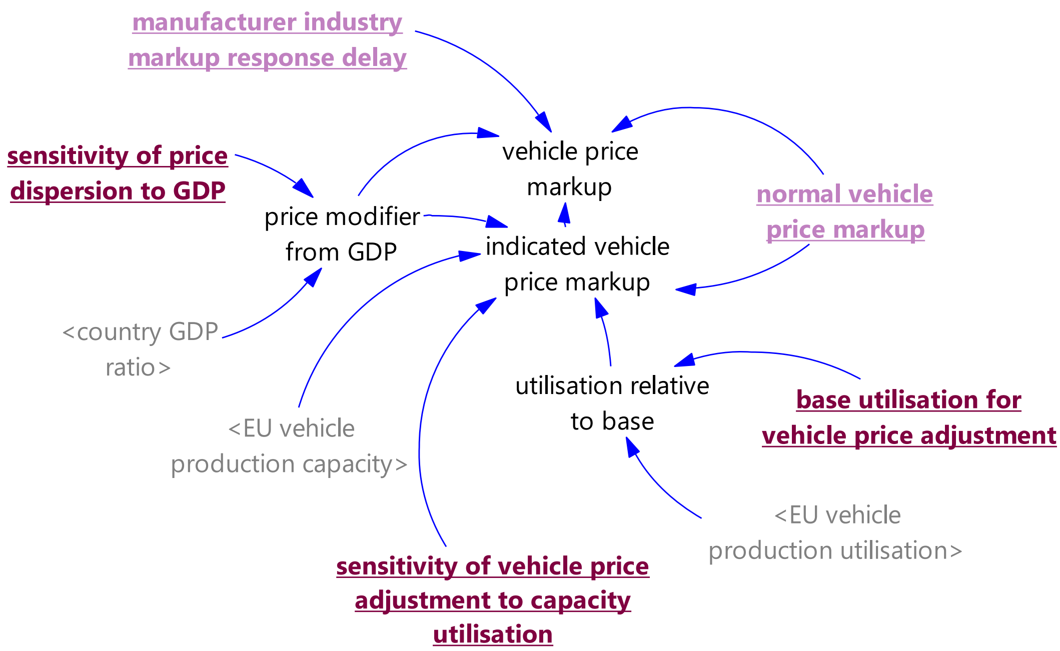

Figure 23: Price mark-up

$$Price\ markup_{C,P,S} = \left(\frac{Vehicle\ production\ utilisation_{P,S}}{Base\ utilisation\ for\ price\ adjustment}\right)^{Sensitivity\ of\ adjustment\ to\ utilisation} \times Normal\ price\ markup\ \times GDP\ ratio_C^{Sensitivity\ of\ price\ dispersion\ to\ GDP}$$

Equation 45: Price mark-up

Vehicle production utilisation = See 3.1.1
Base utilisation for price adjustment = 0.7
Sensitivity of adjustment to capacity utilisation = 0.2
Normal price mark-up = 10% (Internally calibrated – see 7.1)
GDP ratio = Derived from [41, 48]
Sensitivity of price dispersion to GDP = 0.2

3.3 Research & Development Investment

The European car industry's Research and Development (R&D) activities underscore its pursuit of an active CO_2 reduction agenda based partly on technological advance. The industry spends over €26 billion annually or about 5% of its turnover on R&D and much of this spending contributes to reducing the environmental impact of cars, including CO_2 emissions [89]. The vast majority of R&D effort is done independently, with each manufacturer pursuing its own initiatives, so the desire to achieve a competitive advantage is strong in this area [90]. R&D of the *Manufacturer* group (Figure 24) drives improvement in components that characterise each powertrain and thus the attributes that influence *User* group purchase decisions (2.2.4). Total funds for R&D are determined from revenue and allocated depending on relative attractiveness for investment.

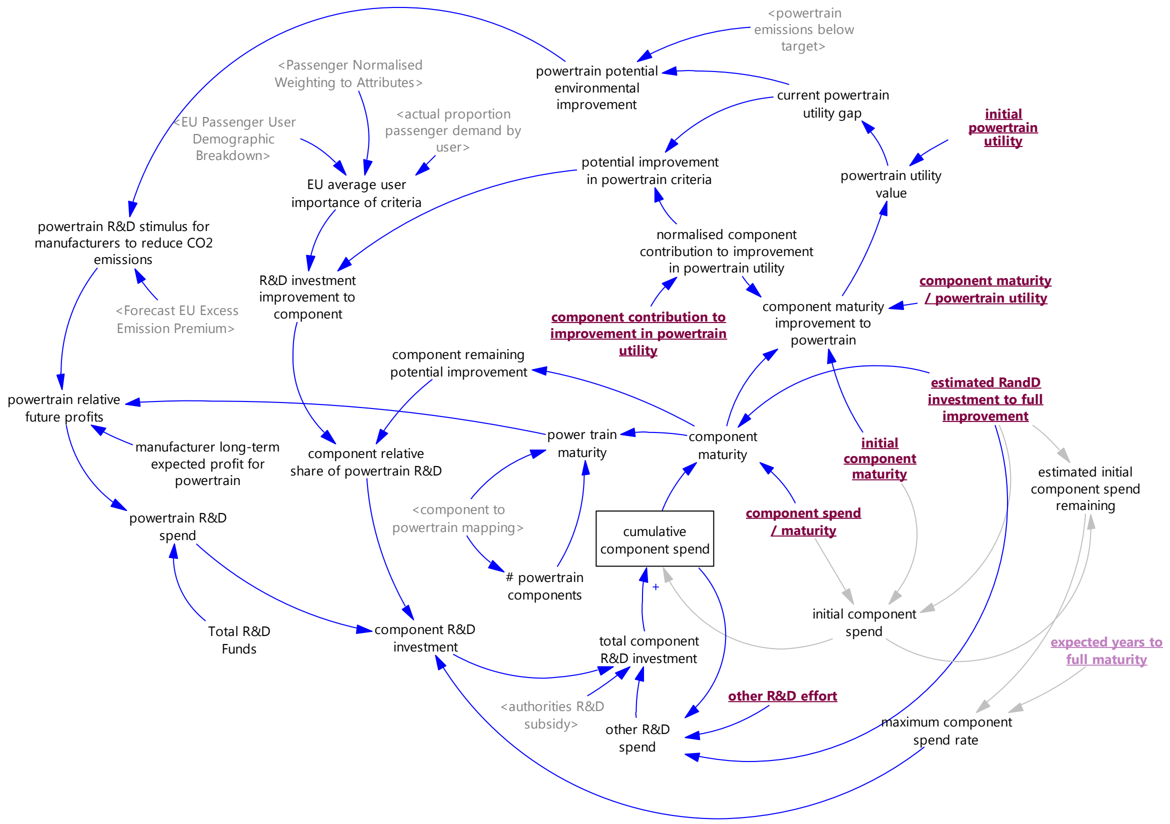

Figure 24: R&D

3.3.1 Available R&D Investment Funds

Available R&D investment funds (Equation 46) are assumed to be a fraction of the total revenue. Total revenue (Equation 47) includes both EU (domestic and export) and assumed RoW revenue. RoW revenue consists of endogenously assumed sales based on EU new registrations (2.3), RoW utility (2.2.6), a calibrated EU share of global sales (0.3326) and an average vehicle revenue based on the EU average. In addition to R&D investment EU revenue is also used in the determination of production and pricing.

$$Total\ R\&D\ investment\ funds = R\&D\ share \times R\&D\ intensity\ \times EU\ total\ revenue$$

Equation 46: Total R&D funds *(euro/year)*

R&D share (of revenue for powertrain improvements) = 0.75 [89]
R&D intensity (of modelled components) = 0.056 [90]
EU total revenue = See Equation 47

$$\begin{aligned} EU\ total\ revenue &= (New\ registrations \times (1 - EU\ import\ percentage) + (New\ registrations \\ &+ RoW\ sales) \times\ EU\ export\ percentage\ \times\ RoW\ margin\ ) \\ &\times (Vehicle\ price - Subsidies) \end{aligned}$$

Equation 47: Total revenue *(euro/year)*

New registrations = See 2.3
EU import percentage =9.2765% (Internally calibrated – see 7.1)
RoW sales = See text
EU export percentage = 8.824% (Internally calibrated – see 7.1)
RoW margin = 1
Vehicle price = See 3.2
Subsidies = See 5.1

Manufacturer investment in a particular component is an allocation from available funds to each powertrain and its components based on the attractiveness of the investment and subject to a maximum rate of investment determined by a calibrated years to full maturity. This structure ensures that the component will mature no more rapidly than this estimate, should sufficient R&D funds be expended. The allocation is first made between powertrains (3.3.2), and then components (3.3.3).

3.3.2 Powertrain R&D Investment

The investment in R&D for a particular powertrain is the total R&D funds weighted by the expectation of relative future profits for that powertrain, arrived at using Equation 48.

$$\begin{aligned} &\mathit{Powertrain\ R\&D\ investment} \\ &\qquad = \mathit{Long\ term\ expected\ profit} + \mathit{Penalties\ stimulus} \times (1 - \mathit{Powertrain\ maturity}) \end{aligned}$$

Equation 48: Powertrain R&D investment *(euro/year)*

Long term expected profit = See 3.3.2.1
Penalties stimulus = See 3.3.2.2
Powertrain maturity = Sum of component maturities (see 3.3.3.3)

3.3.2.1 Long-term Expected Profit

Potential future profits (both EU and RoW) to be made from each powertrain, may have an influence. These forecasts are comprised of projections from current sales plus an assessment of speculative future sales (3.5), taking the maximum expected profit from the forecast or speculative sales. These forecasts are used to assess the possible likely benefit of investing in component R&D and assist in the allocation of R&D effort between powertrains. It is forecast from current potential profit (Equation 49) using a standard assumed 3 year forecast and averaging period and 5 year R&D forecast horizon.

$$\begin{aligned} &\mathit{Potential\ profit} \\ &\qquad = \left(\mathit{Vehicle\ price}_{P,S} - \mathit{Unit\ cost}_{P,S}\right) \\ &\qquad \times (\mathit{New\ registrations} \times (1 - \mathit{EU\ import\ percentage}) + (\mathit{New\ registrations} \\ &\qquad + \mathit{RoW\ sales}) \times \mathit{EU\ export\ percentage}) \end{aligned}$$

Equation 49: Potential profit *(euro/year)*

Vehicle price = See 3.2 (including mark-up and taxes)
Unit cost = See 3.2.1
New registrations = See 2.3
EU import percentage =9.2765% (Internally calibrated – see 7.1)
RoW sales = See text
EU export percentage = 8.824% (Internally calibrated – see 7.1)

3.3.2.2 Stimulus from Potential Future Emissions Penalties

Any potential future penalties arising from a failure to meet emissions targets (see 5.4) is used as an additional stimulus for investment in those powertrains most likely to reduce emissions. This takes the form of a simple financial addition of the forecast emission penalties to the potential value of R&D, weighted by the relative potential improvement in the *Environment* attribute (2.2.4.3) for each powertrain, derived using Equation 50. Avoidance of future penalties means more profits for the industry and so investment in those components contributing most to carbon reduction would seem in line with the current European industry sentiment.

$$Potential\ environmental\ improvement_P = (Target\ vehicle\ emissions_P - Average\ vehicle\ emissions_P) \times (1 - Environment\ utility_{P,S})$$

Equation 50: Potential environmental improvement *(g/km)*

Target vehicle emissions = See 5.4.1
Average vehicle emissions = See 5.4
Environment utility = See 2.2.4.3

3.3.3 Component R&D Investment

Investment in R&D for a particular component, Equation 51, is comprised of two streams; investment from the manufacturers and investment from other sources. The subsidy is an exogenous input coming from authorities and "other" represents that from non-industry sources (eg academia), expressed as an annual fraction of the remaining investment required to reach full maturity.

$$Component\ R\&D\ investment_C = \sum_P \left(Powertrain\ R\&D\ investment_P \times Component\ share\ of\ R\&D_{P,S}\right) + Subsidy_C + Other\ R\&D\ investment_C$$

Equation 51: Component R&D investment *(euro/year)*

Powertrain R&D investment = See Equation 48
Component share of R&D =See 3.3.3.2
Subsidy = See 5.1
Other R&D investment = 0.5%/year

3.3.3.1 Manufacturer Component Investment

The *Manufacturer* component investment is a share of powertrain investment (3.3.2), subject to a constant maximum rate of investment (Equation 52). This structure ensures that the component will mature no more rapidly than this estimate, should sufficient R&D funds be expended.

$$Maximum\ investment\ rate = \frac{Investment\ for\ full\ improvement - Initial\ investment}{Years\ to\ maturity}$$

Equation 52: Maximum investment rate for each component

Investment for full improvement / Initial investment / Years to maturity = See Table 6

Component	Investment for full improvement (€b)	Initial investment (€b)	Years to maturity (calibrated)	Maximum investment rate (€b/Year)
Electric drive system	100	50	7.446	6.715
BEV battery	100	36.67	8.678	7.298
HEV battery	100	50	8.134	6.147
PHEV battery	100	36.67	5.126	12.36
IC engine	1500	950	30	18.33
H_2 storage tank	100	36.67	7.237	8.751
Body materials	300	170	30	4.333
Fuel cell system	100	30	5	14

Table 6: Component investment

The components share of the powertrain R&D investment is due to the relative attractiveness of the investment, based on the product of the remaining possible improvement of the component and a weighting to the component (see 3.3.3.2), both of which are reliant on the current maturity of the component (see 3.3.3.3). Equation 53 is used to calculate the remaining component improvement and recognises that mature components will yield a lower ROI than those with more modest maturity.

$$Remaining\ improvement = (1 - Maturity)$$

Equation 53: Remaining maturity for each component

Maturity = See 3.3.3.3

3.3.3.2 R&D Investment Weight to Component

In order to allocate effort across components based on future powertrain profits, the potential improvements in powertrain criteria are accounted for in accordance to the user importance rating. Those components contributing to powertrain utility with the greatest potential for improvement (Equation 54) and of high interest to the end users (see 2.2.3), will receive the greater proportion of R&D effort. The potential improvement relies on exogenous input assumptions of the relative contribution to a maximum improvement in powertrain utility criteria from a maximum improvement in component, and the current powertrain utility criteria (see 3.3.3.4).

$$\begin{aligned} &Potential\ improvement\ to\ utility_{P,Ct,Cr} \\ &\qquad = Relative\ contribution\ to\ utility\ improvement_{Ct,P,Cr} \times (1 - Utility_{P,Cr}) \end{aligned}$$

Equation 54: Potential improvement to utility criteria

Relative contribution to utility improvement = See example in Table 8
Utility = See Equation 55

3.3.3.3 Component Maturity

Powertrains comprise of a number of components, and for each of these the evolution of their development is represented through growth in the component maturity. The initial maturity of each component is a proportional measure of their current status in relation to a maximum assigned by expert judgement, as in Table 7. Component maturity is driven by financial investment and this relationship between investment and maturity is controlled by a number of assumptions. The cumulative spend is compared to an exogenous estimated R&D investment to full improvement to determine the fractional achievement of the theoretical investment required to reach full maturity. The relationship between fractional achievement and actual maturity is non-linear and governed by a standard assumed s-shaped lookup table.

Electric drive system	BEV battery	HEV battery	PHEV battery	IC engine	Hydrogen storage tank	Body materials	Fuel cell system
0.50	0.30	0.50	0.30	0.70	0.30	0.60	0.20

Table 7: Initial component maturity

3.3.3.4 Utility Criteria

The maturity of a component influences the utility criteria (attributes) that characterise the powertrain(s) (see 2.2.1). It follows that improvements to a particular component may benefit more than one powertrain and so cross-benefits of component improvement are handled in the model. Component maturation may improve its contribution to emissions reduction. For example, improvements to the internal combustion engine (ICE) reduce emissions for all those powertrains making use of the ICE for propulsion. Similarly, component improvement (as it matures) can increase the performance of the powertrain(s). Increases in efficiency of the ICE, for example, have led to increased performance while electric drive system improvements enhance the performance of those vehicles using electric motors for propulsion. The initial utility is the proportion of the maximum utility criteria that each powertrain/vehicle size has at the start of the simulation, assigned using expert judgement. This feeds into the utility value, Equation 55, as it evolves over time, proportional to an initial utility gap (to full improvement) and the improvement in the contributing components. This maturity improvement is a non-linear relationship controlled by a lookup table which takes the growth in maturity of the component as its input, returning the improvement to the powertrain with the aid of the input assumption of the relative contribution to utility improvement. In other words, each component of the powertrain makes a certain contribution to each utility criteria, based on their potential improvement from initial to full maturity, as in the example given in Table 8 for the *Electric Drive System* contribution to Petrol HEV utility criteria.

$$Utility_{P,Cr} = Initial\ utility_{P,S,Cr} + (Initial\ utility_{P,S,Cr} \times Utility\ improvement\ at\ current\ component\ maturity_{P,Ct,Cr} \times Relative\ contribution\ to\ utility\ improvement_{Ct,P,Cr})$$

Equation 55: Utility criteria

Initial utility = See Table 3
Utility improvement at current component maturity = Look-up table
Relative contribution to utility improvement = See example in Table 8

Utility Criteria	Contribution
Environment	16.67%
Performance	20.00%
Reliability	50.00%
Safety	33.33%
Convenience	100.00%

Table 8: Potential contribution of electric drive system to each utility criteria

Petrol HEV, from initial to full maturity

3.4 Marketing

Marketing, as depicted in Figure 25, affects the exposure of a powertrain and influences the users' willingness to consider by the marketing of the option by manufacturers and others such as magazines, newspapers and television shows [91]. The marketing effort (which influences environmental utility) is transposed to a marketing effect.

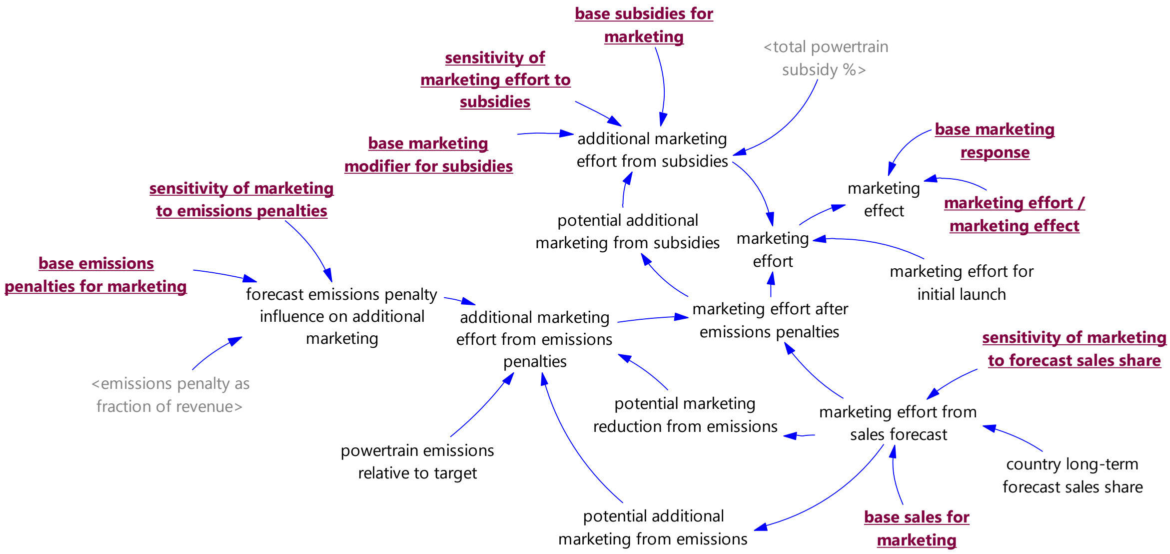

Figure 25: Marketing

3.4.1 Marketing Effort

Marketing effort is a measure of the intensity of marketing a powertrain in a particular country across all available channels, measured on a zero (no marketing) to one (saturation) scale, and influences the importance of the environmental attribute of a powertrain. There is a specific marketing effort at the initial launch of a powertrain, and thereafter it is chiefly dictated by the manufacturers' forecast market share for the powertrain, but is also modified by a number of other factors enabling the marketing effort to respond to other pressures, such as emission penalties and subsidies.

3.4.1.1 Launch of a New Powertrain

A new powertrain becoming available will receive a great deal of marketing effort prior to its launch in order to generate improved knowledge and acceptance of the type. This initial marketing effort is assumed to begin 1 year prior to the launch of the powertrain and continues for a certain period of time (default being 5 years, though this may be conservative). During this period, marketing effort is an exogenous assumed initial marketing effort of 100% and all other marketing influences are ignored*.*

3.4.1.2 Potential Future Sales.

The base level of marketing effort is driven by the maximum share of sales forecast or speculated (3.5) for the powertrain. Sales are forecast from current growth and a 3 year forecast horizon. This share is translated into a marketing effort using Equation 56.

$$Marketing\ effort_{C,P} = \left(\frac{Long\ term\ forecast\ sales\ share_{C,P}}{Base\ sales\ share\ for\ marketing_{C}}\right)^{Sensitivity\ of\ marketing\ to\ sales\ share}$$

Equation 56: Marketing Effort (base level – from sales forecast)

Long term forecast sales share = See text
Base sales share for marketing = 0.35
Sensitivity of marketing to sales share= 1.2

3.4.1.3 Potential Emission Penalties

Manufacturers would likely wish to minimise any future penalties (5.4.3) from failure to meet emissions reduction targets by encouraging users to adopt powertrains with lower emissions. Additional marketing of lower-emission powertrains is, therefore, a likely outcome of the emissions penalty policy, through Equation 57. Also, powertrains whose emissions are above the target may have their marketing effort reduced below that determined by the forecast market share. The emissions of each powertrain are compared to the target to obtain an additional marketing effort from emissions penalties, measured as a fraction of the potential additional marketing from emissions (to 100%) (Equation 58). This additional marketing effort is added to the base marketing effort from Equation 56. As the sensitivity is currently set to 1, this is currently a linear relationship.

$$Penalties\ marketing\ effort_{C,P} = Emissions\ relative\ to\ target_P \times Penalties\ influence\ on\ marketing \times Marketing\ effort_{C,P}$$

Equation 57: Penalties marketing effort (when Emissions < Target)

Emissions relative to target = See 5.4
Penalties influence on marketing = Equation 58
Marketing effort = Equation 56

$$Penalties\ influence\ on\ marketing = \left(\frac{Penalties\ as\ fraction\ of\ revenue}{Base\ penalties\ for\ marketing}\right)^{Sensitivity\ of\ marketing\ to\ penalties}$$

Equation 58 : Influence of penalties on marketing

Penalties as a fraction of revenue= See 5.4.3 and Equation 47
Base penalties for marketing (as proportion of turnover) = 0.01
Sensitivity of marketing to penalties= 1

3.4.1.4 Vehicle Price Subsidies

An announcement of subsidies to a particular powertrain price (3.2) would likely be accompanied by enhanced marketing of the opportunity. The subsidy level is compared to a reference value (assumed to be 25%) and an estimated proportion (50%) of a reference marketing modifier applied. The elasticity of the relationship between subsidies and degree of additional marketing is described by a sensitivity (currently set at 1, so a linear relationship). This additional marketing effort is also added to the marketing effort.

$$Subsidies\ Marketing\ Effort_{\ C,S} = \left((1 - (Marketing\ effort_{C,P} + Penalties\ marketing\ effort_{C,P})\right) \times Base\ modifier\ for\ subsidies_C \times \left(\frac{Subsidy_{C,P}}{Base\ subsidy\ for\ marketing}\right)^{Sensitivtity\ of\ marketing\ to\ subsidies_C}$$

Equation 59: Subsidies Marketing Effort

Marketing effort =See Equation 56
Penalties marketing effort = See Equation 57
Base modifier for subsidies= 0.5
Subsidy = See 5.1
Base subsidy for marketing (proportion of nominal price) = 0.25
Sensitivity = 1

3.4.2 Marketing Effect

Marketing effect, which influences willingness to consider (2.2.2), is the annual proportion of the population exposed to the marketed powertrain. The effort of marketing is translated into effect through an exogenous lookup table relating the marketing effort (as an input) to the fractional achievement of a maximum marketing outcome (set as 0.025 though [34] felt this was optimistic). As marketing effort increases the resulting effect increases but not in a linear fashion. Low-levels of marketing effort can have very little return while, as marketing effort approaches saturation, there are diminishing returns in terms of outcome.

3.5 Forecast and Speculative Demand

Manufacturers could consider future demand (and therefore revenue) in one of two ways: through forecasting demand based on previous sales and standard forecasting periods, or through a more speculative approach based on current sales. This is necessary for powertrains that are either not yet available or have only just become so and have no historical data on which to base forecasts on. Speculative demand, which would increase marketing effort, planned production etc through speculating on powertrain success, is used by manufacturers in the calculation of capacity investment (3.1.2) and R&D investment (3.3.2.1), as well as investments by *Infrastructure Providers* (4.1.4).

For capacity investment decisions, an exogenous expert judgment of speculative forecast share reflects *Manufacturers*' assumptions regarding the EU growth potential of the powertrain over a 3 year period. It is applied to the current (endogenous) total vehicle sales in the EU (2.3). This is further adjusted by an assumed fraction by size and an endogenous modifier of accuracy based on past speculation and a 1 year adaption period, as in Equation 60. Since there may be a large discrepancy between speculation and actual demand, a structure has been included to allow for adaption of any future speculation as a result of understanding the accuracy of such speculation. Should speculation be consistently higher than the eventual reality, then speculation for additional future periods would be dampened to reflect the lowered confidence in the forecast. For R&D investment (3.3.2.1), a speculative future demand is used to determine speculative profit, determined also using Equation 60, but the input speculative forecast shares are assumed over a 5 year period rather than 3.

$$\begin{aligned} Speculative\ demand_{P,S} \\ &= Speculative\ forecast\ share_P \times New\ registrations \times Size\ fraction_S \\ &\times Accuracy\ modifier_{P,S} \end{aligned}$$

Equation 60: Speculative demand *(vehicle/year)*

Speculative forecast share = See text
New registrations = see 2.3
Size fraction = S: 0.27; M: 0.58; L: 0.14
Accuracy modifier = See text

4 The Infrastructure Providers Agent Group

Each powertrain option is supported by infrastructure for the supply of energy (refilling stations, charging stations, etc) and for the repair and maintenance of vehicles (garages etc). In contrast to the established petrol and diesel fuel infrastructure, alternative fuel supply is especially undeveloped, making it difficult for manufacturers to sell alternative powertrains, even when these have higher utility than conventional vehicles. 'Chicken-and-egg' situations may arise when the low number of alternatively fuelled vehicles discourages energy companies from investing into related fuel supply infrastructure, which in turn discourages consumers from adopting alternative vehicles and manufacturers from building them in the first place [92-95]. *The Infrastructure Provider* market agent group (representing all individual infrastructure and maintenance providers, but not the production of fuel itself) makes decisions on the type and amount of infrastructure to provide based on signals from *User*s, *Manufacturers* and *Authorities*. The main influence on the amount of infrastructure present is the investment in the infrastructure itself, and there are two main drivers of infrastructure growth: market and policy. Market-induced investment describes decisions driven by the prospect of future profits, i.e. decisions based on forecasted ROI. Policy-induced investment is especially crucial at the onset of commercialisation, when investment risks are too high and/or expected ROI are too low to induce sufficient private infrastructure investment [96, 97]. *Infrastructure Providers* influence the convenience of powertrains for users and the decision rules which define this agent group are:

- ***Invest in refuelling*** (4.1) ***and recharging*** (4.2, 4.3) ***infrastructure***
  Based on demand and leading to a desired return on investment.

- ***Provide maintenance facilities*** (4.4)
  Providing greater coverage as non-OEM maintenance providers.

- ***Offer V2G revenue to users*** (4.5)
  If above a threshold and would provide extra incentive.

4.1 Refuelling Infrastructure

Within the model, the *Infrastructure Providers* agent group deals with the availability of particular (liquid/gas) fuel types in the given refuelling infrastructure, and therefore separate from the charging infrastructure (4.2). The refuelling infrastructure (Figure 26) influences, amongst other things, the convenience of using powertrains using the particular fuel (2.2.4.2). A measure of EU effective infrastructure is the proportion of refuelling stations carrying the fuel type which then feeds into the convenience criteria of the powertrain utility. The number of EU stations carrying fuel, which is a stock in the PTTMAM, must be sufficient to support the powertrains using the fuel or demand for the powertrains would be affected. As a stock, the number of fuel stations is thus governed by the rate of increase and decrease of stations offering fuel types as in Equation 61. The initial installed infrastructure is determined as the minimum between either an exogenous input (of incomplete historical data 1995-2013 from various sources) and an endogenously determined sustainable level of stations from the endogenous stock of vehicles using each fuel divided by a sustainable Vehicle to Refuelling station Index (VRI). The VRI is based on the vehicle stock and number of petrol stations at the beginning of the simulation.

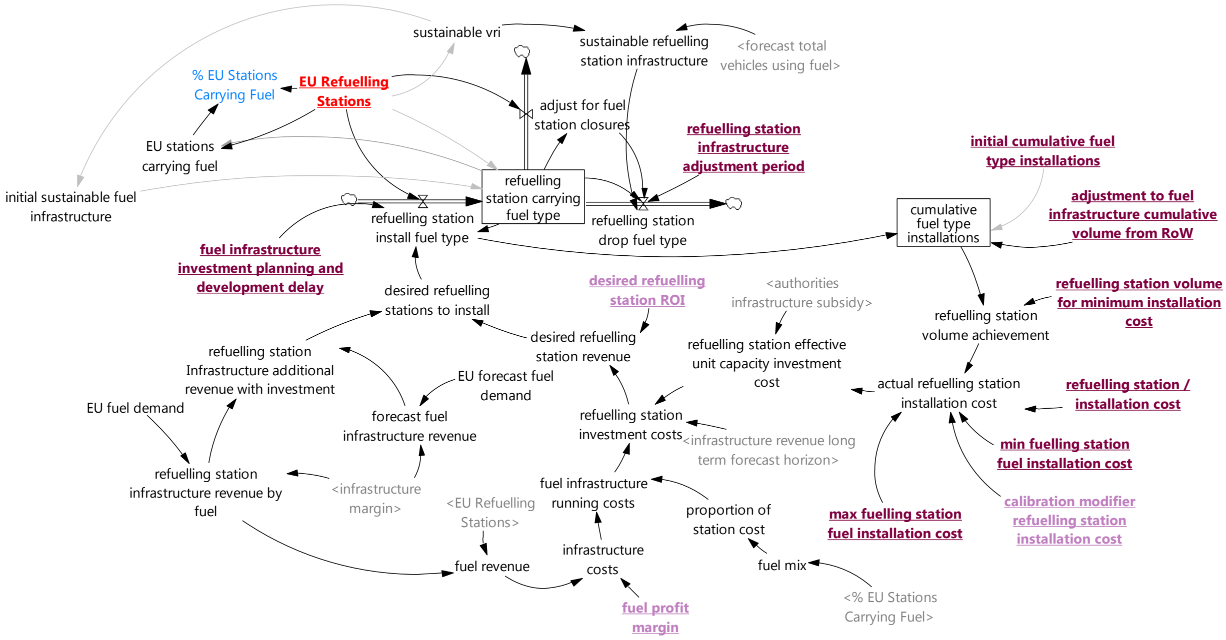

Figure 26: Refuelling infrastructure

Blue parameter is a calibration payoff (see section 7.1)

$$Refuelling\ stations\ carrying\ fuel\ type_{C,F} = Initial\ refuelling\ stations_{C,F} + \int_0^t \left(Refuelling\ station\ installation\ rate_{C,F} - Refuelling\ station\ removal\ rate_{C,F}\right) dt$$

Equation 61: Refuelling station stock *(stations)*

Initial refuelling stations = [61, 62] and national oil industry associations
Refuelling station installation rate = See text and Equation 62
Refuelling station removal rate = See text and Equation 63

The number of refuelling stations carrying a particular fuel type can be increased only if the infrastructure providers estimate that additional profitability would be achieved should additional stations carry the type, as in Equation 62. These are installed over an adjustment period currently assumed to be of 1 year, thus determining the installation rate.

$$Desired\ refuelling\ stations\ to\ install_{C,F} = \frac{Forecast\ additional\ fuel\ revenue\ with\ investment_{C,F}}{Refuelling\ station\ investment\ costs_{C,F} \times (1 + Desired\ refuelling\ station\ ROI_C)}$$

Equation 62: Desired refuelling station installations *(stations)*

Forecast additional fuel revenue with investment= See 4.1.3
Refuelling station investment costs = See 4.1.4
Desired refuelling station ROI = Internally calibrated (See 7.1)

A measure of sustainable refuelling station infrastructure is used to determine the removal of fuel types from refuelling stations Equation 63. The rate is determined from this and an adjustment period of 0.5 years.

$$Refuelling\ station\ drop\ rate_{C,F} = Refuelling\ station\ stock_{C,F} - \frac{Forecast\ vehicle\ stock_{C,F}}{Sustainable\ VRI_{C}}$$

Equation 63: Refuelling station drop rate (infrastructure removal) *(stations)*

Refuelling station stock = Equation 61
Forecast vehicle stock = See 3.5
Sustainable VRI = See text

4.1.1 Fuel Demand

Fundamental to the provision of fuelling infrastructure is the demand for fuel, both currently and in the future (Figure 27). Current fuel demand is determined endogenously, and for most powertrains is the product of the annual fuel consumption (2.2.5.3) and vehicle stock (2.4). For the biofuel flex fuel vehicles the demand is adjusted to account for alternative fuel usage (see 4.1.1.1). The PHEV option can use either conventional fuel or electric, and the proportion of fuel being used is an exogenous input (assumed to be 20%). The forecast fuel demand takes a forecast of the number of vehicles on the road using each fuel type, assessing a maximum between forecast (see 3.5 - using current stock figures and a forecast horizon of 3 years) and speculative growth (see 4.1.2) in powertrain use allowing for the possibility of investment in infrastructure in advance of actual powertrain sales. Should these speculative sales not transpire, it's likely that the stations would drop the fuel type due to lack of demand.

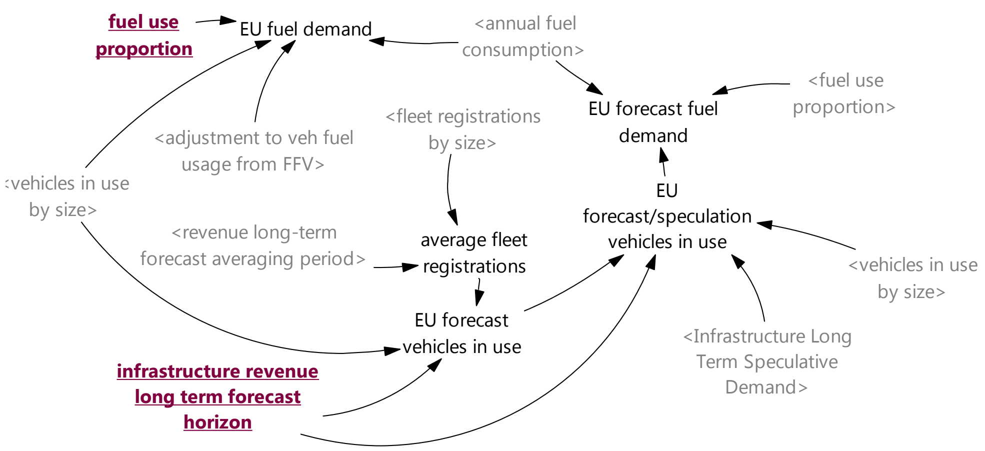

Figure 27: Forecast fuel demand

4.1.1.1 Adjustment from Flex-Fuel Vehicles

Fuel demand for conventional and biofuels is adjusted based on the difference between the additional (Equation 64) and lost demand (Equation 65) from the use of flex fuel vehicles (FFV), shown in Figure 28. Those powertrains included in the model that run on biofuels (either biodiesel or bioethanol) are assumed capable of also making use of conventional diesel and petrol. Such vehicles are termed flex-fuel vehicles and there is a need to adjust fuel demand within the model to account for the mix of conventional and biofuels used. The relative tank fill-ups between conventional and biofuels is based on an assessment of the relative price of each fuel modified by the availability of suitable filling stations. The relative price of the biofuels is adjusted by a premium users would allow the fuel for its green credentials and used as input to the lookup table between the biofuel price (calculated endogenously) and proportional usage. This assumes two extreme points; firstly that a biofuel price twice that of the conventional equivalent would result in zero fill-ups using biofuel. Secondly, a biofuel price equal to conventional would result in 100% of fill-ups using biofuel. Research has to date found no evidence for these actual figures but the key model outputs appear insensitive to this curve. It's worth noting that this is only a desire and that the absence of sufficient biofuel infrastructure would reduce the actual share of fill-ups with biofuel, so the relative effective infrastructure of biofuels is used as a modifier, with initial infrastructure a calibrated value. Demand is then calculated using current vehicle stock.

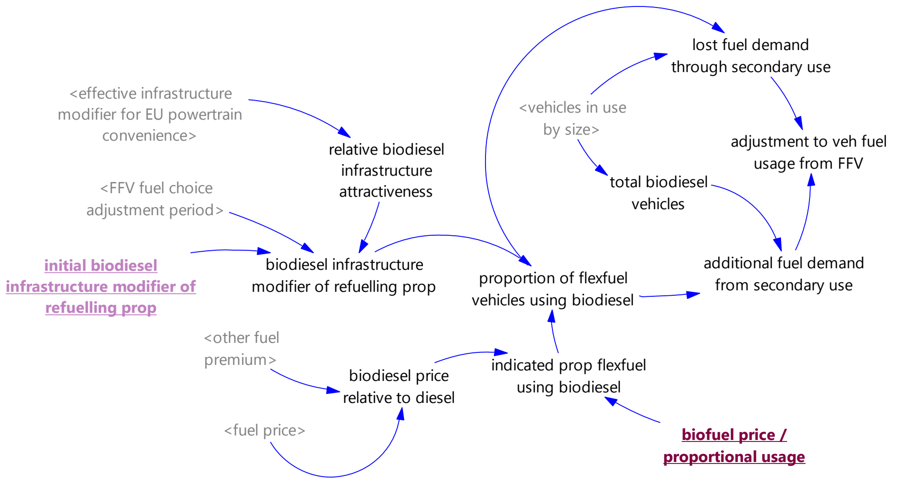

Figure 28: FFV (bioethanol calculated in same way)

$$Additional\ conventional\ fuel\ demand_{C,P,S} = (1 - Proportion\ of\ biofuel\ usage\ at\ current\ price) \times Biofuel\ vehicle\ stock_{C,S}$$

Equation 64: Additional conventional fuel demand from FFV *(vehicles)*

Proportion of biofuel usage at current price = Look-up table
Biofuel vehicle stock = See 2.4

$$Lost\ biofuel\ demand_{C,P,S} = \left(1 - \left(Proportion\ of\ biofuel\ usage\ at\ current\ price \times \frac{Biofuel\ effective\ infrastructure_C}{Conventional\ effective\ infrastructure_C}\right)\right) \times Vehicle\ stock_{C,P,S}$$

Equation 65: Lost biofuel demand from FFV *(vehicles)*

Proportion of biofuel usage at current price = Look-up table
Effective infrastructure = See 2.2.4.2
Vehicle stock = See 2.4

4.1.2 Speculative Demand

For powertrains that are lacking in historical demand data required for forecasting, a speculative approach is required to increase marketing effort, planned production etc through speculating on powertrain success. This is also used by *Manufacturers* in the calculation of capacity investment (See 3.1.2) and R&D investment (3.3).

$$Speculative\ demand_{C,P,S} = \frac{Total\ sales_C}{Total\ sales} \times Manufacturer\ speculative\ demand_{P,S}$$

Equation 66: Speculative Demand *(vehicle/year)*
Total sales = See 2.3
Manufacturer speculative demand = See 3.5

4.1.3 Fuel Revenue

Once the demand for fuel has been determined it can then be used within the model to calculate the current and expected fuel revenue required for investment decisions. Total current fuel revenue per refuelling station in an individual country is calculated using Equation 67. Potential future revenue is accounted for in a similar way as this but using forecast rather than current demand.

$$Fuel\ revenue_C = \frac{\sum_F \left(Fuel\ demand_{C,F} \times \left(\left(Fuel\ cost_{C,F} \times Fuel\ margin_{C,F}\right) - Subsidy_{C,F}\right)\right)}{Refuelling\ stations\ stock_C}$$

Equation 67: Fuel revenue (euro/year)
Fuel demand = See 4.1.1
Fuel cost = [64]
Fuel margin = Internally calibrated (See 7.1)
Subsidy = See 5.1
Refuelling station stock = Equation 61

4.1.4 Investment Costs

Refuelling station investment costs accounts for the cost of installing and running a refuelling station with a particular fuel type over the considered investment period. This assumes an infrastructure investment decision to precede vehicles sales by 3 years, leaving enough time to build and deploy the required equipment, and giving comfort to consumers. The installation cost is determined using Equation 68, which employs a look-up table connecting cost savings to refuelling station stock. The cost of installing a particular fuel type may be very high for new alternative fuels, at least initially, but as the installed base grows, unit installation costs are reduced through a process of learning and economies of scale, to around 1/3rd of the initial costs [98].

$$\begin{aligned} Refuelling\ station\ installation\ cost_{C,F} \\ = \Big(Maximum\ installation\ cost_F \\ - \Big(\left(Maximum\ installation\ cost_F - Minimum\ installation\ cost_F\right) \\ \times Current\ installation\ cost\ savings_F \times Country\ modifer_{C,F}\Big)\Big) \times \left(1 - Subsidy_{C,F}\right) \end{aligned}$$

Equation 68: Refuelling station installation cost *(euro/station)*
Maximum installation cost = See Table 9
Minimum installation cost = See Table 9
Current installation cost savings = Look-up table
Country modifier = Internally calibrated (See 7.1)
Subsidy = See 5.1

	Biodiesel Fuel	Bioethanol Fuel	CNG Fuel	Diesel Fuel	Hydrogen Fuel	LPG Fuel	Petrol Fuel
Maximum	45,000	45,000	250,000	45,000	1,600,000	400,000	45,000
Minimum	15,000	15,000	67,000	15,000	450,000	67,000	15,000

Table 9: Refuelling station installation cost

The average running costs for a fuelling station are assumed to be a proportion of the total operating costs for a station, which themselves are governed by the fuel revenue (4.1.3) as shown in Equation 69.

$$Refuelling\ station\ running\ costs_C = (Fuel\ revenue_C \times (1 - Fuel\ profit\ margin_C)) \times \frac{1}{\frac{Refuelling\ station\ stock_{C,F}}{Refuelling\ station\ stock_C} + 1}$$

Equation 69: Refuelling station running costs *(euro/year.station)*
Fuel revenue = Equation 67
Fuel profit margin = Internally calibrated (See 7.1)
Refuelling station stock = Equation 61

4.2 Electricity Infrastructure

The infrastructure available to powertrains making use of mains electricity is determined by the accessibility of charging locations, as the proportion households with access to public and/or private charging (Figure 29 and Equation 70), and the proportional achievement of rapid charging locations. This effective infrastructure is required within the *Convenience* attribute and also limits the willingness to consider plug-in powertrains (see 2.2.2). The overall effect is to restrict the purchase option for these powertrains to those with private or standard public (ie non-rapid) charging access. The private locations can either be available at home or place of work but they can also be supplemented by a public charging network. Rapid charging availability does not contribute to the purchase restriction, but does increase the convenience for those charging on the go. There is no consideration in the PTTMAM of the technical aspects of the charging posts, simply the provision thereof, though the rapid charging network is considered separately to a "standard" public charging network.

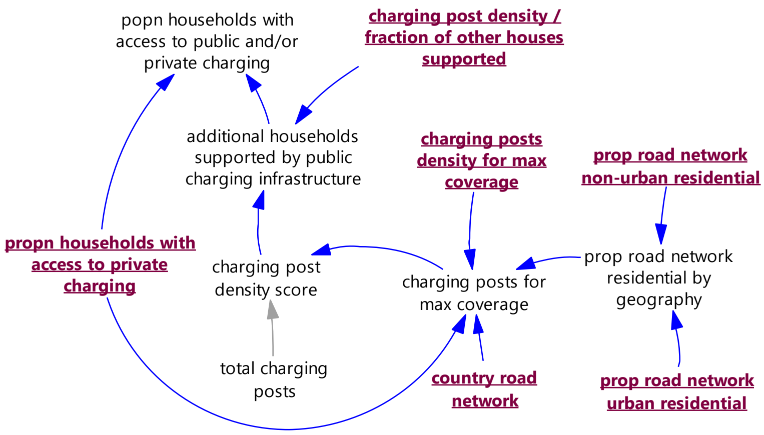

Figure 29: Accessibility to public (standard) and private charging infrastructure

$$
\begin{aligned}
&Proportion\ of\ households\ with\ access\ to\ charging_{C,G} \\
&\quad = Proportion\ of\ households\ with\ access\ to\ private\ charging_{C,G} \\
&\quad + \left(1 - Proportion\ of\ households\ with\ access\ to\ private\ charging_{C,G}\right) \\
&\quad \times Additional\ households\ supported\ by\ public\ charging_{C,G}
\end{aligned}
$$

Equation 70: Proportion of households with access to charging
Proportion of households with access to private charging = Urban: 25%; Non-urban: 42%
Additional households supported by public charging = Look-up table

The additional households support by public charging is determined through a look-up table relating charging post density to a fraction of supported households (those households without charging access at home or place of work). The shape of the curve reflects the slow increase in access as the density of charging posts increase (due to geographical concentrations in profitable areas first) followed by expansion into other areas and, finally, reducing returns as hard-to-access remote locations are reached. The density score is a measure of the achievement of total charging posts out of charging posts for maximum coverage. This maximum is determined from a number of exogenous input parameters as in Equation 71. Total charging posts accounts for the installed standard (slow) public charging posts only (4.2.3).

$$
\begin{aligned}
&Charging\ posts\ for\ maximum\ coverage_{C,G} \\
&\quad = Charging\ post\ density\ for\ maximum\ coverage \times total\ road\ network\ length_{C} \\
&\quad \times Proportion\ of\ network\ residential_{C,G} \times (1 \\
&\quad - Proportion\ of\ households\ with\ access\ to\ private\ charging_{C,G})
\end{aligned}
$$

Equation 71: Charging posts for maximum coverage *(posts)*
Density for maximum coverage = 200 posts/km
Total road network length= [99]
Proportion of network residential = Urban: 6%; Non-urban: 4%
Proportion of households with access to private charging = Urban: 25%; Non-urban: 42%

4.2.1 Public Charging Post Revenue

Similar to the refuelling infrastructure network, infrastructure providers are assumed to install public charging posts if the expected additional revenue from the installation be sufficient to satisfy a desired public charging post ROI. The main parameters relevant to the calculation of current and forecast revenue can be seen in Figure 30.

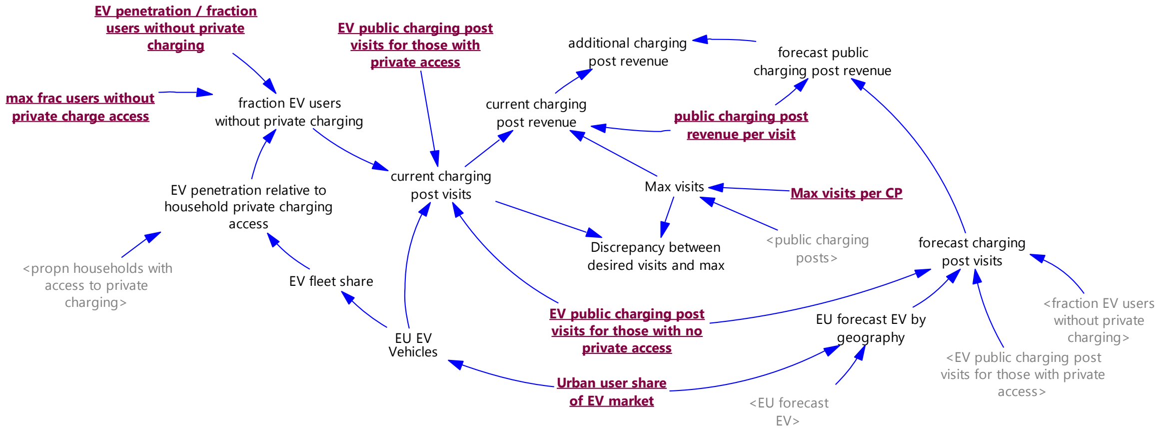

Figure 30: Charging post revenue

The current annual revenue per charging post is determined using Equation 72. The current fraction of non-private users (Equation 73), is determined from a look-up table comparing the current EV penetration relative to private charging access. Early adopters of EV are likely to be those with private charging access. As penetration increases, it is more likely that some EV users would be making sole use of public charging network. Forecast revenue is also determined by Equation 72, but using a forecast EV stock (as described in 4.1.1). Both current and future revenue is limited by a maximum possible annual visits to each charge post of 1460, assuming a 4 hour average charge [100] and additionally assuming 8 hours per day plug-in time or other time without charge (for example if a car is plugged in for the whole night while it only needs 4 hours for a full charge).

$$
\begin{aligned}
&\mathit{Current\ charging\ post\ revenue}_{C,G} \\
&\quad = \mathit{PiEV\ vehicle\ stock}_{C,G} \times \mathit{Revenue\ per\ visit} \\
&\quad \times \Big(\big(\mathit{Charge\ post\ visits\ for\ nonprivate\ PiEV\ users}_{G} \\
&\quad \times \mathit{Fraction\ nonprivate\ PiEV\ users}_{C,G}\big) \\
&\quad + \big(\mathit{Charge\ post\ visits\ for\ private\ PiEV\ users}_{G} \\
&\quad \times (1 - \mathit{Fraction\ nonprivate\ PiEV\ users}_{C,G})\big)\Big)
\end{aligned}
$$

Equation 72: Current charging post revenue *(euro/year)*

PiEV vehicle stock = See 2.4 (Assuming 80% of users are urban)
Proportion of visits to revenue generation posts = See text
Revenue per visit = €3
Charge post visits for non-private EV users: 120/year
Fraction non-private EV users = Equation 73
Charge post visits for private EV users: 52/year

$$
\begin{aligned}
&\mathit{Fraction\ of\ nonprivate\ EV\ users} \\
&\quad = \mathit{MAXIMUM}\big(\big(\mathit{Maximum\ fraction\ of\ nonprivate\ users} \\
&\quad \times \mathit{Current\ fraction\ of\ nonprivate\ PiEV\ users}_{C,G}\big), \\
&\quad \Bigg(\left(\frac{\mathit{PiEV\ stock\ share}_{C,G}}{\mathit{Proportion\ of\ households\ with\ private\ charging}_{C,G}} - 1\right) \\
&\quad \times \big(1 - \mathit{Proportion\ of\ households\ with\ private\ charging}_{C,G} \\
&\quad - \mathit{Maximum\ fraction\ of\ nonprivate\ users}\big)\Bigg)
\end{aligned}
$$

Equation 73: Fraction of non-private EV users

Maximum fraction of non-private users[9] = 0.2
Current fraction of non-private users = Look-up table
PiEV stock share = See 2.4 (assuming 80% of users are urban)
Proportion of households with access to private charging = Urban: 25%; Non-urban: 42%

4.2.2 Public Charging Infrastructure Costs

Installation costs (Equation 74) fall as the number of installed posts increase, representing a combination of learning effects and economies of scale. An exogenous assumed look-up table is used that relates the charging post installation savings to a proportional achievement of charging posts (out of an assumed volume for maximum

[9] This value indicates the fraction of EV users with no private access if the EV share of the fleet is the same size as the fraction of population without private charging.

reduction of 1.4M posts). The resultant infrastructure cost is then the installation cost plus annual running costs over an assumed 3 year forecast horizon. The running cost is also determined using a look-up table, between €500 and €1000 [101, 102].

$$\begin{aligned} &\mathit{Charging\ post\ installation\ cost}_C \\ &\quad = \mathit{Maximum\ public\ charging\ cost} \\ &\quad - \big((\mathit{Maximum\ public\ charging\ cost} - \mathit{Minimum\ public\ charging\ cost}) \\ &\quad \times \mathit{Current\ installation\ cost}\big) \end{aligned}$$

Equation 74: Charging post installation cost *(euro/post)*

Maximum public charging infrastructure cost = €6000 [103]
Minimum public charging infrastructure cost = €1000
Current installation cost = Look-up table

4.2.3 Public Charge Post Installation

Infrastructure Providers are assumed to install public charging posts should the expected additional revenue from the installation be sufficient to satisfy a desired public charging post ROI. Similar to revenue, this is limited to a maximum number of possible annual visits. *Authorities* have a part to play here too; they may support the roll-out of EV through subsidising the installation of public charging posts. The desired charge posts to install are determined by Equation 75. The stock of charging posts is thus governed by this alone, assuming zero installed at the start of the installation and no decommissions occur.

$$\mathit{Rate\ of\ installation} = \left(\frac{(\mathit{Forecast\ revenue}_{C,G} - \mathit{Current\ revenue}_{C,G})}{\mathit{Charging\ infrastructure\ costs}_C \times (1 + \mathit{Desired\ ROI})} \Big/ \mathit{Response\ time}_G \right)$$

Equation 75: Rate of installation of standard public charging posts *(post/year)*

Authorities installed charging posts = See 5.1.3
Forecast revenue = See 4.2.1
Current revenue = Equation 72
Charging infrastructure costs = See 4.2.2
Desired ROI = 0.2
Response time = Urban: 2 years; Non-urban: 5 years

4.3 Rapid Charging Locations

Rapid charging locations cover all technologies enabling electric vehicle batteries to be charged rapidly, and there are assumed to be 2 posts at each location. Installation dynamics are presented in Figure 31. As with other infrastructure, the endogenous rate of installation is governed by the need for infrastructure providers to achieve a desired ROI, which for rapid charging is also 0.2. The cost of installing and running a rapid charging location over the desired investment period is used to generate the desired rapid charging revenue to be made per potential new location. Installation costs vary between a maximum rapid charging installation cost (€25,000 and minimum rapid charging installation cost (assumed to be €15,000), using a look-up table as the number of installed rapid charging locations increases, representing a combination of learning effects and economies of scale. Minimum cost is achieved at 28,000 installed locations. Running costs are also determined using a lookup table and very between €2500 and €1500.

Current and forecast rapid charging revenue is a product of total current or forecast EV stock, frequency of visits (assumed to be once per month) and revenue per visit (assumed to be €12), with a limit of visits assuming a 30 minute charge and no night time visits. The total additional rapid charging revenue forecast to be made over the investment period (from a forecast rapid charging visits) is then used to determine the desired rapid charging stations to install, in a similar way as the standard charging infrastructure. This is limited by the availability of the technology, which is assumed to be from 2011. Further to this, the actual number of desired installations is limited by a maximum of one location per 60km of highway network in each country [100]. The proportional achievement of this measure is the contribution that rapid charging makes to the convenience attribute. The current rapid charging revenue is used to determine the sustainable rapid charging infrastructure, a measure of the current revenue shared over the running costs. Should this be below the current number of rapid charging locations, infrastructure providers would seek to redress the balance through rapid charging locations shutdown. Thus, the stock of rapid charging locations is determined using Equation 76.

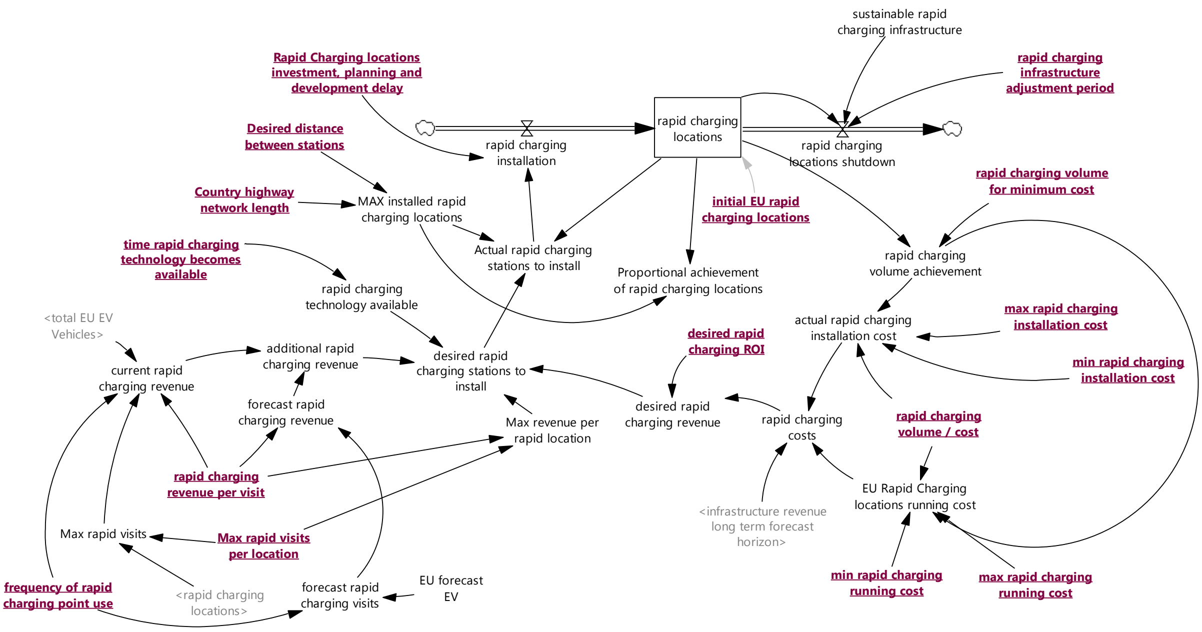

Figure 31: Rapid charging infrastructure

$$
\begin{aligned}
&Rapid\ charging\ locations_C \\
&= Initial\ rapid\ charging\ locations_C \\
&+ \int_0^t \left(\frac{MAX\ [0, (Forecast\ revenue_C - Current\ revenue_C)]}{Running\ costs\ \times Infrastructre\ revenue\ forecast\ horizon + Installation\ cost_C} \Big/ Delay \right) \\
&- \left(\frac{Rapid\ charging\ locations_C - Sustainable\ infrastructure_C}{Adjustment\ period} \right) dt
\end{aligned}
$$

Equation 76: Stock of rapid charging locations *(stations)*

Initial rapid charging locations = 0
Forecast / current revenue / Installation cost / Sustainable Infrastructure = See text
Running costs = See 4.2.2
Infrastructure revenue forecast horizon = 3 years
Delay = 3 years
Adjustment period = 0.5 years

4.4 Maintenance

The maintenance network, shown in Figure 32 also feeds into the *Convenience* attribute of a powertrain (2.2.4.2). A lack of competition in after-sales maintenance will likely mean not only higher costs (affecting user decisions on the affordability of the powertrain option) but also a perception of poor overall support. Both of these would lead to a reduction in market share. Following the necessary initial investment in maintenance facilities required in order to launch new models, other manufacturers and specialist maintenance providers enter and expand within the market. The assumption is that, as a powertrain gains more popularity it becomes more attractive for garages to invest in the equipment necessary to provide a maintenance service, determined by Equation 77. The fraction of total vehicles on the road of a particular powertrain is compared to a minimum fraction (0.02) before garages would even consider supporting the powertrain and, should this threshold be reached, also to a maximum fraction (0.25) before full maintenance support from independent garages. The fractional attainment of share of the fleet is translated into a total desired % Non-OEM maintenance network serving powertrain through the look-up table powertrain proportion / Non-OEM Maintenance Infrastructure, following a typical S-curve growth.

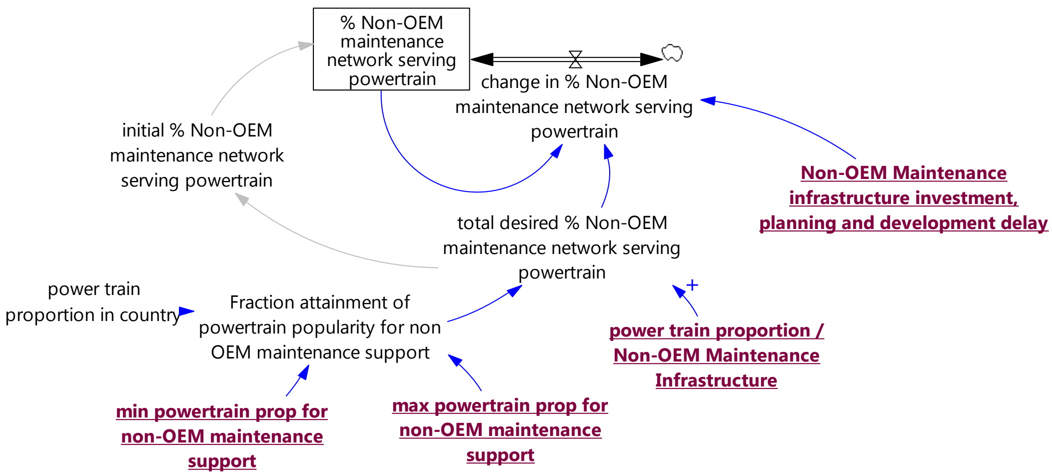

Figure 32: Maintenance network

$$Current\ nonOEM\ maintenance_{C,P} = Initial\ nonOEM\ maintenance_{C,P} + \int_0^t \frac{MAX\left[0, \left(Desired\ nonOEM\ maintenance_{C,P} - Current\ nonOEM\ maintenance_{C,P}\right)\right]}{Delay}\, dt$$

Equation 77: Non-OEM maintenance network *(% coverage)*

Initial non-OEM maintenance = Look-up table
Desired non-OEM maintenance = Look-up table
Delay = 1 year

4.5 EV Revenue

A number of analysts anticipate that users of EVs may be able to earn revenue in the future through vehicle-to-grid (V2G) services and/or by selling used batteries for use as stationary backup power sources [104]. The EV revenue generation opportunities provide additional incentives to potential buyers of EV and feeds back into the TCO (See

2.2.5.1). V2G networks enable EV users to sell demand response services to grid operators by either discharging electricity back into the grid or by endogenously adjusting their charging rate to the needs of said operators. The degree of revenue generation possible (Figure 33) would be determined by the potential benefits to the energy providers, a simple measure of EV as a percentage of the vehicle fleet as a proxy for revenue and/or other benefits (such as load balancing). Should this be above a threshold value then a typical non-linear function defines the level of financial benefit to EV users as EV become more popular. This curve only provides output (in terms of a multiplier of some maximum financial value to EV users representing the revenue opportunity as a fraction of 40% of electricity costs "redeemed" or saved through V2G payments) if EV popularity (market share) is within the range bounded by the maximum (0.04) and minimum (0.01) reference points. Any revenue attained is fed back into annual fuel costs.

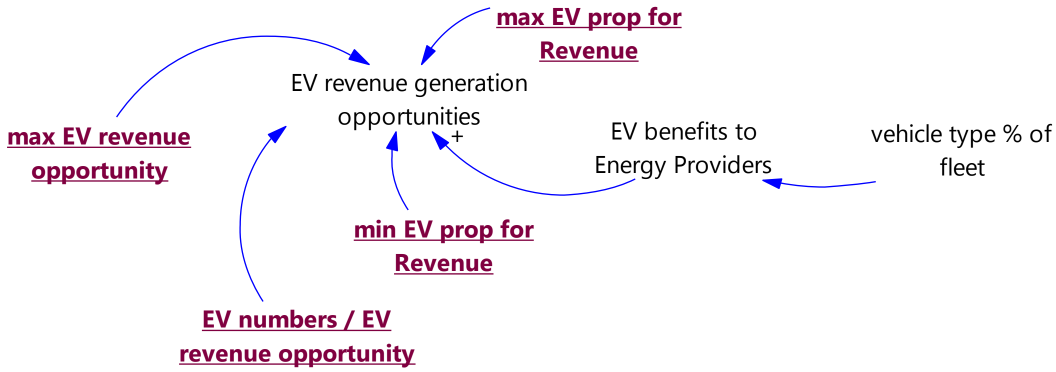

Figure 33: V2G EV Revenue

5 The Authorities Agent Group

Authorities, as a market agent group, represent government intervention at country and European-wide levels. Authorities provide financial support and other incentives in order to support the growth of one or more powertrain/fuel options. Authorities are able to support the achievement of pan-European CO_2 reduction targets by encouraging the use of lower-emission vehicles and the reduction of emissions from traditional ICE-powered vehicles. As with other market agents, *Authorities* are treated as one body within this model, though many inputs are subscripted by country. The main decision rules of the *Authorities* market agent group are:

- ***Offer subsidies*** (5.1)
  On refuelling/recharging infrastructure, powertrain purchase tax and cost, fuel tax/price, biofuels, parking/congestion charges and R&D.

- ***Adjust taxes*** (5.2)
  Circulation and registration taxes in individual member states may be adjusted in relation to relative environmental impact of powertrains.

- ***Introduce scrappage schemes*** (5.3)
  Financial incentives may be introduced to remove older vehicles from the fleet and response is governed by sensitivity parameters.

- ***Set emissions targets and calculate penalties*** (5.4)
  Targets are set according to current Regulations, but actual penalties are dependent on manufacturer response.

5.1 Subsidies

Authorities may set subsidies to assist *Users*, *Infrastructure Providers* and *Manufacturers*. These are an exogenous input used to define policy scenarios.

5.1.1 Powertrain Purchase Subsidies

Numerous subsidies may be made to the nominal vehicle price (Equation 38) as shown in Figure 34 and Equation 78. Both *Authorities* and *Manufacturers* may choose to support particular powertrains through subsidising the cost to the user. Once costs and taxation have been accounted for (5.1.4), a competitive price for the alternative powertrain relative to the Petrol ICEV is derived using Equation 79, taking into account any premiums for the reduction in environmental impact. This is based on a standard non-linear relationship with regards to the country GDP and an exogenous input of user value of environmental impact of each powertrain. If this competitive price is lower than the nominal price the manufacturers would charge, then a subsidy would be required in order to make the powertrain more attractive. The degree to which this subsidy is offered by the *Authorities* is an exogenous input and at an EU level represents the fractional subsidy support of the price differential between the alternative vehicle nominal and competitive price. This approach enables *Authorities'* subsidies to taper as alternative powertrain costs fall relative to conventional powertrains (endogenous). Alternatively, the subsidy can be entered at a country level as a monetary amount.

Further to this, *Manufacturers* themselves may implement subsidies should they wish to influence purchase decisions beyond any authority subsidy, and this is also an exogenous input of a monetary amount taken off the price after the authorities subsidy, and can be by country or EU wide.

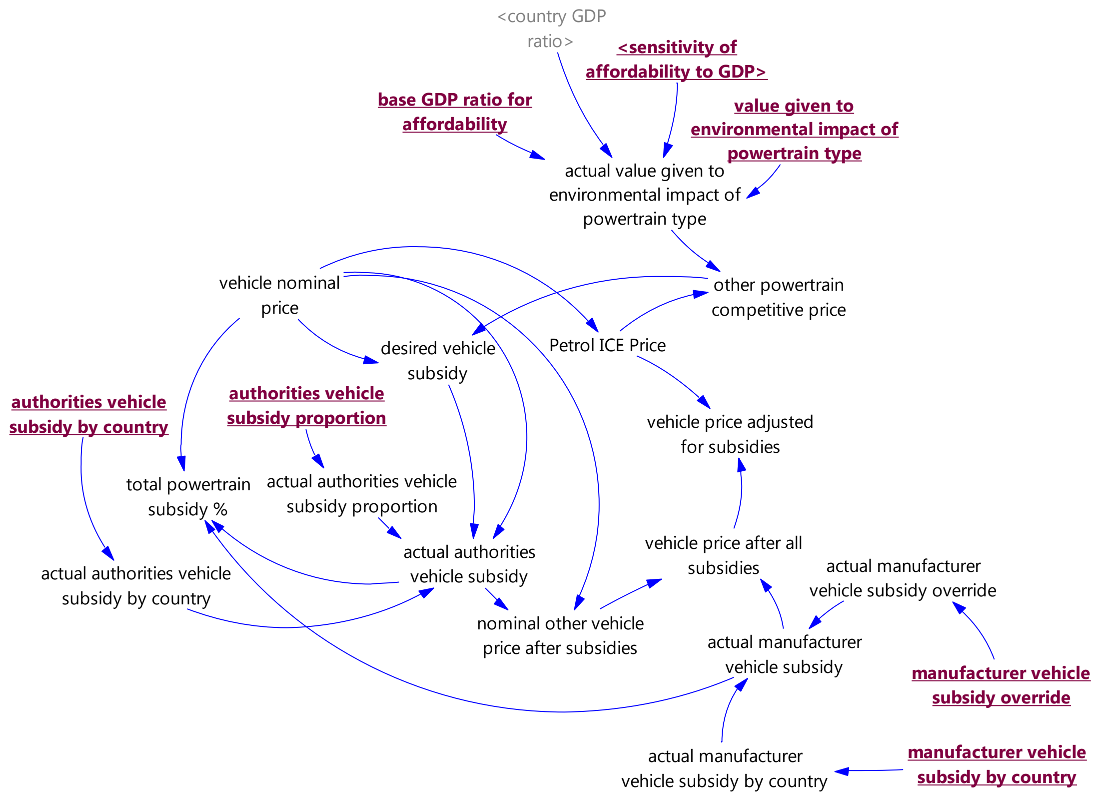

Figure 34: Vehicle price subsidies

$$\begin{aligned}&Vehicle\ price\ after\ subsidies_{C,P,S}\\&\quad = Vehicle\ nominal\ price_{C,P,S} - Authorities\ subsidy_{C,P,S} - Manufacturer\ subsidy_{C,P,S}\end{aligned}$$

Equation 78: Vehicle price after subsidies *(euro/vehicle)*

Vehicle nominal price = Equation 38
Authorities subsidy = See text
Manufacturer subsidy = see text

$$\begin{aligned}&Alternative\ powertrain\ competitive\ price_{C,S,P}\\&\quad = Petrol\ ICEV\ price_{C,S}\\&\quad \times \Bigg((1 + Value\ of\ environmental\ impact_P\\&\quad \times \left(\frac{GDP\ ratio_C}{Base\ GDP\ ratio\ for\ affordability}\right)^{Sensitivity\ of\ affordability\ to\ GDP}\Bigg)\end{aligned}$$

Equation 79: Alternative powertrain competitive price *(euro/vehicle)*

Petrol ICEV price = See 3.2
Value of environmental impact = See Table 4
GDP ratio = Derived from [41, 48]
Base GDP ratio for affordability = 1.5
Sensitivity to GDP = 0.5

5.1.2 Refuelling Infrastructure Subsidies

This subsidy is given to infrastructure providers to lower the cost of building alternative refuelling infrastructure, which in turn impacts on the user convenience criteria (2.2.4.2). Fuelling station subsidies work in an analogous way to the subsidies on alternative vehicles (5.1.1), but relating to the installation or construction of refuelling facilities for corresponding fuels (4.1). Similar to vehicles, we are dealing with a subsidy lowering the fuelling station invested capital and therefore raising profitability. This sort of financial support can be granted by the government, the fuel industry or together with car manufacturers, but in this model comes under the *Authorities* market agent. This infrastructure subsidy is an input and can be set for each individual member state or for all states. The figures are entered as a percentage support to the cost of installation.

5.1.3 Charging Infrastructure Subsidies

The development of the EV charging infrastructure network was described in Section 4.2. Authorities may support EV uptake through the installation of public charging posts as represented in Figure 35. As with refuelling infrastructure (5.1.1), the amount of support is an exogenous input assumption representing the percentage of support to the costs of installation, as a percentage of a desired charging posts in the country to be installed by authorities (which may be set for whole EU or individual member states). In the base scenario no subsidies are included. This number is determined by an exogenous (EU wide) input of the desired ratio of vehicles to charge post, which in the base model is set as 10, in line with the Alternative Fuels Infrastructure Directive [12]. Forecast EV is assessed and a charging post shortfall determined; it is this shortfall authorities may seek to reduce. The actual support will vary as private charging posts are also installed and as the desired penetration of posts changes (endogenous).

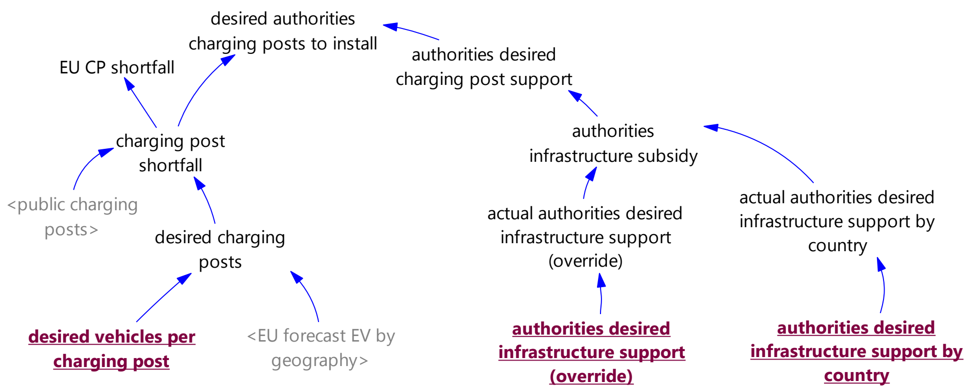

Figure 35: Charging infrastructure subsidies

5.1.4 Powertrain Tax Subsidies

To assist in creating a competitive purchase price for alternative powertrains, authorities may wish to reduce the VAT associated with powertrain purchase (this is separate to any registration or circulation tax described in Section 5.2). This is an exogenous input entered at either country or an EU wide level that represents a proportional reduction in the amount of VAT charged on a vehicle. The VAT in each country is based on exogenous inputs from historical and forecast data. This resultant VAT rate is then applied to the vehicle manufacturer price (based on manufacturing cost and desired margin – see 3.2) to obtain a vehicle nominal price, as demonstrated in Figure 36 and Equation 38.

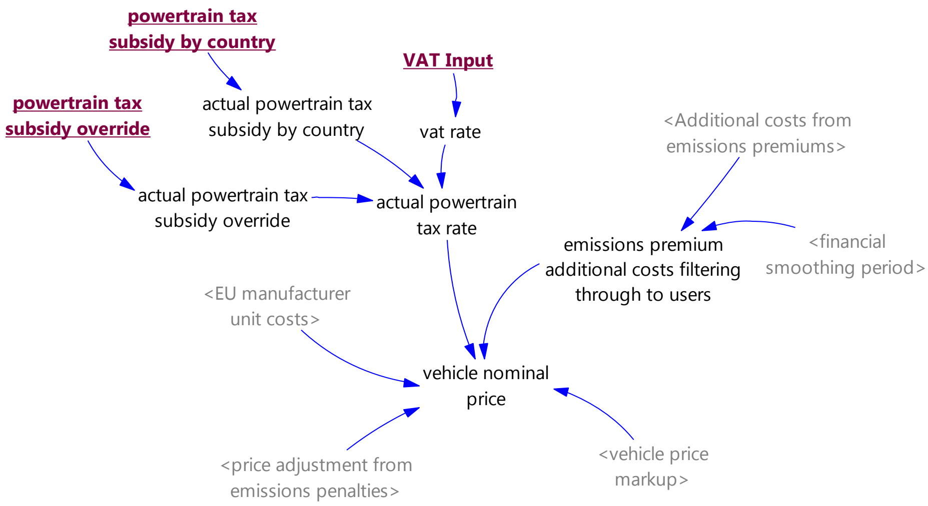

Figure 36: Powertrain tax subsidy

5.1.5 Fuel Tax Subsidies

In much the same way as authorities encourage adoption of lower-emission vehicles through direct vehicle price subsidies, they may also encourage this adoption through support to the operating costs. A fuel tax rate for each fuel type is assumed as exogenous data. In the model, taxes on alternative fuels can be modified through *Authorities* subsidising the tax on alternative fuels. The fuel nominal price to the *User* is determined from fuel costs and taxation as in Figure 37, Equation 80 and Equation 81.

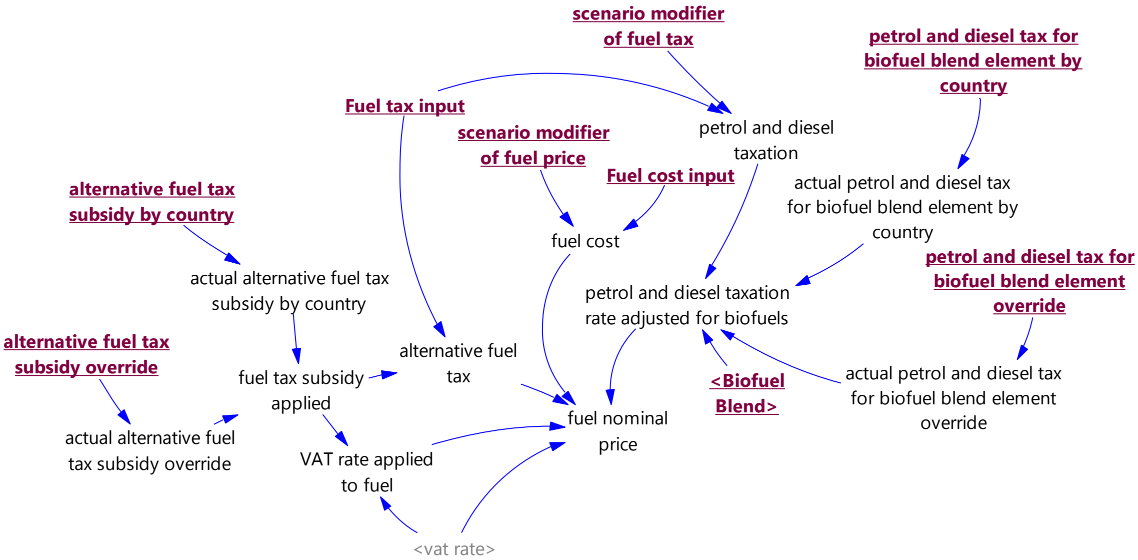

Figure 37: Fuel nominal price

$$\begin{aligned} &Alternative\ fuel\ nominal\ price_{C,F} \\ &= \Big(Fuel\ cost\ input_{C,F}\ \times Fuel\ price\ modifer_F \\ &+ \Big(Fuel\ tax\ input_{C,F} \times \big(1 - Fuel\ tax\ subsidy_{C,F}\big)\Big)\Big) \\ &\times \Big(1 + VAT_C \times \big(1 - Fuel\ tax\ subsidy_{C,F}\big)\Big) \end{aligned}$$

Equation 80: Alternative fuel nominal price *(euro/energy unit)*

Fuel cost input = [64, 105]
Fuel price modifier = Based on [65]
Fuel tax input = Expert judgement based on various sources
Fuel tax subsidy = User defined scenario input
VAT = [40]

$$\begin{aligned} &Conventional\ fuel\ nominal\ price_{C,F} \\ &= \Big(Fuel\ cost\ input_{C,F}\ \times Fuel\ price\ modifer_F \\ &+ \Big(Fuel\ tax\ input_{C,F} \times\ Fuel\ tax\ modifer_C \times (1 - Biofuel\ blend_F) \\ &+ \big(Fuel\ tax\ input_{C,F} \times\ Fuel\ tax\ modifer_C \times\ Biofuel\ blend\ tax_{(C)} \\ &\times Biofuel\ blend_F\big)\Big)\Big) \times (1 + VAT_C) \end{aligned}$$

Equation 81: Conventional Fuel Nominal Price *(euro/energy unit)*

Fuel cost input = [64, 105]
Fuel price modifier = Based on [65]
Fuel tax input = Expert judgement based on various sources
Fuel tax modifier = User defined scenario input
Biofuel blend = [106, 107]
Biofuel blend tax = User defined scenario input
VAT = [40]

5.1.6 Fuel Price Subsidies

In addition to supporting a particular fuel type through tax reduction, authorities may subsidise the price of the fuel in order to help ensure the fuel is competitively priced, as shown in Figure 38. Once costs and taxation have been accounted for (5.1.5), a competitive price for the alternative fuel is derived using Equation 82. This is based on the emissions of the alternative powertrain relative to petrol ICEV, and the emissions are determined in the same way to those considered by *Users* in their purchase decision (2.2.4.3) and similar to the determination of taxation rates (5.2), and for the calculation of emission penalties for *Manufacturers* (5.4). If this competitive price is lower than the price the *Infrastructure Providers* would charge (Equation 83), then a subsidy would be required in order to make the fuel more attractive. The effect is to reduce the cost to the user while maintaining (or at least supporting) the margins for the infrastructure provider. Similarly, the *Infrastructure Provider* may wish to provide a further subsidy to the user to stimulate sales of a particular fuel type. This is represented as the proportion of the price after the *Authorities* subsidy to make the price more competitive (Equation 84). The *Infrastructure Provider* may then set a final fuel price after the *Authorities* and *Infrastructure Provider* subsidies by taking an additional (exogenous) proportion of the cost margin between nominal and competitive price.

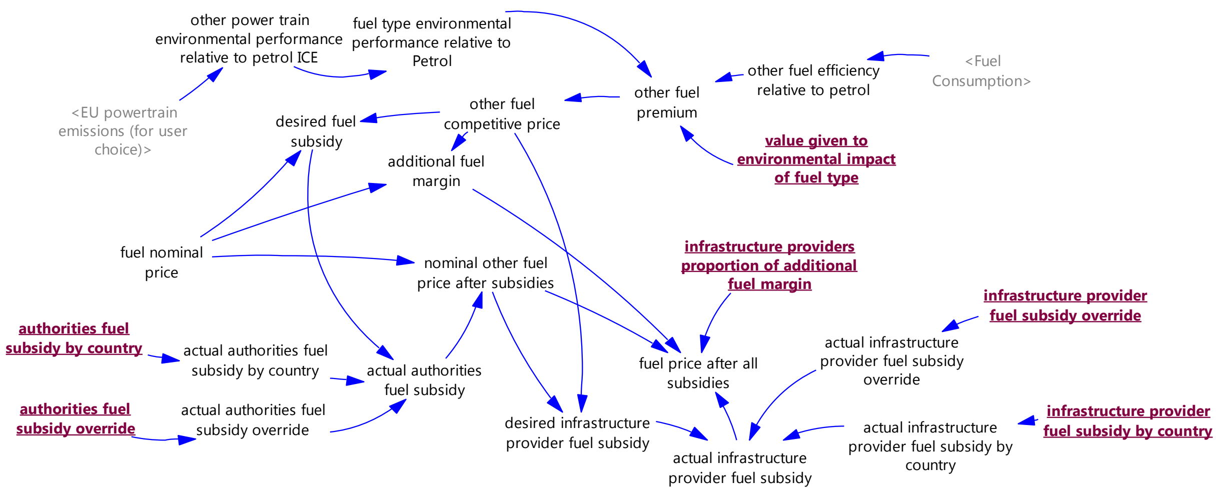

Figure 38: Fuel price subsidies

$$Alternative\ fuel\ competitive\ price_{C,F} = Petrol\ price_{C} \times \left(1 + \frac{Powertrain\ WTW\ emissions\ _{C,Petrol\ ICEV,S}}{Powertrain\ WTW\ emissions_{C,P,S}} \times \frac{Fuel\ consumption_{Petrol\ ICEV}}{Fuel\ consumption_{P}} \times Value\ of\ environmental\ impact_{F}\right)$$

Equation 82: Alternative fuel competitive price *(euro/energy unit)*

Petrol price = Equation 81
Powertrain WTW emissions = Equation 18 and Equation 19
Fuel consumption = See 2.2.5.3
Value of environmental impact of fuel = 0.05 for all alternative fuels

$$Alternative\ fuel\ authorities\ subsidy_{C,F} = Authorities\ fuel\ subsidy\ proportion_{(C),F} \times \left(Fuel\ nominal\ price_{C,F} - Alternative\ fuel\ competitive\ price_{C,F}\right)$$

Equation 83: *Authorities* alternative fuel subsidy *(euro/energy unit)*

Authorities fuel subsidy = User defined scenario input
Fuel nominal price = Equation 81
Alternative fuel competitive price = Equation 82

$$Alternative\ fuel\ Infrastructure\ Providers\ subsidy_{C,F} = Infrastructure\ Providers\ fuel\ subsidy\ proportion_{C,F} \times \left(Nominal\ fuel\ price_{C,F} - Alternative\ fuel\ competitive\ price_{C,F} - Authorities\ fuel\ subsidy_{C,F}\right)$$

Equation 84: *Infrastructure Providers* alternative fuel subsidy *(euro/energy unit)*

Infrastructure Providers fuel subsidy= User defined scenario input
Fuel nominal price = Equation 81
Alternative fuel competitive price = Equation 82
Authorities fuel subsidy = User defined scenario input

5.1.7 Parking/Congestion Subsidies

Another operating cost which authorities may wish to subsidise for the user is that associated with parking and congestion charges. This is included in the model at a high level of aggregation. In line with current existing policies, it is assumed that the authorities may wish to reduce or eliminate the exogenous input charges associated with parking [67] and congestion in towns and cities (expert judgement of an average €250 pa based on existing schemes, though subscripted by member state for those with more accurate data available eg London), for the least CO_2-emitting vehicles. The subsidy is an exogenous input (for either individual member state or whole EU) and represents the fractional reduction of any charge for one or more of the powertrain types. Although the congestion charge is assumed to be an annual amount, the parking is calculated based on average annual mileage [40].

5.1.8 R&D Subsidies

This exogenous input is a straight cash injection to the manufacturer into the R&D effort (3.3) for each component reflected in the model and does not account for R&D effort undertaken directly by authorities.

5.2 Registration and Circulation Taxation

Circulation taxes are the annual tax on a vehicle whereas registration taxes are a one-off cost when a vehicle is bought new. In the PTTMAM the average historic taxes [40] are exogenously entered for each country and vehicle size and modified to reflect the environmental impact of each powertrain. Subsidies can be applied on these taxes as an exogenous input.

5.2.1 Circulation Tax

An average annual circulation tax is entered for each country and this can be adjusted upwards or downwards by applying an emissions modifier to circulation tax, as described by Equation 85. This modifier, an external input that represents the fractional average increase/decrease in circulation taxes for powertrains whose emissions are greater or lesser than the average emissions of vehicles on the road, takes the powertrain emissions relative to an average value and adjusts the tax accordingly. This method was found to be the most suitable when considering all 28 countries of interest and the variety of methods (not just between countries but over time) used to calculate circulation taxes. It is the relative advantages / disadvantages of each powertrain that are of interest in this model, so highly-detailed representations of the taxation structures was deemed unnecessary. Alternatively, given the move by many member states to concentrate on electric powertrains, an exogenous input modifier of a reduction in tax for these vehicles only can be applied. Any savings from circulation tax modification or exemption can be accounted for in a demand kick to market shares (2.3.1).

$$Annual\ circulation\ tax_{C,P,S} = Average\ cicrulation\ tax_{C,S} \times (1 + Relative\ emissions_{C,P,S} \times Emissions\ modifer_{C}) \times (1 - EV\ modifier_{C})$$

Equation 85: Circulation taxes *(euro/vehicle.year)*

Average circulation tax = Derived from [40]
Relative emissions = Derived using Equation 86 and **Error! Reference source not found.**
Emissions modifier / EV modifier = User defined scenario input

The emissions used in Equation 85 is based on an average per powertrain size/type from the total stock of emissions from each powertrain at any one time, from both new (<2 years) (Equation 86) and old (>2 years) (Equation 87) vehicles. It is based on the same emissions calculation as that for *User* choice (2.2.4.3) and fuel price subsidies (5.1.6), so changes over time in relation to evolving environment utility value, itself determined from *Manufacturers* R&D investment decisions (3.3). The only difference is that the TTW portion is modified to account for "real world" (RW) use, which is assumed to be higher than type approval. This RW adjustment is included as it is the relative emissions that are of interest for the tax calculation, and it was felt that RW should be included. It differs from the emissions values used for calculating emissions penalties (5.4), which is based on only TTW emissions and with no accounting of real world use as they are based on type approval testing.

$$Total\ WTW\ RW\ emissions\ of\ new\ vehicle\ stock_{C,P,S} = Initial\ average\ WTW\ emissions_{P,S} \times Initial\ new\ vehicle\ stock_{C,P,S} + \int_0^t (New\ registrations_{C,P,S} \times Powertrain\ WTW\ Emissions_{C,P,S} \times RW\ adjustment) - \left((New\ vehicle\ deregistrations_{C,P,S} - New\ vehicles\ aging\ rate_{C,P,S}) \times \left(\frac{Total\ WTW\ RW\ emissions\ of\ new\ vehicle\ stock_{C,P,S}}{New\ vehicle\ stock_{C,P,S}} \times (1 + Age\ bias) \right) \right) dt$$

Equation 86: Total WTW RW emissions of new vehicle stock *(vehicle.g/km)*

Initial average WTW emissions = (at start of simulation) Based on [108]
Initial new vehicle stock / New vehicle stock / New vehicles aging rate = See 2.4
New registrations = See 2.3
Powertrain WTW emissions = Equation 18 and Equation 19
RW adjustment = 1.2 [109]
New vehicle de-registrations = See 2.3.2
Age bias = 0.2

$$Total\ WTW\ emissions\ of\ old\ vehicle\ stock_{C,P,S} = Initial\ average\ WTW\ emissions_{P,S} \times Initial\ old\ vehicle\ stock_{C,P,S,A} + \int_0^t \left(\frac{WTW\ emissions\ of\ old\ stock_{C,P,S,A}}{Existing\ vehicle\ stock_{C,P,S}} \times (1 + Age\ bias) \right) \times (Previous\ age\ cohort\ vehicle\ aging\ rate_{C,P,S,A} - Old\ vehicle\ aging\ rate_{C,P,S,A} - Old\ vehicle\ deregistrations_{C,P,S,A} - Old\ vehicle\ scrappage_{C,P,S,A})\ dt$$

Equation 87: Total WTW RW emissions of old vehicle stock *(vehicle.g/km)*

Initial average WTW emissions = (at start of simulation) Based on [108]
Initial old vehicle stock/Old vehicle stock/Old vehicle aging rate/Previous age cohort vehicle aging rate=See 2.4
WTW emissions of old stock= See 2.2.4.3
Age bias = 0.2
All but new vehicle de-registrations = See 2.3.2
All but new vehicle scrappage = See 2.3.3

5.2.2 Registration Tax

In much the same way as with the circulation taxes, an adjustment to an average registration tax can be made should the powertrain emissions be lower or higher than the average, or by a direct reduction for electric powertrains. This simple structure enables quick analysis of possible penalties/incentives based on emissions while avoiding the detail of schemes within each country whose variation (even within the same country but at different times) would require complex modelling structures for little or no additional benefit. The only difference in this calculation to that for circulation taxes (Equation 85) is that, as would be expected, powertrain emissions are relative to the average of other new vehicles, not the whole fleet. By default, registration costs are accounted for within fixed ownership costs (2.2.5.3), but alternatively may be included within purchase price which may have a greater influence on the purchase decision, and in which case would be included in the purchase price subsidy.

5.3 Scrappage Schemes

At various times authorities may wish to encourage the removal of older, higher-emission vehicles from the fleet to be replaced by newer, lower-emission vehicles. In the PTTMAM, this is achieved by an exogenous input offering a financial incentive to those owning vehicles over a certain age. In the current set up of the PTTMAM, vehicles must be over 10 years old to qualify for scrappage. Vehicles are simultaneously removed from the relevant age cohort and added to the new vehicle demand. The mix of powertrains removed and replaced is determined by a number of factors [71] and replacements are described at 2.4. As there are many factors influencing the mix of powertrain types scrapped under each scheme, due to varying scheme conditions etc, a simple powertrain scrappage proportion bias has been added to enable a relative mix to be generated through calibration. This is applied to the powertrain mix in the relevant age cohort enabling the proportions to adjust for the response to regulatory and psychological effects. Scrappage effects can be activated or disabled by the model user. The final scrappage for each country is determined using Equation 88.

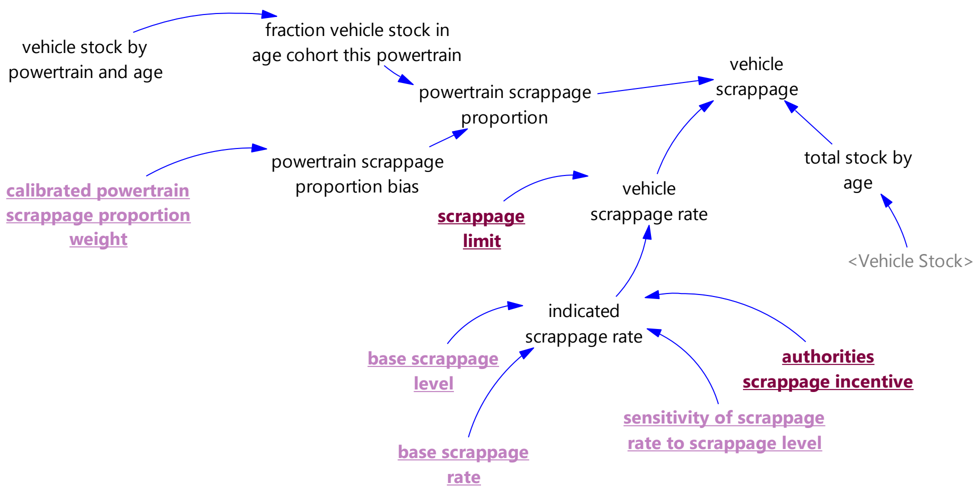

Figure 39: Scrappage

$$Vehicle\ scrappage_{C,P,S,Cl,A} = Vehicle\ stock_{C,Cl,A} \times Fraction\ of\ oldest\ cohort\ in\ vehicle\ stock_{C,P,Cl,A} \times Powertrain\ scrappage\ proportion_{C,P} \times Base\ scrappage\ rate \times \left(\frac{Scrappage\ incentive_C}{Base\ scrappage\ level}\right)^{Sensitivity\ of\ rate\ to\ incentive_C}$$

Equation 88: Scrappage *(vehicle/year)*

Vehicle stock / Fraction of oldest cohort of vehicle stock = See 2.4
Powertrain scrappage proportion = (fraction of powertrains scrapped) (Internally calibrated – see 7.1)
Base scrappage rate = (of eligible vehicles) 0.4935/year (Internally calibrated – see 7.1)
Scrappage incentive = User defined scenario input (euro/vehicle)
Base scrappage level = 3798 euro/vehicle (Internally calibrated – see 7.1)
Sensitivity of rate to incentive = Internally calibrated – see 7.1)

5.4 Fleet Emission Regulations

Under current Regulations (EC 2009; 2011b; 2014b; a), manufacturer fleets are assessed for an average CO_2 output and penalties charged for those fleets with averages above a specified threshold.

5.4.1 Emission Targets

Figure 40 shows the determination of the target per vehicle, and Equation 89 is an interpretation of the calculation included within the Regulations that accounts for vehicle mass within the desired average fleet emission. The introduction of light-weight materials may, therefore, not only reduce the CO_2 emissions of a particular vehicle but also any penalty resulting from excessive average emissions, although the target CO_2 threshold for lighter vehicles is lower than that for larger, heavier types. In the default model, although new registrations are determined endogenously (see 2.1), the mass of an individual powertrain is an exogenous input that does not currently change over time.

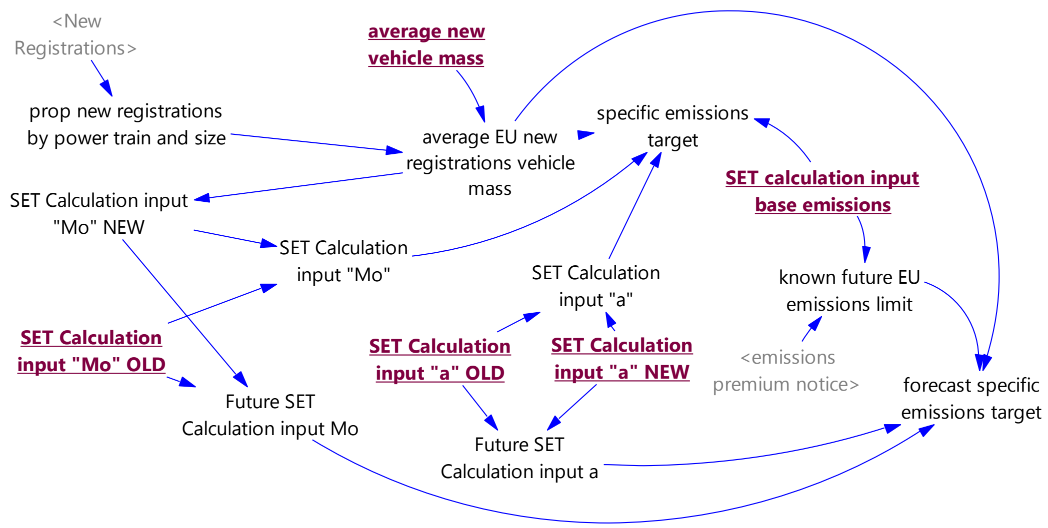

Figure 40: Emission target

$$Emissions\ target = Base\ target + a \times Average\ mass - Mo$$

Equation 89: Emissions target *(g/km)*

Base target = PC 130 g/km; 95 g/km from 2021. LCV 175 g/km; 147 g/km (defined in Regulations), then user defined scenario input
a = 0.457; 0.333 from 2020 (defined in the Regulations)
Average mass = based on [83]
Mo = 1372kg up to 2016; three year average thereafter (defined in the Regulations)

5.4.2 Excess Emissions

Excess CO_2 emissions (Figure 41) can cause an excess emission premium and this is designed to incentivise the manufacturers to invest in low carbon vehicle technology. The excess emissions are determined by comparing the target from Equation 89 to the actual average emissions of new registrations. Certified emissions per powertrain are determined endogenously and an average is obtained from new registrations (also endogenous), accounting for a regulation defined "phase-in" (65% in 2012, 75% in 2013, 80% in 2014, 100% from 2015 onwards), "super-credits" (each new passenger car with specific emissions of CO_2 of less than 50g CO_2 /km shall be counted as: 3.5 cars in 2012, 3.5 cars in 2013, 2.5 cars in 2014, 1.5 cars in 2015, 1 car from 2016) and "manufacturer pooling". Manufacturers are able to "trade" emissions through "pooling" whereby emissions from one element of a manufacturer's fleet can be pooled with another manufacturer in order to reduce the average CO_2 emissions. This further rewards those manufacturers with the lowest emissions as they can generate revenue from pooling with those above the emissions threshold. The degree of manufacturer pooling will affect the Excess CO_2 Emissions and is entered as an assumed 0.05% net reduction in overall EU emissions as a result of manufacturer pooling. This part of the model is set up for passenger cars and so a modifier for light commercial vehicles is applied, assuming they are 1.2 times higher. Forecast excess emissions are based on standard forecasting horizon of 3 years and an assumption that manufacturers may have 3 years notice of the level of the emissions penalty.

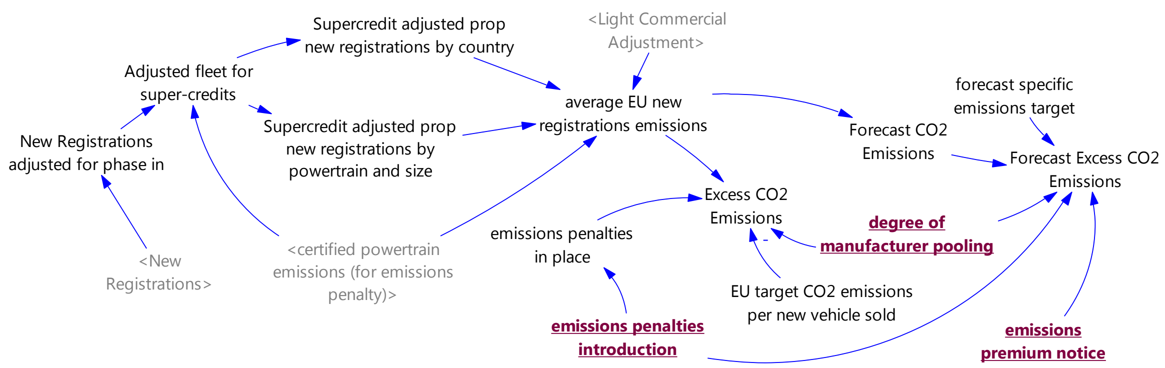

Figure 41: Excess emissions

For emissions penalties only TTW emissions are of interest, though WTW and "real-world" emissions are applied elsewhere within the model for *User* choice (2.2.4.3), subsidies (5.1) and taxation (5.2). For comparison to emission targets, Equation 90 is employed. This is the same as Equation 18 (used by *Users* and *Authorities*), but without the WTT element. Future emission reduction is determined by the change in the environmental utility of the powertrain (itself affected by the R&D activities of the Manufacturer (3.3.3)).

$$Powertrain\ TTW\ Emissions_{C,P,S} = \frac{Initial\ TTW\ emissions_P \times Size\ relative\ emissions_S \times Country\ modifier_C}{Environmental\ utility\ relative\ to\ initial_{P,S}}$$

Equation 90: Powertrain TTW emissions (non-zero emission powertrains) *(g/km)*

Initial TTW emissions = Medium segment derived from various sources [13, 63-65]
Size relative emissions = Internally calibrated (See 7.1)
Country modifier = Internally calibrated (See 7.1)
Environmental utility relative to initial = See 3.3.3.4 and Table 3

5.4.3 Emission Penalties

The emission penalties (Figure 42) are thus determined from the excess emissions over the emission target and the current emission penalties set in the regulations. This is determined using an exogenous look-up table. If the average CO_2 emissions of a manufacturer's fleet exceed its limit value in any year from 2012, the manufacturer has to pay an excess emissions premium for each car registered. This premium amounts to €5 for the first g/km of exceedance, €15 for the second g/km, €25 for the third g/km, and €95 for each subsequent g/km. From 2019, the cost will be €95 from the first gram of exceedance onwards. Furthermore, the penalties are regularly reviewed endogenously by *Authorities* (a commitment of the regulations) and can be adjusted as necessary to achieve the emissions reduction goal using Equation 91. Excess emissions are averaged over a policy smoothing period of 3 years. The intention of these targets is to incentivise manufacturers to reduce carbon emissions and not necessarily to cause hardship through excessive financial penalties. The manufacturers, having knowledge of upcoming changes to the emissions targets, will be able to forecast the likely excess emissions - it is this forecast that drives behavioural change. *Manufacturers* use their forecasts on powertrain demand and emissions to estimate their exposure to excess emissions premium payments which in turn influences their behaviour.

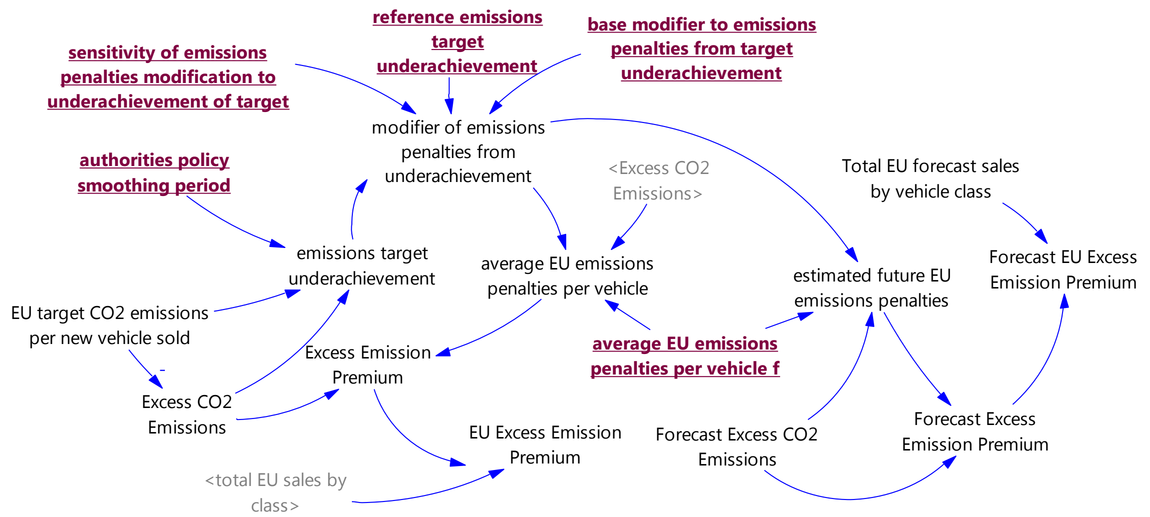

Figure 42: Emission Penalties

$$
\begin{aligned}
&\mathit{Emission\ target\ underachievement\ penalty\ modifier} \\
&= \mathit{Base\ modifier\ from\ underachievement} \\
&\times \left(\frac{\mathit{Excess\ emissions}}{\mathit{Emissions\ target}} \Big/ \mathit{Reference\ emissions\ target\ underachievement} \right)^{\mathit{Sensitivity\ of\ modification\ to\ underachievement}}
\end{aligned}
$$

Equation 91: Emission penalties underachievement penalty modifier

Base modifier from underachievement= 0.1
Excess emissions = See 5.4.2
Emissions target = See 5.4.1
Reference emissions target underachievement = 0.2
Sensitivity of penalty modification to target underachievement= 0.1

6 Baseline Scenario

It was important during the development phase that a flexible structure was retained, in order that scenarios designed to characterise exogenous factors such as future market conditions and/or policy options of interest could be easily implemented. This may be achieved by modifying the input parameters. As the main focus of this report is on the presentation of the model, a baseline scenario is presented in detail to show two key output parameters of the model (new sales shares and CO_2 emissions). For more detailed examples of model scenario analysis the reader should refer to [110-112] The focus is on EVs as these are currently considered as the main option for decoupling road transport from the environmental and energy security risks posed by climate change and oil [97, 113-116].

6.1 Description and Assumptions

The Baseline (or reference) scenario is designed to reflect the current EU projections of the exogenous variables. Therefore, in this way, it is not a *Business as Usual,* per se, moreover a best estimate of a moderately optimistic scenario based on current trends. By adopting this rationale, future low and high case scenarios for comparison may be designed appropriately[10]. Due to the great number of model inputs there is not the space to describe each of these in detail in this report, though many have been mentioned in the model description sections. Some key parameters regarding market conditions are presented in Table 10. Further to this, it is worthwhile describing two key policy variables that characterise our baseline, being purchase subsidies and new car fleet average emissions. Although we implement somewhat optimistic conditions regarding these, we believe these are representative of current European and global policy.

Variable	Historic Trend	Future Projection
Population	[48]	EU Reference Scenario [65]
Average household size	EU Reference Scenario (2013)	
GDP per capita	[117]	Calculation based on EU Reference Scenario [65]
Demographic breakdown	World Urbanisation Prospects [58]	
Average annual KM	TRACCS [40]and trend extrapolation	
Road network length	[99, 118] and expert assumption	
Growth in oil price	Extrapolation from EU Reference Scenario [65]	
Growth in alternative fuel price	Expert assumptions based on growth in oil price	
Electric fuel cost	[105]	EU Reference Scenario [65]
ICEV fuel cost	[64, 119] and expert assumptions	
Hydrogen fuel cost	Expert assumptions based on other fuel costs	
Electricity CO_2 intensity	EU Reference Scenario [65]	
Hydrogen CO_2 intensity (EU)	[13]	
Biofuel blends (EU)	EU Energy Statistics [106]	EU Reference Scenario [65]
VAT	TRACCS [40] and trend extrapolation	
Circulation Tax	TRACCS [40] and trend extrapolation	
Registration Tax	TRACCS [40] and trend extrapolation	
Fuel Tax growth	[64]	
Fuel Tax	[64]	

Table 10: Sources for key variables under baseline conditions
For inidvidual member states unless marked EU

[10] The reader should recall that the advantage of the PTTMAM is in the comparison of scenarios, and therefore the impact of their characterising parameters, not detailed analysis of one set of conditions.

6.1.1 Vehicle Purchase Subsidies

Vehicle purchase subsidies within our model refer to the proportion of the incremental vehicle cost relative to the cost of ICEV that is supported by authorities. In our baseline scenario we implement European-wide subsidies. Tax credits and purchases subsidies for EVs in the range of €2000 to €7000 have been proposed or are active in a number of countries, notably the US, France, Japan and the UK [120-124]. In the PTTMAM, subsidies are applied as a proportion of the price differential between the price of the subsidised powertrain and the petrol ICEV counterpart (5.1.1). The baseline assumption of a 50% subsidy between 2011 and 2013, then 25% for a further two years are based on the authors' estimate of what is in line with proposed, current and also past cases of global subsidy programmes [125-129].

6.1.2 Fleet Average CO_2 Standards for New Registrations

Under current Regulation, light duty vehicle manufacturers operating in the EU must reduce Tank-to-Wheel (TTW) CO_2 emissions from new passenger cars (PC) sold in Europe to a fleet average of 130gCO_2/km by 2015, and 95g/km by 2021 [3, 5], and 175g/km and 147g/km respectively [4, 6] for light commercial vehicles (LCV). The 2030 TTW value for the Baseline scenario, of 70g/km for PC and 120g/km for LCV, is adopted from an indicative 2025 passenger car target of 68-78 gCO_2/km approved by the EU Environment Committee though not finally adopted by the European Parliament [130], alongside recommendations and assumptions from other relevant studies [131-136]. For 2050, it is assumed that transport CO_2 emissions in 2050 should be around 70% below the 2011 levels [137] when average EU new passenger car TTW gCO_2/km was 136g and light commercial vehicles was 180g [9], so is set at 41 and 54g/km.

6.2 Analysis of Baseline Scenario Results

In this section, two key outputs (at EU level) from the baseline scenarios are described and, where required, explanations for the observed behaviour are offered. These outputs are the market shares of new registrations of vehicles and the resultant effect on CO_2 emissions. We consider the whole light-duty fleet, which comprises mainly passenger cars (around 90%).

6.2.1 New Sales Market Share

Figure 43 shows the evolution of the market shares of the powertrain types in the EU under the Baseline scenario. Technology transitions occur when alternatives are introduced to the market and Users are both aware of and attracted to their characterising attributes. The market share of the conventional ICEV class decreases from 100% to around a third from 1995 to 2050, when it becomes almost equal to HEV, the dominant alternative powertrain. This dominates not only because it is the first available alternative, allowing greater initial uptake before further powertrains enter the market and compete, but also because it's attributes most closely match the conventional ICEV, matching user preferences. Furthermore it remains highly financial attractive for most of the period. Of the electric powertrains, PHEV and BEV follow HEV into the market after 2010 and FCV starts to appear after 2030, having assumed to become commercially viable in 2020. PHEV, which has the most attractive attributes to the user, is the market leader, and gains around 25% of market share. Neither BEV nor FCV reach much more than 10% of market share combined. Because a significant share is never gained, this restricts the development of supportive infrastructure and exposure of the powertrains, which are key for users to be willing to consider them in their decision set in the first place. This competition between alternative powertrains is, therefore, in itself a limiting factor to their success. Thus, in our baseline, although ICEV sales are reduced by two-thirds, they are mainly replaced by HEV and PHEV, and so would not be successful in achieving ambitious emission reduction or urban vehicle targets

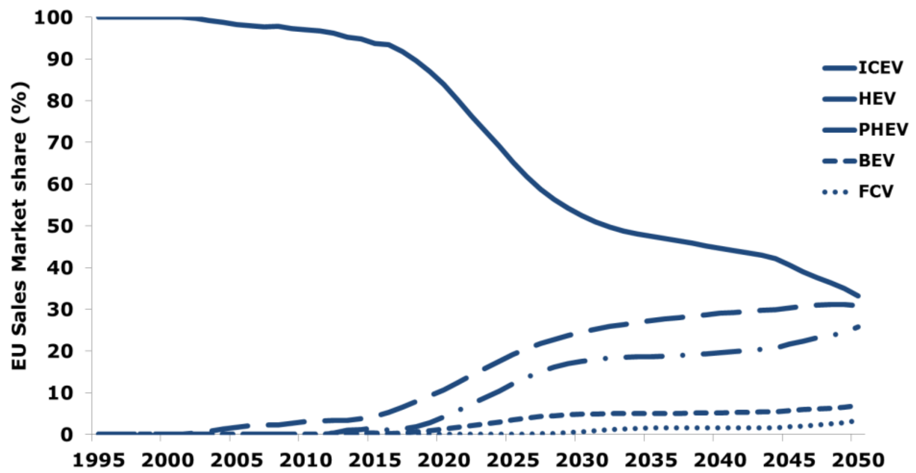

Figure 43: New sales market share of powertrains under the Baseline scenario

It is worth highlighting that an obvious result of these sales on the overall stock of vehicles is that the same trends are followed, but lag behind as stock needs time for vehicles to age and be deregistered. GDP, population and overall vehicle demand are assumed to grow over time. Therefore, in 2050, ICEV class vehicles retain their fleet dominance, still comprising around 50% of total stock, HEV stock is around one quarter of total, PHEV accounts for 16%, BEV almost 5% and FCV less than 2% of total stock so may be considered to be either niche markets or market failures.

6.2.2 CO_2 Emissions

Figure 44 shows the trend in total annual emissions between 1995 and 2050. Real world Well to Wheel (WTW) emissions are used for numerous reasons. These emissions are likely to be higher and more informative than certified emissions used in assessing policy, as they include next to the use phase also emissions from fuel production, and there is evidence to suggest that real world driving conditions result in greater emissions than test conditions. It should be noted however, that as emissions are not the central focus of the PTTMAM, they are not modelled to a great level of detail and as such subject to the limitation of numerous assumptions, so results should be taken as indicative trends only. Following historical trends and PRIMES projections, between 1995 and 2050, the PTTMAM baseline scenario assumes an increase in EU vehicle demand from around 15m to 22m. As such, even with more vehicles on the road, the baseline scenario results in an almost 30% reduction in annual total emissions over the time period. As such, under baseline conditions, ambitious EU carbon reductions would seem to not be met, demanding the implementation of stronger policy.

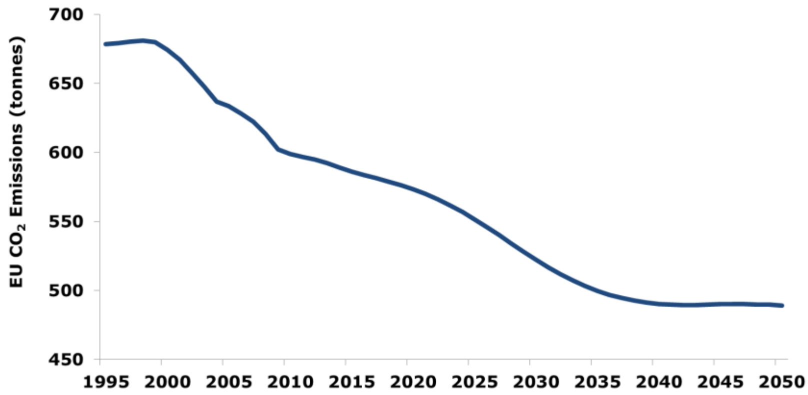

Figure 44: Annual EU RW WTW Emissions (tonnes CO_2)

As the rise in stock may mask the actual impact of the technology transitions, it is therefore useful to also consider the average g/km rather than total emissions, shown in Figure 45. This gives a more optimistic spin to the baseline scenario as the emissions are approximately halved during the time period. Although these emissions are RW, rather than type approval, it would seem that the Regulations are successful, as PC targets (around 90% of the market), are met. Although one policy conclusion of this may be the requirement to prevent any rise in stock or activity during this time, in reality this would not be achievable or practical, as the witnessed emission reduction is highly interconnected with the same market conditions that lead to the increased stock and activity.

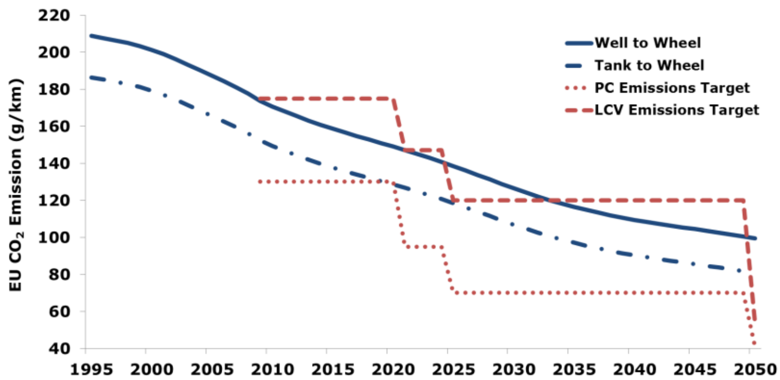

Figure 45: Annual EU RW emissions and targets (gCO_2/km)

7 Model Validation

During the initial development of the model the authors continually assessed the structure, outcomes and input data in order to enhance confidence in the model. Verification efforts included automated and manual checks for unit (of measurement) consistency, mass balance and syntax errors. The model was fully documented using the in-built comments tool within the Vensim equation editor, and subsequent model versions (with their changes) are summarised in one document. All input data is fully referenced within the input spreadsheet. This section deals with four aspects of validation supported by Vensim technology: Calibration, Extreme Case Testing, Sensitivity Analysis and Reality Checks. They are summarised here but greater detail is provided in the Annexes.

7.1 Calibration

In order to increase confidence in the model output it is necessary to validate the model structure. One approach is to compare model-generated output with historical data over a defined historical period. Calibration involves finding the values of model constants that make the model generate behaviour curves that best fit the real world data. If the model can be shown to closely replicate historical behaviour for the right reasons then the user will have greater confidence in the lessons learned from the simulator. Manual calibration is a slow, painstaking process involving manipulation of the input assumptions, the running of the model, and the visual assessment of 'goodness of fit' for a range of performance indicators. Over the years, SD software tools have evolved in order to assist in this process, the most notable being the use of optimisation algorithms. In the so-called 'calibration optimisation', the payoff is calculated as the accumulated differences between each historical and model-generated data point, the minimisation of which will result in a tendency to select model constant values minimising the difference between the historical data and the results generated by the model over the same historical period. Once a good fit has been achieved, the software provides a list of the constant values selected during calibration and these can be automatically used as input assumptions for future simulation runs.

In total within the PTTMAM there are 71 calibrated parameters, most of which are also subscripted to some degree. In order to make an efficient use of resources, many calibrated parameters are grouped into calibrations which run multiple optimisations. These were carried out across seven combined calibrations which are detailed in the Report Annex, including examples of the calibration results. Although there are many more data input parameters which may have a degree of uncertainty, only those where the historical data availability allowed, could be subjected to the calibration process. For some parameters, although there was a poor range of available data and so the calibration was far from perfect but allows for some guidance over the parameters. In addition, further parameters may have had historical data available but the model sensitivity (see 7.2) was such that a more precise figure was not required and so effort would have been wasted. Furthermore, some of the calibration may appear distorted as recent historical data from 2008 is affected by the financial crisis. Shown in the annex are examples of the calibration output. Although not all results have accurate fits to historical data, they were carried out with the best data available at the time, and will be subject to improvement when better data or knowledge becomes available.

7.2 Sensitivity Analysis

This model requires a great deal of data in order to perform a simulation run. There are, however, concerns regarding the data, as would be expected in any modelling tool. Firstly, over and above initial data assessment, sourced data may be inaccurate or inconsistent. For example, total vehicle sales for a country not being the same as the sum of vehicle sales for individual powertrain types. Secondly, many data elements require estimates using expert judgement or associations with similar values elsewhere. For example, comparing unknown costs for new components with costs for similar existing components. It is useful, therefore, to analyse the sensitivity of the results from the model to changes in the data input assumptions. By varying the values of our major input assumptions and monitoring the change in key model outputs (such as EV sales and emissions), a picture of the sensitivity of the model to data assumptions emerges. The process followed for this, and the results, are presented in the Annex.

7.3 Reality Checks

In order to validate the usefulness of a model, it is important to determine whether things that are observed in reality also hold true in the model. This validation can be done using formal or informal methods to compare measurements and model behaviour. Another important component in model validation is the detailed consideration of assumptions about structure. Agents should not require information that is not available to them to make decisions. Between the details of structure and the overwhelming richness of behaviour, there is a great deal that can be said about a model that is rarely acted upon. If you were to complete the sentence *"For a model to be reasonable when I (X), it should (X)_"* you would see that there are many things that you could do to a model to find problems and build confidence in it. Reality Check is a Venism tool for assessing the model assumptions and processes that adds significantly to the ability to validate and defend models. With this, a modeller can set up equations that provide a language for specifying what is required for a model to be reasonable. It is a straightforward way to express statements that must be true about a model for it to be useful. It can also focus discussion away from specific assumptions made in models onto more solidly held beliefs about the nature of reality. Detail on these checks, including constraints such as *no population, no sales* or test inputs such as n*o forecast demand* are presented in the Annex.

7.4 Extreme Case Testing

When validating any model the developer will exercise the model with extreme values of input assumptions and evaluate the model response for reasonable behaviour given the extreme conditions set. This is a continual process and helps to validate new structures as they are added to the model. A number of representative extreme-case tests have been evaluated, each with one change from the baseline, as described in the Annex. The model behaves as would be expected in these cases, with emission targets and fuel costs having the greatest influence.

8 Conclusion

The goal of the EU's sustainable transport policy is to ensure that our transport system meets society's economic, social and environmental needs. Effective transport systems are essential for Europe's prosperity, having significant impact on economic growth, social development and the environment. Road transport plays an important role in this context and it covers a significant proportion of the European transport needs, but also emissions. Due to factors such as globalisation, changing customer needs, and a range of economic and environment pressures, road transport is continually undergoing transformations. One such transformation is technology innovation with regards to propulsion technology.

Several new propulsion technologies are currently under development and some have recently entered the market. But there exists great uncertainty about the market viability and the future market penetration of the technologies. It is of critical importance to base policy on a solid foundation, amongst others taking into account the main drivers and parameters influencing technology transition.

In this technical report, a market-agent based simulation model is presented to the research community. Its aim is to assist in the understanding of the impact of policies on likely technology transitions on future propulsion technologies in the passenger car and light commercial vehicle sector. Within the project time and resource constraints, available literature and expert knowledge was analysed in order to provide evidence of the likely influences within the system in order to form the basis of the simulation model.

The model is a comprehensive representation of light duty vehicle fleet evolution in Europe and includes feedback between all major stakeholder groups influencing the evolution of the powertrain market shares in each of the 28 member states of the European Union. Through the use of this simulation tool, the JRC is able to evaluate the possible impacts of policies on the behaviour of the system and ultimately support the design of the best policy options to reduce the environmental impact of transportation. The baseline discussed in this document goes some way to explaining the use of the model and how it could be used to investigate the possible transition pathways for passenger and light commercial vehicle powertrains, especially as more information comes to light regarding the performance of powertrains only just coming onto the market or, indeed, yet to be commercialised.

As outlined previously the robustness of the model has been tested under a range of conditions and assumptions. In all cases, the model performed reasonably well and the model responses were evaluated vis-à-vis historical time series where available. It is accepted, however, that by the very nature of the boundaries of modelling and the living system being modelled, that continual development, testing and evaluation is necessary in order to increase confidence in the model. This can only come from continual use and iterative improvement to the model structure and the database of information required for the model to function.

The model is extensive and detailed, but remains a simplified representation of the decision processes of representative market players. The purpose of the model is to capture system interactions and feedbacks as concisely as possible and focus on impacts that system changes can make on overall outcomes, with a view of understanding the key relationships and tipping points within the system being studied. The attraction of this is that recommendations for changes can be made without needing details of all other elements of the chain. Many assumptions have been made to ensure that the model is as simple as possible, though the model is adaptable enough to be improved over time with continued learning. Future reiterations may also include other under-researched system elements such as differing business models employed by the manufacturer or modal shifts adopted by the consumer. Going forward, much more detailed analysis, focusing on sensitivities and tipping points at an individual country level, will be carried out over a greater range of scenarios to reflect on further policy options. Such analysis can be further enriched by linking with other models such as detailed emission, GIS, power dispatch or energy system models. Furthermore, the model boundaries must be recognised as limitations in data application, as are interpretation of all scenario results only relevant in the context of the baseline scenario described here, rather than taking any insight from absolute numbers in isolation.

The model is a useful tool for identifying policy levers and studying their likely impacts on technology transition towards a more sustainable road transport sector in the EU. The model can be further improved, for example through insights on the likely impact of interactions between market agents, improving detail at a subscript level, or revising constraints and assumptions. In additional to continual improvements in data and model structure as new information and resources become available, some specific areas of improvement that are currently under review and development are:

- The User choice model, including movement towards a nested structure and the determination of more suitable preference parameters;
- Vehicle market segmentation to better reflect vehicle model types (eg super mini through to SUV or niche vehicles such as high performance sports cars);
- Charging infrastructure provision, pricing and utilisation; and
- New forms of ownership and business models (eg shared ownership, service provision rather than selling artefacts).

Glossary

AFV	Alternative Fuel Vehicle
BEV	Battery Electric Vehicle
CLD	Causal Loop Diagram
EC	European Commission
EU	European Union
EU28	The 28 member states of the European Union
EV	Electric Vehicle (PHEV+BEV+FCV)
FCV	Fuel Cell Vehicle
FFV	Flex Fuel Vehicle
GDP	Gross Domestic Product
HEV	(conventional) Hybrid Electric Vehicle
ICEV	Internal Combustion Engine Vehicle
IET	Institute for Energy and Transport
JRC	Joint Research Centre
LCV	Light Commercial Vehicle
MS	Member State
NPV	Net Present Value
OEM	Original Equipment Manufacturer
PC	Passenger Car
PHEV	Plug-in Hybrid Electric Vehicle
PiEV	Plug-in Electric Vehicle (PHEV + BEV)
PTTMAM	Powertrain Technology Transition Market Agent Model
R(D)&D	Research, (Demonstration) and Development
ROI	Return on Investment
RoW	Rest of World
RW	Real World
SD	System Dynamics
SFD	Stock and Flow Diagram
TA	Type Approval (of tested vehicle emissions)
TCO	Total Cost of Ownership
TTW	Tank to Wheels
VRI	Vehicle to Refuelling Station Index
WtC	Willingness to Consider
WTT	Well to Tank
WTW	Well to Wheels

ANNEX 1: CALIBRATION ROUTINES

Production Calibration

Number of Simulations	2187
Best Payoff	-8.35223e+012
Calibration Payoffs	
global vehicle production **[138]**	
total EU Imports **[139]**	
EU28 production **[138]**	
EU28 vehicle exports **[138]**	
Calibrated Parameters	
EU Exports as percentage of global sales	
EU Imports as percentage of EU demand	
EU production capacity decrease period	
EU production capacity increase period	
EU28 average share of global shares	
Maximum unit capacity investment cost	
Minimum unit capacity investment cost	
Minimum manufacturer ROI	
Reference adjustment for utilisation	
Sensitivity of production adjustment to utilisation	

Table 11: Production calibration details

Vehicle Demand Calibration

Number of Simulations	1105
Best Payoff	-5.37065e+014
Calibration Payoff	
indicated calibrated passenger new registrations (endogenous – compared to Historic Total Vehicle Demand)	
indicated calibrated light commercial new registrations (endogenous – compared to Historic Total Vehicle Demand)	
Historic Total Vehicle Demand **[9, 42-47]**.	
total country stock (endogenous – compared to Primes Stock)	
Primes Stock **[41]**	
Calibrated Parameter	
coeff 1[Country]	
coeff 2[Country]	
coeff 3[Country]	
LCV coeff 1[Country]	
LCV coeff 2[Country]	
LCV coeff 3[Country]	
calibrated initial light commercial demand[Czech Republic, Luxembourg]	
calibrated initial light commercial demand[Luxembourg]	
calibrated initial passenger demand[Czech Republic, Slovakia, Romania]	

Table 12: Vehicle demand calibration details

Vehicle Stock Calibration

	PC	LCV
Number of Simulations	2255	2452
Best Payoff	-2.02353e+006	-1058.8
Calibration Payoffs		
PC Vehicle Stock Age Distribution **[73]**		
PC Vehicle Stock [Country] **[68]**		
LCV Vehicle Stock Age Distribution [Country, Age] **[74]**		
LCV Vehicle Stock [Country] **[75]**		
Calibrated Parameter		
PC Lamda Coefficient [Country]		
PC K Coefficient [Country]		
LCV Lamda Coefficient [Country]		
LCV K Coefficient [Country]		

Table 13: Vehicle stock calibration details

Financial Calibration

Number of Simulations	3325
Best Payoff	-4.75414e+006
Calibration Payoff	
average manufacturer revenue per vehicle **[76]**	
average vehicle pre tax price **[13]**	
component cost **[82, 83]**	
global manufacturer net income margin (endogenous – compared to manufacturer net income margin)	
manufacturer net income margin **[76]**	
Calibrated Parameter	
calibration adjustment to unit fixed costs [PICEV, DICEV, PHEV, DHEV, PPHEV, DPPHEV, BEV, FCV]	
calibration adjustment to unit production cost	
EU manufacturer other costs	
expected years to full maturity [EDS, PHEV/BEV/HEV BATT, FCS, H2ST]	
initial component cost [EDS, PHEV/BEV/HEV BATT, FCS, H2ST; by size; calibrated separately]	
manufacturer industry markup response delay	
max economies of scale effect on costs	
maximum component cost reduction through maturity [EDS, PHEV/BEV/HEV BATT, FCS, H2ST; calibrated seperately]	
minimum cumulative production for learning effects	
normal vehicle price markup	
RoW costs relative to EU	
RoW manufacturer other costs	

Table 14: Financial calibration details

Scrappage Scheme Calibration

Number of Simulations	431
Best Payoff	-320115
Calibration Payoff	
Cumulative Country Scrappage in 2009 Scheme **[DE, IT, UK, FR, ES, NL, AT, RO, GR, SK, PT] [71]**	
Calibrated Parameter	
Base Scrappage Level	
Base Scrappage Rate	
Sensitivity of scrappage rate to scrappage level [DE, IT, UK, FR, ES, NL, AT, RO, GR, SK, PT]	

Table 15: Scrappage scheme calibration details

Country Vehicle Calibration[11]

Number of Simulations	351 – 2552
Best Payoff	0.0154544 - 13.5887
Calibration Payoff	
% EU stations carrying fuel [country] **[61]**	
Average CO2 emissions of new vehicles in country **[9, 42, 44, 47, 140, 141]**	
fractional annual powertrain sales by country **[9, 40, 42-44, 47, 139, 141, 142]**	
fractional vehicles in use by type **[40, 68, 143-146]**	
Fuel price **[147-150]**	
Calibrated Parameter	
base demand kick for running costs subsidies[Sweden]	
base demand kick for subsidies[Sweden]	
base subsidies for demand kick[Italy]	
base subsidies for demand kick[Sweden]	
base subsidies for running cost demand kick[Sweden]	
calibration modifier refuelling station installation cost [BD, BE, CNG, LPG] (LT NO LPG, UK + H2, P)	
country adjustment wtc [PHEV, DICEV, CICEV, BDICEV, BEICEV] (PO +PICEV)	
country adjustment wtc[Italy,CNG ICEV]	
country adjustment wtc[Italy,LPG ICEV]	
country modifer to initial emissions	
desired refuelling station ROI	
fuel margin for infrastructure provider [BD, BE, CNG, LPG] (LT NO LPG)	
fuel profit margin	
initial EU market share[Italy,CNG ICEV,Light Commercial]	
initial EU market share[Italy,CNG ICEV,Passenger]	
initial EU market share[Italy,LPG ICEV,Light Commercial]	
initial EU market share[Italy,LPG ICEV,Passenger]	
intial EU market share [PASSENGER, LCV] (IT CICEV, PO LICEV)	
proportion passenger powertrain type [LICEV, CICEV, BDICEV, BEICEV] (BE NO CICEV,CY, DE, UK)	
Proportion Passenger Powertrain Type[Italy,CNG ICEV]	
Proportion Passenger Powertrain Type[Italy,LPG ICEV]	
sensitivity of demand kick to running costs subsidies[Sweden]	
sensitivity of demand kick to subsidies[Italy]	
sensitivity of demand kick to subsidies[Sweden]	
sensitivity of scrappage replacement skew to relative incentive price	
sensitivity to popularity of prevalence	
user demand responsiveness to subsidies[Italy]	
user demand responsiveness to subsidies[Sweden]	
vehicle size relative emissions [S, L]	

Table 16: Country vehicle calibration details

[11] This calibration was carried out separately for each country, each having up to 32 calibrated parameters.

ANNEX II: SENSITIVITY ANALYSIS

The sensitivity analysis performed in the development of the PTTMAM was a three stage process as follows:

- Using the Vensim optimiser, an automatic "parameter percent" sensitivity analysis is made. This takes each input and modifies it by + then – a certain percentage, then runs a simulation and records the change in the selected payoff function.
- Ranking each input in order of the size of the impact its change makes on each payoff function.
- Taking the top 10 ranked inputs and performing Vensim sensitivity analysis, recording the range of outputs for a number of KPI.

In order to perform the sensitivity analysis, 146 input constants were chosen but, because of the combinatorial effect of the subscripts, this necessitated 2,777 values be changed for +20% and for -20% from the baseline. Using a desktop PC (Intel® Core™ i7 CPU, 2.66 GHz, 12 GB RAM, Windows 7 (64-bit OS)) the entire sensitivity analysis timed at a little over 9 hours. The top 20 inputs influencing the uptake of EV and total emissions are shown at Table 17.

PARAMETER	Base	Largest % Change to 2050		Emissions Rank
		EV	Emissions	
initial base unit production cost [Petrol ICEV,Small]	8000	12.28	-1.69	8
annual change in passenger importance of criterion [Environment,Fleet,Urban]	0	8.68	-2.68	1
annual change in passenger importance of criterion [Environment,Private,Urban]	0	8.20	-2.44	2
reference minimum price differential for wtc	0	7.40	-1.03	11
initial powertrain utility [Diesel ICEV,Medium,Environment]	0.67	5.47	-1.98	5
annual change in passenger importance of criterion [Choice,Fleet,Urban]	0	5.26	-1.82	6
annual change in passenger importance of criterion [Popularity,Fleet,Urban]	0	4.81	-2.05	4
annual change in passenger importance of criterion [Popularity,Private,Urban]	0	4.74	-1.752	7
initial base unit production cost [Petrol HEV,Small]	8000	4.49	-0.09	130
annual change in passenger importance of criterion [Choice,Private,Urban]	0	4.40	-1.41	9
initial powertrain utility [Petrol HEV,Medium,Environment]	0.7	4.22	-0.26	53
initial powertrain utility [Petrol HEV,Small,Environment]	0.77	4.12	-0.14	89
initial powertrain utility [Petrol ICEV,Small,Environment]	0.803	4.05	-1.37	10
initial base unit production cost [Petrol HEV,Medium]	9000	3.87	-0.06	190
Base WtC Decay	0.15	3.86	-0.18	68
annual change in light commercial importance of criterion [Urban,Environment,Fleet]	0	3.37	-0.89	15
initial base unit production cost [Biodiesel ICEV,Medium]	9000	3.18	-0.04	226
initial base unit production cost [Bioethanol ICEV,Small]	8000	3.07	-0.10	114
initial base unit production cost [Petrol ICEV,Medium]	9000	3.04	-0.50	27
initial powertrain utility [Petrol ICEV,Medium,Environment]	0.73	2.94	-2.12	3

Table 17: Sensitivity analysis top parameters

In the table above, each of the top 20 parameters are listed with the percentage impact on cumulative EV sales and on cumulative emissions as a result of a 20% increase or decrease in the value of the parameter. The high sensitivity to costs and passenger importance indicate the need to concentrate on ensuring confidence in the input values. The parameters are ranked in order of magnitude of influence on cumulative EV sales with their equivalent impact on cumulative emissions ranked in the final column. Of the top 20 influences on cumulative EV sales, 13 are also in the top 20 influences on cumulative emissions. It is clear that costs, *User* importance of attitudes and utility are all key inputs that affect the model outputs. It is for this reason that the next update of the PTTMAM will include a review of these parameters and the related choice model structure. The next step was to carry out further sensitivity testing based on the top ten parameters from Table 17, as listed in Table 18.

Parameter	Baseline	Range
initial base unit production cost [Petrol ICEV,Small]	€8000	€6000 - 10000
annual change in passenger importance of criterion [Environment,Fleet,Urban]	0	-5 – 5%
annual change in passenger importance of criterion [Environment,Private,Urban]	0	-5 – 5%
reference minimum price differential for wtc=RANDOM_UNIFORM(0,0.25)	0	0 – 0.25
initial powertrain utility[Diesel ICEV,Medium,Environment]	0.67	0.5 – 0.8
annual change in passenger importance of criterion[Choice,Fleet,Urban	0	-5 – 5%
annual change in passenger importance of criterion [Popularity,Fleet,Urban]	0	-5 – 5%
annual change in passenger importance of criterion [Popularity,Private,Urban]	0	-5 – 5%
initial base unit production cost[12] [Petrol HEV,Small]	€8000	€6000 - 10000
annual change in passenger importance of criterion [Choice,Private,Urban]	0	-5 – 5%

Table 18: Further tested parameters

In this standard Vensim multivariate sensitivity analysis, 200 simulations are carried out with the programme randomly selecting values for the parameters within the range indicated in Table 18. In the following graphs of our key indicators, confidence bounds using the percentiles 50%, 75%, 95% and 100% are shown as coloured bands. These are computed at each point in time by ordering and sampling all the simulation runs. Thus, for example, for a confidence bound at 50, 1/4 of the runs will have a value bigger than the top of the confidence bound and 1/4 will have a value lower than the bottom. To interpret this, 50% of all the sensitivity runs fall within the central 50% band, 75% within the 75% band (and including those in the 50% band) and so on.

Emissions

Figure 46 shows the range of possible outcomes when Vensim randomly samples values taken from the table above. By 2050, WTW emissions range from around 475 to 515 Mtonne/year with a mean around 500.

[12] Cost of the "vehicle glider" (the car without powertrain components.).

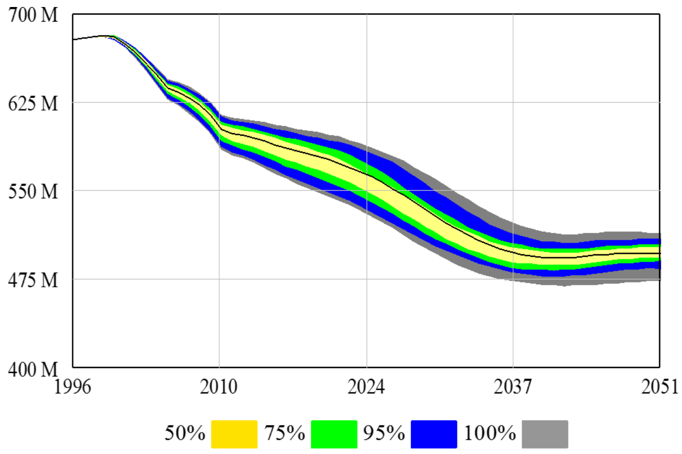

Figure 46: Sensitivity analysis - emissions

Market Shares

The range of outcomes is more clearly illustrated when it comes to market share. Figure 47 shows market share for all the powertrain classes and clearly demonstrates the wide range of possible outcomes given the distribution of input values, understandable given the extreme time horizon for prediction.

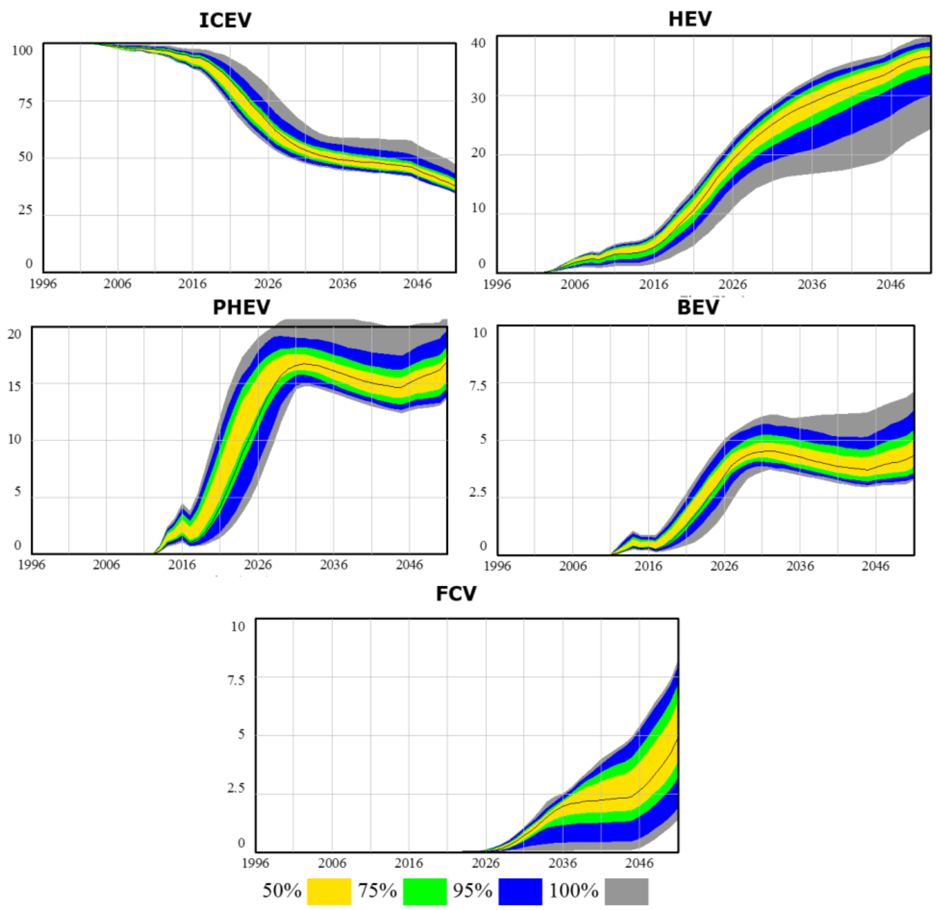

Figure 47: Sensitivity analysis - market share

ANNEX III: REALITY CHECKS

There are two types of equations that can be defined in Vensim to make use of the Reality Check functionality: Constraints and Test Inputs. Constraints make statements about the consequences that should result from a given set of conditions. They are called Constraints because they specify the way in which the Test Inputs should constrain behaviour. The violation of a Constraint indicates a problem with the model. Test Inputs are a way of specifying the conditions or circumstances under which a Constraint is binding.

Test Inputs allow you to define alternative conditions by changing equations for a variable in the model. You can only use Test Inputs in the conditional portion of a Constraint equation. The major reason for defining Test Inputs is to give a name to the experiment being conducted. This can make reading the Constraint much easier. Constraints take the form:

name :THE CONDITION: *condition* :IMPLIES: *consequence*

:THE CONDITION: and :IMPLIES: are special keywords in Vensim. *condition* and *consequence* are logical expressions described below. The name of a Constraint must use letters and numbers just as other variables in Vensim. Constraints use a condition and a consequence that are both defined as logical expressions. An example of this would be:

no capital no production :THE CONDITION: Capital = 0 :IMPLIES: production= 0

When testing Reality Check equations, Vensim will force a condition to be true whether the model generated values suggest it should be true or not, and test the consequence for truth. When the condition is true, but the consequence is not, Vensim reports the problem as a Reality Check failure. Reality Check equations involve systematic intervention in the basic structure of the model. They are qualitatively different from sensitivity analysis in that there are not any well-defined pathways of influence. Test Inputs and Constraints can cause changes to be made at almost any point in a model. In order to accomplish the changes involved in running Reality Check equations, Vensim restructures the model, adding equations and modifying the sequence in which equations are computed to match. After completing Reality Check equations, Vensim returns the model to its original structure.

The Reality Checks carried out in the validation of the PTTMAM are set out in Table 19. Example countries and powertrains were chosen as representative of the model.

Name	Test Input	Description	Outcome
No population, No sales	**No population** (sets population for Germany to zero)	If there is no population, then there should be no vehicle demand	Initially failed as scrappage schemes did not account for population size. Minor technical adjustment to ensure no sales if no population
No population, Country stock decline	**No population** (sets population for Germany to zero)	If there is no population, any stock should decline at a rate governed by average vehicle life. This is an unrealistic test as zero population should simply mean zero stock, this test is simply allowing for the effect of zero sales	Passed
No population, No registration tax revenue	**No population** (sets population for Germany to zero)	If there is no population, then there should be no tax revenue from vehicle registrations	Passed
No willingness to buy, No sales	**No willingness to buy** (sets willingness to buy Petrol ICEV in Germany to zero)	If there is no willingness to buy a powertrain, then there should be no sales	Initially failed as willingness to buy was influencing indicated market share which is then smoothed to provide an actual market share. This is an error as willingness to purchase should be an immediate impact. This was rectified by including willingness to buy after the smoothing function
No demand, Production capacity reduces to zero	**No export demand** **No domestic demand** (sets exports / domestic sales for Medium size Petrol ICEV to zero)	If there is no domestic or export demand, production capacity should be shed at a rate governed by the average time to reduce capacity	Passed
No demand, No production	**No export demand** **No domestic demand** (sets exports / domestic sales for Medium size Petrol ICEV to zero)	If there is no domestic or export demand, then there should be no production	Passed
No forecast demand, No capacity expansion	**No forecast demand** (sets forecast future demand for Medium size Diesel ICEV to zero)	If there is no forecast future demand for diesel vehicles, then there should be no manufacturer capacity growth	Passed
No charging infrastructure, No BEV sales	**No urban charging infrastructure** **No non-urban charging infrastructure** (sets access to charging infrastructure in urban / non-urban areas in Germany to zero)	If there is no access to a charging network, then there should be no sales of BEV	Passed
No fuel demand, Infrastructure declines	**No fuel demand** **No fuel demand** forecast (sets fuel demand / forecast fuel demand for Biodiesel in UK to zero)	If there is no current or future forecast demand for a fuel, then any infrastructure supplying that fuel should be withdrawn at a rate determined by the speed at which infrastructure can be shut down	Passed
No fuel demand, No infrastructure growth	**No fuel demand** **No fuel demand** forecast (sets fuel demand / forecast fuel demand for Biodiesel in UK to zero)	If there is no current or future forecast demand for a fuel, then there should be no growth in any infrastructure supplying that fuel	Passed

Table 19: Reality checks

ANNEX IV: EXTREME CASE TESTING

Most extreme cases do not result in significant deviation from baseline on the KPIs presented here. VHET lead to a great reduction in emissions, whilst NET results in significantly higher emissions. In terms of EV share, VHET defines the potential of EVs as it yields 100% EV sales by 2050 (leading to 2050 annual emissions over half that of the base case), whereas the EV market stagnates under NET.

Test	Description	2050 EV[13] Sales Market Share (%)	2050 CO_2 Emissions (Mtonnes/year)
Base	Base level scenario as described in Section 6	26.32	497
Very High Subsidies VHS	*100% of cost differential of PHEVs, BEVs and FCVs from 2011 through to 2050*	50.88	465
No Subsidies NS	*No subsidies for any powertrain or period*	30.41	493
Very High Learning Rates VHLR	*Electric drive system, BEV battery, HEV battery, PHEV battery, Hydrogen storage tank, Fuel cell system are all at 50%*	40.64	482
Very High Emissions Targets VHET	*A target of 0 g/km from 2015 through until 2050*	99.88	218
No Emissions Target NET	*No targets*	3.85	645
FCV Reduced Costs FCVCR	*FCV costs assumed same as BEV*	37.68	487
Charging Infrastructure Subsidy CIS	*100% support to charging-post infrastructure from 2015 to 2050*	37.55	487
Very High Hydrogen Fuel Support VHHFS	*100% subsidy for hydrogen fuel price and tax from 2000 and 100% support to infrastructure from 2015 to 2050*	36.96	488
Very High Biofuel Subsidy VHBS	*100% subsidy for biofuel price and tax from 2000 to 2050*	25.52	475

Table 20: Extreme case tests

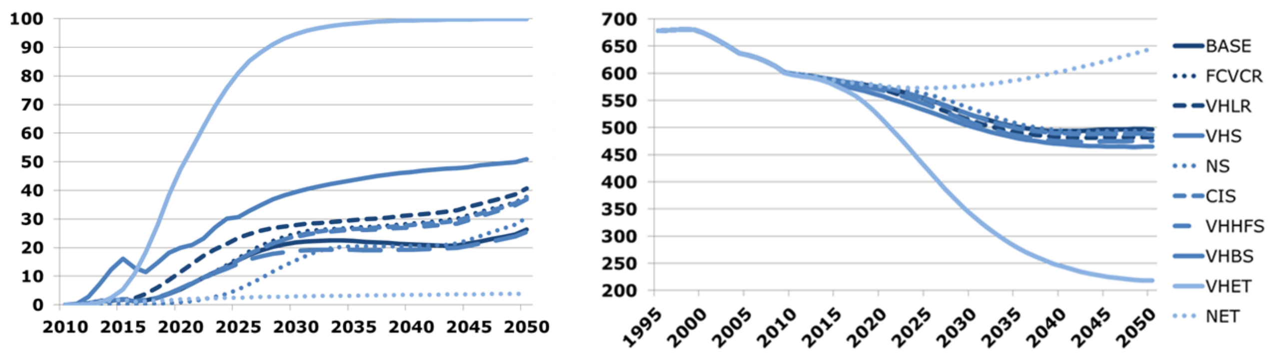

Figure 48: Extreme case test results

Left: EV market share; Right: CO_2 emissions (RW, WTW, MT/year)

[13] BEV, PHEV and FCV

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List of Tables

List of Figures

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