Attitudinal Tension & Moral Dilemma Dynamics: The Role of Psychological Determinants in Overcoming the Behaviour Inertia in Car Use

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ABSTRACT

Tackling climate change has become a priority of the political agenda in many countries around the world. The problems related to global warming have been mainly attributed to human actions, as anthropogenic behaviours are responsible for the excess of CO_2 and other greenhouse gases. Therefore, understanding the factors that drive these behaviours are the first step to create effective policies, in order to know how to change people's non-environmentally friendly behaviours.

This thesis assesses the usefulness of system dynamics to create a simulation model that can explain the main theories proposed in environmental psychology to reduce car use. In the UK, transportation has become one of the major responsible for emitting more greenhouse gases than any other sector. Therefore, understanding the psychological determinants that impede drivers to consider alternative transport modes becomes essential to fight climate change.

Based on the data collected by Department for Transport (UK), this thesis tests several changes on psychological determinants that can trigger important changes in the levels of car use. The factors involved in explaining car use are described, as well as the causes that play a key role in determining the behavioural intention towards car use. The study reveals several feedback loops that explain individual's car choice. It also demonstrates that creating multi-level interventions may be designed, so as to obtain important behavioural changes in this matter. For example, modifying car habit, as well as personal norms, and attitudes lead to faster changes than focusing on one variable at a time. In theoretical terms, the model reveals the supremacy of changing factors related to the Theory of Planned Behaviour (TPB), suggesting a reason it has become so popular. Nevertheless, the model demonstrates that modifying TPB alongside other factors from other theoretical frameworks lead to more satisfactory results.

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1 Introduction

In the last 20 years, scientists have increased the volume of research on understanding how people can be encouraged to increase their ecological behaviour (Carrus, et al., 2008; Lanzini & Khan, 2017) since human quality of life depends on environmental factors. Addressing environmental issues is not easy as contemporary environmental problems, such as climate change and resource depletion, can only be solved if deep structural changes in transport, energy, agri-food and other systems alter the overall configuration of natural resource consumption by humans (Elzen, et al., 2004; Geels, 2011). In achieving that structural change, researchers, non-governmental institutions and governments have been trying to enact and predict people's ecological behaviour to diminish negative environmental consequences, and this is because scientists have concluded that pro-environmental behaviour has become a key factor of building and changing societies towards a more sustainable growth (Coelho, et al., 2017).

Environmental problems such as climate change, mass extinction, air pollution and resource depletion (e.g. deforestation) have been reported as a great challenge for society because their solutions require deep structural changes in the economic systems that lead modern societies (Geels, 2011). Transport, energy, water and agri-food are complex systems that imply the actions of multiple actors for their production and consumption. Therefore, a sustainable growth will only be possible if there is an effective coordination and cooperation between firms/industries, international organisations (e.g. WWF), charities, policy makers, politicians, consumers, small communities, universities and researchers (Geels, 2011). So far, different theoretical frameworks have been proposed across a wide range of research fields such as economics, behavioural economics, social marketing, environmental psychology, energy policy, engineering and transportation (Knoflacher, et al., 2000; Kollmuss & Agyeman, 2002; Abrahamse, et al., 2005; Beckenbach & Kahlenborn, 2016).

To better explain pro-environmental behaviour (PEB), researchers have decided to carry out more integrative works (see: Kollmuss & Agyeman, 2002; Bamberg & Moser, 2007; Vij, et al., 2013; Unsworth, et al., 2013; Chng et al., 2018) because the PEB mechanism is so complex (Kollmuss & Agyeman, 2002; Carrus, et al., 2008; Abrahamse, et al., 2009; Chng, et al., 2018) that no single theory can perfectly explain people's behaviour by itself (Kollmuss & Agyeman, 2002; Chng, et al., 2018). Therefore, multidisciplinary research fields have been crucial to helping policy makers to better approach the representation of the real world and PEB. This complexity arises because people's environmental behaviour relies on a problem of consistency. In other words, there is a considerable discrepancy between people's environmental awareness and their actual actions in terms of everyday experiences (Uusitalo, 1990; Diekmann & Preisendörfer, 1998). For instance, everyone knows that use of private cars is one of the main sources of pollution problems (Gärling, et al., 2002; Bamberg & Schmidt, 2003; Abrahamse, et al., 2009). However, in the 1950s, less than 20% of households in the UK owned a car, a percentage that is far away from today because of the 74% of households that own at least one car (Marsden, et al., 2018). Similarly, Pichert and Katsikopoulos (2008) found that people usually say that they prefer a green source for electricity, but do not generally use it, even though there are a lot of sources of green electricity available.

1.1 Pro-environmental behaviour: definition and antecedents

Pro-environmental behaviours can be defined as any behaviour that avoids the negative side effects of people's action on the natural world (Stern, et al., 1999). For instance, energy-saving (Steg & Vlek, 2009), reducing car use (Abrahamse, et al., 2009), and recycling (Ulli-Beer, et al., 2010) can be seen as pro-environmental behaviours, because when executing them the anthropological impact on the environment decreases.

Currently, understanding what influences an individual's engagement in more green activities is a complex issue that is still a work in progress (Coelho, et al., 2017). For that reason, different areas (e.g. psychology, transport, behavioural economics) have been taking various approaches to propose a better explanation of what triggers a pro-environmental behaviour and what it takes for a green intervention to be successful base on environmental performance indicators.

The oldest models proposed in the early 1970s to explain PEB were based on a linear progression that presented environmental attitude as the predictor of pro-environmental behaviour and environmental knowledge as the predictor of environmental attitude (Kollmuss & Agyeman, 2002). Therefore, for a long time, it was believed that promoting a pro-environmental behaviour would be addressed by educational interventions (Kollmuss & Agyeman, 2002). However, environmental scientists have proved that this linear assumption is far from being true because, in many cases, increasing the environmental knowledge did not make people engage in pro-environmental behaviour (Hines, et al., 1987; Kollmuss & Agyeman, 2002; Bamberg & Möser, 2007; Carrus, et al., 2008; Unsworth, et al., 2013; Chng, et al., 2018).

That complexity was introduced to studies of PEB in the 1980s, when Hines et al. (1987) presented a more sophisticated and integrative study that synthesised the main factors that predicted responsible environmental behaviour. Based on the Theory of Planned Behaviour (TPB) and using a meta-analysis of 128 studies related to PEB, they concluded that green behaviours are predicted by: (1) Problem awareness, (2) Knowledge of action strategies, (3) Locus of control (self-perception about if I can perform a friendly environmental behaviour), (4) Attitudes, (5) Verbal commitment, and (6) Individual sense of responsibility. Twenty years later, Bamberg and Moser (2007) performed a new meta-analysis to test the relationships reported by Hines et al. (1987). By analysing 57 effect sizes from 46 independent studies, the authors constructed a matrix of pooled correlations to not only confirm the relationship proposed by Hines et al (1987) but also, in a second step, to run a structural equation modelling, to quantify the causal relationships. As a conclusion, Bamberg and Moser (2007) recognised that, in the two decades since Hines et al.'s work, important efforts had been made in environmental psychology research to identify central psycho-social determinants of people's intention to engage in pro-environmental behaviour.

Two theoretical models have been largely used to predict a pro-environmental behaviour in the last decades (Bamberg & Möser, 2007). All of those who see PEB essentially as pro-social behaviour roused, frequently utilise the NAM (Norm-activation model) (Schwartz, 1977), while researchers that see PEB as a rational way of thinking, which is triggered by self-interest motives, regularly use the TPB (Ajzen, 1991). The main reason to explain this preference is because both theoretical models have been applied to an extensive variety of contexts (Sawitri, et al., 2015), showing empirical results and relevant insights into predicting pro-environmental behaviours (such as travel behaviour, waste composting, water use, etc.) (Steg & Vlek, 2009). For instance, TPB has gained a lot of popularity due to meta-analytic reviews that have proved good levels of the explained variance for attitude and behavioural intention constructs (Bamberg, 2002). However, several authors have demonstrated that these models can improve its explanatory capacity in PEB

(Stern, et al., 1999; Bamberg & Schmidt, 2003; Carrus, et al., 2008; Chng, et al., 2018) by merging different theoretical frameworks.

Among the most remarkable models in environmental psychology, based on TPB and NAM, are: the value-belief norm (VBN) model (Stern, 1999), which emerges from the integration of the value and the norm-activation theories, so as to improve the capacity of explanation from a pro-social perspective in pro-environmental behaviours; Bamberg and Möser's (2007) model, which includes the most significant constructs proved to predict pro-environmental behaviour from TPB and NAM; the Stage Model of Self-Regulated Behavioural Change (Bamberg, 2013), a new model that aimed to explain behavioural change and which was created by extending the model action-phase (MAP) (Heckhausen & Gollwitzer, 1987) with the constructs proposed by NAM and TPB due to its lack of clarity to define the formation of intention (goal intention, behavioural intention and implementation intention); and CAUSE (Chng, et al., 2018), which intends to explain car use by integrating several models that include psychological determinants proposed by NAM and TPB.

1.2 Pro-environmental behaviour and the 'value-action gap'

Controlling major environmental problems represents a huge social challenge as it requires an effort from different actors such as individuals, communities, businesses, governments and environmental organisations (Blake, 1999). Currently, more research has been conducted about understanding the sources and the causes of global warming and what actions need to be performed so as to prevent an environmental catastrophe in both home and workplace settings. However, research has found that, even though awareness about the environment is spread across the population, the responsibility of acting is often absent among the environmental stakeholders. This lack of correspondence between verbal and actual commitment has attracted the attention of many environmental psychologists (Chung & Leung, 2007; Flynn, et al., 2009), looking for mediators and moderators that can give an explanation for why this happens. This problem has been documented as the 'value-action gap', widely known as well as 'attitude-behaviour gap' (Harrison, et al., 1996; Chung & Leung, 2007).

Unfortunately, accepting, implementing and achieving sustainable goals are closely related to how environmental concern (EC) is translated into action. EC is defined as the degree to which people are aware about environmental issues and climate change (Dunlap & Van Liere, 1978); therefore, it becomes necessary, but not sufficient, to trigger a pro-environmental behaviour as it is the process of rationalisation and not the action itself. In fact, when individuals do not have an integrated attitudinal aspect towards the environment, EC is outweighed as a set of others' attitudes (Blake, 1999) or goals (Unsworth, et al., 2013), or are more relevant in an individual's life or immediate context, triggering a lack of interest or commitment to prevent future acts that could harm the environment. For this reason, decades of research in understanding how to translate environmental concern into action have been carried out, clarifying the process with models that include psychological factors such as knowledge, norms, values, emotions and habits (Hines, et al., 1987; Fransson & Gärling, 1999; Bamberg & Möser, 2007; Carrus, et al., 2008). For example, the role of affective aspects (Coelho, et al., 2017) has been gaining more attention in explaining PEB. Human beings are considered as individuals that connect emotionally with nature, so individuals with high emotional affinity towards the environment tend to feel more responsible and attached to the idea of protecting it (Vaske & Kobrin, 2001; Coelho, et al., 2017). Additionally, researchers have concluded that high levels of people's positive affect increase the probability of paying more attention to information concerning the environment; thus, this psychological dimension could accelerate the adoption of PEB (Markowitz, et al., 2012). Additionally, place attachment has proven to be a strong factor to promote various pro-environmental behaviours (Brown, et al., 2016).

On top of discovering additional psychological determinants that mediate and moderate the relationship attitude-behaviour, researchers have defined series of contextual aspects and barriers that determine people's environmental action such as sense of individualism (Blake, 1999), discretionary time available (Chai, et al., 2015), direct vs indirect experiences with natural environments (Rajecki, 1982), ascription of responsibility (Bamberg & Schmidt, 2003), psychological distance to climate change (Spence, et al., 2012), goal efficacy and attractiveness (Unsworth, et al., 2013), individual's identities (Gatersleben, et al., 2014), organisational support and sustainable initiatives at work (Unsworth, et al., 2020), goal setting and feedback provided (Davis, et al., 2020), and environmental stressors (Homburg & Stolberg, 2006), among others. Therefore, there is no simple explanation of how to overcome the 'value-action gap'.

In the next chapter, an extensive explanation will be offered regarding the most relevant theoretical models proposed in environmental psychology and transport to explain car use, which is the topic addressed in this thesis. The next section will develop the rationale behind the selection of the pro-environmental behaviour under study in this thesis.

1.3 Modelling in environmental psychology

As was discussed earlier, understanding why, when and how people can engage in environmental activities is a complex task to solve as multiple explanations have been given. Each theory, with its pros and cons, has faced the challenge to foresee the psychological conditions that predict a pro-environmental behaviour. For example, Bamberg and Schmidt (2003) compared empirically the predictive power of three models (TPB, NAM, and TIB)[1] in the context of car use, in which they found that personal norms do not play a key role in predicting car use, finding a better capacity of explanation from TPB and TIB. However, TPB did not have the capacity to capture the complexity of the effect of subjective norms, leading the researchers to conclude that a more self-generated expectation is not represented. These differences led the researchers to suggest that the models should be seen as supplementary models, reaffirming that predicting a pro-environmental behaviour still requires integration of different theoretical frameworks to achieve a comprehensive understanding. Chng et al. (2018) faced the same challenges, proposing a more extensive model (CAUSE) than TPB, and NAM, repeating that explaining pro-environmental behaviours needs more integrative works.

Nevertheless, some researchers still criticise these approaches, arguing that the unidirectional models widely used in psychology to predict observable outcomes are not consistent with the complexity described by the theoretical frameworks (Hirsch, et al., 2007). Moreover, the lack of temporal representation reflects a contradiction as many psychologists believe psychological conditions occur and evolve over time, but regression modelling or structural equation modelling are incapable of dynamically capturing changes over time. All of this criticism is in fact because people's travel behaviour has been recognised as a complex system (Bamberg, 2013; Chng, et al., 2018; Klöckner & Blöbaum, 2010; Kroesen, et al., 2017; Schröder & Wolf, 2017). A complex system is a system composed of several interconnected elements that interact with each other in a non-linear way, in which cause-effect relationships are not necessarily closely linked in time (see chapter 2 for more details about complex systems). For that reason, modellers in psychology have

[1] Theory of Planned Behaviour model, norm-activation model and the theory of interpersonal behaviour.

pointed out that new methodologies are needed, in order to overcome multiple barriers presented in the current statistical models, including dismissal of multi-level interactions across time (Schröder & Wolf, 2017), denial of bi-directional relationships (e.g. attitude-behaviour) (Kroesen, et al., 2017), time taken for psychological determinants to form (Andrighetto, et al., 2010), and lack of feedback loops (Ulli-Beer, et al., 2010).

Many advances have been seen in the application of computational-based tools in psychology and environmental psychology. For example, Ulli-Beer et al. (2010) presented a System Dynamics (SD) model to explain how social norms change dynamically over time, affecting behavioural patterns in the context of recycling. In car sharing, Schröder and Wolf (2017) constructed InnoMind, an agent-based model that attempts to explain the evolution of environmental attitudes and behaviours. Another example is Struben and Sterman's (2008) SD model, which explains the adoption of alternative fuel vehicles (AFVs), in which policy implications were proposed to accelerate the acceptance of this market. Feola et al. (2011), used the Theory of Planned Behaviour in a system dynamics model to understand in which conditions it is more probable that people will wear personal protective equipment against pesticide use.

The acceptance of using more computational approaches in environmental psychology, gives solid confidence that SD can help to develop the theoretical framework established in this thesis. SD can facilitate the understanding of the complexities behind car use from environmental psychological perspectives, ensuring the possibility to study the underlying conditions that create long-term changes towards a more desirable behaviour in the context of climate emergency.

1.4 System dynamics

System dynamics (SD) was introduced in the 1960s at Massachusetts Institute of Technology as a modelling and simulation methodology for the long-term decision-making analysis of dynamic problems (Forrester, 1961). At the beginning, SD was mainly applied to solve managerial problems, in which one of the first applications was to understand the employment instability at General Electrics (GE) during the 50s/60s. After obtaining promising results, the SD research field attracted real interest, establishing a group of researchers led by Jay Forrester at MIT, who formalised the practices to develop a computational-based model. Years later, the first non-corporate SD simulation model was introduced in the book “Urban Dynamics”, which was an attempt to study and evaluate urban development policies, showing counter-intuitive policies. Currently, the application of SD is uncountable as the methodology has been found in a wide range of different fields including transportation, marketing, economy, sociology, environment, agriculture and construction.

SD is in principle a computational-based technique originated from the feedback control theory. The fundamental idea of SD is to understand the effect of feedback loop structures embedded in a system that emerge from the complexity of dynamic systems because the variables in the system are not related unidirectionally, but in a loop[2]. For example, the hydrological cycle of the Earth represents a system with multiple circular causality-based relationships.

One of the main critiques of system dynamics relies on the simplicity of representing a real-life situation. By design, SD models are a simplification of how variables in a system are related,

[2] Some variables can affect others in the system, and then be affected by the subsequent outcome of that interaction (Sterman, 2000; Morecroft, 2015).

combined with, and they are also a representation of the modeller's mental model; therefore, the models lack perfection as they have individual biases in how the world is perceived and the functioning of the systems. Criticism of their imperfections has been widely discussed by SD modellers including Forrester, Sterman, Morecroft, Meadows and Barlas, who have given answers concerning to how to treat SD modelling in the context of policy analysis and managerial problem-solving processes: all SD models are imperfect as by nature they represent a simplified version of a real-life situation within reasonable boundaries; therefore, the simulated system's behaviours are not entirely caused by all the potential variables involved. In practice, it is impossible to include all the variables and try to give them an endogenous explanation simply because SD models are born from mental models, which implicitly have cognitive limitations to interpret how systems behave. Modellers can integrate external knowledge (e.g. experts) to improve a model's confidence, but worldviews are widely spread among mental models as humans differ in their recognition, organisation and understanding of external stimuli; thus, assumptions and biases are inherent in the process of designing a simulation model. For this reason, SD models have to be taken as a tool that helps to uncover one's biases, in order to expand one's critical thinking skills. Instead of thinking that an SD model tries to reveal the Truth, the fundamental idea must be based on its capacity to help one's judgement through providing a new lens to see the world. More details about system dynamics methodology will be provided in Chapter 3.

As well as system dynamics, discrete event simulation (DES) and agent-based modelling (ABM) are also popular simulation approaches in areas such as operational research (Maidstone, 2012), social psychology (Schröder & Wolf, 2017; Smith & Conrey, 2007), health care (Cassidy, et al., 2019), and business & management (Chen, et al., 2008). DES models a process as a sequence of separated events in time. With this simulation approach, a real-life system is decomposed into a set of logically discrete processes, where each event has a defined role, and can only occur when a specific trigger is activated at a particular time. The result of each event can be an outcome that serves as an input to one or more other events. This approach is widely used to study queue behaviours or transport network (Maidstone, 2012; Pfaffenbichler, 2003). ABM is also a computational technique that allows to model the interaction of autonomous self-directed agents in a simulated space. In it, each agent has a set of rules predefined to determine its decision-making progress in the system. Agents can execute one or several actions within the system, which in turn influence the behaviour of other agents. These several interactions lead to the emergence of higher-level system properties, which determine the behaviour of the system (Schröder & Wolf, 2017). For this reason it is known as a bottom-up simulation technique, due to the behaviour of the system that it is under study arises from these multiple and complex interactions among the agents and the agents with the simulated environment. More details about these two other modelling approaches are discussed in section 3.2 and 3.3.

1.5 Topic selection: pro-environmental behaviour and transport mode choice

Among all the possibilities to achieve sustainable growth, such as recycling, reducing water, low-carbon mobility and energy consumption, the focus of this research is to describe and simulate the mechanism of English commuters' willingness to reduce car use. Globally, transportation is one of the main sources of greenhouse gas (GHG) emissions, which causes 26% of the worldwide CO_2 production. Policy makers have noted that, for the sake of the environment, car use has to decrease significantly in the near future (Bamberg & Schmidt, 2003), but the increase in motor vehicles seen in the last decades has created a feeling of uncertainty regarding whether this is feasible or not. The expansion of the car market has increased its contribution to climate change in many areas around the world (Chapman, 2007; Abrahamse, et al., 2009; Buehler, 2011; Lind, et al., 2015), and, if governments do not normalise the current trend of individuals' choice of travel (Lanken, et al., 1994), it is expected that the global demand for road travel will be double in 2050 in comparison to 2018 (International Energy Agency, cited in Chng, et al., 2018).

In the UK, the tendency remains the same, where the transport sector generated the largest share of greenhouse gas emissions in 2016, compared with energy supply (25%), business (17%), residential (14%), and agriculture (10%), among others (Department for Business, 2018). Car and taxis accounted for 57% on average of domestic transport's GHG emissions between 1990 and 2018 (see Figure 1). However, the most concerning issue is that the estimation of the amount of pollution coming from cars might be underestimated. The Australian Automobile Association Commission found that on average new cars (2014 models or newer) were 25% less fuel efficient than manufacturers claimed (60% in some cases)[3]. Therefore, even when there is no clear definition of an eco-friendly method of transport, as each transport mode has a level of pollution associated with it (Lind, et al., 2015), it is clear that part of the solution requires the decrement of car use as any other alternative such as rail, buses or active transportation has a lower impact per person on climate change (Bamberg, 2002; Lind, et al., 2015). Thus, this thesis assumes that accepting an alternative transport mode to the car is by definition a pro-environmental behaviour (Bamberg, 2002; Abrahamse, et al., 2009; Brown, et al., 2016).

[3] For more information, visit: https://www.theguardian.com/business/2017/mar/27/new-cars-far-less-fuel-efficient-than-manufacturers-claim-research-finds

Figure 1. Greenhouse gas emissions by domestic transport in the UK.

Source: Own elaboration by using Table ENV0201 (TSGB0306) from the Department for Transport UK. Bars represent the share of pollution of each source, while the lines (total domestic transport) represent the total amount of greenhouse gas emissions in million tonnes of carbon dioxide equivalent.

The benefits of reducing car use are undervalued. Diminishing it is not only more efficient regarding energy[4] and traffic decongestion (Archetti, et al., 2018), also public transportation or active transportation (e.g., walk) modes improve the environment without pressuring governments to impose new regulation or taxes (Marsden, et al., 2018). However, cultural values and environmental infrastructure have been supporting car use and ownership, thereby affecting the development of more efficient means of transportation (Brown, et al., 2007). More than 80% of the passenger kilometres recorded during 2016 was by car, taxi or van (Department of Transport,

[4] According to the key world energy statistics report (International Energy Agency, 2017) the energy used to transport one passenger-kilometre fluctuates between 0.2 and 0.6 (MJ/pkm), which is much lower than car passengers (over than 2 (MJ/pkm).

2017), in which cars accounted for 62% and 78% of the trips and distances (share of mode[5]) made by passengers, respectively. Related to this, commuting was the second most common reason for travelling within the UK population (19% of the trips), in which the usual mode of travel was by car (67% of the trips), followed by walk and rail (10% each), bus (7%) and other types of transport (5%) (Department of Transport, 2017). Therefore, the transport sector and the method of commuting constitute a significant target group, in which important decarbonisation levels can be reached by discouraging car commuters.

Based on these facts, this thesis's interest lies in understanding car use in the context of commuting to answer how this behaviour can be reduced. To achieve this aim, an extensive review of the psychological and transport theoretical frameworks was carried out, so as to acquire the necessary knowledge for the integration and modelling of the most relevant cognitive models in predicting car choice. Alongside the continuous revision of the literature, data collected from interviews with experts was gathered to consolidate a broad, integral and complete conceptualisation of why people use cars. The following chapters will show the process of developing a simulation model with psychological determinants to predict the behaviour towards car use.

1.6 Decarbonising the UK: what is the plan?

Currently, the Climate Change Act implies that the UK must reduce its emissions by up to 80% before 2050. Fulfilling this rule involves a short-term goal where 26% of emissions must be

[5] The percentage represents the fraction of trips made by car and compared to buses, rail network and active transportation.

reduced before 2030 (Marsden, et al., 2018). To achieve it, the Committee on Climate Change proposed that the low-cost approach to decrease that amount of carbon emission needs 60% of new sales of cars and vans to be ultra-low emission vehicles (e.g. electric or hybrid cars) and 32% of conventional cars need to increase their efficiency (Marsden, et al., 2018). Moreover, the report also claimed that the demand for biofuels needs to rise to 11% and travel demand decrease by 5% below the baseline by 2030. However, in 2018, it was found that transport pollution had risen three years in succession' to its most elevated amount since 2009 (Marsden, et al., 2018).

By analysing this proposal, it is possible to see that there is a rising interest in improving car efficiency, in changing fuel market consumption and in developing more engineering efforts for innovating in eco-friendlier cars. However, this approach is ignoring how to encourage people to limit car use as even electric cars produce non-exhaustive pollutants. Researchers have demonstrated that, even though technology has been used as a positive effort to reduce the negative impact of cars (e.g. more efficient engines), people's behaviours overturn those positive side effects because of trends like increased car ownership and increased frequency of car use (Abrahamse, et al., 2009). For example, technology has made car sharing (e.g. Uber) more accessible, which is gaining further popularity among British and German populations (Marsden, et al., 2018). However, although those services seem to reduce the amount of car ownership, in both Germany and the UK the number of miles/vehicles per 1000 population went up by 30% and 28%, respectively (Marsden, et al., 2018).

It is crucial for a sustainable transport system to integrate the theoretical frameworks used to explain travel demand across disciplines by combining transport and environmental psychology research. Environmental psychology research has been exploring people's cognitive and affective factors to explain car use or public transportation preference (Bamberg, 2002; Carrus, et al., 2008;

Chng, et al., 2018), whereas transport research has been developing simulation models to predict travel demand across time by understanding the distribution of the cities, the implementation of public transportation networks, the application of new technology (e.g. Uber service), the demographic stages of populations, the economic and population growth, and the attractiveness of using cars (Gilbert & Foerster, 1977; Mackett, 1990; Cervero, 1986; Filion, et al., 2004; Pfaffenbichler, et al., 2010; Archetti, et al., 2018). For this reason, the focus of the thesis will be on designing a generic mathematical structure to discourage the behaviour towards car use, so as to suggest generic model properties that allow other researchers to integrate a more complete psychological perspective to specific dynamics systems in the decision-making process of travel mode choices.

The thesis concentrates on 3 research questions, which help to structure the discussion within the case study, and help to focus the theoretical contributions that come from both the model and environmental psychology studies. With each question, a greater understanding of how psychological factors behave in a non-linear system is developed. The questions take into account the lack of simulation modelling in environmental psychology (RQ1: Can system dynamics be used to construct a non-linear model to model individual's behavioural intention towards car commuting?); the general weaknesses presented in linear modelling, which can be improved by using SD modelling (RQ2: How useful is SD in understanding the behavioural intention towards car commuting, in terms of its ability to gain insight into its dynamic characteristics and integrating the environmental behaviour theoretical frameworks?), as well as the challenges of changing car commuters' behaviour in the UK (RQ3: How does the modification of psychological factors from key environmental psychology theories affect the level of behavioural intention towards car commuting in a simulation over time in the UK?). The combination of these questions provides a comprehensive explanation to the action-value gap largely discussed in environmental behaviour (Stern, 1999; Blake, 1999; Barr, 2006; Chaplin & Wyton, 2014; Babutsidze & Chai, 2018) and car commuting (Bamberg, 2002; Abrahamse, et al., 2009; Klöckner & Blöbaum, 2010; Chng, et al., 2018).

Because of the aforementioned points and the research questions, the contributions of this thesis are to:

(1) Explore and propose a theoretical Causal Loop Diagram to map all the cause-effect relationships that might affect the dynamic of people's travel mode choice. This map includes transport and environmental psychology theoretical frameworks to take into account all the potential determinants that affect people's decisions when they commute.

(2) Represent by modelling a generic structure of people's behaviour towards car use and alternative transport mode use, to adequately combine psychological and transport determinants into one model which includes general properties to explain people's decision making regarding alternative transport modes.

(3) Identify the challenges to sustaining low levels of attitudes towards car use in the long term. Instead of depending on a market reaction by changing car preference acquisition and alternative fuel use, high levels of decarbonisation can be reached through understanding how car commuters increase their willingness to consider alternative low-carbon mobility and how it is stable in the long term (Bamberg & Schmidt, 2003; Bamberg & Möser, 2007; Chng, et al., 2018).

(4) Open the opportunity to environmental psychology to consider simulation as a useful approach to conduct research. Environmental psychology has recognised that the psychological determinants in PEB and travel mode choice are a complex system, where

attitudinal and normative process change across time. However, to date, research in environmental psychology has predicted travel behaviour predominantly based on linear models with unidirectional links.

(5) By using the simulation outcomes, acknowledge the focus of policy creation that should be considered in the future when policies are targeting attitudinal factors.

1.7 Thesis overview

In this chapter, the main concepts developed in this thesis were introduced. Reducing car use can be seen as a pro-environmental behaviour as its results impact positively in the efforts invested towards climate change control. Many efforts have been made to study the underlying mechanisms that explain travel behaviour; however, there are still improvements to be made in order to understand how psychological determinants play a dynamic role in predicting the behaviour towards car use.

The following chapters will be divided as follows: **Chapter 2** sets the literature review, which offers the explanation of the main theoretical models used in environmental psychology and transportation, in order to predict people’s travel behaviour. **Chapter 3** describes the methodology used in the development of this project, reflecting all the steps used, from the mental model to the formulation of the simulation model. **Chapter 4** explains the development of the first mental model, which was meant to be constructed to place solid knowledge before formalising the mathematical model and conducting a series of interviews with experts. **Chapter 5** reports and explains the insights obtained during the qualitative phase, which was meant to be the second source of external knowledge to improve the mental model presented in the thesis. **Chapter 6** presents the formalisation and mathematical development of the final causal loop diagram, where a series of equations are shown, in order to clarify how the behavioural patterns of this model are produced. **Chapter 7** shows the model validation, in which a series of tests were carried out, so as to conclude the level of confidence the model has to replicate the behaviour in question. **Chapter 8** aims to show the potential of this simulation model in studying strategies to decrease the behaviour regarding car use as it runs several scenarios by using data from England. Finally, **Chapter 9** concludes the thesis, highlighting the research contributions, discussing the weaknesses of the project, and suggesting future research.

2 The theoretical underpinning of travel mode choice

This chapter provides an extensive review of the theoretical models available to be used in the construction of the mental and mathematical model. Travel mode choice has been studied profoundly by transportation, economics, environmental psychology, sociology and geography, in which multiple perspectives have been proposed to understand people's travel choices. In this thesis, the construction of the mental and mathematical model was based on a cross-sectional review between transportation and environmental psychology, as in both research fields extensive lists of factors from different disciplines have been studied and empirically tested in predicting car use and alternatives. The reasons for narrowing the search of knowledge into these two research fields are: (1) transport research is the oldest field working on travel mode choice research, and so there is a large accumulation of topics relevant to this thesis, and (2) environmental psychology has offered multiple explanations about psychological mechanisms involved in people's travel behaviour, which is the main topic of this thesis. Transport and environmental psychology are not exclusive, but complementary.

Transport models tend to treat psychological determinants such as attitudes or social norms as exogenous variables, narrowing the boundaries of transport mode choice. However, there is plenty of research that has demonstrated that predicting the behaviour towards car use is closely connected to cognitive and emotional antecedents, which are affected by certain psychological conditions such as habits or conflicting attitudes, which in turn reinforce the selection of certain outputs; therefore, behaviours are embedded in a feedback loop. In the same vein, psychological models equally commit the same errors by omitting the dynamics of external sources that can affect the given behaviour. For example, income and travel time are functional variables that can determine the perception of how easy/difficult driving is. Hence, omitting them creates a bias because the prediction does not contemplate dynamically the changes that functional sources can provoke in perceptions, then the influence of changes in petrol prices or congestion levels are not reflected. That is why it is believed that reviewing both research fields is necessary to fulfil the purpose of the model – simulating dynamically the psychological determinants associated with car usage. In both, the impacts of economic, demographic, cognitive, social, emotional and functional variables (e.g. travel time) have been studied in the context of commuting. Therefore, this provides reassurance that this critical feedback is supported by the literature. Moreover, authors have already demonstrated that psychological variables add value to functional variables in the context of transportation (Moody & Zhao, 2020).

1.2 Car use and its implications

Many societies have been defined as car-dominated since governments and transport engineers around the world have been prioritising the design of many streets to accommodate high volumes of cars (Brown, et al., 2016). Transportation is a vital part of people's modern life style, but cars have contributed to multiple problems in a wide range of areas such as health (Smith, et al., 2013), environment (Abrahamse, et al., 2009), land use (Pfaffenbichler, et al., 2010) and traffic congestion (Verhoef & Rouwendal, 2004). For these reasons, researchers have been interested in finding effective policies to reduce car use.

Regarding the environment, scientists are divided about the strategies available to tackle climate change in the context of transportation. As pollution is the result of exhaust product emissions, scientists have proposed strategies such as boosting the adoption of AFVs and electric cars (Struben & Sterman, 2008), and encouraging eco-driving[6] (Ünal, et al., 2018). However, detractors of these ideas argue that they are short-term solutions. Electric vehicles still exhibit a great threat to the environment as their construction increases anthropogenic pollution, water toxicity and metal exploitation (Hawkins, et al., 2013). Moreover, there is evidence that car weight has been linked to more emissions of particulate matter (PM) from non-exhaust sources, which is a problem as electric cars have been found to be heavier than the equivalent internal combustion engine (Timmers & Achten, 2016). In terms of eco-driving, researchers have studied all the potential motivators to encourage this practice, but it is still unclear how it can really work out in the long term (Dogan, et al., 2014; Ünal, et al., 2018). For that reason, some researchers are more inclined towards strategies that tackle car use by promoting the intention to reduce its use (Abrahamse, et al., 2009; Chng, et al., 2018), and encouraging active transportation.

There are multiple reasons to explain car use, in which transport and environmental psychology have a large number of studies testing different factors including time saving, comfort, personal norms, habits, values, freedom and independency (Nilsson & Küller, 2000; Abrahamse, et al., 2009; Bamberg, 2013). As well as individual attributes, social aspects have been considered as cars have a strong symbolic and affective meaning in modern societies, establishing a way to reflect social status and personal image (Moody & Zhao, 2020). This evidences the fact the psychological understanding of travel behaviour remains partially unclear (Chen & Chao, 2011; Chng, et al., 2018), and why promoting alternatives is a difficult task to be approached with a single intervention.

[6] Eco-driving is understood as a style of driving that looks for diminished fuel consumption by, for example, avoiding explosive acceleration or checking the tyre pressure.

For many years, developing a car infrastructure was a priority for the political agenda as travelling has always been necessary to improve people's wellbeing and business productivity (more places connected and fastest travelling times by car). The old-fashioned thinking process to reduce traffic congestion was based on increasing the number of new roads and lanes – more roads, more space for cars to travel, less travel time, hence fewer traffic jams (Sterman, 2000). However, this procedure was misplacing a reinforcing loop: more roads call for more cars, which in turn increases traffic congestion. For that reason, it is not surprising to see that most of the urban areas around the world are struggling to develop plans for complete streets[7], as most of the space on the roads is used for private cars and public transportation, which do not allow comprehensive and safe access for all users when travelling (e.g. pedestrians and bicyclists).

The following sections will review the main theoretical frameworks, approaches and findings in transportation and environmental psychology regarding people's travel behaviour.

2.1 Transport research explaining travel mode choice

This literature review will start with the transportation research field. By its nature, this field has been the main area studying transportation issues. The fast growth of urban developments and population has caused severe environmental and transport issues. For that reason, decision makers are continuously looking for new policies that can deal with urban-distribution planning, transport infrastructure and economic development, in order to manage urban agglomeration.

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[7] The concept 'complete street' refers to streets that are designed to ensure a safe journey for all users, including pedestrians, bicyclists, motorists and transit riders (Brown, et al., 2016).

Transport engineers aim to provide governments and policy makers with valuable sources of information to support and formulate transport policies that have economic, urban and transportation implications. In consequence, land use, traffic congestion, travel times, public transportation connectivity, transport infrastructure and vehicle technology are the main topics of transport research to create the future of transport (see Appendix 2). To discover insights in these areas, the transport literature has covered a wide range of methods to understand travel behaviour, in which the most popular approaches found are land use and transport interaction (Pfaffenbichler, 2003), travel-activity approach (Jones, 1979), latent classes analysis (Ardeshiri & Vij, 2019) and behavioural models (Schröder & Wolf, 2017).

2.1.1 Cognitive factors in transport research

During the 70s, transport researchers began to question the transport models' power of prediction (Recker & Golob, 1976; Dobson, et al., 1978; Tischer & Phillips, 1979; Gilbert & Foerster, 1977), arguing that transportation forecasting was missing the representation of 'behavioural aspects' in the models' formulation (Hartgen, 1974). Arguments given back then were related to the lack of understanding the underlying mechanisms of attitudinal factors, as well as the lack of consistency in the definition of motivational factors. This encouraged to many researchers to clarify and develop formal integration of psychological models in transport research. The result of this triggered a change in thinking in some researchers, making them migrate from utility-maximisation-based principles[8] to including motivational factors to determine the conditions that trigger car-dominance and modal shift (Steg, et al., 2001; Vij & Walker, 2016).

Since then, a large stream of theoretical contributions coming from an individual's characteristics, cognitive factors, location and lifestyle (Vij, et al., 2013) have been presented, in order to enhance the prediction of travel mode choice (Bolduc, et al., 2008). The so-called hybrid choice models (HCMs)[9] and structural equation modelling have served for this purpose, in which researchers have been able to predict variables such as residential location decisions based on transport preferences (Walker & Li, 2007), mode choice (Galdames, et al., 2011), transport habits (Şimşekoğlu, et al., 2015), mobility classes (Krueger, et al., 2018; Kitamura, 2009) and future greenhouse emissions (Keskisaari, et al., 2017; Vij, et al., 2013). Some examples of latent variables incorporated in these models include individuals' attitudes (Maldonado-Hinarejos, et al., 2014; Kamargianni & Polydoropoulou, 2014; Paulssen, et al., 2014), memory skills (Prato, et al., 2012), perception of travel time (Ben-Akiva & Bierlaire, 1999), values (Paulssen, et al., 2014), commute satisfaction (Abou-Zeid & Ben-Akiva, 2011), perception of fairness in road pricing (Di Ciommo, et al., 2013), environmental consciousness (Daziano & Bolduc, 2013), acceptable and ideal conditions regarding attributes to commuting (Hess & Stathopoulos, 2013), personal safety (Chen & Li, 2017), flexibility (Vredin Johansson, et al., 2005) and perception of comfort (public transportation) (Glerum, et al., 2014).

[8] An individual's or household's decisions are made based on which option returns the highest utility by combining instrumental factors such as income, travel time, cost, speed, gender, etc.

[9] HCMs are discrete choice models that integrate latent variables and forecast travel mode choice alongside observable data (Temme, et al., 2008; Sottile, et al., 2019).

Nevertheless, these contributions are not widely seen in simulation modelling in transportation. Instead, computational-based models are still running under the assumptions of rational behaviour, undervaluing changes in motivation, personal norms or beliefs when creating transport policies. The next section will review simulation modelling in transport.

2.1.2 *Simulation modelling in transport research*

Simulation modelling has been used by transport researchers as a tool for improving policy makers' comprehension about complex behaviours that require multiple cause-effect relationships, time delays, if and then functions, and feedback loops. More than predicting future behaviours, simulation modelling is intended to understand the behavioural patterns observed in the real-world system to prevent future undesirable outcomes. However, this does not mean that simulation models do not integrate any of the forecasting techniques explained in the previous section, but, because the rationales for using a simulation model or an econometric model differ in terms of the outputs and implication expected, it makes sense to review them separately. For example, discrete choice modelling has been seen in simulation models as part of their mathematical conceptualisation.

On this side of the research efforts, transport engineers have attempted to understand the high levels of complexity that have emerged from the interaction between economic, transport and land-use issues. In simulation modelling, it is common to find the so-called LUTI models (Land Use Transport Integrated), which aim to find relevant insights that enable policy makers to plan new transport infrastructure developments in accordance with land-use changes (Hunt & Simmonds, 1993). In the last decades, numerous models have been proposed to model land use and land-use-transport interactions such as the Herbert-Stevens (Wheaton, 1974), the Lowry Model (Wong, et al., 1998), MARS (Pfaffenbichler, 2003), Martin Centre models (Echenique, 1994), ITLUP (Integrated Transportation and Land-use Model Package) (Putman, 1974) and LILT (Leeds Integrated Land-use Transport) model (Mackett, 1983). Researchers have been working on improving these theoretical frameworks as many transport engineers have recognised that land use and transportation are embedded in a dynamic feedback loop that needs to be considered in the planification of future transport infrastructure if cities are looking for a more sustainable development (Pfaffenbichler, et al., 2010).

Apart from LUTI models, another family of models identified were models working on understanding the interaction of population growth, travel demand and environmental externalities. Authors in this area of modelling claimed that the current studies in transportation choice were missing important feedback loop mechanisms created from urban developments, population growth and economic development as dependent of environmental issues. Ercan et al. (2016) built an SD model that aimed to explain the underlying structures that were causing low public transportation use in the US. Jifeng et al. (2018) developed an SD model to understand how the urban development dynamics were affected by environmental and economic forces.

Finally, the list of models can be ended with the recognition of behavioural models, which attempt to understand travel mode choice by integrating psychological determinants. By using system dynamics and agent-based models, transport engineers look for an understanding of the cognitive, emotional and normative processes involved in adopting more sustainable transport modes. One example is the model called InnoMind (Schröder & Wolf, 2017). This is an agent-based model, which uses a multi-level interaction approach between how similar individuals' decision-making processes relate and affect social behaviours. Based on cognitive, attitudinal and persuasion theoretical frameworks from psychology, the model explains the effectiveness of marketing campaigns to promote car sharing. In alternative fuel vehicles (AFVs), Struben and Sterman (2008) developed an SD model which uses the diffusion modelling principle to understand how the adoption of AFVs grows. The model has one sub-system that simulates the dynamics of the 'individual's willingness to consider AFVs', which is based on the level of marketing, number of adopters (social exposure force) and word-of-mouth influence. Another example can be found in travel mode choice, in which Bajracharya (2016) developed an SD model to explain private car use and public transportation by using the Theory of Planned Behaviour. The list could be endless, as simulation models in behavioural studies have attracted a lot of attention. The next section will review the psychological theoretical frameworks adopted to explain car use.

2.2 Environmental psychological research explaining travel mode choice

In general, psychologists focus their theories and models on understanding, explaining and changing human behaviour. In the case of travel mode choice, the debate has been always divisive, as various theoretical positions have been taken to promote more friendly transport modes (normative vs cost/benefit theoretical frameworks) because travel mode choice is a complex mechanism that involves contextual factors (e.g. transport mode accessibility) and psychological determinants. Additionally, pro-environmental behaviours have been proved to be heterogeneous in terms of the characterisation given by different psychological conditions. These issues have led researchers to study a wide range of psychological factors, including emotions (Carrus, et al., 2008), moral norms (Hunecke, et al., 2001), feedback perception about eco-driving practices (Dogan, et al., 2014), environmental-oriented values (Ünal, et al., 2018), attitudes (Şimşekoğlu, et al., 2015; Chng, et al., 2018), implementation intention (Bamberg, 2002) and habits (Verplanken, et al., 2008).

It is a fact that a big fraction of people accepts the existence of the climate change crisis, but behavioural changes towards more eco-friendly actions do not necessarily follow, especially when it comes to car use (King, et al., 2009). For that reason, models that have emerged in the field go beyond studying car pollution awareness, expanding the explanation by adding more complex mechanisms including intentional processes (Ajzen, 1991; Bamberg, 2013), normative processes (Schwartz, 1977) and habitual processes (Bamberg & Schmidt, 2003; Chng, et al., 2018), among others. In addition to the diversified nature of research regarding psychological determinants, researchers have agreed that enhancing the approaches to explain PEB or travel behaviour requires a unification of theoretical frameworks that can capture pro-social and self-interest motives as, in many contexts, integrative models have shown a greater proportion of the total variance explained (Han, 2015; Bamberg & Möser, 2007).

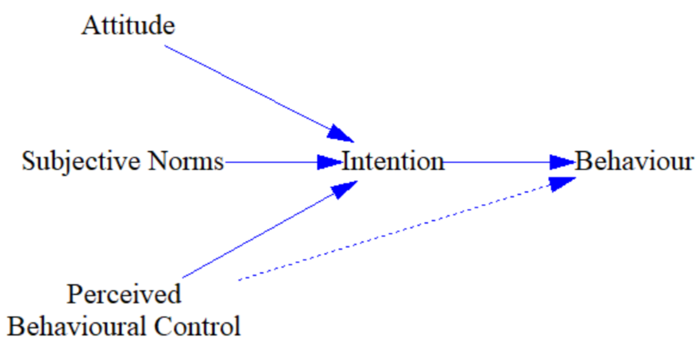
The Theory of Planned Behaviour (TPB) and the Norm-Activation Model (NAM) have been the classical models to prove a cause-effect explanation for psychological determinants in the domain of environmental actions (Stren, 2000; Kollmuss & Agyeman, 2002; Bamberg, 2007; Carrus, et al., 2008; Abrahamse, et al., 2009; Klöckner & Blöbaum, 2010; Chng, et al., 2018). However, the two theories differ regarding how to explain the relationship between the normative process (personal norms vs social norms) and the behaviour (self-interest motives vs pro-social motives). Each model has been shown to over- and underestimate the effects of important psychological aspects that have been proven to be significant in different approaches. For example, TPB and NAM do not address the effect of habit formation (Klöckner & Blöbaum, 2010) or the role of emotions (Carrus, et al., 2008). For this reason, some researchers have tried to integrate the two theories (Klöckner & Blöbaum, 2010; Chng, et al., 2018) and/or extend the psychological determinants proposed (Bamberg, 2007; Carrus, et al., 2008), improving the degree of variation in explained of behaviour (Kollmuss & Agyeman, 2002; Bamberg & Schmidt, 2003; Abrahamse, et al., 2009; Klöckner & Blöbaum, 2010; Bamberg, 2013). The following sections will explain the most common theoretical approaches in environmental psychology to explain people's travel choice.

2.2.1 Theory of Planned Behaviour

The Theory of Planned Behaviour (TPB) (Ajzen, 1991) is an extended version of the Theory of Reasoned Action (Ajzen & Fishbein, 1980), which incorporates the concept of perceived behavioural control to explain a wider type of behaviours. TPB assumes that a given behaviour is primarily preceded by an intention, which reflects the willingness to perform the action.

The model has been claimed to be one which can explain complex behaviours that depends on considering available information to form attitudes (rational-based-choice evaluation), individual's perception on whether or not they feel capable of performing a given behaviour, and social context. This means that individuals are more likely to perform an action when they hold positive evaluations towards the behaviour in question (positive attitudes), they have high expectations of what their important reference group would think (subjective norms), and they perceive few impediments or obstacles (perceived behavioural control) when executing the action. In this sense, the model follows an expectancy-value rationale as TPB dictates that an individual's behaviour is the result of a cost/benefit analysis. When an individual has multiple behavioural alternatives, the decision will be made based upon which alternative returns higher positive behavioural consequences (Bamberg & Schmidt, 2003). Figure 2 shows a graphical representation of TPB.

Figure 2. TPB model.



Source: Own elaboration. Model was drawn on VENSIM. Attitude reflects an overall evaluation of how desirable the expected consequences are when performing the behaviour. Subjective norms represent the perceived peer pressure to engage in the behaviour. Perceived behavioural control is the belief about how easy/difficult it is to perform the behaviour, based on skills and resources.

TPB is one of the most popular models used to predict behaviour in the transport setting, demonstrating great adequacy to forecast travel behaviours such as car commuting (Abrahamse, et al., 2009), speeding (Forward, 1997), pedestrians' intention to break the law regarding traffic regulations (Diaz, 2002), and car ownership (Belgiawan, et al., 2017). However, regardless of its popularity, relevant modifications and concerns have been proposed in transport research:

(1) The attitude-behaviour link has been proved to be a bi-directional relationship, which is intensified over time because travelling is a long-term stable behaviour (Kroesen, et al., 2017).

(2) In the context of commuting, the intention to use a car and the intention to reduce car use are explained by different psychological sources. The intention to reduce car use depends more on the existence of a feeling of moral obligation, while car use is more explained by self-interest determinants (attitudes and perceived behavioural control) (Abrahamse, et al., 2009).

(3) Researchers have pointed out that the 'subjective norms' construct in TPB is probably imprecise to predict a behavioural intention towards car use. This is because it only reflects

perceived peer pressure, hence the impact of a more internal norm (personal norms) or a descriptive norm (Bamberg & Schmidt, 2003) is not acknowledged on the intentional process.

(4) The influence of attitudes towards behavioural intention has been proven to vary across travel mode choices and different distances. In the case of commuting by car, positive attitudes have been proved to predict the intention to use a car in both long- and short-distance settings, whereas positive attitudes towards public transportation were only relevant to predict intention for long-distance commuters (Lo, et al., 2016).

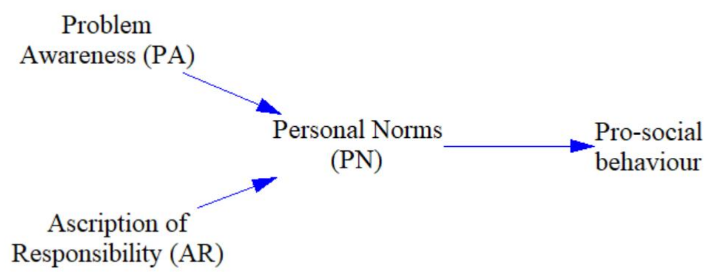
(5) In explaining public transport use, TPB improves the behavioural prediction when personal norms and the interaction between intention and PBC are considered (Heath & Gifford, 2002).

(6) The inclusion of habits in the TPB model has shown better results in understanding modal shift, explaining why car users do not tend to consider alternative transport modes (Chen & Chao, 2011).

2.2.2 Norm Activation Model

The norm activation model (NAM) is a normative-driven model proposed by Schwartz (1977) to offer an explanation regarding how pro-social behaviours are activated. The model has gained a lot of popularity among pro-social researchers that try to explain behaviours from an altruistic perspective. The theory states that the drive behind behaving pro-socially lies in the influence of personal norms (feeling of moral obligation) towards the behaviour. For this to happen, Schwartz proposed that the activation of personal norms becomes stronger when individuals are aware of the consequences (PA) of this behaviour and feel responsible (AR) for generating these consequences. The mediation version of the NAM model has been the most widely used in the community of pro-environmental behaviour research (Bamberg & Schmidt, 2003; Steg & De Groot, 2010) (see Figure 3), in which PA and AR mediate the formation of a personal norm.

Figure 3. Mediation version of NAM model.



Source: Own elaboration using VENSIM.

In the domain of transportation and environmental psychology, multiple authors have used this model to predict the intention to reduce car use (Liu, et al., 2017), as well as to understand how the acceptability of car restriction policies can be increased (Abrahamse, et al., 2009; Eriksson, et al., 2006) and technology adoption (electric cars) (Nordlund, et al., 2016). For example, Hunecke et al. (2001) found that personal norms have a significant effect in determining travel mode choice, increasing its explanatory effect when external costs are modified. In the case of policy acceptance, Eriksson et al. (2006) found that personal norms are significantly relevant to determine in which conditions the acceptability of travel demand management actions (e.g. tax on fuel) are accepted by the community. Moral considerations and perceived fairness are linked to increasing the probability of accepting higher taxes on fuel, whereas freedom aspects and problems of awareness are relevant to predict the acceptability of public transportation improvements (Eriksson, et al., 2006). Abrahamse et al. (2009) found that perceived behavioural control acts as a moderator between personal norms and the intention towards reducing car use. This effect was more powerful when PBC was lower, meaning that drivers who felt that there were few possibilities to reduce car use, considered themselves more obligated to reduce car use, probably because the individuals with high levels of PBC were already performing behaviours towards car reduction.

Nevertheless, this model has been critiqued for its simplicity. Abrahamse et al.'s (2009) study found 12% of variance explained in car reduction with the NAM framework. The same result was reported by Bamberg and Schmidt (2003), indicating a 14% of explanation from PN to behavioural variance. For the lack of satisfactory levels of explanatory power, some authors have proposed that NAM should be integrated with other theoretical frameworks (e.g. TPB), as in that way better levels of explained variance can be found (Bamberg & Schmidt, 2003; Liu, et al., 2017; Chng, et al., 2018). For example, studies that have integrated NAM and TPB have found that awareness of consequences works better if a direct path to subjective norms is created (Bamberg & Schmidt, 2003; Chng, et al., 2018). Likewise, Chng et al.'s (2018) theoretical review found four studies that demonstrated a significant path coefficient to predict AR from PA. Therefore, it is not only accepted that both predict personal norms, but also that there is a mediation effect between AP, AR and PN.

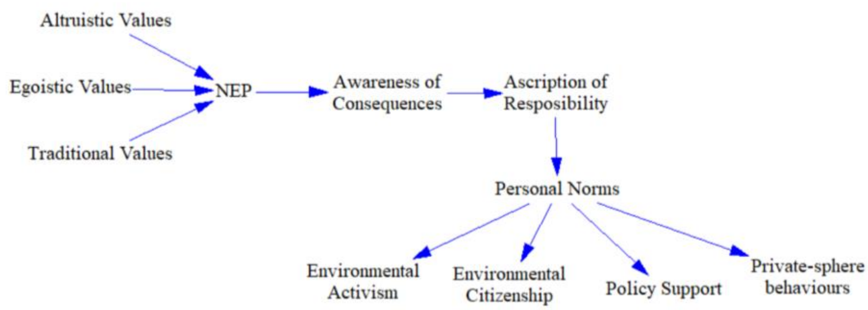
2.2.3 Value-Belief-Norm theory (VBN theory)

VBN has emerged as a new framework to explain significant individual behaviours in the domain of the environment (Stren, 2000). The theoretical framework of VBN based its explanation on linking an individual's ecological worldviews, measured by the New Ecological Paradigm (Dunlap, 2008), the norm activation model and environmental values (see Figure 4). Overall, values are considered to be more stable than attitudes to predict behaviours, as they do not tend to easily change when contextual factors are altered. For that reason, behavioural psychologists have focused their attention on measuring the effect of personal values in a wide range of behaviours (Gatersleben, et al., 2014).

Depending on the context and behavioural settings, it can explain 19% to 35% of the variance of a pro-environmental behaviour (Stern, et al., 1999). However, its usefulness is still debatable in environmental psychology as several authors have demonstrated that other models are better than VBN to predict PEBs. For example, in nature conservation research, researchers have found that the TPB explains more variance than the VBN (Kaiser, et al., 2005). In energy reduction, the behavioural intention was significantly explained by TPB and not by VBN (Abrahamse & Steg, 2011). In the willingness to pay for a natural area, the TPB model showed a better explanatory power for that than VBN (López-Mosquera & Sánchez, 2012). In recycling settings, TPB has been demonstrated to have a greater capacity to predict recycling behaviour of Spanish housewives than VBN (Aguilar-Luzón, et al., 2012). In predicting climate change adaptation and mitigation behaviours in agricultural production, TPB proved to be a better model than VBN to predict adaptation behaviours (self-interest-driven), whereas the latter performed better in predicting mitigation behaviours, which are associated with altruistic motives (Zhang, et al., 2020). Despite the numerous comparisons in which TPB seems to be more efficient than VBN to explain PEB, multiple researchers have concluded that integration of the two models has more promising results (Gkargkavouzi, et al., 2019; Han, 2015).

In the context of transportation, VBN has been used to predict travel behavioural patterns. For example, Ünal et al. (2018) compared the effect of knowledge and value by contrasting two models, VBN and KBN (knowledge-belief norm), in which the study proved that values are stronger motivational factors to encourage eco-driving than environmental knowledge. Additionally, this theoretical framework provided significant results in predicting sustainable travel mode choice, enabling the researchers to quantify the effect of personal norms and situational factors on three different sub-groups of travellers (PT users, car users and active transportation users) (Lind, et al., 2015).

Figure 4. VBN model.



Source: Own elaboration on VENSIM.

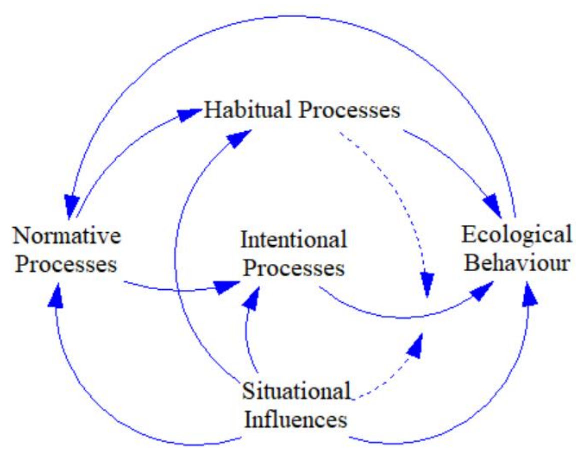
2.2.4 Other models in environmental psychology applied to travel behaviour

As was stated before, understanding people's behavioural patterns requires an extensive revision of contextual factors, attitudinal factors, values, personal capability beliefs (PBC) and habits. For that reason, it is not surprising that new theoretical frameworks have emerged in the last decade. Some researchers in environmental psychology believe that combining existing theory in PEB and travel mode choice can lead to more promising results (Klöckner & Blöbaum, 2010), ergo there is a widespread interest in proposing new theoretical models to address in a more inclusive method the understanding of travel behaviour. In this section, three models are reviewed as they were applied in the transport field and they integrated many psychological determinants considered by TPB, NAM and VBN.

The first model to review is the ‘comprehensive action determination model’ (CADM) (see Figure 5). CADM was proposed by Klöckner and Blöbaum (2010) as an improvement to single models (such as TPB and NAM) to predict PEB. The model incorporated both NAM and TPB theoretical assumptions regarding intentional, normative, situational and habitual factors, giving a wider explanation of behavioural patterns in a larger variety of situations. The authors’ critique is that TPB and NAM underestimate important aspects that characterise an individual’s decision-making proses. TPB underestimates the effect of habits, personal norms, and objective situational restrictions and facilitators (e.g. access to a car), while NAM does it with the role of habits, attitudes, perceived behavioural control and intentions. Additionally, TPB and NAM fail in explaining repetitive behaviours because the models do not incorporate habits or past behaviours in the prediction of current behaviours. This lack of representation associated with routines makes TPB and NAM report different results when the behaviour predicted has been performed multiple times, a few or never before. Previous studies have shown that, when habits are integrated in the TPB model, the intention diminishes its power of influence towards the behaviour because frequent behaviours are expected to be more automatic, and less deliberate, thoughtful decisions (Bamberg & Schmidt, 2003; Eriksson, et al., 2008). This has been fully demonstrated in travel mode choice (Eriksson, et al., 2008; Klöckner & Blöbaum, 2010).

The model has gained important popularity as it has empirically demonstrated significant results in numerous studies (Klöckner, 2013). In its conception, the model was tested to prove its prediction power in the domain of travel mode choice, in which the results stated that CADM had a great model fit, explaining a larger proportion of the variance when predicting behavioural patterns in comparison to TPB and NAM (Klöckner & Blöbaum, 2010). The CADM works as follows: a pro-environmental behaviour is affected primarily by habitual, intentional and situational processes. The normative process's effect (social and personal norms) on behaviour is mediated by the intentional and habitual processes. The normative process is believed to be affected by past behaviours; therefore, a behaviour feedback is considered in the theoretical proposition. Moreover, the model assumes that PEB behaviour combines an expectancy value analysis, dictated by attitudes, and moral motivations, making the prediction of decision-making outcomes more accurate (Nayum & Klöckner, 2014). Finally, CADM considers subjective and objective constraints, meaning that situational restrictions are the combination of people's perceived behavioural control and observable limitations (e.g. car accessibility).

Figure 5. A comprehensive action determination model (CADM).



Source: Own elaboration.

The next model reviewed was the stage model of self-regulated behavioural change (SSBC) (see Figure 6). The model was proposed by Bamberg (2013), in which the author integrated the model of action phase (Heckhausen & Gollwitzer, 1987), TPB and NAM. Interested in proposing a behavioural change theoretical framework, Bamberg proposed a phase-driven model which describes how each psychological factor takes a role in the pre-decision, pre-action, action and post-action phases. The author's critique is based on the fact that interventions targeting intentional change normally fail because the explanatory power of intention towards behaviour is very low in the traditional theoretical frameworks. On average, intention explains 35% of the variance of the actual behaviour, hence the intentional process is underestimating all the psychological factors involved.

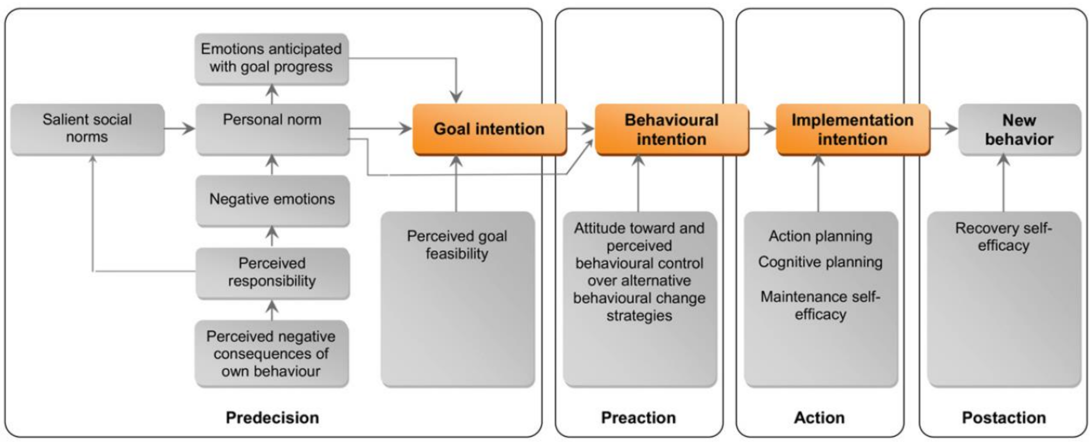
The model deals with the 'intention-behaviour' gap by dividing the intentional process in a time-oriented model. An individual is assumed to perceive a goal intention before acting. In this process, an individual deliberately selects a wish[10], which turns into a goal. The goal emerges by weighting the level of desire regarding achieving the goal and its feasibility. This is followed by the pre-decision phase, in which the individual selects the means which will be used to achieve the goal, as sometimes multiple options are available to achieve the goal. In this phase, the TPB main assumptions explain the selection of the behavioural intention (e.g. deciding to take a car instead of public transport). Finally, before performing the behaviour, the individual forms a mental link between a future situation and the necessary elements needed to perform the action. This is known as the action phase, where the individual plans their actions, in order to 'know what to do' every time a specific situation is encountered (e.g. every morning I should be at the bus stop at 8.20 am to take the bus at 8.30 am to arrive at work at 9 am). Finally, the process ends when the individual compares the expected and actual outcomes from the behaviour performed. If they match, meaning

[10] The model assumes that an individual has a pool of wishes that can be activated at any moment, depending on contextual, normative and emotional factors. Sometimes, these wishes can compete against each other; therefore, the activation of one means the inactivation of another (driving to work to reduces travel time vs decreasing personal carbon footprint). When a wish is selected, a goal intention is formed, which is pursued by the individual in order to achieve the positive outcomes that come when the behaviour is performed (Bamberg, 2013).

the way in which the action was performed was the way it was planned, hence the expected goals were achieved, then the individual assumes the new behaviour better suits the current context and the individual's desires.

The model was tested for the first time to predict people's willingness to reduce car use for daily trips and shift to more environmentally friendly transport modes.

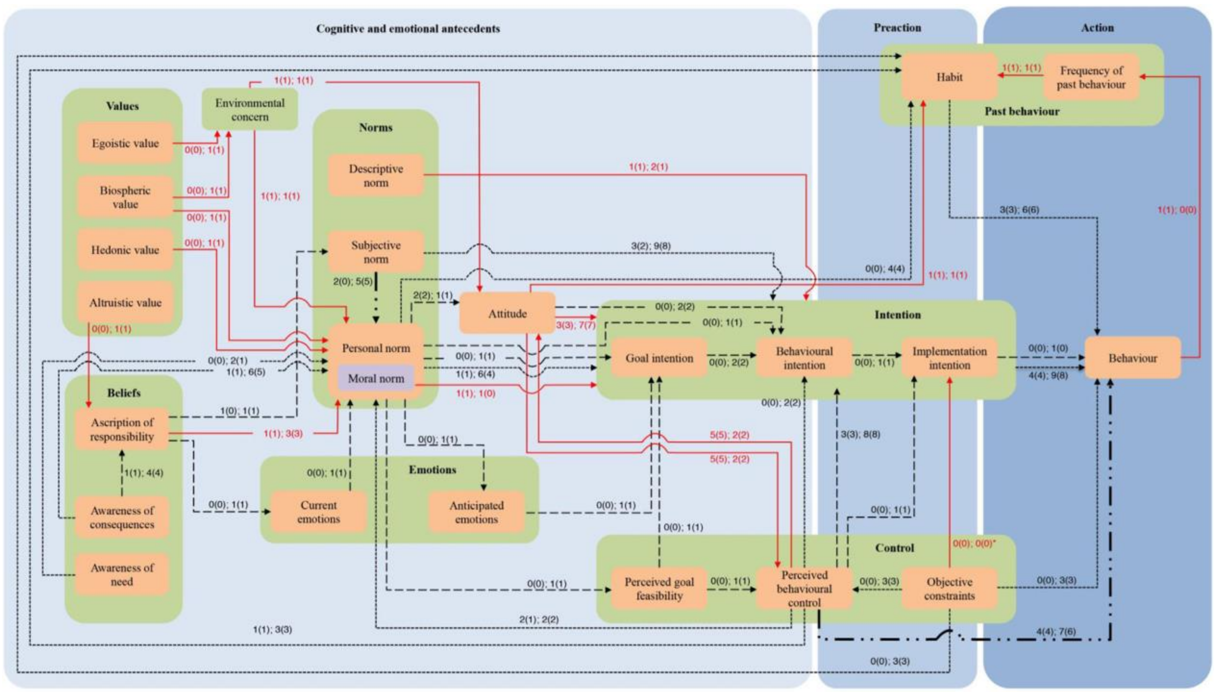
Figure 6. The stage model of self-regulated behavioural change.



Source: Figure extracted from original paper by Bamberg (2013).

Finally, the CAR USE model (CAUSE) (Chng, et al., 2018) is reviewed. Not finding the explanations offered so far by TPB, NAM, VBN, CADM, and SSBC to be satisfactory, Chng et al. (2018) critiqued that none of them present sufficient support to explain car use. In their paper, they explained that CADM and SSBC do not follow a comprehensive lens to study car use as distinctive elements can be found in each model. CADM considered mostly environmental antecedents, whereas SSBC conceptualised car use as a self-regulated behaviour which depends on goal-driven planning and action. For that reason, the authors proposed a new integrative work to explain car use by including all the potential mechanisms that had been proved to be relevant. As they stated, the CAUSE model is not a new framework; instead, it is an integration that is meant to consolidate the existent models to predict car use. The CAUSE model was created based on theoretical revision; therefore, its empirical validation remains pending.

Figure 7. CAUSE model.



Source: Figure extracted from the original paper by Chng et al. (2018). The numbers represent the correlations and path estimations that were found in the papers reviewed by the authors. For example, the numerical figures on top of the arrow that links perceived behavioural control and behaviour should be read as: four correlational studies were found, in which four correlations were significant, and seven studies found a number of path coefficients, in which six were significant.

2.2.5 Other findings outside the previous theoretical frameworks

Important findings have been discovered in studies that did not necessarily test any of the previously mentioned cognitive models; instead, concepts formerly examined in these models and instrumental variables were blended together to predict car use and its reduction. For example, Nilsson and Küller (2000) took specific dimensions from TPB, models in PEB, car frequency and distance travelled, concluding that positive attitudes towards the environment (e.g. environmental concern) are strongly related to the acceptance of traffic restriction to control car use, which is not the case with those who show a positive attitude towards car use. In car ownership, Moody and Zhao (2020) ran a model testing demographic, motivational and instrumental variables, in which they found that car use, car ownership and car pride are closely related through a reinforcing loop, making it harder to encourage alternative transport modes among drivers as the social construction of car ownership shapes individual attributes and social status.

Dogan et al. (2014) empirically tested whether financial or environmental feedback regarding driving would have an impact in engaging eco-driving practices. Surprisingly, the study showed that feedback regarding small environmental gains had a higher impact than financial savings, due to less fuel consumption, on predicting eco-driving practice. Therefore, norms play a key factor in determining PEB practices related to car use.

To sum up, understanding people's travel behaviour is a complex research field where multiple areas have been taking a role in explaining mode choices. Transport researchers have been mainly focusing on developing more complete mathematical tools of analysis to support policy-making processes, in which improvements of the models are mostly explained because data storage is easier and more accessible, large institutions are involved in recollecting data at a national level (e.g. Department for Transport UK), new techniques are available to collect data (e.g. GPS; see Guo et al. (2018)), cross-sectorial research fields are working together, new methodologies have been created (e.g. hybrid models), and more software is available to run complex simulation models. In contrast, environmental psychologists have been mainly focusing on developing more comprehensive theoretical frameworks, so as to improve the variance in explained of behaviours, in which case improvements are principally explained by the integration of normative and rational models (TPB + NAM), redefinition of psychological determinants, the recognition of feedback loops, and the inclusion of more stable determinants (e.g. values). The next section will explain the value of this thesis.

2.3 The reasons for developing an SD model to explain psychological factor dynamics

2.3.1 Complex systems

Much of the literature in environmental psychology and transport suggests people's travel behaviour is a complex system as it is composed of many parts, which define distinctive properties such as feedback loops, time delays and non-linearities (Chng, et al., 2018; Klöckner & Matthies, 2009; Pfaffenbichler, et al., 2010). For this reason, this section aims to explain what complex systems are.

Complex systems are defined as systems created by several components that may interact with each other (and in some cases with the simulated environment), producing non-linear behaviours (Aziza, et al., 2016; Bellomo, et al., 2013). Such non-linear behaviour cannot be derived from summation of individual elements embedded in the system (Morowitz , 2018; Morecroft, 2015). Most importantly, a complex system exhibits hierarchical self-organisation, which is continuously evolving as new interactions and new elements can emerge within the dynamic behaviour of the complex system (Morowitz , 2018). Examples of complex systems are climate change, economies, biological processes, ecological networks, people's behaviour, communication, human brain, and neural networks (Sterman, 2000; Ford, 2020; Morecroft, 2015; Morowitz , 2018; Davis, et al., 2007).

A number of behaviours are typically seen in complex systems. Table 1 illustrates the most common properties that are used to define whether a system is complex or not. It is important to note that a complex system does not need to contain all the aspects described in Table 1. Rather, exhibiting a sub-set of these properties is enough to claim the existence of intrinsic complexity in the behaviour of the system (Aziza, et al., 2016).

Table 1. Common properties seen in complex systems.

Property	**Description**
Emergence	The arising of new patterns, properties, structures, units, or behaviours that have unforeseen aspects. Such new aspects in the system were not programmed; instead, it is the result of a large number of interactions of many individual identities, which are not controlled by a central entity (Elsner, et al., 2015; De Wolf & Holvoet, 2004).
Distributed decision-making	This principle states that the decision-making process is distributed between several entities, meaning that there is no central organisation guiding and managing the overall behaviour of the system (Aziza, et al., 2016).
Multi-level structure	This property describes the capacity of a system to be defined by elements at a micro and macro level. A complex system can display different scale and temporal levels, making the relationship between the macro and micro levels a complex element to characterise (Mittal, 2013; Schröder & Wolf, 2017).
Dynamism and complicated interactions	Entities, elements, structures, and effects in a system are constantly evolving and interacting with each other or with the environment. Hence, the behaviour of the system is by nature dynamic, as multiple changes occur at many time scales (Sterman, 2000; Mittal, 2013). The result of these multiple interactions increases the difficulty of understanding the relationships within the system (Aziza, et al., 2016).

Feedback loops	This property refers to the capacity of a system to exhibit circular causalities. In a complex system, it is thought that its behaviour arises by the interaction of multiples positive and negative feedback processes (Lloret-Climent & Nescolarde-Selva, 2013). More details about feedback loops can be found in section 3.2.2.
Adaptability	The agents' decisions in a complex system change over time as they have the capability to learn, in order to achieve their goals (Sterman, 2000; Mittal, 2013; Aziza, et al., 2016).
Competitiveness and conflict	Entities within a system can work collectively or individually to satisfy their goals (Mittal, 2013).
Non-linear	The capacity of a complex system to exhibit non-linear behaviours due to multiple factors interact in the decision-making process (Morecroft, 2015; Sterman, 2002).
Counterintuitive	In complex systems, time scales take place in a cause-effect relationship. Complex policy arises from the analysis of complex systems (Sterman, 2000).
Policy Resistant	"…Many seemingly obvious solutions to problems fail or actually worsen the situation." (Sterman, 2000 pp. 22).

Source: Own elaboration. This is not an exhaustive list; the study of complex systems is continuously increasing, finding new properties that characterise them.

In environmental psychology and transport, many of the elements mentioned in Table 1 have been described. For example, Kroesen et al. (2017) demonstrated that attitudes and behaviours in the context of travel mode choice are not linear, but rather bi-directional, recognising the existence of a feedback loop structure embedded between the two factors. A similar phenomenon is described in the CARUSE model, which establishes the existence of a feedback loop structure between car use and people's travel habit (frequency of use) (Chng, et al., 2018). Klöckner and Blöbaum (2010), Chng et al. (2018) and Bamberg and Schmidt (2003) identified that the simplicity of TPB or NAM can limit the understanding of travel behaviour as these models do not recognise important levels of other people's processes. All of them proposed extended multi-level models to predict car use. Additionally, multiples studies that have applied green interventions to changes people's travel behaviour have not display satisfactory results in the long term. After removing the incentives, environmental researchers have found counterintuitive behaviours as the results contradict the expected results, opening more questions about filling the attitude-PEB gap (see Fujii and Kitamura (2003), Eriksson et al. (2008)). Finally, (Schröder & Wolf, 2017) have largely discussed in their paper that the decision-making process of car sharing is in fact a dynamic and complex process to describe. Therefore, it requires the use of more complex tools such as simulation, in order to capture the complicated interaction between the elements of the system. Therefore, the study of the behavioural intention towards car commuting can indeed be described as a complex system as feedback loops, multi-level structures (sub-models), counterintuitive behaviours, and dynamic and complicated relationships have been described in the literature.

2.3.2 Simulation and complex systems

The human brain has a common tendency of analysing experiences under an event-oriented approach (Morecroft, 1985; Sterman, 2000). This simplicity in interpreting cause-effect relationships creates a barrier to explaining and analysing problems embedded in a complex system. Figure 8 shows a basic example of how an event-oriented approach would work. When a goal gap emerges from an individual's mind (comparison between his/her desired and perceived goals), a problem arises. For example, the UK is dramatically reducing its greenhouse gas emissions to become a zero-carbon economy by 2050. In 2019, the government announced that the UK released 40% fewer greenhouse gas emissions than in 1990, demonstrating significant progress in the last 30 years (Harrabin, 2021). However, 60% of the emissions still need to be reduced (goal gap), so a set of options are still being considered to address this problem. If immediate actions are not taken, climate change is likely to make the earth hotter, which in turn will bring extreme weather and increase sea levels, affecting all forms of life (problem). Among all the decision that have been taken, the UK has lately announced an investment of £620m in grants to increase the electric charging points in the street (decision), in order to push electric cars in the region. As electric cars do not emit greenhouse gases, it is expected that having more of this type of vehicle on the road will contribute to fighting climate change (result).

Figure 8. Event-oriented approach.

Goal Gap $\longrightarrow$ Problem $\longrightarrow$ Decision $\longrightarrow$ Result

Source: Own elaboration.

This basic example illustrates an event-oriented approach to analysing people's travel behaviour. However, it is clear from transport and environmental psychology research that people's travel behaviour is in fact a complex system. Therefore, simplifying the analysis by thinking that more electric charging points would be an effective way to promote electric cars, can mask side effects which can create unexpected dynamics and make the problem (car pollution) worse.

For example, many actors and elements can influence people's travel behaviour: car manufacturers, governments, road infrastructure, taxes and transit laws. Additionally, an individual goes through several internal processes to decide whether using an electric car (or even using a car) is appropriate to fight climate change. Some psychological constructs involved in the decision are attitudes, emotions, habits, car preferences, previous experiences, beliefs, values, social norms, personal norms and travel satisfaction. All of them have been described to interact and impact on car use (Chng, et al., 2018; Bamberg, 2013; Klöckner, 2013). Additionally, expanding the production of electric vehicles will define the situation that humans will face in the future. The implications of changing all petrol and diesel vehicles in the UK to electric vehicles are devastating (Amos, 2021). Mining extraction activities will need to be increased, as well as energy production and electric car infrastructure. For theses several reasons, people's travel behaviour needs to be treated as a complex system, thus requiring an appropriate methodology to deal with these complexities.

In general, simulation is suggested to analyse complex systems. With this approach, a modeller can imitate how a real-world situation or mechanism works over time (Aziza, et al., 2016) on a computational model, which is then used for experimentation, forecasting and policy creation (Davis, et al., 2007; Morecroft, 2015). Simulation models allow modellers to experiment utilising a low-cost budget, as well as to observe long-term changes in seconds (Sterman, 2000; Aziza, et al., 2016). Additionally, the process allows the construction of complex models with multiple variables, circular causalities, time delays and non-linear relationships. For these reasons, it is preferred to study complex systems.

Among all the techniques available (see next chapter for more details), system dynamics has been used for simulation. It has been described as an approach that enhances people's learning in complex systems due to its flexibility to deal with dynamic complexities. One of the main aims of system dynamics is uncovering and representing feedback loops of a system, along with stock and flow structures, non-linearities and time delays (Forrester, 1961; Sterman, 2000). Therefore, to study people's travel behaviour, SD can fit the purpose of this study as it will be possible to represent feedback loop structures between attitudes and behaviours, as well as the latter with habits. It will enable us to understand why, for so long, car use has been stable in the UK, even when there is an urgency to decrease car pollution for the sake of protecting the environment. SD will be the methodology to understand under which conditions the environmental attitude towards low carbon mobilities can overcome the attitude towards car use.

The benefits of using simulation (and system dynamics) are clear; however, people's travel behaviour (from a psychological point of view) has not been widely approached with it. The next sections will review the application of simulation in environmental psychology and the reasons why it is necessary to understand people's travel behaviour under a computational-driven view.

2.3.3 Simulation for environmental psychology

Despite the wide range of theories, techniques and models available to explain people's travel behaviour, cross-field work between transport and psychology seems to be more absent than unified. This section will develop the arguments to justify why a system dynamics model in the field of environmental psychology can fill the 'theory-operationalisation' gap in the transportation research field, as well as why an SD application can expand the understanding of current psychological theories.

The methodology chapter will explain system dynamics and the benefits of using it in social science. Therefore, to avoid any redundancy, this section will just provide a basic definition of it. SD is a computational-based approach which is used to understand non-linear behavioural patterns of a system by modelling internal feedback loop structures, stock-and-flow variables, and time delays (Sterman, 2000). Feedback loops are structures that emerge from sequential relationships, where the output variables are routed back to the origin of the cause-effect chain (Morecroft, 2015). Stock-and-flow variables are elements in the system that accumulate information or material proceeding from previous internal calculation in the model. This way, a stock-and-flow mechanism is composed by a flow, which can take the form of an inflow variable or an outflow variable, and a stock, which is filled or drained by these variables (Forrester, 1992). Finally, time delays refer to a fundamental assumption in SD. In reality, changes in variables are not expected to happen immediately; instead, it is assumed that they will happen after the change takes place. With these elements defined, the following sections will propose the value of system dynamics in behavioural theories and transport modelling, as well as will explain the research questions of this project.

2.3.4 Transport research applying psychological theories: bias of conceptualisation and fear of operationalisation

Most studies on transport research describe modal choice by objectively measurable variables such as distance, location, density, land use and travel time. However, some researchers have argued in favour of including cognitive and normative variables as, to some extent, travel mode choice cannot be explained from a utilitarian point of view, which means that the decision is not fully driven by the trade-off between time, distance and cost (Muñoz, et al., 2016). This practice of including psychological factors has been widely seen in purely data-driven models. For example, in forecasting travel demand, some transport researchers have proposed the use of the so-called hybrid models[11] to work with attitudinal and perceptual variables (Vij & Walker, 2016). This type of statistical methodology allows researchers to predict travel mode choice with hard and soft variables, in order to enhance the representation of an individual's decision-making process (Ben-

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[11] Hybrid models are discrete choice models with the integration of latent variables (e.g. attitude) to predict modal choices.

Akiva & Bierlaire, 1999; Ben-Akiva, et al., 2002; Bolduc, et al., 2008; Paulssen, et al., 2014; Bouscasse, 2018; Vij & Walker, 2016; Bahamonde-Birke, et al., 2017).

This theoretical development has not taken the same form across simulation modelling, specifically in system dynamics (SD). Three main reasons can be found regarding this absence of representation of behavioural aspects in SD. One is the avoidance of using the so-called soft variables, the second is the simplification of behavioural patterns, and the third is the lack of computational-based representation of the psychological theories.

2.3.5 Avoidance of using soft variables

In SD, it is possible to find two sources of data, hard variables and soft variables. Hard variables are understood as any numerical data, which can lead to statistical tests to determine the parameters of a model (Sterman, 2002; Roy & Mohapatra, 2003), whereas soft variables can be interpreted in different ways. Some researchers have referred to soft variables as variables that are computed from pseudo-algebraic expressions, which are artificially created to make the model mimic the behavioural patterns observed from the data (McLucas, 2003)[12]. Another group of researchers have described soft variables as categorical data, which normally represents latent variables such as motivation and dissatisfaction (Roy & Mohapatra, 2003). Finally, it is possible to interpret soft variables as any variable that has been estimated purely subjectively; in this case, the value of a parameter in the model that cannot be derived from a statistical test is intuitively determined from

[12] Mclucas' (2003) paper illustrates an example in which the organisational performance is calculated by the $\sqrt{(Qualifications\ Held\ \_By\ \_Individual\ x\ Individual\ 's\ \_Motivation\ \_Level)}$. In this case, the author stated that this equation is dubious as the representation of the equation might not represent what really happens in the real world.

qualitative data (e.g. interviews) (Sterman, 2002). It is important to note that these interpretations correspond to the type of data that is used to construct a simulation model. In the methodological chapter, it will be explained that qualitative data can be gathered as well to construct a conceptual model, which serves as the input of the mathematical model. The implication of developing the conceptualisation of a model with qualitative data is not discussed as it is widely accepted by hard and soft modellers (Kunc, 2017).

Modellers are divided between the acceptance of soft variables in simulation modelling. On the one hand, detractors of the use of soft variables defend the rejection because the assumptions behind these variables are erroneous, as the equations (or parameters) are conveniently created (adjusted) in order to mimic the reference mode (McLucas, 2003). This practice produces inaccurate mathematical expressions to represent how the observed behaviour is actually produced in real life. Moreover, the integration of soft variables can lead to meaningless results as their measurements are not clear (Roy & Mohapatra, 2003), and their estimations cannot be verified (Roy & Mohapatra, 2000). For these reasons, there is a general avoidance of using soft variables. On the other hand, researchers defending the inclusion of soft variables justify their use by answering if these variables are relevant parts of the real system[13], meaning that, if they play a key role to fulfil the purpose of the model, then they should be included (Lane, 2000; Luna-Reyes & Andersen, 2003). In fact, these researchers have claimed that the non-inclusion of soft variables because of the lack of numerical data, is less scientific than subjectively choosing a number to

[13] A system in system dynamics refers to the group of variables that are related to produce a behavioural pattern observed in real life. The cycle of water is a system, in which the evaporation, condensation, precipitation and infiltration are the main mechanisms to explain the process. Each of these mechanisms has its own set of variables to be explained.

represent the parameter based on judgement (Forrester, 1961; Sterman, 2002). Omitting variables could lead researchers to produce biased conclusions as the representation of the simulation model (with only hard variables) can be hiding potential cause-effect-relationship outcomes that end in issues related to policy resistance (Sterman, 2000), behavioural inertia (Ulli-Beer, et al., 2010), or underestimation of feedback loops' dominance[14]. For this reason, a sense of judgement has to be deployed alongside external validity to make soft variable inclusion (and assumptions) reasonable (Coyle, 2000; Lane, 2000; Sterman, 2002).

Currently, many areas of research in psychology and sociology have offered plenty of documentation and support about measuring latent variables. Moreover, in environmental psychology, there is a large community of researchers empirically demonstrating their theoretical frameworks to explain the influence of attitudes, beliefs, norms and values on travel mode choice (Bamberg, 2013; Carrus, et al., 2008; Şimşekoğlu, et al., 2015; Chng, et al., 2018; Abrahamse, et al., 2009; Klöckner, 2013; Eriksson, et al., 2006; Bamberg & Schmidt, 2003; Jakovcevic & Steg, 2013). Therefore, avoiding soft variables because of their metrics and/or a lack of understanding of how they influence travel mode choice (which can be used to create soft variables equations), is becoming a less strong argument, as some researchers in psychology and behavioural transport have presented robust studies to back up the soft variable measurements, as well as theoretical explanations to clarify the cause-effect relationships among them.

Regarding the issues of reliability and the lack of actual measurements of soft variables, plenty of studies in environmental psychology have presented empirical studies to determine the cause-effect relationship, offering covariance parameters that can be used as references for parameters

[14] See The death spiral in mass transit model (Sterman, 2000).

inside the simulation model. Moreover, databases with psychometric measurement are becoming more common; hence, it is currently possible to observe their fluctuation over time, diminishing doubts about their temporal behavioural patterns. For example, the Department for Transport in the UK through the national travel survey (NTS) offers a wide range of attitudinal parameters[15] which can be used as a reference for simulation models (reference modes will be discussed in the methodology chapter). In fact, the simulation model developed in this thesis used attitudinal data collected by the Department for Transport (DfT) as a reference mode.

For all these reasons, the rejection of soft variables cannot be considered if they play a crucial role in describing the behavioural pattern that is observed in the real world. In this case, attitudinal and other psychometric variables have been supported by plenty of researchers as important factors to explain the causal mechanism that triggers travel mode choice. Ultimately, travel behaviour portrays different travel patterns even within homogeneous groups in the population, based on their socio-economic and socio-demographic factors (Van Acker, et al., 2011). Therefore, purely hard variable-driven models in travel behaviour are committing a poor theoretical development as cognitive aspects are not being captured, decreasing model confidence (in terms of psychological aspects), and not offering a clear understanding of how travel mode choice emerges in real life.

2.3.5.1 Simplification of behavioural patterns

Regarding the second point, simulation models in transportation do not offer a comprehensive explanation of people's behaviour from cognitive, normative and intentional processes. For

[15] https://www.gov.uk/government/collections/statistics-on-public-attitudes-to-transport#public-attitudes-towards-electric-transport-modes-and-climate-change.

example, MARS (Pfaffenbichler, 2003) calculates 'car attractiveness' as a combination of car availability, commute cost, time and zone attractiveness. Attractiveness is defined as "*the quality of causing interest or making people want to do something"* (Cambridge Online Dictionary, 2021); therefore, 'attractiveness by car' is implicitly measuring an evaluation about commuting by car based on time and cost. In this sense, someone can claim that the MARS model is using 'attractiveness by car' as a mechanism of expectancy-value analysis regarding the qualities of the transport mode – if the time and cost of driving increase (attributes), then car commuting is perceived as less attractive (beliefs about these attributes), which in turn would affect the number of trips by car (the behaviour). Nevertheless, attitudinal aspects to predict behaviours have been largely discussed in psychology, proving that attitude is a complex mechanism predicted as well by emotions, beliefs, values and norms (Chng, et al., 2018), and previous behaviours (Kroesen, et al., 2017), which are crucial aspects to study in transport, when it is well known that cognitive aspects can alter people's perception of time (Droit-Volet & Meck, 2007) or rational thinking (Tversky & Kahneman, 1974).

The same conceptual bias is committed by Struben and Sterman (2008). The model develops a reinforcing loop, in which willingness to consider *i* (alternative fuel vehicles or internal combustion engines) and attractiveness cause the consumer's choice. The definition given by the Oxford Dictionary (2021) for willingness is "*the quality or state of being prepared to do something; readiness*"; in other words, a declaration of commitment to perform an action. In TPB, this is defined as intention, which indicates the willingness that an individual shows about how hard he/she will try to perform an action. In TPB, the model explains that attitude affects intention, which in turn affects behaviour, but Struben and Sterman's model established that attractiveness (proxy for attitude) and willingness (proxy for intention) jointly cause behaviour, a proposition that breaks a basic law discussed in behavioural models.

The same misconception or absence of psychological aspects can be found in other simulation models, such as the mass transit death spiral model (Sterman, 2000), ASTRA (Fiorello, et al., 2010), IMULATE (Maoh & Kanaroglou, 2009), TRANSIMS (Smith, et al., 1995), SUTRA (Fedra, 2004) and the urban transportation system (Jifeng, et al., 2008), among others.

The lack of an important subset of behavioural factors leads to problems of consistency in representing people's travel choices that are observed in reality (Gilbert & Foerster, 1977; McFadden, 1974; Lanken, et al., 1994; Van Acker, et al., 2010), especially when transport mode choice is situated in a social context (Sterman, 2000; Schröder & Wolf, 2017). The exclusion of cognitive, emotional and normative components impedes theoretical frameworks from dealing with the explanation of irrational decisions regarding modal preferences in transportation. For these reasons, the SD model developed in this project opens a new way of communication between transportation and psychology. A more rigorous definition of psychological constructs and their relationships in an SD model can serve as a new language for transport modellers to use, in order to integrate the complex theoretical models developed by environmental psychologists. In fact, the increasing availability of behavioural variables (e.g. attitudes towards bicycles) captured by institutions such as the UK government Department for Transport, gives more opportunities to integrate and operationalise psychological determinants in simulation modelling. Currently, reference modes are easier to construct and visualise, hence the fear of constructing variables using solely one's judgement can be set aside.

It is important to acknowledge that this thesis aims to develop a generic design of a behavioural model in SD, to bring psychological theories closer to transport simulation. The benefits of such a focus do not extend to forecast modelling, such as discrete choice modelling. As previously discussed, traditional transport models (e.g. regression modelling) have already been heavily debated by psychologists and transport engineers, and good progress has been made in the integration of the two fields. Therefore, the value of this thesis is limited to all the approaches presented in transport research. Nevertheless, it is believed that future research will take more advantage of simulation techniques as technology and software development has made simulation more accessible in research.

Having discussed the values of an SD model to represent psychological theoretical frameworks dynamically, the next section will explain why developing a simulation model brings relevant benefits to psychology research as well.

2.3.6 Environmental psychology and the lack of representation of feedback loops and time delays

Although environmental psychology has highlighted relevant insights to explain travel behaviour, it is apparent that new theoretical frameworks used to predict behaviours have been generated through a rigid methodology that has not changed in the last 40 years. By reviewing the progress made in the area of behavioural psychology, one can notice that the main strategy to improve the understanding of people's behaviour has been through the continuous integration of old theoretical frameworks. This is not necessarily objectionable or negative, but this procedure has therefore only progressed in one mathematical property: linearity.

When the theory of reasoned action was launched in 1980 (Ajzen & Fishbein, 1980), psychologists (especially in environmental behaviour) entered into a heated debate about which model was able to capture the highest amount of variance in the prediction of behaviours. Although there are evident methodological violations committed in many psychometric-based studies, such as endogeneity, multicollinearity, normality and Likert-continuity assumption, the problem focused on in this thesis is that the theoretical efforts have only used integrating linear models. This issue goes against the discovery and interpretability of more complex mechanisms observed in the real world: feedback loops, time delays and accumulation of materials or information.

So far, environmental psychologists have claimed successful application of their theories by demonstrating larger explained variances than older models; therefore, giving a statistical argument to say why their theoretical proposition is superior to the previous one. However, this systematic way of working restricts the development of one's thinking processes, as it limits the understanding of the phenomena in one mental model type: reductionist, linear and unidirectional. Controversially, the theoretical models presented in the field have recognised the existence of feedback loops and attitudinal or normative evolution. However, they rarely test non-linear relationships, feedback loops or the evolution of psychological determinants.

For example, habit has been increasingly included in new frameworks as its importance in predicting behaviours has been demonstrated. Psychologists use habits to represent the influence of old behaviours towards a current behaviour (Klöckner & Blöbaum, 2010; Chng, et al., 2018). However, the application of habit in psychological models far from represents how the 'habit-behaviour' relationship really works. In theory, many researchers have acknowledged that old behaviours strongly affect current behaviours regarding car use (Eriksson, et al., 2008), as humans prefer to be inserted in routines rather than consciously take new transport decisions (Eriksson, et al., 2008; Nordfjærn, et al., 2014). Methodologically however, habits are unidirectionally affecting car use, undermining the real effect created in the long term. From an SEM model, it is only possible to conclude "there is an effect"; although it is not possible to picture how strongly and quickly this relationship evolves across time because the relationship is not embedded in a reinforcing loop mechanism. This can lead to wrong policy creation as the linear association between habits and behaviour can undermine how hard it is to break a routine with a simple intervention. Another feedback loop recognised in theory, but not demonstrated, is the normative-intention-behaviour loop in the 'comprehensive action determination model' (Klöckner & Blöbaum, 2010). The authors claimed that personal norms and environmental behaviours are interrelated in a reinforcing loop, as personal norms are activated not only by social interactions, but also by the revision of one's previous behaviours.

In overcoming the lack of feedback loop recognition, Moody and Zhao (2020) and Kroensen et al. (2017) run SEM models to demonstrate their existence. Without focusing the discussion on endogeneity problems, the authors found relevant insights regarding the reinforcing effect between car use-car pride-car ownership and car use-attitude. However, this is once again going against the non-linear representation that a reinforcing loop creates, generating similarly biased results as habits.

In the case of time-oriented thinking, linear models in environmental psychology usually use cross-sectional data analysis, limiting obtaining observations about behavioural patterns across time. In fact, several studies from psychology have demonstrated that motivational factors change over time in the context of transportation (Steg, et al., 2001). This puts at issue the method of theoretical validation. For example, Bamberg (2013) and Klöckner and Blöbaum (2010) developed their models under the assumption that psychological conditions or behavioural change are best conceptualised as events that evolve across time, which implicitly means that time delays and accumulation are part of the nature of latent variables. If the models work under a time-oriented sequence, then the results should be able to capture how the cause-effect relationships contain time delays. This is not possible to see as, once the model is determined, it is not possible to extrapolate the results further in time, impeding the possibility of understanding the transitional process of activation and internalisation of psychological determinants (e.g. personal norms). Consequently, it cannot be claimed from the data that personal norms (PNs) are actually a transitional process as it cannot be observed when or under which conditions PNs are activated, deactivated and/or internalised.

These limitations are enough to justify the development of new techniques that allow researchers to explore the understanding of psychological determinants dynamically. If statistical assumptions are expected to not be violated, then this opens the opportunity for different methodological approaches to deal with non-linearity, endogeneity, time delays, and accumulation of material or information. And, even if one day a model can fully explain 100% of the variance of the behaviour[16], linearity is still inadequate in explaining feedback loops; in other words, the dynamics between habits-behaviour, norm-activation process and attitudinal-behavioural change. For example, the model that will be presented in the following chapters demonstrated the importance of habits in the behavioural change resistance, giving it a more extensive revision as the reinforcing loop between current behaviour and old behaviour can create strong difficulties in traying to persuade a car commuter to consider alternative transport modes. The fact that habit-behaviour is not linearly related provides evidence that behavioural change in car commuting requires more than one intervention, which should be spread across all the psychological factors.

[16] Bamberg (2003) proved that NAM antecedents explained 14% of the variance in car use, whereas TPB accounted for 45% of the behaviour in question, and all the theoretical frameworks together accounted for 65%. Klöckner and Blöbaum (2010) demonstrated that their model explained 65% of the given behaviour, which was higher than TPB (51%) and NAM (54%).

2.4 Research questions

In the previous section, three distinctive gaps in the literature were identified, providing the focus for this thesis. Based on these gaps and the literature review, 3 research questions are formulated and sought to be answered by this project. The first research question seeks to answer whether it is possible to create a new tool to study an individual's behavioural intention towards car commuting. Therefore, the following research question is proposed:

RQ1: Can system dynamics be used to construct a non-linear model to model an individual's behavioural intention towards car commuting?

To answer RQ1, this project will develop a SD model based on experts' knowledge and environmental behavioural theories, in order to develop a tool that can help deal with non-linear cause-effect relationships, as well as study long term behavioural patterns.

The second research question considers the need to develop non-linear methodologies in order to gain in depth insights from studying feedback loop structures in the domains of environmental psychology and car commuting.

RQ2: How useful is SD in understanding behavioural intention towards car commuting, in terms of its ability to gain insight into its dynamic characteristics and in integrating the environmental behaviour theoretical frameworks?

To answer RQ2 (the theoretical contribution), this thesis will demonstrate the ability of the SD model developed to both explain how the behavioural intention towards car commuting can emerge from feedback loop structures and time delays, as well as inform how these dynamic properties can be modified in the long term, giving a new perspective on analysing environmental psychological frameworks such as Theory of Planned Behaviour, Norm-Activation Model, and Value-Belief Norm Model. This theoretical contribution will be discussed in Chapter 6 (where there is a detailed explanation of the simulation model), Chapter 7 (model validation), and Chapter 9 (section 9.2), where the quality, the significance, the completeness, and the originality of the analysis and model are reviewed.

The third research question addresses the empirical contributions gained from using the model, to evaluate potential changes in the system that can help decrease car commuting in the UK. In this case, the following research question was formulated:

RQ3: How do modifying psychological factors from the main environmental psychology frameworks (e.g. TPB) impact the level of behavioural intention towards car commuting over time in the UK?

The usefulness of this SD model is not limited to only theoretical contributions, but the modelling power increases when the model has the ability to explain a real life-situation (Sterman, 2000; Morecroft, 2015). For that reason, the third research question was explored through a case study. Case study research is defined as an empirical method that helps study a phenomenon in depth based on its real-world context (Yin, 2009). It is particularly useful when the research question requires an in depth exploration of complex events or phenomenon in real-life contexts (Crowe, et al., 2011), as well as a comprehensive understanding of causal links and pathways that emerge from new policy initiatives (Yin, 2017). In this sense, it is appropriate to demonstrate the answer of RQ3 by using a case study, as it helps to test specific questions about how the system works when deliberately manipulating the structure (Crowe, et al., 2011), which in turns help to develop or improve theory (Davis, et al., 2007). Chapter 8 and 9 explain the outcomes and reflections obtained from the case study used in this thesis.

2.5 Summary

In this chapter, a diversity of theoretical frameworks and methodologies were reviewed. The broad aim of transport and environmental psychology is based on the search for more sustainable transport systems, as part of the challenge to tackle climate change is strongly centred on transportation issues. Different methodologies and techniques were found in the spectrum of travel behaviour in both areas, in order to provide more answers for environmental difficulties and better recommendations for urban development plans and policy makers. Whereas transport research focuses on forecasting travel mode choice by using observable variables such as socio-economic factors, residential locations, urban distribution, travel time, distance of travelling, cost and trip purposes, psychologists have been focusing on understanding more psychographic variables, as they enable more complex explanations underlying people's transport choices to be built. Both approaches have found valuable insights, which have served as the main input for the development of this model.

Important joint work between transport and psychology has been seen in forecasting travel mode choice, in which researchers in the field of transport have proposed the use of 'Latent class choice modelling', which is a discrete choice model integrated with latent variables normally measured with psychometric scales. Despite the critiques around this type of integration, there is an overall agreement that psychologys add enormous value to the understanding of transport preferences. However, there is still an important gap in simulation modelling, which is expected to be addressed by this thesis.

Discussing the methodological concerns regarding the dynamism of psychographic factors in transport and psychology in simulation, this chapter justified the necessity of more cross-sectoral work in this area, and the value of shifting from linear to non-linear thinking through modelling.

The recognition of feedback loops, time delays and accumulation of information in psychology was evaluated and discussed. This thesis aims to propose a system dynamics approach to deal with the absence of psychological dynamism in simulation. The following chapter will present the research method, which specifies the specific aims of the SD model in this thesis, the limitations and benefits of modelling, and the steps deployed in the construction of the SD model.

3 Research design

This chapter presents the research design for formulating the behavioural intention SD model, by understanding the role of psychological determinants. The nature of this investigation is defined as both data driven and abductive[17], as the questions of this thesis are:

(1) What are the roles of psychological determinants in dynamically characterising reasoning behind commuters' choice to use a car, and their consideration of alternative travel modes? What can we learn in terms of psychological dynamics based on England's commuting behaviour?

(2) What is the potential impact of changing green attitudes to increase alternative transit use? Is there a way to increase people's alternative considerations in the short term?

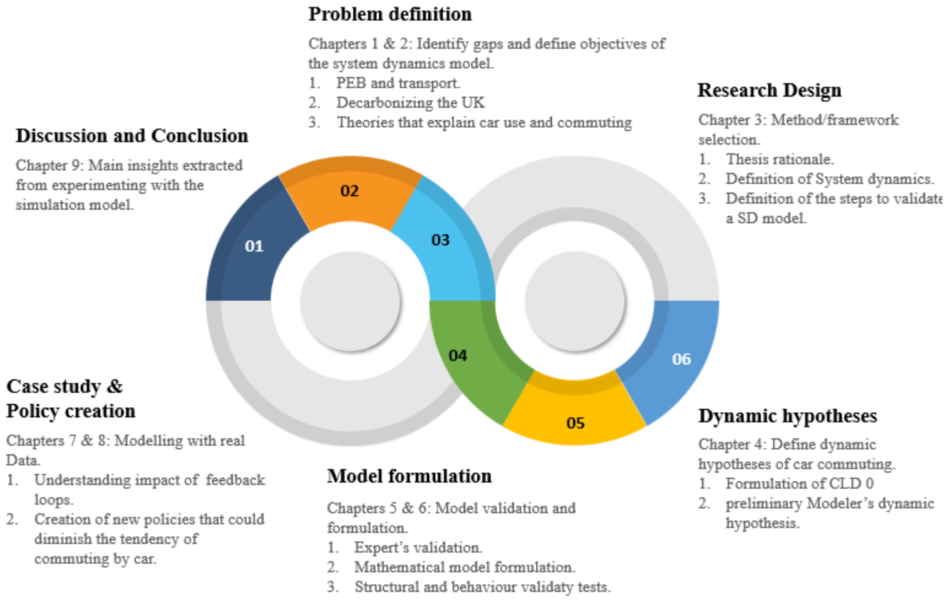
Figure 9 shows the research design for this project. The first step was reviewing the existing literature on car pollution, pro-environmental behaviour, people's travel behaviour, commuting, travel demand, system dynamics models in transport research, car use, behavioural theories, travel mode shifts and alternative transport mode acceptance (see chapters 1 and 2). Chapter 4 considers the dynamic hypotheses formulated from the literature review, and insights from other models and

[17] To deal with weaknesses associated with a deductive approach (all the theoretical premises must be true to produce reliable conclusions) and an inductive approach (the insights cannot be generalised as not enough empirical data is available to build a theory), abductive reasoning can be set as an alternative rationale. This decision is taken when the researcher finds empirical facts that cannot be fully explained by the current range of theories; thus, a pragmatic perspective is adopted to ensure that the conclusions offer the best explanation among many others. This encourages the researcher to combine qualitative and quantitative techniques, as some parts of the research question can be answered by verbal analyses (e.g. construction of the causal loop diagram), while others can be approached by adopting numerical techniques (e.g. differential equations). The key goal is to produce a plausible alternative explanation that can enhance the understanding of what has been previously observed and studied. In this case, the attitude-behaviour gap in car use is still an important topic in environmental behaviour as no ultimate answer has been given (Chng, et al., 2018), but many theoretical frameworks are currently available to explain part of the big picture. For this reason, an abductive approach works better in this particular case, as the researcher is developing an integrative theoretical framework based on multiple theories and mental models.

authors, which led to the creation of the causal loop diagram (CLD 0). The aim of this phase was to create a mental model considering functional and psychological factors from the literature review, to understand the dynamics in a bi-modal environment (car choice vs public transportation choice). This way, a preconception of travel mode choice was generated, enabling the development of the essential knowledge to carry out in-depth interviews with a group of experts in travel behaviour. As expected, causal loop diagram 0 helped to focus the discussion, making it easy to identify the most important factors involved in encouraging/discouraging car use and alternative transport modes. Moreover, CLD 0 set the focus of the project and the starting point to improve the mental model regarding travel mode behaviour (CLD A). This wide and holistic conceptualisation was necessary to construct the formal model, in order to visualise the complexity of travel mode choice and to spot the role that psychological factors take in people's decisions.

The main analyses are presented in chapters 5 and 6. This consists of the methods and results of the process of informal model construction (the mental model), formal model construction (mathematical integration) and validation (structure and behavioural validity). Chapters 7 and 8 highlight the key outputs from a practical point of view, as the model will be applied to a case study to see its usefulness and scope. Finally, Chapter 9 contains the discussion and conclusion of the thesis.

Figure 9. Research design: main topics developed in this thesis.



Source: Own elaboration.

The remainder of this chapter is organised as follows: firstly, the rationale behind this project is put into context to justify the methodology. Secondly, a description of computer modelling in social science is offered to understand why simulation could be a valid approach to address the problem. Subsequently, this chapter explains what system dynamics (SD) is and the principles on which the use of dynamic systems is based. Finally, the project validation steps are reviewed.

3.1 Computer modelling to explain social phenomena

The factors involved in explaining people's willingness to consider an alternative transport mode create a complicated map of cause-effect relationships. One way to test the effect of different interventions that could change people's travel behaviour is by running real-life experiments.

However, as researchers have claimed, this could be a very expensive and time-consuming way to test theory in practice. For this reason, modelling has been gaining more and more attention in research (Morecroft, 2015). Modellers use simulation models to assist policy makers and researchers in the process of decision making to give them the possibility to analyse actions and consequences in the long term (Forrester & Senge, 1980; Forrester, 1992). A simulation model is defined as a method that uses computer software to model a process of the real world using mental models, which establish logical relationships between two or more variables (Sterman, 2000; Davis, et al., 2007).

Simulation models can address multiple connecting factors, time delays (e.g. when x increases, y decreases after a certain amount of time) and non-linear effects of feedback loop structures (Forrester, 1961; Bala, 1999). For this reason, this method can help researchers and policy makers to better describe the real-world complexities, since more compound mental models can be developed. This way, the analysis is not restricted by simple/linear mental models which arise from the limited cognitive capabilities, long time frames between cause-effect actions, or an overwhelming amount of information (Sterman, 1994).

These dynamic complexities that are intrinsic to the representation of the system have arisen (Forrester, 1961; Barlas, 1989; Barlas, 1996; Bala, 1999; Sterman, 2000; Davis, et al., 2007) because of: (1) **Dynamic interactions:** some variables interact in different time scales, for example, product sales and production; (2) **Multiple links**: in the real world, variables are often interlinked; (3) **Feedback structures**: it is expected that actions produce consequences which alter the state of a situation, and this can lead to new decisions having to be made; (4) **Non-linearities**: effects are seldom proportional to causes, and those relationships can alter multiple states inside a given system; (5) **History-Dependent:** many actions are irreversible, so some actions need to be studied in the long term (e.g. people's attitudes) because doing and undoing actions are placed in different time scales; (6) **Time-Space:** cause-effect links are usually distant in time and space. Dynamic complexity has to be studied within the understanding of the founding structures involved in the system, rather than estimated predictor coefficients, which can easily change when a perturbation occurs in the system.

With the revolution of technology in computers and data storage, it is currently easier to use simulation models; therefore, modelling has become an accessible method for different purposes. It has been documented that simulation modelling has the following advantages (Pidd, 1988; Ingallis, 1988; Sterman, 2000; Davis, et al., 2007; Sokolowski & Banks, 2011; Shepherd, 2014):

1. **Cost.** Experimentation requires a lot of time and thorough planning, so, when empirical tests are being carried out, the results rely on the precision and accuracy with which the experiments are carried out.
2. **Time saving.** A simulation model allows the researcher to explore cause-effect relationships in the long term, without waiting for data collection to carry out an analysis.
3. **Replication**. Using simulation, it is possible to explore potential mechanisms that could emerge in the long term due to feedback loop structures and time delays in different scenarios. Designing a new experiment consumes more time than setting up new variables in the initial condition represented in a simulation model.
4. **Minimum safety protocols are required.** An experiment risks being impacted by human error, and could put subjects of the study in danger. In a simulation model, on the other hand, simulating extreme conditions is risk free, as no one is put in the real situation.

5. **Comprehensive understanding.** Since simulation is a methodology which explores long-term effects with multiple relationships, researchers can anticipate problems related to policy resistance[18].

Because of these advantages, simulation is a method that has been gradually growing as a feasible approach for theory development, as it can offer insights into multipart theoretical relationships, especially when there is a lack of empirical data or time/budget to address the research question (Davis, et al., 2007).

3.2 Computer modelling methods: agent-based modelling and simulation, discrete event simulation, and system dynamics

Computer simulation has been described as a mathematical approach, as well as an empirical research method because observations, experimentation and data coming from surveys can be involved (Wolf, 2008; Harrison, et al., 2007; Wang, et al., 2009). A number of simulation techniques are available to evaluate dynamical systems and solve problems that scientists observe in the real world. Discrete event simulation, system dynamics and agent-based simulation are among the most popular methods (Maidstone, 2012; Cassidy, et al., 2019; Davis, et al., 2007; Nasirzadeh, et al., 2018). Each of these techniques has its own advantages and disadvantages, therefore it is important for the modeller to select the appropriate methods based on the properties

[18] It is believed that policy makers attempt to resolve a problem but often make it worse because they do not look for long-term side effects. This phenomenon is known as policy resistance, whereby a system tends to destabilise from the equilibrium immediately after applying an intervention or policy, but will eventually return to its original state (Sterman, 2000). Hence, no structural change is achieved permanently in the system. One explanation for this is that it is based on people's tendency to problem-solve in a linear and unidirectional series of steps (Morecroft, 2015) so no feedback loops are analysed, and this is responsible for the system's inertia (Ulli-Beer, et al., 2010; Harich, 2010).

of the real-life system, the goals of the project, and which best addresses the problem formulated by the modeller (Davis, et al., 2007; Tako & Robinson, 2009; Jeon & Kim, 2016).

In the following sections, a conceptual review of discrete event simulation (DES), agent-based model (ABM) and system dynamics (SD) will be provided, as well as a set of reasons why SD was selected as the approach for this thesis. As DES and ABM are not the methodologies applied in this project, the following section will not review in depth the technical aspects of these techniques; instead, it only aims to describe the main elements of each technique, in order to provide sound knowledge for the reader to understand the reasons behind the selection of the simulation technique[19]. After describing the key elements of DES and ABM, a more extensive section will be dedicated to SD as it is the methodology selected to develop the model of this project, therefore explaining the conceptual and technical aspects of it are essential in this thesis.

3.2.1 Discrete event simulation (DES) and agent-based model (ABM)

The first one to review in this section is discrete event simulation (DES). In this simulation technique, the dynamics of a system are represented by a series of discrete events which change as time passes (Robinson, et al., 2010). Specifically, entities of a DES model (e.g. subjects, patients, people, customers, etc.) are thought to go through a sequence of separate events in the system (e.g. a customer moves from point A to point B); this sequence is triggered by resources or objects inserted into the model, and thus an inflow and outflow rate between two events is created (Robinson, et al., 2010; Maidstone, 2012; Jacobson, et al., 2006; Fishman, 2013). This simulation

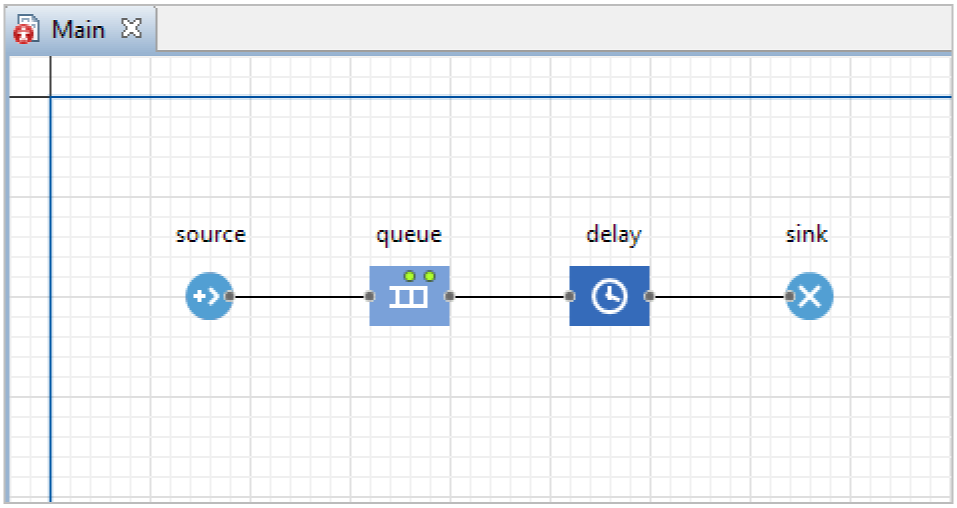
[19] See https://www.anylogic.com/use-of-simulation/ for a deeper description of ABM and DES.

method is mainly used for modelling queuing systems and server networks (Robinson, et al., 2010; Maidstone, 2012).

Figure 10 shows a simple example of a DES model, which intends to simulate a queue system in AnyLogic[20]. In this model, the source is defined as the starting point of the flowchart which generates entities, the queue is the stage where the source queues the entities before going to the next stage, the delay is the time that it takes an entity to leave the queue and move to the next point, and the sink is the destination or exit of the process. The properties of each flowchart block can be fixed, determining aspects such as arrival time to the queue, delay time that takes for an entity to arrive at the sink, the distribution of the delay time (e.g. triangular distribution), and the capacity of the queue. In this case, this flowchart can be used to represent a simple queuing system of a bank. People (source) arrive at the bank till at random times. If the bank clerk is free, the customer is served and leaves the bank, otherwise the customer waits in the line. In this example, two events are defined - ‘customer arrival’ and ‘customer departure’.

[20] https://www.anylogic.com/

Figure 10. Queuing system: flowchart defined in AnyLogic

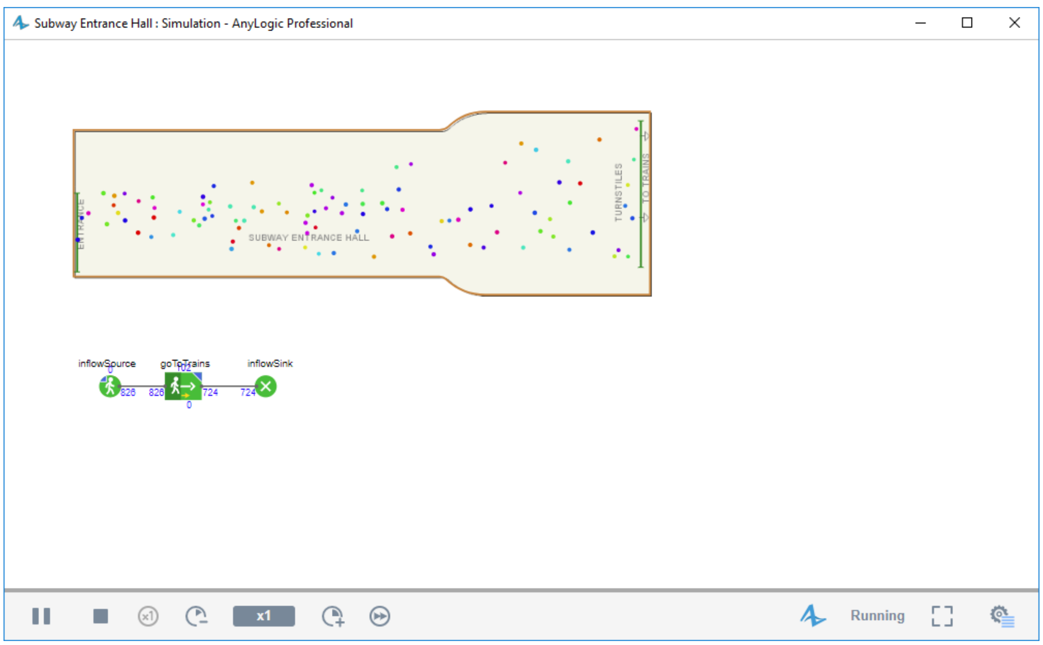


Source: Image extracted from AnyLogic documentation (https://anylogic.help/).

The next simulation approach to review is the so-called agent-based model. ABM is a method widely use in business, healthcare systems, transport, social science and psychology (Schröder & Wolf, 2017; Davis, et al., 2020; Gold, et al., 2020; Cassidy, et al., 2019). In ABM, the modeller creates a computational environment for self-directed agents to interact autonomously between themselves and with the simulated space, by following a series of predefined rules to accomplish their goals (Schröder & Wolf, 2017; Davis, et al., 2020; Maidstone, 2012; Wilensky & Rand, 2015). From these many autonomous interactions, a non-intuitive population behaviour emerges, which defines the dynamics on a system level (Wilensky & Rand, 2015). Based on the nature of ABM, modellers normally use it when they are interested in describing disaggregated parts of a system (Schröder & Wolf, 2017).

Figure 11 shows the introductory example offered in AnyLogic to simulate a simple pedestrian flow: how people move inside a subway entrance. In the example, the pedestrian dynamics simulation model is placed inside the subway entrance hall drawing, which is labelled as the layout that determines how the agents will move inside this building. One the layout is set, the modeller creates the flowchart to define the pedestrian flow (the entrance of the building, the exit, the direction of the flow, etc.), which in Figure 11 is the set of blocks labelled as InflowSource (block that generates pedestrians), GoToTrains (block that moves pedestrians from the entrance to the exit), and InflowSink (block that represents the exit point). This example can be more complex if other stages of the process are added, such as fare gates and ticket vending machines[21].

Figure 11. Agent-based model example.



Source: Image extracted from AnyLogic documentation (https://anylogic.help/).

[21] Phase 3. Displaying pedestrian density map – AnyLogic Documentation.

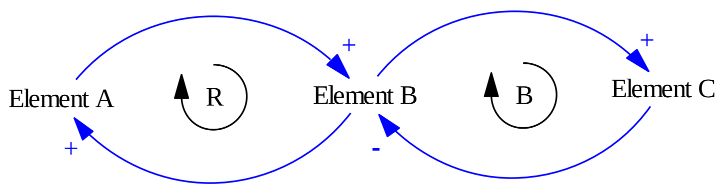
As the method approach selected for this thesis is system dynamics, the next section will develop a deeper review of the technique. System dynamics has been defined as a highly abstract modelling technique as it focuses more on explaining complex relationships of an aggregated system instead of defining individual properties or discrete events. For this reason, it has been preferred to explain long-term system behaviour (van den Belt, 2004; Ford, 2020), aiming to describe the stable states of the system and how the system behaviour emerges from the system structures (van den Belt, 2004). In section 3.3, a series of reasons will be offered to justify why System Dynamics was chosen over ABM and DES to develop a simulation model to describe the behavioural intention towards car commuting.

3.2.2 System dynamics

System dynamics typically builds non-linear behaviour emerging from combinations of feedback loops, time delays, and stock-and-flow structures (Forrester, 1992; Sterman, 2000). This approach is particularly useful because it tries to understand the dynamic characteristics of real-life systems, which are defined and influenced by interactions between multiple elements.

Figure 12 shows the basic notation used in a simple causal loop diagram (CLD) between three elements (Sterman, 2000; Morecroft, 2015). The + signs at the arrowheads show that the effect is positively related to the cause: an increase in element A causes an increment in element B to rise above what it would have been (and vice versa). The – sign at the arrowhead between C and D shows that the effect is negatively related to the cause: an increase in element C shrinks element B to drop below what it would have been (and vice versa). In this example, a reinforcing (letter R) and balancing (letter B) loop are exhibited because A-B and B-C relationships are bi-directional, so the diagram reflects the feedback dependency of both pairs of variables. The complexity of systems rises when more feedback loops appear, reflecting the non-linearity and multiple relationships between variables of a given system.

Figure 12. Causal loop diagram (CLD) notation.



Source: Own elaboration.

As Figure 12 shows, causal loop diagrams are a particularly useful tool for system dynamics modellers (Forrester, 1961) as they contain information (qualitative data) about structures, feedback loops, cause-effect relationships and boundaries of a dynamic system gathered from mental models (Bala, 1999; Sterman, 2000). A mental model (in system dynamics[22]) is a mental image or a verbal description (Forrester, 1961) that reflects an individual's representation of real-world situations that underlie his/her beliefs, values and assumptions to explain cause-effect relationships (Forrester, 1961; Senge, 1990; Binder, et al., 2004; Maani & Cavana, 2007; Groesser & Schaffernicht, 2012; Morecroft, 2015). Therefore, because mental models are an individualistic process to interpret and make sense of the real world (Sterman, 1994; Sterman, 2000; Groesser & Schaffernicht, 2012; Morecroft, 2015), multiple problems arise when one individual attempts to

[22] For further details about the difference between traditional mental models used in other research fields and system dynamics see Groesser and Schaffernicht (2012).

mentally solve a dynamic problem: (1) one's mind has a biased perspective when viewing the problem, thus limited concepts and relationships can be elicited to explain it (Bala, 1999); (2) humans are incapable of fully understanding a dynamic behaviour that is created by the accumulation of processes (stock-and-flow failure) (Cronin & Gonzalez, 2007; Groesser & Schaffernicht, 2012); and (3) humans tend to see a problem as a linear sequence of events, without recognising time delays and feedback relationships (Sterman, 2000; Moxnes, 2004). For these reasons, it becomes crucial to contrast, iterate and validate a modeller's mental model with pre-existing validated models/theories and experts' mental models to build a satisfactory representation of a real-world system from different perspectives (Luna-Reyes & Andersen, 2003) and translate verbal representations into formal models to support the decision-making process (Forrester, 1961; Sterman, 2000)[23].

SD is useful in discovering and representing feedback structures and non-linear behaviours, that subsequently characterise the dynamics of a given system (Bala, 1999). For practical purposes of this section, a simplified description[24] is given of how to move from a mental model to a formal model (mathematical integration): first, modellers create and confirm the causal loop diagram by using other studies that support the theoretical relationship proposed in the diagram and/or applying deep interviews with an expert from the research field (qualitative approach) (Barlas, 1989; Forrester, 1992; Barlas, 1996). This step plays an important role in system dynamics because the causal loop diagrams show the potential causal hypotheses during the model development

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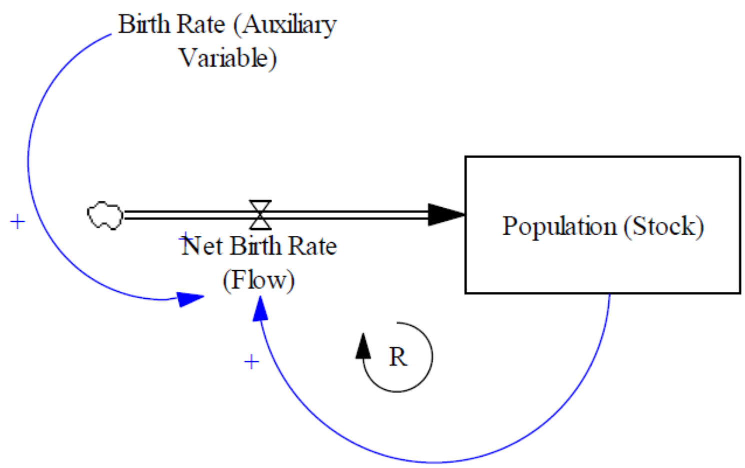
[23] See Sterman (2000) or Morecroft (2015) to find practical examples of when SD was useful to support the decision-making process of companies.

[24] A detailed description of how to validate a simulation model is offered in the next section (model validity).

(Forrester & Senge, 1980) and they simplify the illustration of the system proposed (Sterman, 2000). After that, to perform an SD model (quantitative approach), modellers translate the causal loop diagram by building blocks known as stock-and-flow variables, inserting auxiliary variables to represent rates and constants (Jones, 2005). SD simulates the diagrams of stock-flow via a system of differential equations (Chaerul, et al., 2008; Kunc, 2016). The stocks are variables that accumulate material, money or information as the model progresses over time, whereas the flows are variables that represent the rates at which the accumulation is increased or decreased when the time goes by (Sterman, 2000).

A simple diagram of SD dynamics notation is represented in Figure 13. In this example, Population is the stock variable, which increases its level by accumulating new births across time. It is expected that more people lead to more births if everything else is constant (factors such as economic growth or life expectancy). Net Birth Rate represents the flow variable, which changes the stock variable by adding newborns. Birth Rate works as an auxiliary variable, and is the factor of increment at which the Net Birth Rate changes over time.

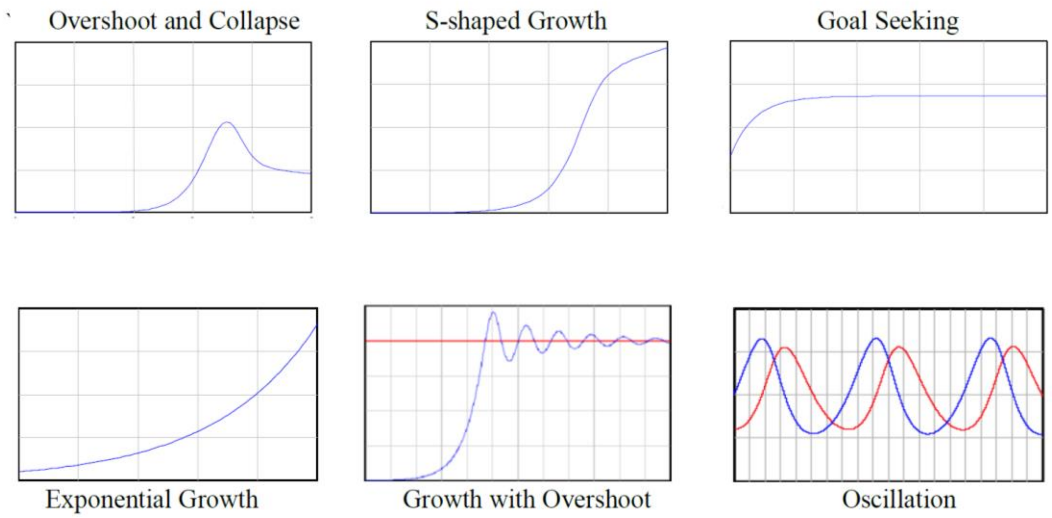
Figure 13. Basic Element of SD.



Source: Own elaboration by using Vensim DSS.

It is important to understand how the components inside a system are related because the most complex behaviours represented in a model usually arise from the interaction of two or more variables (feedback loops), rather than the complexity of the components themselves (Bala, 1999; Sterman, 2000). As previously highlighted, these feedback loops can be positive (or self-reinforcing) and negative (self-correcting), and, depending on how they are related and represented in time, it is possible to find six common behaviours: (1) Exponential Growth; (2) Goal Seeking; (3) S-shaped Growth; (4) Oscillation; (5) Growth with Overshoot; and (6) Overshoot and Collapse (Figure 14). For example, exponential growth, which is a common structure and behaviour to represent population growth (Sterman, 2000), is created by one feedback structure (a reinforcing loop). More complex behaviours like overshoot and collapsed loop structures arise because of the interaction between one reinforcing loop and two balancing (also known as self-correcting) loops.

Figure 14. Most frequent behaviours in system dynamics.



Source: Own elaboration using Vensim DSS x32.

System dynamics modelling has been used in a wide range of different research fields, such as business, ecology, economy, agriculture, politics and environment, to represent a range of feedback systems (Sterman, 2000; Dyson & Chang, 2005; Chaerul, et al., 2008). In terms of environmental and transportation concerns, the application has covered several issues, including control of goods transportation by applying a carbon tax (Piattelli, et al., 2002), urban transportation system representation (Jifeng, et al., 2008), the challenges for adopting alternative fuel vehicles (Struben & Sterman, 2008), CO_2 mitigation in China's inter-city passenger transport (Han & Hayashi, 2008), greenhouse gas mitigation policies and the transportation sector (Stepp, et al., 2009), urban planning process towards stabilising CO_2 emissions (Fong, et al., 2009), integration of land use and transport models to represent urban transportation (Pfaffenbichler, et al., 2010), transportation policies testing (Fiorello, et al., 2010) and highway development to reduce the impact of transportation pollution (Egilmez & Tatari, 2012).

3.3 Why is system dynamics selected as the approach to modelling people's behavioural intention towards car commuting?

For this project, DES modelling was discarded as the nature of the variables that are thought to be simulated is not appropriate to be described as a sequence of separate events. First of all, cognitive dissonance (one of the key elements in this simulation model) is described as a parallel processing as the nature of the dissonance emerges from a state of having simultaneous conflicts of attitudes, beliefs, or emotions towards a behaviour (Festinger & Carlsmith, 1959; Brehm & Cohen, 1962). This state of discomfort has been described in travel-related attitudes and behaviours, finding empirical results about how the conflict is resolved in travel mode choice and residential location choice (De Vos & Singleton, 2020). Therefore, representing this project's system as a sequence of separate events would not be appropriate as the conflict emerge from two processes happening simultaneously (e.g. a person holds two opposite positive; an attitude towards protecting the environment, as well as an attitude towards commuting by car). Second of all, the lack of feedback loops generation in the techniques limits the possibility to represent certain psychological mechanisms. Several authors in environmental psychology and transport have recognised the existence of feedback loop structures between habits and behaviours, as well as attitudes and behaviour (Chng, et al., 2018; Kroesen, et al., 2017; Klöckner & Matthies, 2009). Hence, the sequence-centric process behind DES modelling would limit the possibility of developing a simulation model based on feedback loop structures.

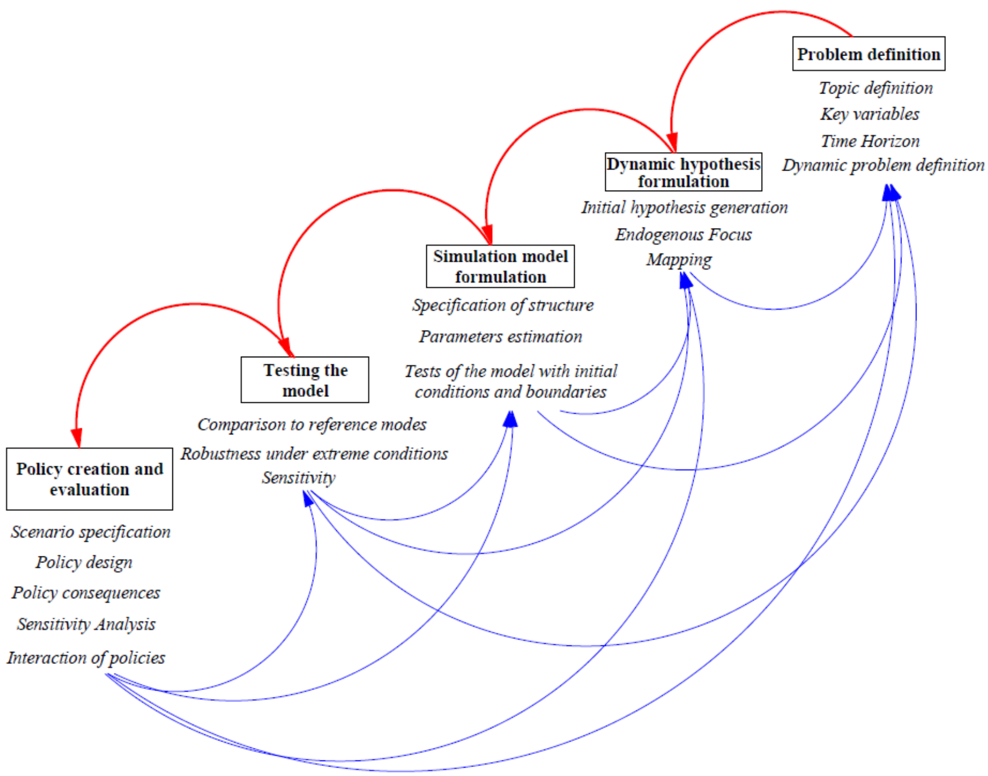
In case of ABM, three reasons guided the decision to select SD for this project. First of all, this project aims to understand the behavioural intention towards car commuting in England. This psychological process is normally described in an aggregated level in environmental psychology (Abrahamse, et al., 2009; Bamberg & Schmidt, 2003; Klöckner & Blöbaum, 2010; Carrus, et al., 2008; Steg, 2005; Bamberg, 2002; Bergstad, et al., 2011). Additionally, the data available from the Department for Transport to construct the long-term patterns of trends in car commuting (reference mode) are aggregated at a population level. Therefore, there is no benefit with identifying individual behaviours as the statistics distributions available in a large scale are generalised to the population. Third of all, the emphasis of the model lies on an individual-level mechanisms of attitudes, behaviour, and personal norms, hence, there is no need to recreate interactions between commuters to understand a bottom-up dynamic behaviour as forming a behavioural intention towards car commuting is more an individual mechanism than multi-level interactions between commuters. Often, a system dynamics approach is more preferred when the internal process of an agent is needed to be described (Bradhurst, et al., 2015). Finally, under the Agency Theorem for system dynamics (Macal, 2010), a well formulated SD model has an equivalent formulation in ABS. However, ABS tend to use more computational resources than SD (Maidstone, 2012). Thus, for all the aforementioned reasons, the purpose of the study and characteristics of the problem fits perfectly with system dynamics.

3.4 The modelling processes

System dynamics (SD) was born as a practical approach to address and solve problems that dynamically change across time. The process of simulation modelling with SD is not a rigid procedure in principle. By definition, SD is framed as a feedback process because it is constantly iterating, questioning, testing and adjusting the simulation model (Forrester, 1961; Barlas, 1989; Forrester, 1992). In this sense, SD does not follow a linear sequence of activities; instead, the modeller dictates the boundary and scope of the simulation model, which could change as the understanding of the problem escalates. However, modellers usually include the following aspects

(Sterman, 2000): (1) understanding and framing the problem presented, (2) articulating the hypothesis or theories to explain the causes of the problem, (3) creating a simulation model to test the dynamic hypothesis, (4) adjusting and calibrating the model until the purpose of the model satisfies the problem addressed, and (5) designing and evaluating possible policies that can mitigate the causes of the problem.

Figure 15. The modelling process in system dynamics.



Source: Own elaboration. Information extracted from the book Business Dynamics, by Sterman (2000).

The modelling process starts with the conceptualisation of the problem. In this phase, the problem of interest is defined, in which its context and characteristics are described. This step is important because it helps to clarify the purpose of the model and how it is capable of addressing the problem formulated. Usually, the modeller develops an initial articulation of the problem through discussion with experts in the field, data collection, interviews, and direct observation or participation (Sterman, 2000). The results of these activities allow the modeller to build a **reference mode**[25] and set the **time horizon.** The reference mode is especially useful at the beginning of the process because it helps to clear doubts about the problem in graphical terms. Moreover, the reference mode might reflect the dynamic behaviour of the variables of interest based on historical facts, so that can support the process of model construction by setting up the base-line conditions.

Following the problem definition, modellers must develop a dynamic hypothesis (DH). The dynamic hypothesis is a working theory that provides an explanation of how the problem is characterised dynamically and endogenously. Thus, a DH helps as a guideline for the modeller to know what to focus on in terms of modelling the structures contained in the simulation model. Since usefulness is a key factor in fulfilling the purpose of an SD model, modellers tend to discuss the problem and theories about the causes of the problem with the people related to the project, and with experts who could have vast knowledge of the topic. This phase ends with mapping the cause-effect relationships of all the endogenous variables included to simulate the behaviour of interests; this map is normally called the Causal Loop Diagram (CLD).

The next step of an SD simulation study involves the conversion of the CLD into a set of mathematical equations that allow simulation of the given dynamic behaviour. This is referred to

[25] The reference mode is the process where the modeller uses a set of graphs to describe the problem over time. These graphs can be created from numerical data, and sometimes, when historical data is unavailable, from verbal descriptions of the system.

as the formulation phase. As Figure 15 showed, the modeller creates the condition to simulate the base case behaviour. Thus, it is necessary to determine and specify the parameters of each variable and set up the basic behaviour by simulating the model with the initial conditions and boundaries. This phase can be time-consuming as the simulation model is constructed gradually, and reviewed several times with experts before finishing the final product.

Finally, an experimental phase is developed. In this stage, the modeller seeks insights into the base case behaviour by adjusting and changing the initial conditions of the model. For this reason, several tests take place to evaluate the sensitivity of the model and the behaviour of the system in different contexts.

Everything explained in this section has been presented as a sequential list of actions. However, it is important to note that the process has been performed as a continuous iterative procedure. In other words, the phases from Figure 15 were all reviewed and reformulated more than once during the construction of the model. For example, in this thesis, during the formation of the causal loop diagram, the literature review was completed again in order to improve the explanation of some relationships that were not clear. Likewise, during the sensitivity test (post-defining the initial parameters), some auxiliary variables were adjusted again because they created floating point errors in the model. For this reason, the structure of this thesis should not be taken as the way in which it was completed and executed. This is important to clarify as, for practicality purposes, the thesis will not be able to show these back-and-forth modifications; thus, many ideas here will be explained from the latest iterative step and with all the modifications already made.

3.5 Challenges of system dynamics and its philosophical position

Since a simulation model is a simplified representation of reality, all models have limitations in capturing all the variables involved in a given context (Doyle & Ford, 1998). For this reason, the challenge of modelling is focusing on how much it improves the decision maker's thinking process (Sterman, 2002), and this is constrained by the human's cognitive capabilities (Lane, 2000), and the extent to which simulation models allow the scientists to provide long-term recommendations (Sterman, 2000).

In this sense, the nature of simulation methods has led to a change in stance of the research question, from generalisations about accelerating learning and thinking systems, to constructing supportive tools that modellers use to help societies understand the system complexity and create better policies (Sterman, 1994; Sterman, 2000). That is why modellers in social science have claimed that their thinking process is based on a holistic, long-term dynamic view of the world, instead of a reductionist, short-term static one, since their cognitive capabilities to conceptualise a problem are supported by computer simulation techniques that help them deduce the behaviour of a system over time (Sterman, 2000; Lane, 2000).

In system dynamics, this rationale has been criticised by other researchers, putting in doubt if SD is really a useful element to understand the systems that comprise the world, and to describe the principles of hierarchy, feedback and openness in institutional processes (see Hayden (2006) for more details). These critiques have argued that simulation methods are not sufficiently accurate to represent the reality, because of the application of unrealistic assumptions (quality of the conceptualisation of the problem) and the subjective procedures to validate it (Ansoff & Slevin, 1968; Zellner, 1980; Davis, et al., 2007). Even when quantitative sources can be used as an input to feed the model outcomes, the system's behaviour is elicited by judgmental data that the mental model is capable of capturing, in order to explain the variable cause-effect relationships and loop structures. In other words, the level of quality when working with SD depends on the level of understanding and reasoning that the modeller can develop and establish on a given situation (Lane, 2000).

In response to these critiques, system dynamics modellers have offered rigorous steps of model construction and validation (Barlas, 1996; Lane, 2000; Sterman, 2002; Radzicki & Tauheed, 2009), in order to clarify when and how SD can be useful for the analysis (Davis, et al., 2007), and to achieve acceptable standards when it comes to model validation (Barlas, 1996). Many of these proposed steps are informal and qualitative in nature (e.g. interviews with experts) (Barlas, 1996) since causal-descriptive models, like SD, require generation of an accurate and convincing description of how the internal structure of such models works. These steps cannot be demonstrated with the standard statistical tests due to problems of autocorrelation (e.g., feedback loops) and multicollinearity (Barlas, 1989). The internal structure of the model must be assessed with qualitative tests that can guarantee that the simulation model matches the mental model articulated by the modeller and experts. In other words, there is a degree of judgement about the quality of the conceptualisation of the internal structure, and that cannot be approached by purely mathematical techniques as it involves a verbal process. For this reason, it is suggested that modellers describe and specify all the variables, assumptions and theoretical frameworks used to demonstrate a strong internal validity (Forrester, 1961; Doyle & Ford, 1998; Davis, et al., 2007). The protocols/activities used in this thesis will be developed in the explanation of the qualitative and quantitative phases in the next sections.

The rationale behind the mix of qualitative and quantitative approaches to develop a simulation model comes from the philosophical position normally taken in SD[26]. The system dynamics paradigm assumes the existence of causality in every system (real-world representation) and takes a philosophical approach that is functional, relativist and holistic to give answers (Meadows, 1980; Barlas & Carpenter, 1990). By nature, SD embodies a theory about how a system works in real life (causal-effect relationships, feedback loops, material/information accumulation) with some limitations (Sterman, 2000) because the articulation and conceptualisation of the problem are restricted by cognitive capabilities, which allow the modeller to translate a mental model into a dynamic hypothesis (Morecroft, 2015). A dynamic hypothesis is understood as the explanation given to describe a certain dynamic behaviour (Lane, 2000). For this reason, every model will be liable to an element of subjectivity since the process of model development may take different perspectives (from each modeller/decision maker involved) in attempting to describe real situations. That is why no particular SD representation can claim complete objectivity (Barlas & Carpenter, 1990). However, some models can prove to be more effective than others.

Going from Manchester (MCR) to Leeds (LDS) can be done by many different methods (train, driving, walking, cycling, private jet) and by many different routes. By assuming that there are no financial or transit mode availability restrictions, the decision regarding which combination will be taken will depend on what the purpose of the trip is: on the one hand, an individual might want to go from MCR to LDS for recreational purposes, so the train could suit them better as the landscape can be appreciated and there is more flexibility to enjoy the trip. On the other hand, the individual

[26] In system dynamics it is possible to find models that have only developed the explanation of the mental model, without offering a mathematical expression for it. Therefore, quantitative techniques are not being used to construct the model and demonstrate model validity. An example can be found in a paper by Harich (2010).

might need to do that journey because it is a business trip, so the decision might be taken based on time/cost effectivity. Whichever decision is taken, the process of selection is driven by the traveller's goals; therefore, some alternatives will better suit the purpose of the trip in a given context. This is the rationale behind SD. Constructing a simulation model can take different approaches, but how the model fulfils the purpose of the project determines the success of an SD model, which can be tested by judging the degree of usability.

When the purpose of the model is clear, its construction becomes feasible, and it is more likely to be utilised as its strengths and weaknesses are visibly understood. For this reason, the construction and validation of the model develop a gradual process of multiple iterative revision between multiple actors (or mental models) as practicality and usability are dictated by decision makers who will use the model to create new policies or new managerial decisions (Barlas & Carpenter, 1990). In other words, SD is a matter of social construction where multiple actors give input into the creation, testing and validation of a model.

In this sense, the SD approach cannot be restricted to solely numerical empirical validation (Meadows, 1980). Semi-formal and subjective components are implicitly involved to have the capability to judge the model's purpose. Without a purpose, the model loses its validity, its justification to exist and the sense behind using computational resources, so it does not matter if the variables of the model can be mathematically formulated and related (e.g., speed = distance/time); constructing a model requires non-technical, informal and qualitative techniques to evaluate if the research goal or the managerial problem is being addressed by the computer simulation (Forrester, 1961; Barlas, 1996; Sterman, 2000), and if the model shows that it is a practical tool to enhance learning and understanding of complex systems (Sterman, 2000).

Considering this, the philosophical position of this thesis is based on a pragmatic approach, so as to exploit the advantages of empiricism and interpretivism, normally related to quantitative and qualitative methods, respectively (Sale, et al., 2002; Johnson & Onwuegbuzie, 2004; Onwuegbuzie & Leech, 2005). The researcher in this project conducted a study by using the literature review, semi-structured in-depth interviews, and data collection, to test and validate the structure of the system.

3.6 Validity considerations: how to validate an SD model?

Theoretically, system dynamics validation is driven by two main assumptions during the modelling formulation and construction (Forrester, 1961): (1) all SD models are built to fulfil a purpose (Forrester, 1961; Overton, 1977), and (2) the internal structure of the model originates its behaviour (Sterman, 2000; Qudrat-Ullah & Seong, 2010). In practice, this is translated into two groups of formal procedures that it is highly recommended to include to validate a system dynamics model (Barlas, 1989): (1) Structural validity and (2) Behaviour validity tests.

3.6.1 Structural validity

Structural validity tests are driven by several tests that aim to check the structure of the model is close to the real structure (Forrester & Senge, 1980; Barlas, 1989). This type of validity begins with the formulation of the **causal loop diagram**[27] (Binder, et al., 2004), in which a **boundary**

[27] Causal loop diagrams are mental representations of a system that helps to define the basic causal mechanism hypothesised to explain a behaviour observed in a real system over time (reference mode) (Binder, et al., 2004; Qudrat-Ullah & Seong, 2010).

adequacy test and **structure verification** of the mental model need to be performed (Forrester & Senge, 1980; Barlas, 1989; Qudrat-Ullah & Seong, 2010).

The structure verification is the phase where the mental model is directly compared with the conceptualisation of a real system that come from experts and literature. In other words, to pass the structure verification test, the relationships and loops proposed by the modeller need to find a logic justification in highly knowledgeable sources that can provide enough evidence to not contradict the expected structure of the real system (Forrester & Senge, 1980). For this reason, interviews, historical data, previous studies and relevant theory related to the given problem are used to build the conceptualisation of the simulation model; then that provides reassurance that the logic behind the model follows a pattern that can be seen in the real system. In this thesis, the structure verification test was performed in three phases:

1. By constructing the causal loop diagram 0 (CLD 0) from the literature: relevant authors and theories were considered to explain how the transit mode choice system works.

2. By constructing causal loop diagram A (CLD A) from the feedback received in the interviews (qualitative phase): causal loop diagram 0 was used as the first input to contrast and test the proposed relationship with experts in transit mode choice. The experts evaluated the proposed relationship and they either supported, rejected and/or modified the conceptualisation of some of the relationships. More details can be found in the following chapter.

3. By constructing causal loop diagram B (CLD B) from the interviews and relevant literature: as will be explained later in this thesis, the final causal loop diagram emerged from the revision and comparison of CLD A with the literature to offer a detailed description of how the psychological constructs that explain car commuting are related.

The boundary adequacy test is designed to test if the level of aggregation is appropriate and if the model has included all the relevant relationships and feedback loop structures (Qudrat-Ullah & Seong, 2010). To decide whether or not the boundary adequacy is satisfactory, the dynamic hypothesis is qualitatively tested, asking if it is convincing enough to address the explanation of the behaviour expected from the real system (Barlas, 1996). In this case, the dynamic hypothesis was formally tested twice: during the last section of the interviews (dynamic hypothesis for CLD 0) and later, when the original dynamic hypothesis was extended and fully detailed by focusing only on the explanation of the psychological factors, in which, in this case, the PhD guidance gave the additional support needed to evaluate the quality of the explanation exposed in this thesis.

When those tests are completed, the modeller can continue with a **dimensional consistency test** and **parameter verifications** tests when the mathematical model is created (Forrester & Senge, 1980; Barlas, 1989). The dimensional consistency test requires that, once the mathematical model is written in the software, all the measurement units are well defined in the model. The parameter verifications test consists of contrasting the parameters in the model with empirical data; thus, it is possible to verify if the parameters relate theoretically and mathematically to real life (Forrester & Senge, 1980). In this thesis, the parameters were extracted from previous studies that demonstrated a significant effect in the behaviour given. More details about the sources from where the parameters were extracted can be found in the explanation of the model.

Once the operational model is running, the modeller needs to perform an **extreme condition test** (Sterman, 2000; Qudrat-Ullah & Seong, 2010). This test is to evaluate the model’s outcomes when key variables take extreme values. The extreme condition test helps the modeller to discover flaws in the model structure and omitted variables (Forrester & Senge, 1980). The judgement about whether or not the extreme condition is logical can be tested by running the SyntheSim feature on

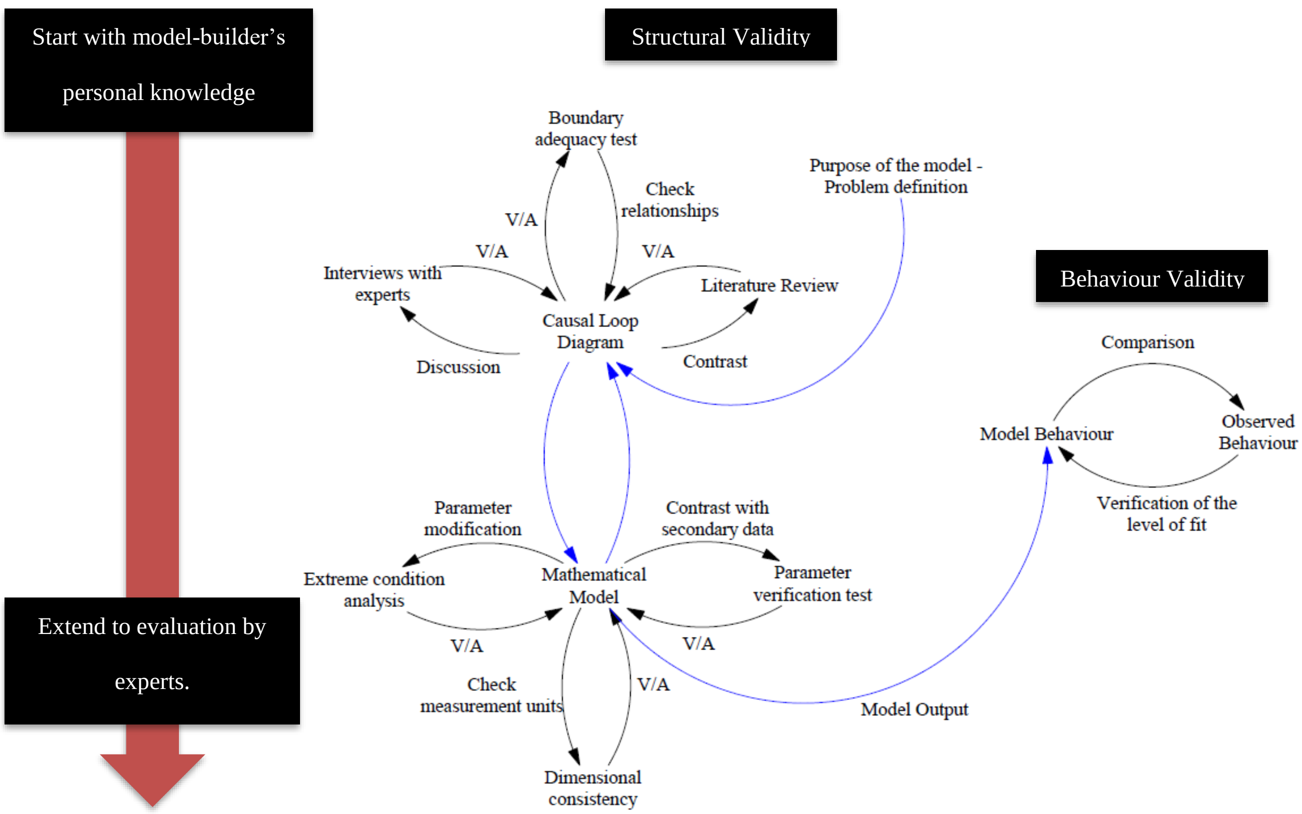
Vensim DS, which allows the modeller to change multiple variables and observe the model behaviour immediately. Examples of extreme condition tests are shown in the next chapters.

3.6.2 Behaviour validity

Behaviour validity tests normally occur when the structure of the conceptual and mathematical model has been verified (Barlas, 1989; Qudrat-Ullah & Seong, 2010). In this step, the outputs generated by the model are contrasted against real-world data to compare how well the behaviour of the system dynamics model fits real-world observations (Barlas, 1989; Sterman, 2000). This phase consists of two parts:

1. **Behaviour prediction tests**: to determine whether the patterns exhibited by the model match the behaviour of the real system (Barlas, 1989). In this case, the output of key variables was contrasted against empirical data. The results of this test are presented in the calibration section.
2. **Structurally oriented tests**: to evaluate the behavioural sensitivity of the model (Qudrat-Ullah & Seong, 2010). In other words, the modeller changes the values of a few parameters, one at a time. This way, it is possible to observe how the behaviour of the main variables is affected when these changes take place in the model. The modeller can run this test to detect major structural flaws (Barlas, 1989), as some changes are expected to affect the system behaviour of the key variables in real life.

Figure 16. Formal validation process of a system dynamics model.



Source: Own elaboration. V/A means verification/analysis.

3.7 Chapter summary

This chapter has described the research design of the project. While there are a few steps that all system dynamics modellers go through, modelling is certainly creative. For that reason, more than establishing a formal procedure, system dynamics modellers and researchers (Bala, 1999; Sterman, 2000; Shepherd, 2014; Morecroft, 2015) have agreed certain key elements that should always be included for a successful system dynamics application: problem articulation, dynamic hypothesis generation, data collection, model formulation (mental and formal), validation testing and analysis.

Modelling is a continuous iterative process by nature; thus, modellers go back and forth reviewing and adjusting each step of the project. In this thesis, the sequence of activities started with the literature review and data collection (from the Department for Transport, UK) to define the problem, to state the first mental model and to generate the dynamic hypotheses. Followed by this, 22 interviews took place to continue with the structural validation of the mental model. Once the model was improved and adjusted with the insights obtained from the experts, a second literature review was performed. After defining the boundaries of the model and establishing the final causal loop diagram of people's commuting behaviour, the formal model was completed. Finally, the thesis concluded with multiple analyses to validate the simulation model and test potential strategies to diminish car commuting.

4 Formulation of the dynamic hypothesis based on the literature review

This chapter presents the critical review of the literature that was undertaken to identify the main factors that explain transport mode choice. Although the simulation model will only focus on the psychological determinants to explain car use, a wide view of travel mode choice is needed beforehand to understand how the whole system works and how it is influenced by external and internal structures. Additionally, the simulation model will need to assume a bi-modal environment due to feasibility constraints; for that reason, it is important to set the knowledge around how private car use and public transportation use influence each other. Moreover, in the transport domain, predicting travel behaviour involves multiple areas and the nature of the sources that affects it covers not only psychological factors, but also variables including transit infrastructure, people’s income, population growth, transit accessibility and land use (Pfaffenbichler, 2003; Vij & Walker, 2014; Shepherd, 2014); hence, it is important to review what has been studied and the insights that surround these topics. Furthermore, this step was necessary to ensure that the vast existent knowledge about mode choice was reviewed and comprehended before contrasting it with the insights obtained from the experience of the expert interviewees. In consequence, the strategy proposed in constructing the mental model was to draw a preliminary version as wide as possible, in order to have a well-grounded knowledge about all the components involved in travel mode choice and their effect on psychological determinants.

During this phase, important decisions were clarified: (1) the definition of the purpose of the model, (2) the boundaries of the model, (3) the initial dynamic hypothesis to explain how transport mode choice works, and (4) the modeller's mental model. The following sections will explain these points as well as introducing the mental model that was used later during the interviews.

4.1 Clarification of the model's purpose

Before showing the process of constructing the mathematical model from the conceptual model in the following chapters, it is important to define the purpose of the model. Having a well-defined purpose helps to focus on what needs to be included and what needs to be excluded from the model (Sterman, 2000).

The first aim of this project was to offer an integrated framework between the most important and influential models in psychology and transportation research to develop a detailed conceptual model to understand all the factors involved that explain car use, public transit use and active transportation choices (chapters 1, 2, 4 and 5). The second aim was to study the sensitivity of different psychological aspects to evaluate the difficulties of discouraging car use when commuting (Chapter 8). The third aim was to offer a useful tool to analyse car commuting in England, in order to enable policy makers to understand the individual's behaviour towards car use (chapters 8 and 9). The fourth aim was to translate the theoretical frameworks used in environmental psychology into a system dynamics model, so as to observe dynamically how psychological factors are activated and form across time and to complement the efforts done so far to understand car behaviour (chapters 7, 8 and 9). The final aim was to show different leverage points from a psychological point of view, where policy makers can intervene to discourage car use significantly in England (chapters 6 and 7).

The target audience for this project is mainly environmental psychologists and transport policy makers who work on intervention programmes that look to discourage car use. Additionally, the audience can be extended to consultants, charities, environmental engineers and behavioural psychologists that work on interventions to change behaviours.

The expected outcomes from constructing and developing the simulation model include: the exploration of the difficulties to overcome the attitudinal strength towards car use, the formulation of a dynamic process to form and activate a moral obligation for reducing car use, and the improvement of the understanding of how the loop structures restrict or encourage car use.

4.2 The most relevant structures to explain travel mode choice (boundaries of the mental model)

To construct CLD 0, an extensive search of papers was conducted, in order to find theoretical frameworks related to people's transport behaviour and pro-environmental behaviour towards driving to commute. Selected articles were drawn from the Thomson Reuters Web of Science, Google Scholar, and University of Leeds Library. Document search included terms like "people's travel behaviour", "pro-environmental behaviour", "commuting", "car use", "public transportation", "active transportation adoption", "eco-friendly transport modes", "transport modes comparison", "system dynamics in transport", "computer simulation in transport", "transport modelling". More than 200 articles were reviewed.

As was explained in the previous chapter, multiple models are available in environmental psychology and transport to explain car use. In environmental psychology, the most common theoretical frameworks applied to predict car use are: the Theory of Planned Behaviour (Ajzen, 1991), the norm-activation model (Schwartz, 1977), Theory of Cognitive Dissonance (Festinger & Carlsmith, 1959), Model of determinants of script-based driving choice (Gärling, et al., 2001), Value Belief Norm Theory (Stern, et al., 1999), Comprehensive Action Determination Model

(Klöckner & Blöbaum, 2010) and the Stage Model of Self-Regulated Behavioural Change (Bamberg, 2013). In transport, multiple models are available to predict travel demand and land use, such as Citilabs' CUBE[28], Emme[29] (Multimodal Transport Planning Software), TransCAD[30], VISUM[31], MINUTP, MARS (Pfaffenbichler, et al., 2010) and Tmodel[32].

In transport research, predictive modelling and simulation of transportation normally bases its conceptualisation on five main topics: (1) demand (e.g. demographic characteristics), (2) land use, (3) distribution, (4) modal split and (5) characterisation of the routes available. The core rationale behind many of the transport models is based on the utility maximisation theory, where behavioural patterns are predicted by using discrete choice models (Vij & Walker, 2014), which compare multiple options based on whichever reports the highest utility (Walker & Ben-Akiva, 2002). This way, the models explain or predict an individual's mode choice based on modes' attributes, journey times, costs associated with travelling, transport options available, etc. On the other hand, in environmental psychology, travel mode choice (as a pro-environmental behaviour) has been seen as a mixture of rational and irrational choices since not only cognitive skills are involved, but also values, beliefs and emotions (Kals, et al., 1999; Carrus, et al., 2008). For this reason, environmental psychologists have concluded that travel mode choice can be better explained when theoretical frameworks reflect psychological determinants to estimate the influence of an individual's self-

[28] https://www.bentley.com/en/products/brands/cube.

[29] https://www.inrosoftware.com/en/products/emme/.

[30] https://www.caliper.com/tcovu.htm.

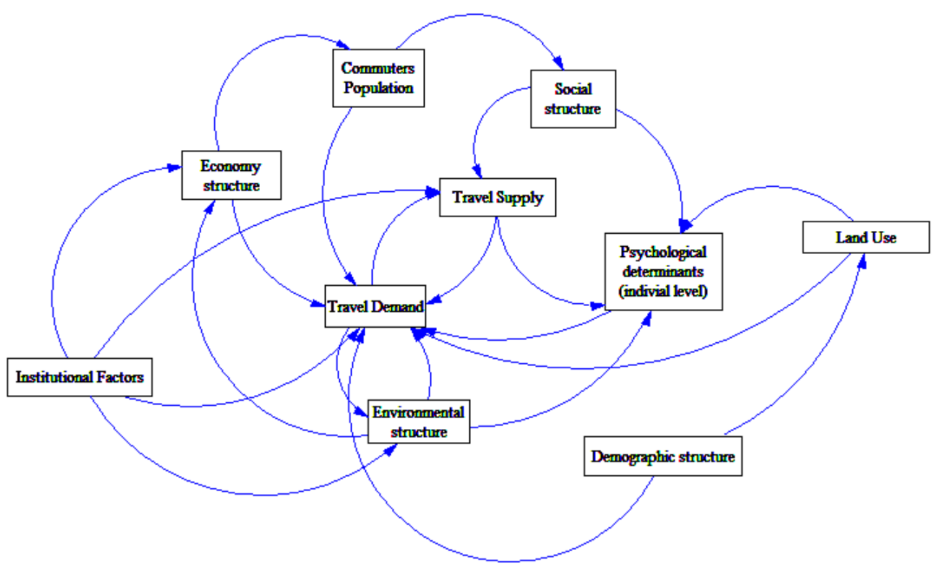
[31] https://www.ptvgroup.com/en/solutions/products/ptv-visum/.

[32] https://www.mottmac.com/en-US/transportation-planning/travel-demand-modeling.

interest (e.g. Theory of Planned Behaviour) and pro-social (e.g. norm-activation model) motives (Bamberg & Schmidt, 2003; Chng, et al., 2018).

Based on the literature review on both lines of research (transport and environmental psychology), multiple themes were found relevant in predicting people's habitual travel behaviour. Figure 17 shows these structures and how they are related to each other, in order to establish a conceptual reference for the dynamic hypothesis and the first mental model. These structures reflect the boundaries of the mental model and the sources of the cause-effect relationships.

Figure 17. Relationships among structures.



Source: Own elaboration. The colour of the arrows does not mean anything more than it was a way to make it easier for the reader.

Economy structure: the economy has always been perceived as an important factor in travel model choice as it reflects the driving forces of transport development and people's travel behaviour (Jifeng, et al., 2008; Noonan, 2021). Income and travel demand have a strong relationship, especially in developing countries. In developed countries, researchers have been debating whether or not car use has reached its peak, as growing income no longer means more car use (Metz, 2013; Dargay & Hanly, 2007). For this reason, it has been suggested that a more complex function is necessary to predict travel behaviour, which includes population growth, urbanisation, employment and population ageing.

Dargay (2007) found that car travel increases over time in accordance with a household's income, reaching its plateau when the household's head achieves the age of 50 (and declines after). Noonan (2021) noticed that it is more likely for children living in the highest income households in the UK, compared to children from lower-income households, to be driven to and from school during their childhood and adolescence. Paulley et al. (2006) observed that public transport fare elasticity is affected by the relative weight that the value of the ticket has on people's current income, showing higher elasticity ratio with low fares. Dargay and Hanly (2007) concluded that high levels of car use are more likely to happen among employed people. Heinen and Mattioli (2019) explored the levels of multimodality in England, in which they found that inequalities in transport mode choices may have been emerging since 1995 as multimodal choices are significantly different among quintiles.

As income and car use are closely related, governments have opted to create road pricing schemes, so as to discourage car use and its externalities (traffic congestion, noise and pollution). However, these measurements are often criticised as they have a bigger impact on low-income drivers (Metz, 2013), and in some cities they have been politically opposed when submitted to a vote in local referenda (De Borger & Proost, 2012).

Institutional factors: in general, there is an agreement that local authorities are continuously working on improving access to services and employment, as travel access and choices are seen as part of the development of human wellbeing (Metz, 2013). For a long time, substantial investments in the transportation system were normally allocated for developing car infrastructure, facilitating car use as it became possible for longer journeys to be made at a higher speed and in less time and more cities were connected by motorways (Sterman, 2000; Metz, 2013). For this reason, transport authorities are facing a wide range of challenges today that impede the decline of car use for the sake of the environment, meaning that now more than ever a much stronger political will and investments are required to encourage other alternative transport modes (Noonan, 2021). Some common examples of regulations are implementing a diverse plan of incentives to encourage electric car use and strict regulations to punish the use of cars that emit too much CO_2 (Hofer, et al., 2018).

Commuters' population: as was stated before, population growth plays an important role in determining travel demand. The UK is expected to grow from 66.80 million people in 2019 to 72.03 million by 2041. This will be a great challenge for transport authorities. If the fraction of people that drive to work and the trip rate remain the same, then there will be a substantial growth in the number of travellers, making it more challenging to understand and manage how employment and residency location distribution evolve (Metz, 2013).

Population growth and travel demand create one of the most important reinforcing loops studied in transportation: more people available to drive, more cars on the roads, which in turn decreases current road capacity and increases traffic congestion levels (negatively affecting travel time). This process leads people to pressure governments to develop more roads and access, as travel time is one of the most important factors related to trip satisfaction. Politicians normally solve problems that can increase the wellbeing of the majority of the people as they are under the pressure of popularity and re-election; therefore, if the driver population is large enough, then it has the power to demand more roads for cars. These demands would result in more road capacity, which calls for more cars, and, undoubtedly, will increase carbon emissions (Sterman, 2000).

Travel demand & supply: for a long time, cars have been identified as the dominant transit mode in most developed cities (Metz, 2013; Hartgen, 1974). Some changes regarding car use have been observed in the last decades; for example, in England the trips per person per year by car when commuting[33] decreased by on average 21.3% between 2002 and 2019. However, car access in this region has been relatively steady in the last 20 years, with the percentage of households with a car fluctuating between 79.7% and 81.9%[34]. Therefore, car use still represents a large market and a potential threat to the environment. For that reason, transport researchers have proposed to transport authorities that public transportation needs to be seen as a competitive-oriented service as its attractiveness is always under the pressure of a changing consumer market regarding cars (Golob, et al., 1972; Şimşekoğlu, et al., 2015).

The main concept of conventional transport economic analysis has been created on the basis of travel time saving (Metz, 2008), which is why transport plans have been created around the rationale on providing different ways to reduce travel time (e.g. paid motorways). However, new evidence has proved that transport economic analysis should involve not only travel time saving, but also accessibility, as there is a solid indication that, in the long run, more transport opportunities are desirable even when travel time is conserved (Metz, 2008; Metz, 2013). Therefore, new investments in transport infrastructure are suggested to re-focus the priorities.

[33] NTS0409: Average number of trips (trip rates) by purpose and main mode: England, from 2002 (Department for Transport statistics).

[34] Data from NTS0704 (Department for Transport, UK).

Environmental structure: it is undoubtable that high levels of pollution have harmful consequences for human beings. For decades, travel demand has increased, exacerbating anthropogenic sources of pollution due to low oil prices and a dominant car-centric influence (Stepp, et al., 2009).

Reducing pollution levels is not an easy task. Large cities around the world are facing greater challenges regarding transportation, health care and pollution, as more than half of the world's population live in cities (United Nations, et al., 2015), and car use and car access have reached levels which increase the threat of climate change (Abrahamse, et al., 2009). For that reason, several policies have been proposed so as to restrict car use based on fuel sources and air quality (Nordhaus, 2000; Greene, et al., 2005). For example, Chile limits car use during winter by restricting the daily numbers of cars that are allowed to be used on roads, because greenhouse emissions normally exceed the safe levels of pollution accumulated in the air.

Social structure: predicting the impact of transport policies requires a cross-dimensional analysis, which implies an understanding of societies' techno-socio-economic complex systems (Stepp, et al., 2009). That is why the social structure has been considered in the mental model. In this case, the term social structure refers to the construction of social norms inserted in travel demand.

Researchers have been studying the effects of these components, concluding that the symbolic connotation about the different transport modes can determine the strength of social norms. For example, buses are generally seen as less attractive as people normally perceive them as slower, less reliable, used by people that cannot afford a car and less secure (Metz, 2013). This conceptualisation of public transportation limits its possibilities to contribute to decreased carbon emission as people avoid using the services. In fact, societies that are economically and culturally solid demonstrate a vast use of alternative modes of transport as cars do not become essential; therefore, transport infrastructure can be redesigned to redistribute the road space for pedestrians, bicycles, taxis, trams, etc. (Metz, 2013).

Demographic structure: demographic characteristics have been acknowledged as important factors to predict travel demand. Among demographic predictors, research has highlighted the role of gender, age, income and life cycle (Dargay, 2007; Simsekoglu, 2018; Bergstad, et al., 2011). Important differences have been found regarding demographic characteristics, such as the decreasing levels of car ownership and driving licences among young men after the beginning of the 2000s (Kuhnimhof, et al., 2012). A significant proportion of younger people have established their employment and social life in urban centres, facilitating the use of alternative transport modes, such as bicycles, and decreasing the necessity of owning a car (Metz, 2013). Likewise, some researchers have identified differences in driving between men and women, finding that men drive more than woman (Polk, 2004). Noonan (2021) described how car use for school journeys is more likely when school goers are in childhood than in adolescence, demonstrating an evident prevalence of habitual car use for school journeys. Dargay (2007) showed how car travel is closely related to income and age, illustrating that after the age of 50 people tend to reduce its use. These and other similar findings have helped to create promising interventions to change behavioural patterns into a more sustainable way as researchers have found that life events (e.g. change in residential location) can lead to an opportunity to break up mobility habits (Sattlegger & Rau, 2016).

Land Use: land use is always discussed in transport management, in order to set the most suitable transport policies for the cities/towns. During the last decades, both improving living standards and economic and urban development have driven the necessity of more urban transport (Pfaffenbichler, et al., 2010). For that reason, important observations have been made regarding people's density, new workplace development and residency location. For example, car use has been identified as being higher among households located in rural areas than in urban areas (Bergstad, et al., 2011). In contrast, researchers have reported that highly dense cities and diverse walkable destinations make it more likely that people will opt for active transportation (Saelens & Handy, 2008).

The pressure of a growing population has often led major cities to accelerate the construction of alternative transport modes to the car to connect the most important employment areas. London is an example of a city that has experienced a continuously growing population in the last two decades, but has controlled car trips by not expanding road capacity (Metz, 2013). The results have positively impacted on public transportation use as use of the underground and the buses in London grew by 44% and 27% between 2002 and 2019, respectively[35].

Psychological determinants: in transport research, the recognition of psychological determinants for forecasting of travel mode choice has been discussed since the 1970s. Hartgen (1974) was one of the first transport researchers to recognise the importance of attitudinal and situational variables, providing critical findings to be considered in models used to forecast travel mode choice in the long term. Researchers since then have provided a vast array of evidence that travel mode choice is dependent on several constructs including beliefs, values, attitudes, habits, norms and intentions (Bamberg, 2013; Vij & Walker, 2014; Chng, et al., 2018). A significant amount of research is investigating behavioural change in travel mode choice as the recognition of psychological determinants has led to an understanding of when people's behaviour changes

[35] NTS0409: Average number of trips (trip rates) by purpose and main mode: England, from 2002 (Department for Transport statistics).

gradually over time (e.g. life cycle) or suddenly after a one-time event (e.g. changing to a new job) (Lee, et al., 2017).

The psychological determinants in predicting travel mode choice were discussed in the previous chapter, so, to avoid redundancy, please review Chapter 3 and the theoretical frameworks proposed to predict behaviour towards transportation.

4.3 First mental model construction (Causal loop diagram 0)

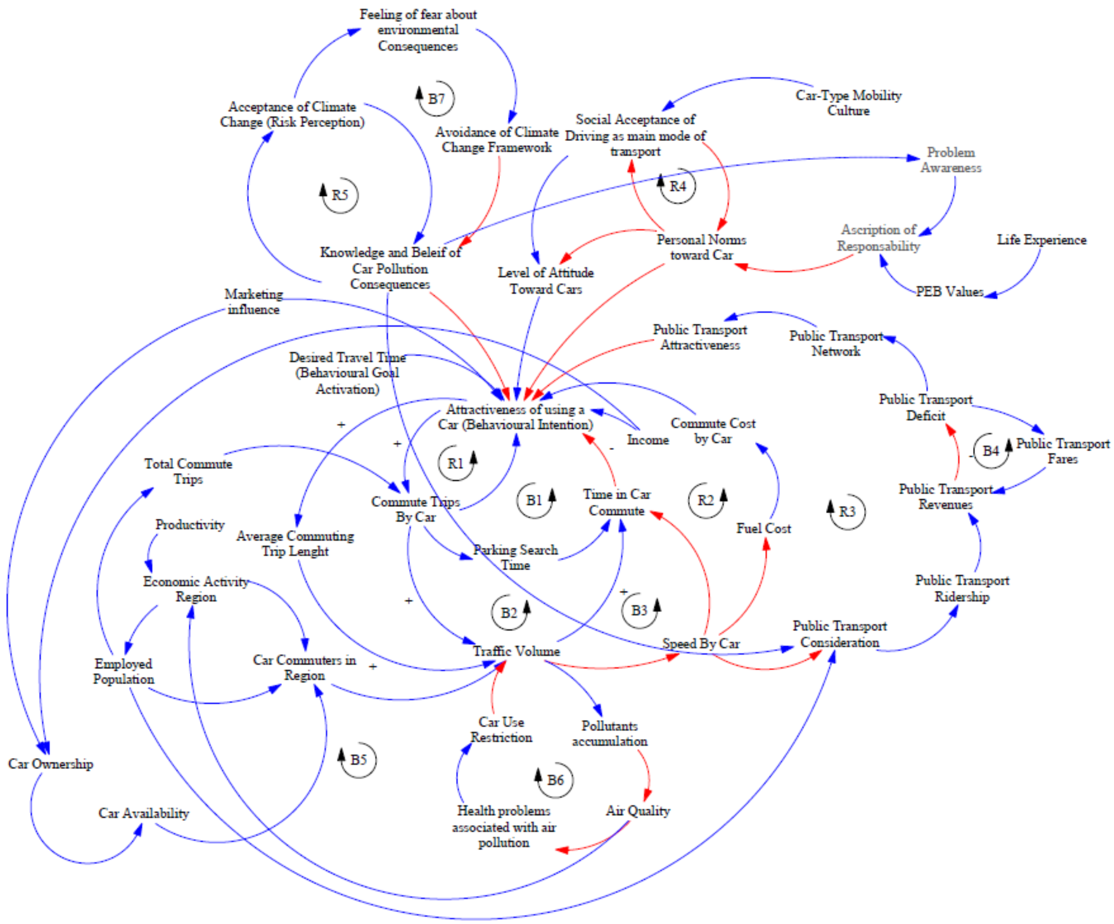
In SD modelling, a conceptual model is always developed before constructing the simulation model as it helps to understand and represent the basic structures underlying the behavioural patterns under study. This conceptual model is often expressed as a causal loop diagram (CLD) because it captures the basic feedback loop structures that emerge from the multiple, and sometimes bi-directional, relationships between the variables in the mental model. This process involves a qualitative approach to identifying stakeholders, endogenous variables (the set of variables explained by the model) and the cause-effect relationships. To carry this out, a literature review, data visualisation (reference modes) and interviews with stakeholders were used to gather the necessary knowledge to build a CLD (Dhirasasna & Sahin, 2019). The result of this gave birth insights from CLD 0 (based on the literature review), CLD A (an improved version of CLD 0 by using interviews), and CLD B (a small, but detailed conceptual description of a fraction of CLD 0, which is focused on the psychological dynamic system).

A preliminary causal loop diagram (CLD 0) was built portraying the insights from the literature review in transport and environmental behaviour (Figure 18). Several reasons justify the construction of CLD 0 in this project. First, CLD 0 worked as the initial referral to the conceptual model, therefore it facilitated the reflection on all the potential systems involved to explain the behavioural patterns regarding travel mode choice. Second, it helped as the starting point to improve and understand travel choice as a vast amount of knowledge is available to explain people's travel behaviour. Finally, it helped to engage the stakeholders during the interviews as they had an input to compare their mental models with the purpose of this project.

As the focus of this thesis was on commuting, CLD 0 does not include aviation and ferry travel (long distances). The first conceptualisation only included the explanation of car and public transportation commuting as they are the main modes selected in England[36]. This is important to mention as it points out the importance of comparing the modeller's mental model with external sources with their own interpretation of the world. During the interviews, those from a transportation discipline revealed the importance of including active transportation (walking and bicycle) in the explanation of people's travel behaviour, which was something omitted in the construction of CLD 0 due to the different disciplinary background. The interviews allowed the project to reflect a more comprehensive travel choice system as active transportation is a trend that is growing fast, especially in populated cities like London and Manchester. More details about this are presented in Chapter 5 (qualitative phase).

[36] See https://www.gov.uk/government/statistical-data-sets/tsgb01-modal-comparisons.

Figure 18. Causal loop diagram 0.



Source: Own elaboration. This causal loop diagram was drawn in Vensim DSS, in which the most important loops were drawn in the illustration as it was impossible to fit in more than 30 loops' symbols. CLD 0 is composed of multiple reinforcing (R) and balance (B) causal loops. Blue arrows represent a positive relationship between the variables, while red arrows are for negative relationships[37].

[37] In SD, a positive relationship (sometimes labelled as + or s) means that the cause-effect relationship follows the same behavioural direction; in other words, if x increases, then y increases. A negative relationship (- or o) reflects the opposite: if x increases, then y decreases. In this project, the decision to represent the notation in the causal loop diagrams in colours was made simply for the sake of clarity as symbols (e.g. +) are hard to read (some are in the CLD to illustrate this point).

4.4 Dynamic hypothesis behind CLD 0

A dynamic hypothesis is the formulation of an idea about how a system works and how its feedback structures replicate a given behaviour observed in real life. Figure 18 is a visualisation of travel mode choice between private car and public transportation. However, in this section, a verbal explanation will be provided to complement the visual description.

The explanation will start with the attractiveness of using a car. Attractiveness is defined as "*the quality of causing interest or making people want to do something*" (Cambridge Online Dictionary, 2021); therefore, the attractiveness of driving is affected by attributes that have a direct impact on people's perception about the attributes that arouse interest towards car use. Travel time is one factor that is commonly used in econometrics analysis to predict travel mode choice (Metz, 2008). As travel time decreases, the attractiveness of driving increases. When a car is accessible and car trips are feasible, increasing the attractiveness overcomes the perceived attributes of public transportation, resulting in more and longer trips (Şimşekoğlu, et al., 2015; Sterman, 2000). In this process, the first reinforcing loop is recognised **(R1)**: the more trips people do, the more likely is the creation of a habit, which in turn increases the perception of feeling highly attracted to car use (Eriksson, et al., 2008).

If the number of trips and length per person increase at a higher rate than the transport infrastructure supply, then the roads and parking spaces start to saturate as insufficient capacity is not able to deal with travel demand, causing significant levels of traffic congestion (Chen, et al., 2020) and lack of available parking (Pfaffenbichler, 2003). The lack of places to park directly affects the commuting time, increasing the amount of time door-to-door, which in turn decreases the attractiveness of commuting by car. This creates a balancing loop **(B1)**.

When congestion increases, multiple variables are affected. Traffic creates unnecessary delays (Yong-chuan, et al., 2011), decreases free flow speed (Jifeng, et al., 2008) and wastes more fuel (Chen, et al., 2020); therefore, congestion impacts on the attractiveness of driving. In this case, two balancing loops and one reinforcing loop are created **(B2, B3, and R2)**. In some countries, car restrictions take place because pollution levels are over the safe recommendations; therefore, another feedback loop controls traffic congestion **(B6)** – the higher the traffic congestion, the higher the emission of pollutants; therefore, more restrictions take place to control pollution. When more pollutants are emitted, poor levels of air quality are expected, increasing the awareness of health problems derived from pollution. This environmental issue pressures governments to bring down the levels of smog by restricting the use of cars, which in turn decreases traffic volume.

Problems with air quality can have enormous impacts on the economy (Jifeng, et al., 2008), affecting the employee population and the number of cars in the region. In this case, a balancing loop emerges (**B5**): when the accumulation of contaminants surpasses the safety levels, the growth of the conventional economy models is limited as environmental issues need to be solved; therefore, highly pollutant industries are affected too, negatively leading to job reduction and decreased incomes, which in turn affect the numbers of cars and the levels of congestion.

If the speed by car is decreased because of high levels of congestion, then it is expected that people might consider commuting on an alternative transport mode (e.g. public transport). It has been reported that increasing the attractiveness of public transport might involve an improvement in terms of convenience and perceived good quality (Brown, et al., 2003), as well as a combination of physical (e.g. distance, housing density), social, behavioural health (moderate-to-vigorous activity) and psychological variables (e.g. pro-city attitudes) (Brown, et al., 2016). Public transportation is mainly funded by external and internal sources[38], the government and passengers; therefore, if longer travel time caused by traffic congestion increases, then travel demand for public transportation will rise as well (Sterman, 2000; Ercan, et al., 2017), expanding its revenues and the trips per person. When more financial resources are internally available (revenues coming from fares), then it is expected that more investments will be carried out to improve the quality of the public transportation network, which in turn should increase the public transportation attractiveness, causing a negative impact on the attractiveness of driving. In this part of the mental model, two feedback loops are identified: **R3**, a reinforcing loop that competes against **R1** and **R2** – reflecting that transport mode choice between cars and PT is based on the feedback loop structure whereby the behavioural pattern is based on habits, satisfaction and quality perceived. **B4** is a balancing loop which reflects dynamically how ticket prices are internally affected by the discrepancy between revenues and financial deficit. In other words, the more deficits the network has, the more difficult it is to cover the fixed costs to run the network; therefore, increases in public transport fares are more likely.

Attractiveness of car use is also affected by psychological determinants. Many authors agree that attitudinal factors play an important role in controlling car use (Abrahamse, et al., 2009; Bamberg, 2013; Chng, et al., 2018). In theory, a person who has a strong positive attitude towards driving a car is more likely to have a strong intention to drive, which in turn increases the probability of actually performing the behaviour. Therefore, in the mental model, when the attitude towards commuting by car increases, the attractiveness of driving increases as well. The attitudinal

[38] For example, transport for London has four sources of income: fares income (internal), commercial activity, grants (external), and borrowing and cash reserves (https://tfl.gov.uk/corporate/about-tfl/how-we-work/how-we-are-funded).

dimension is affected by norms. Social norms and personal norms have been described as a dynamic system in social science (Andrighetto, et al., 2010). Authors have proposed that a person could internalise a subjective norm as a personal norm (Ulli-Beer, et al., 2010; Andrighetto, et al., 2010), when they have a motivation to comply and there is a high expectation to accept the norm from their close relatives, friends, colleagues, etc. (Belgiawan, et al., 2017). In this case, the feedback loop **R4** reflects the process of norm internalisation.

In environmental psychology, the norm-activation process has been described as an internal development that is triggered by pro-environmental values, problem awareness (PA) and the ascription of responsibility (AR) by the individual (Bamberg & Schmidt, 2003; Bamberg, 2013). For that reason, this mental model has included AR, PA and PEB values as the norm-activation model has empirically demonstrated the importance of these to predict behaviours in the domain of environmental psychology and transport mode choice (Bamberg & Schmidt, 2003; Chng, et al., 2018).

Finally, this mental model has included a section to acknowledge what environmental psychologists have been discussing in the last decades: knowledge and beliefs about climate change. As Figure 18 shows, knowledge and belief about car pollution form a reinforcing loop with the acceptance of climate change (**R5**). People that accept that climate change is happening are more likely to believe and to be aware of the negative consequences of car pollution (Corral-Verdugo, et al., 2017). In addition, framing climate change communication in a negative way can decrease the chances for people to engage with climate change actions (Ettinger, et al., 2021); therefore, this model added a balance loop to compete with the reinforcing loop of climate change acceptance (**B7**): the more people are exposed to climate change information, the more likely they are to become insensitive or feel fear about the future, which in turns decreases the motivation to act towards climate change restrictions since people feel that the world is “doomed” (Stoknes, 2014).

4.5 Summary

This chapter described the conceptualisation of the initial causal loop diagram (CLD 0). The feedback loop structures responsible for explaining car and public transport commuting were presented with a basic conceptual model. Travel mode choice finds explanation in a wide range of different research domains, demonstrating that predicting car or public transport use is a complex task. The first dynamic hypothesis was discussed and supported by the extensive literature review. Although this is not the mental model meant to be simulated, its value relies on its capacity to clarify how the system works and how challenging it can be to simulate travel mode choice. Additionally, this first CLD helped to visualise the type of data needed later in this project.

The next phase of the SD involved the improvement of the informal conceptual model by contrasting this first CLD with knowledge from transport engineers, commuters, policy makers, environmental engineers and environmental psychologists. This will be described in the next chapter.

5 Qualitative phase – validating the causal loop diagram

This chapter introduces and develops the interview phase with experts and the results obtained to address part of the structural validity of the model. In this phase, the causal loop diagram 0 discussed in Chapter 4 is evaluated, tested, modified and validated by several respondents in order improve the conceptual model before the interviews, which will be used as an input for the simulation model.

Because the ultimate aim of an SD model is based on the concept of usability, it is important for modellers to construct a simulation model that can best represent the phenomena under question and fulfil the purpose of the project/research question. Otherwise, there is no justification to use such a tool in the decision-making process as the simulated scenarios would be biased from what it is observed in the reality. For this reason, different validation tests are available to build up the confidence for the model, and to prove empirically the accuracy between the model and the reality (Forrester & Senge, 1980).

This chapter is divided as follows: first, a brief explanation of the importance of qualitative data in SD and how this helps to improve the construction of the simulation model is provided. Second, the structural validity process and the activities that were carried out for this project are described. Third, the qualitative phase methodology is defined (e.g., aim of the interviews). Finally, this chapter ends with an explanation of the results obtained and how the formulation of causal loop diagram A (CLD A) helped the construction of the mathematical model.

5.1 Using qualitative data in system dynamics: methods and models

Qualitative data has been suggested as a complementary approach to quantitative data in SD. While SD models are computational-based representations of a system based on equations, many times the information available is not numerical (Luna-Reyes & Andersen, 2003). For that reason, some modellers have encouraged the gathering of qualitative data, in order to fulfil the purpose of the model comprehensively and increase its theoretical representation accuracy (Forrester & Senge, 1980; Sterman, 2000; Luna-Reyes & Andersen, 2003; Morecroft, 2015). Qualitative data has been suggested as a recommendable approach to construct mental models (Luna-Reyes & Andersen, 2003), estimate subjectively[39] parameters in the simulation model (Sterman, 2002) and perform validation (Forrester & Senge, 1980; Sterman, 2000).

In terms of mental model construction, qualitative data has been used to gather experts' views and written data. The way in which people organise, identify and interpret pieces of information differs from person to person. People's past experiences and cognitive skills set up different configurations and processing capabilities in their brains (sensory transduction[40]), shaping a wide range of individual mental models to describe how something operates in the real world (Morecroft, 2015). This cognitive disparity has led SD modellers to propose the inclusion of various experts in the construction of a simulation model, in order to offer a comprehensive description of the real-world procedures, routines or phenomena. It is impossible for an individual to gain enough

[39] In this case, estimation does not refer to statistical inference. Instead, "estimate subjectively" refers to the action that involves the capacity of the modeller to quantify a variable in the model based on previous experience, expert recommendation or theoretical arguments.

[40] Sensory transduction refers to the capacity of converting signals into a form of information that can be processed by the brain (Fain, 2019).

experiences to deeply understand complex situations that involve several factors, feedback loops and time delays (Forrester & Senge, 1980; Sterman, 2000). Even when some people could describe more elaborated mental models, their cognitive skills limit them from holding in the mental map all the concepts and cause-effect relationships involved in a process (McLucas, et al., 2012; Morecroft, 2015). For that reason, qualitative techniques (e.g. interviews) can serve as an appropriate approach to access an expert's mental model or written data (Barlas, 1996; Luna-Reyes & Andersen, 2003; Qudrat-Ullah & Seong, 2010) to contrast, improve and validate the modeller's verbal description of the real-world situation (Randers, 1980).

In terms of model validation, qualitative data has been justified to complement the acceptance of the SD model. SD models aim to fulfil a purpose and accurately reproduce an observed behaviour, which justify the model's usefulness and effectiveness (Forrester, 1961; Forrester & Senge, 1980; Barlas & Carpenter, 1990; Barlas, 1996; Bala, 1999; Sterman, 2000; Luna-Reyes & Andersen, 2003; Davis, et al., 2007; Morecroft, 2015). In this sense, purely data-driven techniques make it impossible to test the internal structure of a system dynamics model since technical issues are involved. There is no formal/objective test to claim that the model formulated is close to the real structure (Barlas, 1996). Additionally, standard statistical tests cannot deal with problems of autocorrelation and multicollinearity because many variables are cross correlated in the creation of a system dynamics model (Barlas, 1996; Sterman, 1984). Therefore, as the evaluation of usefulness and effectiveness has a degree of subjectivity, qualitative components are implicitly present in the validation of the model, complementing objectivity and quantitative elements (Barlas, 1996; Luna-Reyes & Andersen, 2003; Sterman, 2000).

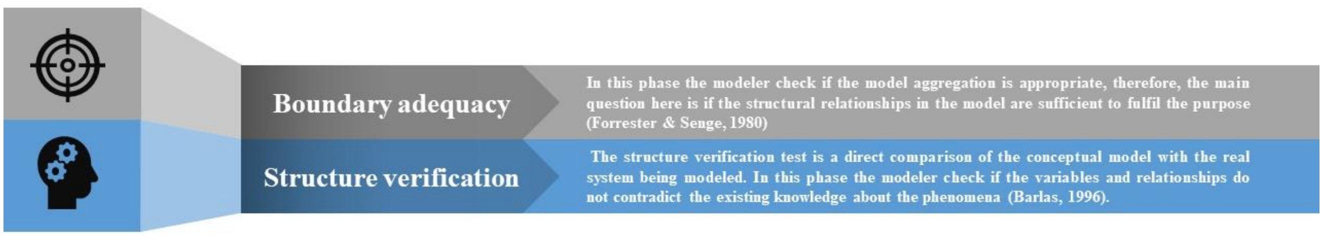
In the case of parameter estimation of unmeasured variables, qualitative data has been justified as a way to approach the lack of numerical data. There is a large debate whether estimating parameters with pure judgement should be accepted in SD (McLucas, 2003; Coyle, 2000) as qualitative data can lead to sensitivity issues (Coyle, 2000). Some authors (Forrester & Senge, 1980; Sterman, 2000; Morecroft, 2015) have suggested that the limitation of numerical data should not restrict the inclusion of variables that are crucial to explain the behavioural pattern observed in real life. In cases when there is a lack of numerical data to estimate parameters, these modellers have suggested that it is better to make an 'estimation' (either as an auxiliary variable or lookup variable) based on judgement than to omit the variable, as doing the latter could imply that the variable is not important in the explanation of the mechanism observed. In other words, ignoring a variable that is essential in the explanation of the theory, narrows the representation of the model, making it theoretically less accurate than adding and quantifying (based on judgement) the 'unmeasured' variable that is important for the explanation of the conceptual model.

For the aforementioned reasons, qualitative data has been acknowledged to be ubiquitous to all stages in constructing the simulation model (Forrester, 1961; Randers, 1980; Richardson & Pugh, 1981; Wolstenholme, 1990; Bala, 1999; Sterman, 2000; Morecroft, 2015), serving as a guide to ensure and enrich the comprehension of the behavioural pattern observed (Luna-Reyes & Andersen, 2003) as well as a supplementing technique to increase the level of efficacy and confidence of the simulation model to represent a real-life situation (Wolstenholme, 1990; Sterman, 2000).

5.2 Structural validity of the mental model

Chapter 3 stated the importance of performing several tests to validate the simulation model (mental and formal). Structural validity tests are specifically designed to check if the structure of the model is a plausible representation of the real system (Barlas, 1989). To pass the structural validity tests, the model structure is compared against the existing knowledge (quantitative or qualitative), to verify that there is no contradiction between the conceptualisation of the simulation model and the real-system behaviour (structure verification test) (Forrester & Senge, 1980; Barlas, 1996). Figure 19 shows the most typical structural validity tests for the mental model[41].

Figure 19. Most typical structural validity tests for the mental model.



Source: Own elaboration.

The boundary-adequacy test involves developing a list, map, summary, etc., of the endogenous and exogenous variables used in the model. Whether a variable is endogenous and exogenous depends on whether or not the variable has a significant impact on the model behaviour or policy application (Barlas, 1996). For that reason, the modeller needs to describe a convincing dynamic hypothesis to demonstrate that the level of aggregation of the sub-models is appropriate to fulfil the purpose and there are no missing relationships or structures inside the simulation model (Forrester & Senge, 1980; Qudrat-Ullah & Seong, 2010). Interviews, literature review and personal knowledge can help to decide if the boundary of the model is well defined or not (Sterman, 2000).

[41] Structural validity tests for the simulation model will be reviewed in the following chapter.

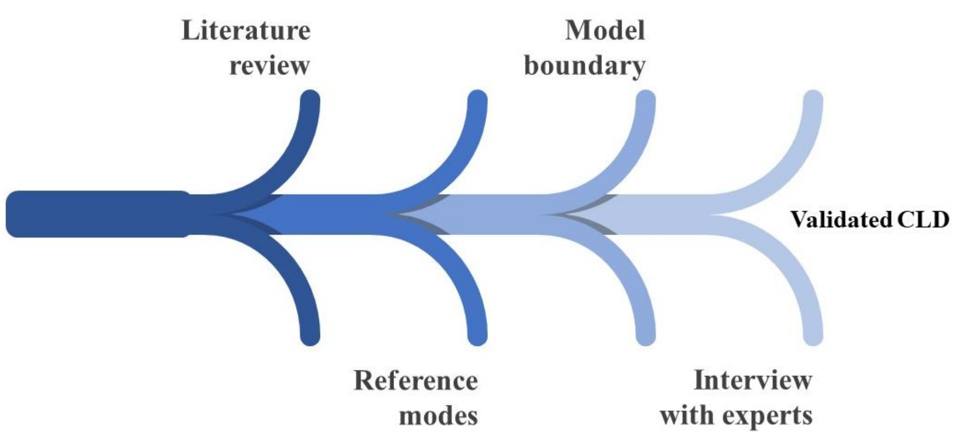
The structure verification tests answer the question: is the conceptualisation of the model a reliable representation of the real system that is being simulated? Thus, in this case, the modeller tests whether the relationships proposed do not contradict the existent knowledge about the phenomena under study (Forrester & Senge, 1980). So, again, the dynamic hypothesis plays an important role to clarify the implied causalities assumed in the model. Reviewing the model with experts in the topic and contrasting the modeller's ideas with relevant literature are key elements to construct, improve and validate the model conceptualisation (Forrester & Senge, 1980; Barlas, 1996; Bala, 1999).

5.3 Structural validity procedure of this project

To identify the appropriate structure representation, the development of the causal loop diagram is necessary. So far in this project, a causal loop diagram was created from the literature review (CLD 0), which was later tested and validated against experts' mental model in transport and environment psychology (see Figure 18), in order to improve the internal structure of the model. Hence, two sources of information are supporting the structural validity of the mental model. The result of this process created an improved causal loop diagram, which has been labelled CLD A.

It must be noted that building confidence is a gradual and iterative process; therefore, the fact that the stages of this thesis are presented in sequence does not mean that the validation steps followed this order. Conversely, reviewing, formulating, adjusting and testing the mental and formal model occurred at each stage of the project; the results of these processes occasionally led to the necessity to go back and change elements of the previous stages. For example, structural validity includes empirical and theoretical direct structure tests (Barlas, 1996) which are oriented to validate the model by direct comparison with knowledge about the real system's internal structure. In this case, the literature review (theoretical test) and numerical data (empirical test) about car use and commuter behaviour in the UK were performed in the early steps of this thesis. Following this, interviews (theoretical test) were performed to continue with the structural validity process, but, in this stage, the literature review was recalled several times, as, after some interviews, papers and reports were recommended and some insights were needed for more thorough clarification.

Figure 20. Structural validity process.



Source: Own elaboration.

5.4 Methodology

After reviewing qualitative and quantitative secondary data (chapters 1, 2 and 3) and setting the boundaries of the problem (Chapter 3), interviews were performed to improve the explanation of the conceptual model. These interviews with experts aimed to test and confirm the conceptual explanation offered with CLD 0 (Chapter 3) as well as to expand and clarify new patterns and cause-effect relationships. The following sections will explain the development of the qualitative data collection as well as the aim and objectives of this phase.

5.4.1 Qualitative phase aims and objectives

Interviews with experienced people working on transport planning, transport research, environmental psychology research and environmental issues, policy makers, and also commuters could be a valid way to achieve the following objectives:

1. Creating an interviewee's mental model about how the person sees the problem of commuting by car and pollution.
2. Testing the causal diagram loop constructed before the interviews (insights from papers that studied people's travel choice).
3. Exploring more psychological and functional factors that the causal diagram loop missed.
4. Discussing future implications of commuting by car and the potential problems related to the environment.

5.4.2 Technique selected to collect qualitative data

In qualitative research, the most common techniques to collect data are: (1) ethnography and participant observation, (2) interviews, (3) focus group and (4) text data from documents as sources of data (Byman & Bell, 2011). In choosing the right qualitative technique to achieve the first research question of this thesis, interviews were performed. Several reasons led this decision:

1. **Usability:** interviews are a straightforward technique that can be used to elicit mental models (Cavaleri & Sterman, 1997; Langan-Fox, et al., 2000).

2. **Flexibility:** interviews are one of the most common and flexible techniques in qualitative research to explore the relevant variables of the phenomena under study (Byman & Bell, 2011; Tesch, 2013). Sometimes, during the discussion of the topic, the modeller can restructure the flow of the interview and go deeper into new definitions or ideas that were not found before (either literature review or previous interviews) or which were thought to not be important for the development of the project because of the specific modeller's lack of knowledge in the topic.
3. **Interactivity:** interview research allows the modeller to interact with the respondent, something which cannot happen with observational fieldwork or data from qualitative sources. In this particular project, this interaction is necessary because the respondent needs direct involvement with the modeller's conceptualisation of the problem to discuss potential variables or relationships that could be missing. This process must be a reciprocal action as sometimes further clarification of definitions is considered necessary from the respondent to ensure reliable data capture (Luna-Reyes & Andersen, 2003).
4. **Neutrality:** as model usefulness and reliable representation of the real system are the key elements to build an SD, several opinions and points of view need to be integrated in the process of conceptualisation to not mislead about or contradict any characteristics of the phenomena under study (Barlas & Carpenter, 1990). It was stated in the previous chapter that mental models are the individual's representation of the real world, and they are one of many ways to describe the real system, since people's cognitive processes are different and limited to their own beliefs and experiences (Morecroft, 2015). That is why a holistic view needs to be taken to prove more efficacy in the representation of the real system.

In this project, interviews were preferred over focus groups because the presence of other people in the same conversation could inhibit an individual and influence their judgement about the research problem (Langan-Fox, et al., 2000). Furthermore, that sometimes could push the participant to express their ideas in a more stereotypical way (Acocella, 2012).

Two types of interview techniques are common in business research: (1) unstructured interviews and (2) semi-structured interviews (Byman & Bell, 2011). In this case, semi-structured interviews were carried out as the research project started with a fairly clear focus on people's travel behaviour. The topic has a vast number of empirical studies to predict travel mode choice, so specific issues needed to be addressed during the interviews. For example, further explanation was needed to explain the gap between travel mode choice and pro-environmental behaviour (Bamberg, 2007; Abrahamse, et al., 2009; Chng, et al., 2018). Therefore, for all the points mentioned previously, it is safe to say that interviewing fits perfectly to this project as the interviewees had a lot of freedom to respond and explain their mental model about people's travel mode choice and ensure the collection of additional information related to pro-environmental behaviour when people commute.

5.4.3 Finding the respondents for the qualitative phase

The aim was to include experts in different areas related to the topic. For this reason, it was decided to invite participation in the study from people who were: (1) transport planning, (2) environmental engineers, (3) environmental psychologists, (4) commuters and (4) policy makers. The total number of interviews per group was a flexible decision since it depended on a sample size sufficient to reach the theoretical saturation (Rowlands, et al., 2016). Theoretical saturation is defined as the process in which the researcher brings new participants to the study until the data set is completed (Bowen, 2008); in other words, nothing new is added in the last interview to answer the aim of the study. In this case, the data collection stopped when the latest interview in each group started to repeat almost all the endogenous variables that were mentioned in the previous interviews. This threshold was reached when the researcher found that all the variables listed in the second section of the interviews were already mentioned in the previous interviews and any new variable was part of the list of the excluded variables in the boundary chart.

To contact the participants, an email was sent with an explanation of the aim of the study and the participant consent form. The groups of commuters and policy makers followed a different strategy. In the case of the commuters, they were contacted as they were required because almost everyone who works commutes; therefore they were subjects easy to contact and set an interview. This means that, after each interview, if new relevant ideas or changes were included in this thesis, then the researcher contacted a new commuter to continue the process. In the case of policy makers, they were contacted after all the groups achieved theoretical saturation. This group was used as a source to discover potential ideas for new regulations and policies that emerged during the interviews. This group was intentionally selected at the end to triangulate the feasibility of potential government interventions that can be included in the system to find a solution to excessive car use.

The recruitment for the groups of transport engineers, transport planners, environmental engineers and environmental psychologists started by contacting people from the most relevant institutions related to the topic, in this case a mix between professionals from important transport consultancy companies and universities/study centres. The result of the contact was a combination of people coming from: ARUP, VECTOS, Institute of Transport Leeds, Manchester Urban Institute, School of Earth and Environment (University of Leeds), School of Applied Social Science (University of Brighton), Environmental Psychology Research Group (University of

Surrey), UK Centre for Climate Change & Social Transformations (CAST), Faculty of the Built Environment (UCL), the Social, Economic and Geographical Sciences (SEGS), Faculty of Health Sciences and Wellbeing (University of Sunderland), Transport for Great Manchester, and Living Streets (charity). The exclusion criteria for this study were related to lack of knowledge in the following three topics: environmental psychology, transport, travel behaviour or travel mode choice. Four people were contacted by phone/face-to-face and 69 emails[42] were sent in total, from which 22 interviews were successfully conducted, enough to reach the theoretical saturation. Forty-six did not answer the email and five rejected the opportunity to participate in the study since they did not feel really prepared to address topics related to climate change, car pollution and people's travel behaviour.

5.4.4 Interview materials and procedures

In a semi-structured interview, the researcher uses, as a guideline, a list of questions to cover all the topics of the research project. The lack of subjective knowledge in the topic might be the impetus to develop the set of questions needed to address the problem (McIntosh & Morse, 2015). In this case, the interview protocol (see Appendix 1) covered the goals of the qualitative phase through four sections. All interviews were recorded in case they had to be reviewed during the analysis. The interview protocol followed similar steps to those presented by Torres et al., (2017).

As a first step, respondents were reminded of the aim of the study, expected outcomes of the project, their right to withdraw from the interview at any time, and detailed information about data

[42] Some email addresses were collected from university websites on the profiles of academic researchers related to the topic. Another group of email addresses were obtained on LinkedIn from professionals related to transport and environmental psychology.

protection and confidentiality. After the five-minute introduction, the interviewees were asked if they felt comfortable with the interview being recorded. All of them approved it, and proceeded to respond to section 1 of the interview protocol.

The first section (knowledge and experience) allowed the participants to contextualise why they had been selected and enabled them to mention all the prior knowledge that they had in people's travel behaviour. In the particular case of transport academics, transport planners, environmental engineers, policy makers and environmental psychologists, this section began with, "Please provide a description of your role in the area [of transportation and/or environment]". This question was framed in this manner to support the decision regarding why they were invited to the interviews, as well as to understand the rationale of their answers.

Regarding commuters, the questions were used in a way to find evidence that they were current commuters, and they were familiarised with habits and decision-making process regarding transportation decisions. The commuter interviews began by asking, "What kind of transport modes do you use to commute? (In case there is more than one) Which one do you use more?", in order to understand respondents' commuter patterns, preferences and attitudes.

The following section aimed to explore the respondents' knowledge on the subject of commuting and car pollution. This section was applied to all the subjects regardless their area of expertise. This last part was useful to 'warm up' before continuing with the respondent's mental model creation. Additionally, this section was expected to help to understand the main strategies car commuters used to form a habit, as well as to elicit a general overview of how the respondent was perceiving the problems related to car pollution. The questions formulated in this section were based on qualitative studies in people's travel behaviour and qualitative phases of system dynamic studies (Jones & Ogilvie, 2012; Torres, et al., 2021; Carr, 2008) and quantitative studies from the Department for Transportation[43]. This section lasted nearly five minutes.

In the second section, all the respondents needed to break down the main factors that can be involved in the decision to use cars or other low-carbon mobilities when people commute. This section asked two main questions, "Could you tell me what are the main factors that impact on the decision of using car for commuting?" and "Could you tell me what are the most important factors that led people to decide to commute in other low-carbon mobility modes?". For this part of the interview, the aim was to inductively seek a wide range of variables and therefore the questions were developed from a methodological perspective rather than from a particular literature. Thus, open-ended questions were used to encourage participants to freely express their thoughts (Jacob, 1988). A list of variables was written down, so it helped as the material for the following section. Each respondent's list captured all the concepts that they mentioned as being important to explain travel mode choice. It is important to acknowledge that each concept was written by the respondent; for that reason, no codification was needed to continue with the next section as the respondent was asked to use the same labels to construct their mental model. Additionally, it was explained to all the interviewees that the process of developing a mental model, as well as validating CLD 0, was completely flexible. Thus, every time a modification (new label) or addition (new concept) was suggested, they were added to the list and posteriori to the mental model, making the necessary amends to consolidate a clear list and an intelligible mental map. This section lasted nearly 7 minutes.

[43] https://www.gov.uk/government/organisations/department-for-transport/about/research

In the third section, the respondents were asked to create a conceptual map with all the variables mentioned before. This time, each participant created their mental model to explain people's travel behaviour. This section also applied an inductive approach. Thus, open-ended questions were formulated to encourage participants to elaborate spontaneously on their mental models. Probing questions were used, in order to motivate interviewees to elaborate on or clarify their mental models and cause-effect relationships. Moreover, participants were frequently asked "why?" to obtain elaborated answers regarding their experiences and their mental models (Torres, et al., 2021). This step also opened the possibility to the researcher to capture more variables that were not mentioned in section 2. This happened because the respondents started to explain the cause-effect relationships between the variables, and sometimes the narrative discourse showed that some variables were missing, or some pathways were incomplete to fully address the explanation for people's travel behaviour. This section was particularly useful to gain and integrate interviewees' perspectives, in order to obtain a holistic perspective of car commuting. The construction of this section was based on previous system dynamics studies found in Sterman (2000). This section lasted approximately 10 minutes.

Finally, the last section aimed to receive feedback from the respondents about the researcher's proposed mental model after reviewing the main theoretical frameworks in commuting and pro-environmental behaviour. In this stage, causal loop diagram 0 was presented and described. The explanation started by clarifying the causal loop diagram created around 'car attractiveness'. After that, more details were given regarding the feedback loop structures created in the public transportation network. This section ended by asking the respondent his/her opinion about how to improve the explanation of car commuting by using CLD 0. The aim here was to compare the cognitive representation of the mental model formulated from the literature review and the experts' views (Torres, et al., 2017; Luna-Reyes & Andersen, 2003; Sterman, 2000), giving robust support to confirm or eliminate causal relationships proposed in CLD 0. This section lasted around five minutes.

The interviews were performed face-to-face, and via Skype call and telephone. The decision varied according to travelling cost, respondents' preference regarding the method of communication and their available times for the interview. Face-to-face and non-face-to-face methods will both bring their own advantages and disadvantages to an interview (Irvine, et al., 2013; Stephens, 2007). In this case, because the interviewees were not the subjects of the study, and car pollution is not typically viewed as sensitive or controversial topic, it was felt that the style of interview would not impact the outcome, making both techniques interchangeable. For example, with a in-person interview there is more physical intimidation from the interviewer (McIntosh & Morse, 2015; Irvine, et al., 2013). Therefore, interviews on a sensitive topic could lead the interviewees to give biased answers as they could feel under stress or embarrassed (Rubin & Rubin, 2011). The interviews were recorded to allow the researcher a second opportunity to review in depth the data collected during the analysis and to be more flexible and focused during the interview. Table 2 provides descriptions of the respondents.

Table 2. Interviewee profiles.

Participant Number	**Job/Current activity**	**Instituion**	**Residential Location**	**Research focus/Job description**
#C1	Marketing and Communications officer	Bolton Council	Manchester	Working as a Marketing Manager
#C2	Speech Therapist	Salford Hospital	Manchester	Adult speech and language therapist
#C3	PhD Student	University of Leeds	Leeds	2nd year PhD student in the Business School
#C4	PhD Student	University of Leeds	Leeds	2nd year PhD student in the Business School
#EE1	Presidential Fellow	University of Manchester	Manchester	His research focuses on political development of the urban

				environment under climate emergency.
#EE2	Associate Professor	University of Leeds	Leeds	Her research focuses on behaviour change for sustainability and how those changes can impact positively on environmental issues.
#EE3	Research Fellow	University of Leeds	Leeds	His research focuses on air quality and pollution, with an extension to atmospheric chemistry modelling.
#TPA1	Lecturer in Transport Management & Resilience	University of Leeds	Leeds	His research is focused on choice modelling, transport and econometrics.
#TPA2	Transport Planner	ARUP	Manchester	With more than six years of experience, the respondent has solid knowledge in transport modelling and travel behaviour.
#TPA3	Lecturer in Business Analytics	University of Leeds	Leeds	Her research has been developing under the interest of policy making and adoption of low-carbon technologies and sustainable mobility.
#TPA4	Transport Planner	VECTOS	Manchester	This participant has been working for VECTOS for more than four years. His areas of expertise are transport planning, travel demand, travel supply, transport assessments, travel plan development.
#TPA5	Research Fellow	University of Leeds	Leeds	His areas of expertise related to this project are resilience, infrastructure, transport and climate change.
EP#1	Lecturer in Psychology	University of Brighton	Brighton	His academic career started with working on theorisation of identity. Now, ecological crisis and climate change are part of his research interests.
EP#2	Human Factors consultant	ARUP	London	He works as a behavioural psychologist to understand behavioural outcomes in different transport projects that ARUP is leading.
EP#3	Lecturer in Environmental Psychology	University of Surrey	Surrey	Her interests are related to topics focused on restorative environments, place experience, and links between environment and wellbeing.
EP#4	Professor in Environmental Psychology	University of Cardiff	Cardiff	She is a professor of environmental psychology and director of the UK Centre for Climate Change and Social Transformations. Her expertise is related to public perceptions, behavioural change, communication and engagement in relation to climate change.

EP#5	Senior Research Fellow	University College London	London	Working on behavioural change, her research is focused on identities, self-determined motivation and other factors that push people to behave in a more environmentally responsible way.
EP#6	Head of the Social, Economic and Geographical Sciences department.	The James Hutton Institute	Aberdeen	His expertise lies in people's attitude towards environmental behaviours. He has participated in different projects related to the protection of the environment: wastewater management, energy consumption, public participation in urban design, among others.
EP#7	Associate Professor in Environmental Psychology	University of Sunderland	Sunderland	Her worked is based on environmental psychology, which looks to understand how built and natural environments influence behaviour, health and wellbeing.
PM#1	Consultant	Living Streets	Manchester	He is involved in projects where they look to encourage primary school students to use active transportation, specifically, walking.
PM#2	Consultant	Living Streets	Manchester	Working on projects in Sheffield and Manchester that are related to infrastructure development and pedestrian facilities.
PM#3	Policy Advisor	Transport for Greater Manchester	Manchester	He is a member of the group of consultants that work for TFGM (working for them fully in the last three years). His personal interest is how societies can make places better from a mobility perspective. Working now on mobility experience.

Source: Own elaboration.

5.4.5 Analysis and implementation of the data collected

In qualitative analysis, it is possible to find different approaches like content analysis, thematic analysis, grounded theory and discourse analysis. Independent of the approach selected, the researcher needs to be sure that the method has followed a trustworthy and credible process in terms of coding, documenting, theming and evaluating data collected (Nowell, et al., 2017). In this project, a combination between content analysis (CA) and thematic analysis (TA) was adopted since the qualitative phase needed to identify, organise, establish, extend and validate systematically parameters, patterns and relationships within the data collected (Rosengren, 1981; Hsieh & Shannon, 2005; Elo & Kyngäs, 2008). A combination of CA and TA has been widely used in qualitative analysis as it has been argued to be a flexible qualitative approach that is adaptable to a wide range of epistemologies and research questions (Hsieh & Shannon, 2005; White & Marsh, 2006; Luna-Reyes & Andersen, 2003).

The basic principle of CA is based on analysing the characteristics of the language which enabled the researcher to focus on the communalities that come from shared meaning and social experiences expressed by the interviewees (Budd, et al., 1967; Hsieh & Shannon, 2005; Tesch, 2013). This process follows a systematic codification and categorisation of textual data to establish trends, as well as importance, relationship with other concepts, and their frequency of appearance (Vaismoradi, et al., 2013). CA is considered an appropriate deductive technique in system dynamics to identify/verify reference modes and behavioural patterns, and estimate parameters from textual data (Luna-Reyes & Andersen, 2003).

TA is defined as a technique to identify common topics by organising and finding patterns of meaning in a set of qualitative data such as transcripts (Braun & Clarke, 2012). Therefore, this technique allows the modeller to consolidate and generate a list of concepts to develop the causal loop diagram, establishing a clear understanding and definition of the concepts included in the analysis (Luna-Reyes & Andersen, 2003). In this case, the TA was carried out when the improved causal loop diagram (from CLD 0 to CLD A) was developed, which was the result of combining all the mental models described by the experts. In such combination, many concepts were repeated by the respondents; therefore, finding common patterns in the description of the cause-effect relationships was crucial to consolidate CLD A.

The source of data for content analysis and grounded theory is the same (Strauss & Corbin, 1994). Normally, data is captured through text that can be registered in verbal, print or electronic form and acquired from narrative responses, open-ended questions in surveys, focus group, unstructured or semi-structured interviews, or articles and papers (Kondracki, et al., 2002). In this case, the strategy to capture the data was by recording the whole interview and taking notes about the relevant points in each question. For sections 3 and 4 of the interviews, the key variables and the mental model were registered on a sheet of paper because that was how to work more easily on the construction of the mental model and keep the flow of the exchange of ideas between the researcher and the respondent.

The process of coding in this study happened at the same time as the interviews. As was explained in the earlier section, each respondent made a list of the variables that they believed were involved in the explanation of people's travel behaviour. Thus, the process of coding and classification of the text data happened in parallel with the narrative responses that the respondents gave when they were selecting/labelling the variables involved in their mental model.

It was not necessary to create any themes or clusters since the aim of this phase was to find cause-effect relationships between each variable mentioned by the respondents. The main output needed for the simulation model was respondents' mental models that were possible to integrate with the researcher's mental model, so as to improve the initial dynamic hypothesis proposed from the literature review.

5.4.6 Limitations of qualitative methods

The quality of qualitative research is still an important debate in academia. Qualitative researchers have always been labelled as too subjective, which means that the quality of the results often relies on the experience and point of view of the researcher (Byman & Bell, 2011). Additionally, quantitative researchers argue that qualitative research is difficult to replicate since many unstructured steps are followed during the data collection (Saunders, et al., 2009). Another standard critique of qualitative research is the "relativist" attitude of the researcher when they analyse the data because there is no systematic rationalisation of the results obtained (Onwuegbuzie & Leech, 2005). Finally, it is argued that the results obtained in a qualitative analysis are restricted to the sample since normally a small sample size is used to run interviews, focus groups, etc. (Byman & Bell, 2011).

The challenges of conducting interviews are related to the bias that can be created when the respondents answer in a certain way to please the researcher (Hsieh & Shannon, 2005). Additionally, social cues (e.g. body language) can give extra information to the respondent to add to their perception of the problem. However, in this case, the interviewees were not the subject under study. While it is true that commuters were part of this project, the conversation was led to capture their opinion about the commonalities in people's travel behaviour, so they were not personally involved as the subject of the study.

The disadvantages of CA and TA are related to the process of construction credibility when it comes to data analysis. CA has been shown to be a flexible research approach since the specific type of content analysis emerges according to the theoretical framework and interest of the researcher and the phenomena under study (Hsieh & Shannon, 2005; Tesch, 2013). That is why novice researchers in qualitative analysis might have problems in rigorously defining the steps of the content analysis. Additionally, using pre-existing theory as material for the interviews (in this case CLD 0) provides more supported than unsupported evidence, which can lead to biased answers to understand the description of the phenomena, as unsupported variables are not discussed, closing new directions for future research.

5.5 Results

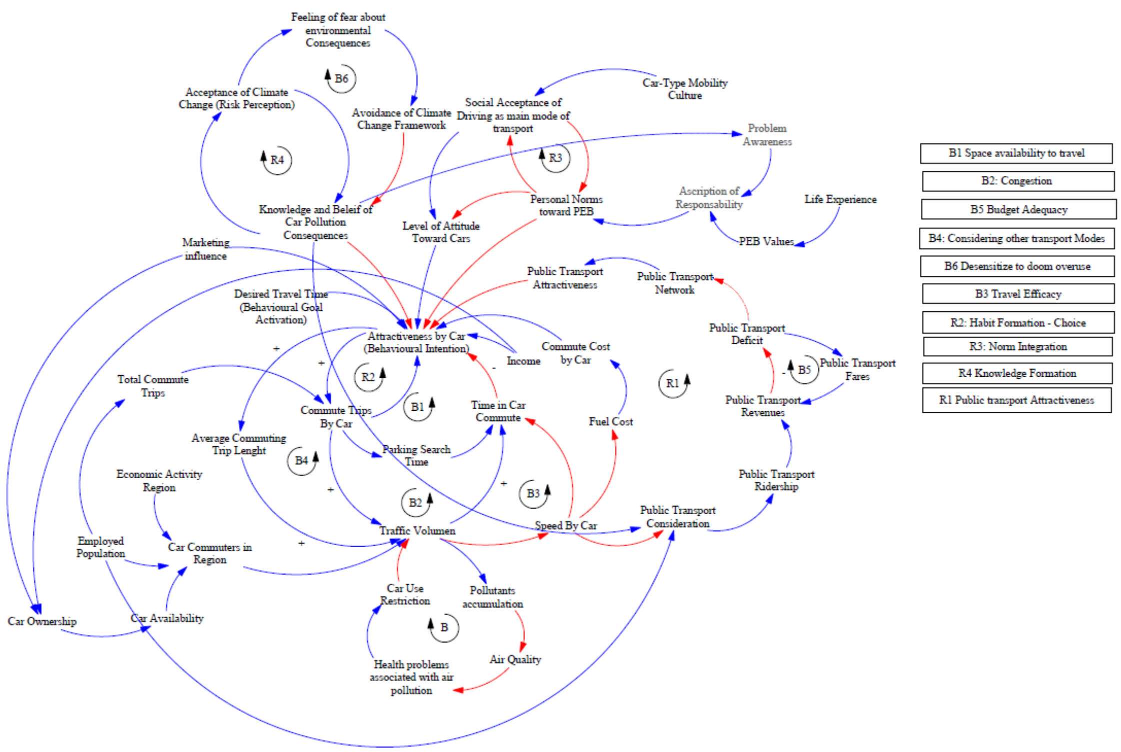
This chapter presents the results of the 22 interviews that were completed with transport planners, environmental engineers, environmental psychologists, commuters and policy makers. The following sections will provide a detailed description of the analysis of each interviewee's responses. This includes individual lists of variables created by respondents, the causal loop diagrams, and insights that were integrated into the proposed project model prior to the qualitative phase of analysis.

For clarification, each interview analysis will have the following sections:

1. **Respondent's recruitment & profile.**
2. **List of variables & respondent's causal loop diagram**: it contains all the variables that came out in the second step of the interviews. Those are the 'top of mind' variables related to explaining why people decide to commute by car and alternative transport modes. Additionally, it presents a diagram which was made by the respondent with the list of variables that they provided in section 2 (see Appendix 11.1). In this step, some respondents extended the previous list as they found that some variables were necessary to include to better explain their ideas for why people decide to commute by car and other types of transport.

3. **Proposed modifications by the participants:** this is a summary to present the insights obtained from the interviews. It explains the modifications made in the original causal loop diagram (Figure 21). Those modifications were either the addition of new relationships or new variables that were not mentioned in any former section.

Figure 21. Original causal loop diagram constructed by using the literature.



Source: Own elaboration. Figure drawn by using VENSIM DSS. To make it easier to read the polarities of causal relationships on the map the symbols (+) and (-) have been changed to colours. Red arrows refer to a negative relationship (-); two nodes change in opposite directions. Blue lines refer to a positive relationship; two nodes change in the same direction (+).

While it is true that there is no agreement on sampling until data saturation is achieved (Guest, et al., 2006; Francis, et al., 2010), the protocol of this thesis (to ensure theoretical saturation) was to conduct interviews until no relevant new idea, variable or cause-effect relationship was found by taking into account all the insights gathered from all the respondents. In this case, 22 interviews were enough to achieve theoretical saturation in the topic of why people commute by car or any other alternative transport mode. Although experts from different areas like transport or environmental psychology focused on different dimensions to explain the social phenomena, all of them were also commuters, so their experiences were implicitly part of their responses during the interviews.

5.5.1 Group 1: Commuters

5.5.1.1 Recruitment and profile of the commuter sample

The recruitment strategy was detailed in Chapter 4. In brief, commuters in the cities of Manchester and Leeds were contacted personally or by email/phone. However, one difference between this group and the others during the selection of cases was that commuters were contacted as they were needed. This strategy was adopted as commuters are easy to access for an interview, everyone who works is likely to commute, so it was not necessary to send a lot of emails to anticipate the necessary number of participants. The sample filter was based on a simple criterion: any commuter living in Manchester or Leeds. The reason for choosing these two cities was just a matter of practical operationalisation of the interviews as the researcher had more flexibility to travel between them. When they were contacted, the researcher explained the purpose of the study and interview. The final sample was a mix between two active transport commuters, one car commuter and one public transport commuter. Those four interviews were enough to reach theoretical saturation.

Recruitment of participants took place from 12th of August 2019 to 25th of November 2019. In this group, all the interviews were conducted face-to-face and lasted between 31 and 42 minutes. Interviews were conducted where the participant preferred (their office or a coffee shop). Table 3 shows some information about their commuting trip and their regular transport mode.

Table 3. Commuters' profiles. Job position and some information about their commuting.

Participant Number	Job/Current activity	Commuting time (estimated on Google Maps)	Distance (estimated on Google maps)	Type of transport used to commute	Age
#C1	Marketing and Communications officer	52 minutes	13 miles	Public transportation	35
#C2	Speech Therapist	12-24 minutes	4.3 miles	Car	31
#C3	PhD Student	8 minutes	0.5 miles	Walk	28
#C4	PhD Student	15 minutes/5 minutes	0.6 miles	Walk/Bike	28

Source: Own elaboration. Times and distances were estimated with Google Maps, the day and leaving time were set up before the estimation was carried out.

5.5.1.2 List of variables and causal loop diagrams of the commuters

Through the collected data it is possible to find that commuters implicitly agree that the decision to commute by car or alternative transport modes is mainly related to economic issues (fuel cost vs bus fares; car ownership vs public transport use), accessibility (car ownership vs bus stop access or bicycle ownership), alternative transport mode's infrastructure (bicycle lanes), reliability and capacity (e.g. buses and tram), perceived comfortability (commuting by car vs taking the bus on a rainy day), distance, commuting time and symbolic motives of car use.

C#1: "*If I had the chance to have access to a car, I would definitely use it when it's raining. Even if I paid more, I'd use the car because I don't like to get wet…. On the other hand, if I have the chance to go to work on my bike, I do it. In summer, I try to use my bike as much as I can, so, even if I had a car, for sunny days I would definitely still use my bike to go to work.*"

C#2: "*Yes, I would [stop using car], if I had better… other options… if the tram and the bus were direct and if it were cheaper… I think people always would choose the cheapest option to commute, and, depending on the resources available (bike, motorbike, car, etc.) and the duration of the journey, people could consider environmentally friendlier decisions".* Also she said, *"Even if it is shorter travelling on the train by 5/10 minutes and cheaper, if it is really uncomfortable because you have to stand up the whole journey, you are still gonna use your car probably."* Referring to image/prestige perceived when people use a car, she continued: "*I don't think it [car demand] will change that much in the next 20 years because it's always gonna be a status symbol… if your image is really important to you, then it will directly affect [your] car use…"*

C#3: "*The greater the distance, the more you use your car… when you are aware about the environment, you choose your place to work to be close to where you live…."* Also, he mentioned: "*If you know that you will not use a car, it is less likely that you will want to own a car"*, adding, "*The more important [social status] is for you, the more is your desire to buy a car."*

C#4: *"For biking, the roads are really bad here… there are no proper bike lanes… the shortest way [to work] would be through the park, but in the park you are not allowed to cycle through the park, so you have to bike all the way around it where the pavement is really bad… that's really annoying… and there are lots of students in the morning so it's hard to go through, and then sometimes I do it on the road but you really have to watch out [for] all the traffic and all the cars…."* He also stated, "*I don't really see a decrease in car demand at the moment. Politicians are proposing switching to electric cars… of course if they are saying that they need to develop the infrastructure more… as long as there's no drastic changes [in England] when it comes to the public infrastructure and rail network, I don't see anything really happening…. As soon as you have an activity out of the city, if you don't have a car, it is quite challenging…."*

Another important point mentioned is the fact that some of them believe that the solution to the problem of car pollution is on young people.

C#3: "*If you look at the car consumption as a fraction of the population… I think it's going to increase, because the population will be bigger [in the future]. But the average consumption per person probably will go down… because more and more younger people are getting aware about the environmental problems… so hopefully they'll encourage [us] to use less cars."*

While other concepts emerged across the interviews, all of the interviewees have a similar way of thinking to explain commuting: The longer the distance to travel between work and home, the more attractive buying and using a car becomes (**C#4**: *"Geographically speaking, do you live in the city? Then you can maybe walk, take the bike, the bus or Uber, whatever… but if you live outside, mostly you have to take your car"*). Alternative transport modes, like the bus or the tram, are considered in the decision of travel mode choice either when they are ease to access, direct and comfortable (**C#1**: *"The improvements of the connectivity and accessibility of the public transportation make its selection easier [for commuting]*) or when people have a low income which does not allow them to buy a car (**C#4**: *"We can see that poor people from very poor backgrounds have to take buses to commute… they can't afford to buy a car"*). In the case of active means of transport (AT), the decision to use it becomes visible when the person lives near his/her workplace. However, the consideration of AT (walk or ride a bicycle) decreases as the distance increases, and the willingness to make a physical effort is less. That is why some people feel that it is feasible to walk long distances to work whilst others prefer to take any alternative means of transport that does not require any psychical effort (**C#3**: "*The fitness of a person probably affects the willingness to do psychical effort, which then affects car use [negatively]")*.

Once a person buys a car, their desire to use it and justify their investment grows (**C#3:** "*If you know that you will not use a car, you will certainly not buy a car… the less you use a car, the lower is your desire to own it"*). As a consequence, the greater the distance a commuter travels, the greater the commuting time, so the greater their dependency on transport modes which can guarantee a feeling of control during the journey (speed up if it is necessary). The distance is also directly related to the fuel consumption: it is expected that, for longer distances, the car will consume more fuel, which in turn increases the cost of travelling by car (making the possibility of considering alternative transport modes more feasible). The cost needs to be a function of fuel consumption and parking space use. As the cost rises the car use falls, as it is less attractive for someone with a limited budget. However, some people might not care about spending more on using a car to commute because cars are always an attractive way to improve people's social status (**C#2**: "*I don't think it [car use] will change that much in the future… because I think it's always going to be a status symbol"*; **C#1**: "*Car manufacturers have been always looking [to influence] the car's image as a product of prestige, comfort and with the power to represent freedom"*) and others will still stick to their cars as public transportation fares are really expensive (**C#4**: *"What we see, trains are quite expensive here, so, for people to be able to always take the train, especially if they need to go further away, it is quite challenging")*. This may be related to the fact that there are some nations that have historically based the development of transportation systems around the automotive industry, which generates an acceptance of the car as the main means of transportation at a cultural level and better infrastructure to use it (**C#4**: *"It's important to look the history of the cars… [in] countries such as England and Germany, these are car nations… so the governments are going to support [those] car manufacturers, so as to push the use of cars…. In Germany, politicians go crazy when you want to do something against cars"*).

Parking availability helps people to perceive that the car could be a more comfortable option to travel because, once they know where to park, the perception of how easy it is to travel by car increases. Finally, the number of people that are living in the same home and need a lift by car, also increases the attractiveness of using a car to commute (**C#1**: *"If you have kids, you feel that it is much easier to drop them to the school in a car than [for them to take] public transportation"*).

In terms of car pollution and car use, the respondents shared a similar opinion about car pollution: pollution will continue to rise, unless governments adequately prepare a transportation system that is consistent with environmental objectives, which in turn allows people to access an efficient and comfortable commuting system at a low price. They think that there are still many people that are not willing to quit comfortability or increase the commuting time to decrease the CO_2 emissions, so that is why the attractiveness of alternative transport modes needs to be increased through comfortability, access, social status and a stronger association with eco-friendly perceptions.

C#1: "*While it is true, they are more consciousness about car pollution, many people neither want to decrease their comfortability nor invest more to decrease CO_2 emissions. There is more consciousness about environmental issues, but it hasn't been able to change behaviour… many people prefer to keep high standards of comfortability and cars are the most comfortable way of transport. In many houses, you can see that many families have at least two cars."* Also, she said, *"More people will acquire electric cars as the market will give better and cheaper options, but I don't think that will be enough to reverse the negative impact of car pollution."*

C#2: "*I think it [car use] will continue going up for a few years and then it'll either go flatter or go down because I imagine at the moment people are trying to… promote and create systems which will make public transport better… because it's the big issue at the moment. Also I don't* *think you can fit any more cars on the road… so that'll be the point where they'll stop building new roads to accommodate cars and they will look for new ways to accommodate travellers. Hopefully, the system will be ready to help with that [reduce car use].”*

C#3: “*I would say, from what I know, in the next 10 to 20 years the demand for cars will be double. However, I think people will use more electric cars, so I think the pollution itself will be less from diesel cars… air pollution should go down [from diesel cars]. But, if you consider then the pollution produced by the construction of an electric engine to build an electric car, then the demand for those cars will make the pollution to go up…. This is a difficult topic…. I also read in a newspaper, for example, that in 20 years cities in Germany are going to increase the bicycle lanes and pedestrian spaces because big roads are not going to be necessary… people will tend to use more 'share car services' so [fewer] cars will be on the roads… so from that point of view pollution should decrease from car use.”*

C#4: “*I think, in general, based on historical developments that we have seen in cars, I don't think much is going to happen in the next 10 years…. Because what we saw in the last 10, 20 years, for example… cars have become more and more efficient, however… cars have become bigger and all the efficiency effects have switched to this rebound effect….”* Also, he said, *“Also, it's important to consider how we are gonna measure pollution by car, are we taking into consideration the whole life cycle of a car, meaning when the car is being produced… or we are only measuring what at the end comes out [the exhaust fumes]? Because that's a big difference.”*

Finally, they feel that, even though the encouragement to be more aware about environmental problems has been increasing, it has not been able to be translated into real actions as it is still possible to perceive that the demand for cars is continuously growing. Currently, governments are not properly taxing the real cost of pollution, and this might be because they want to protect car manufacturers from political pressure. While governments are deploying many actions to decrease pollution, car prices and fuel cost do not properly reflect the real cost of CO_2 emissions. For example, getting a car is easier now than before since consumers have different alternatives to pay for it (e.g. credit, personal loan, hire purchase, personal contract purchase, etc.). That is why it is really important to see how to develop proper interventions and subsidy programmes to reframe the benefits of using alternative means of transport, in conjunction with the companies (**C#4**: *"In the Netherlands, if you go from your job to your office and you take the train your ticket will be subsidised either by your employer or the government. When I worked in Berlin, my employer gave me free tickets to use the public transportation"*).

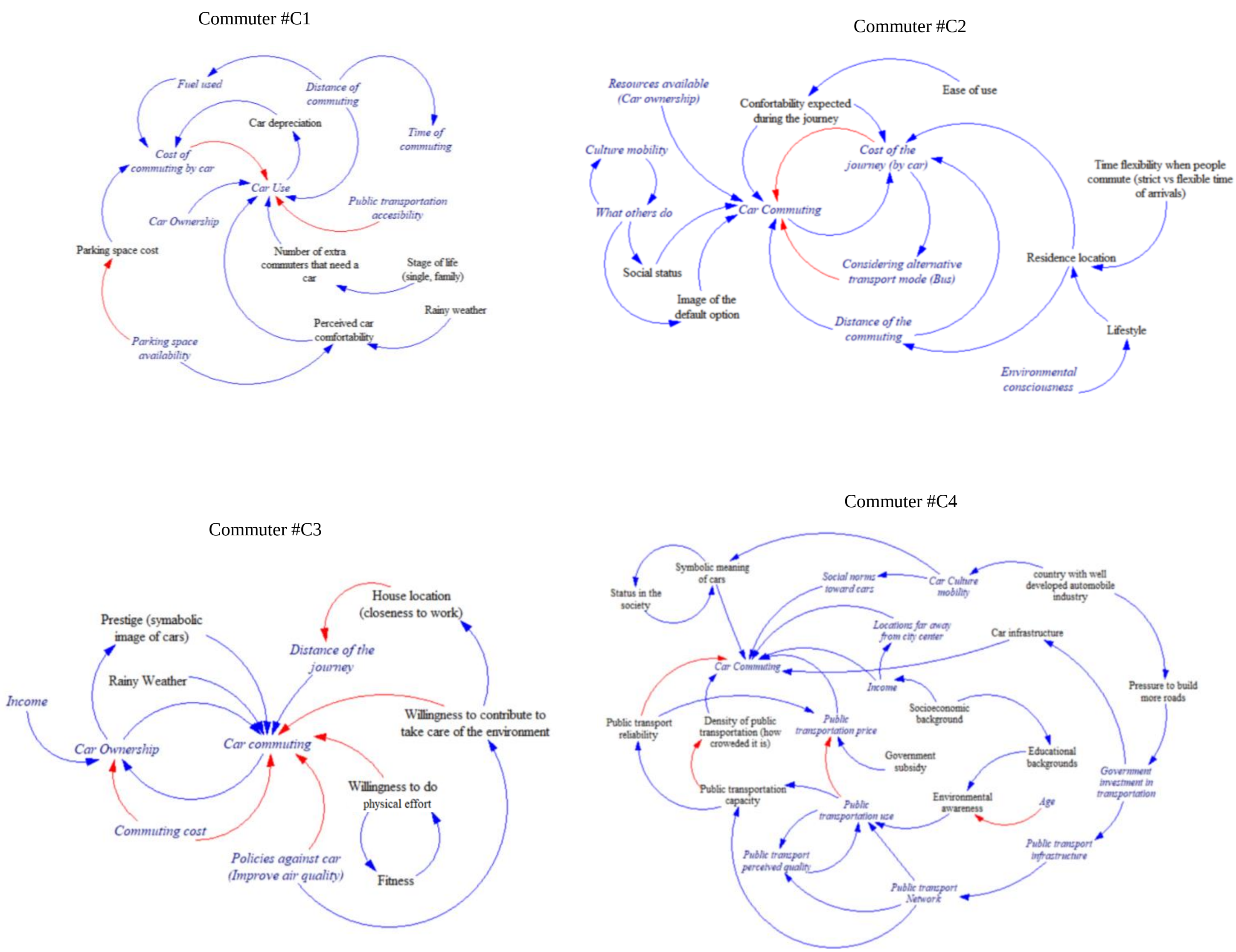
Table 4 shows the variables mentioned during the interviews as factors that influence the decision to commute by car, public transportation and/or active transportation. Eighteen variables were not found in the original causal loop diagram, of which four were mentioned more than once (rainy weather, perceived car comfortability, symbolic image of car and house location).

Table 4. All the variables mentioned by the commuters.

Fuel used	**Number of extra people that depend on your way of transport**	**Willingness to do physical effort**	**Government subsidy**
Cost of commuting by car (3 times)	**Stage of life**	**Fitness**	**Public transport capacity**
Car ownership (3 times)	**Rainy weather (2 times)**	Age	Public transport perceived quality
Parking space cost	**Perceived car comfortability (2 times)**	Social norms towards cars (2 times)	Public transport use
Parking space availability	Income (2 times)	Culture mobility (2 times)	**Educational background**
Car depreciation	**Symbolic image of car (3 times)**	**Public transport reliability**	
Distance of commuting (4 times)	Policies against car use (improving air quality)	**Density of public transportation**	
Time of commuting (2 times)	**House location (2 times)**	Public transport price	
Public transportation accessibility/network (2 times)	Willingness to contribute to [protecting] the environment (3 times)	**Socio-economic backgrounds**	
Car infrastructure	Considering alternative transport modes (bus)	Government investment in transportation	
Country with well-developed automobile industry	**Pressure to build more roads**	Public transport infrastructure	

Source: Own elaboration. The variables in bold are the ones that were not included in the original causal loop diagram.

Figure 22. Causal Loop Diagrams of commuters



Source: Own elaboration. This map was created on VENSIM according to respondents' draft drawings. Red lines mean a negative relationship, blue lines are positive relations, words in black are the variables that were not considered in the original conceptual model (CLD 0), and words in blue italics are the variables that were already integrated into the original mental model.

5.5.2 *Lessons learned from interviews with commuters*

It is clear that for commuters the decision regarding selection of the transport mode is based on a cost/benefit analysis, in which economic aspects (fuel cost, bus ticket, etc.), instrumental attributes (e.g. convenience, accessibility, etc.), physical considerations (distance, commuting time) and individual factors (e.g. image, fitness, mood) are taken into account to estimate which transport mode maximises the benefits. Additionally, available options are important when commuters decide on the transport mode (e.g. car availability vs bicycle).

When income is not a restriction on buying and using a car, it seems that the positive emotion towards driving is triggered by pleasant experiences that give immediate effects (feeling of having control during the journey, independency to travel anywhere, comfortability, convenience, etc.). For this reason, people might not analyse the risks of car pollution in the long term. Each individual driving occasion seems to be marginal to the problem. In other words, people do not feel guilty every time they use their cars because they think that it is unlikely that the environment will collapse the next time they use their cars. There is a lack of capacity to see car pollution as an accumulative process.

Those interviews extended the original causal loop diagram by adding a better explanation of the cost/benefit analysis when a commuter decides on the means of transport for their commute. Comfortability, safety, time flexibility and social norms are important aspects to consider. Additionally, commuters pointed out that in England public transportation is expensive enough to not be immediately considered as an alternative method of transport (unless economic issues do not let the person drive). The reliability (train cancellations, time variability) and convenience (not many direct options to commute for people that live far away) were the main issues that created a bad perception of public transportation. Table 5 shows the variables mentioned by these respondents that were included to improve CLD 0 (in Figure 21 the cause-effect relationship of each variable can be seen in detail).

Table 5. Variables that were included in the final Causal Loop Diagram.

Cost of having a car	Ticket price (and its relationship with car attractiveness)	Willingness to do physical effort	PT reliability
Perceived comfortability	Level of crowdedness	People's fitness	Bike availability
Rainy weather	Comfortability levels	Maximum distance acceptable to walk	Commuting time if walking
Country with well-developed automobile industry	Rainy and/or cold weather	PT frequency	

Source: Own elaboration.

5.5.3 Group 2: Environmental engineers

5.5.3.1 Recruitment and profile of the environmental engineers' sample

Following the same recruitment criteria, emails were sent to contact people (based in the UK) who were working or doing research in the area of environmental engineering, specifically in topics related to climate change, sustainability, air pollution, urban growth, behavioural change and/or air quality. Recruitment of participants took place from 12th of August 2019 to 25th of November 2019. From 28 emails sent, three participants offered to participate in the study. Two of them were researchers at the University of Leeds (School of Earth and Environment) and one was from the University of Manchester (Manchester Urban Institute).

Table 6. Environmental engineers' profiles.

Participant number	University	Department	Research focus/Job description
#EE1	University of Manchester	Manchester Urban Institute	His research focuses on political development of the urban environment under climate emergency.
#EE2	University of Leeds	School of Earth and Environment	Her research focuses on behaviour change for sustainability and how those changes can impact positively on environmental issues.
#EE3	University of Leeds	School of Earth and Environment	His research focuses on air quality and pollution, with an extension to atmospheric chemistry modelling.

Source: Own elaboration.

5.5.3.2 List of variables and causal loop diagrams of the environmental engineers

From the environmental engineers' perspective, transportation policies are still being developed under the paradigm of time efficiency and costs. Transport improvements are mostly focused on how to decrease car congestion (to decrease travelling times) and improve public transportation according to people's demand (lack of connections and travel options in towns). Therefore, this cost/benefit perspective of analysis creates an inevitable disconnection between commuting and environmental aspects, despite the application of interventions to force a behavioural change. The environment and car attractiveness are two poorly coupled systems that are not working together in harmony since cars bring undesirable outcomes (pollution) that negatively affect the other system. And the big problem that those respondents pictured is that cars are seen as the main method of transport. This is the result of the social image construction of cars brought about by car manufacturers and governments, which have been supporting the development of better facilities for cars instead of alternative transport modes. The consequence of this is that environmental protectionists rely on overcoming the resistance to change with the adoption of alternative transport modes that are not really prepared to shift the paradigms of many drivers.

EE#1: "*My hope is it [car pollution] would decrease, right… that we'd see the focus on other transit – walking, biking and other modes of non-car transportation… to an extent [whether] it's actually gonna happen seems open ended. I get the sense there is a big push towards buying electric vehicles and autonomous vehicles… you know, my general sense is that I think cars are technology that ruins cities and exposes us, also, to an important environmental harm. I don't own a car, I don't like cars, I much prefer not to have to use them, but I think there are limitations to that… like, in Manchester, in terms of how you make this landscape more open to public transit….*"

EE#2: *"I can't really see a change [in car demand]… the infrastructure that we have in the cities and transport generally… it's not designed in a way that is reducing car demand… so I don't see an important change over time."*

There are more and more hybrid and electric vehicles on the market, so I would say that, particularly in Europe, car pollution is decreasing… not sure in other countries, like the US…. In the US and Australia, there is a tendency [to have] bigger cars, which means higher pollution... whereas in the Scandinavian countries electric cars are really incentivised, so my hope is that air pollution will be reduced by electric vehicles…."

EE#3: *"I think people's kind of tendency to drive, it's always gonna be there, so I think the number of vehicles is probably going to increase… so that, so obviously it'll increase the demand, which will be a challenge for governments to improve the transportation network."*

That is why environmental engineers' hope is, if active transportation is not feasible for all the population, then car ownership needs to migrate from diesel cars to electric cars as they are seen to pollute less. People are strongly dependent on this means of transport because the infrastructures in cities have been developed around a car-mobility culture. Therefore, it does not look like car demand will change in the short term by a voluntary act from people.

EE#1: *"I think car demand really depends on regulations… I live quite close to here, when I commute to campus… like, I think my perspective is a little bit skewed. In my mind, it's like everyone is walking and riding bikes and stuff, but I think, yeah, a lot of people live further out… so they really depend on cars."*

EE#3: *"I imagine [air pollution] will go down because there are better technologies for electric vehicles, hybrid vehicles… so I think societies will become more environmentally friendly in that sense… and the government… they said that, by 2040 I think, they're gonna take out all diesel/petrol cars… there is a certain target trying to reduce the most threating cars, which is mainly diesel cars at the moment."*

Opposite to the commuters, **EE#1** seemed to be a bit sceptical about young people being the long-term solution because, even though young people might drive less, complementary car services (e.g. Uber) look more to be a competitor for public transportation than a complementary service, so that creates the opposite outcome than that expected from a balanced transport system in a city.

EE#1: "*It's really open…. There's a sense that young people drive less, but I don't know… with the amount of Ubers, taxis, it seems people are still using cars quite a bit…." **EE#1** added that: "Something that I've been noticing here in Manchester is just, like, how many Ubers there are now… I feel that Uber and those kinds of companies try to pitch themselves as a complement to public transportation, but, in reality, they are competitors."*

Overall, respondents see that the solution relies on the implicit system goal of the economic and transport system. In other words, even though people attempt to change their travel behaviour, the resistance is an automatic response from the system as many people are not able to be flexible in the time that they arrive at work; therefore, they have all the incentives to minimise their travel time regardless of the negative impacts that the means of transport can produce.

EE#1: "*…I think if the state [government] is willing to put in place restriction [on] fuel cars, you'll see a change… automobile mobility is such a large-scale problem, it depends on where you are located, where you can drive, where you can park, how much a car costs, fuel cost, …but to me it's like, I don't think people are gonna drive less by choosing to voluntarily buy electric cars, but if you put some regulations [in place], you'll see a change….*"

Environmental engineering participants see the travel commuting decision as follows: travelling by car is triggered by the perception of the difference between the benefits and costs of using the car; the higher the perception of the short-term benefits, the more attractive it is to travel by car.

Benefits are broken down into psychological and functional factors. In the functional factors, distance is one of the most important. Normally, the longer the route between home and work, the less attractive it is to take public transport (**EE#1**: *"In terms of location, is it actually possible to not commute by car? You know, in some places it isn't…"*), since less direct routes are available so it creates a journey with more modal changes, which in turns is perceived as less convenient for the passenger (**EE#2**: *"For example, in Leeds, buses all go to the city centre… there are not many buses that would cross from where I live [and] go directly west to the university; instead, the buses have to go in and out again, so that is less convenient")*. Also, times play a key role in the decision: people tend to think that travelling by car is faster than any other method of transport; for that reason, cars are more attractive.

In the case of psychological factors, perceived cost of commuting (by car or public transport), parking space availability, perceived safety, comfortability, etc., are part of the long list of variables that might influence the decision to drive. Commuting cost by car includes fuel cost and parking space, hence it is expected that these two variables can decrease the attractiveness of driving. Whereas parking space availability can increase it as it improves the experience of commuting by car. In big cities, it is believed that it is always hard (and expensive) to find a parking space in the city centre. However, it seems that people are not psychologically aware about the real fuel cost; instead, they tend to compare the public transportation price before taking the decision since that is an immediate cost (**EE#2**: *"So, running a car… if in your head you look at the true cost it would be quite expensive to drive to work every day, but psychologically I don't think you would calculate the real amount of petrol that was used by the car and all of that stuff, while you are looking at whether it is cheaper to go by public transportation… it's £4 a day to get to the campus by public transport… so that is an immediate decision… if I drive, I don't have to spend £4 today…"*). In the case of public transportation use, its attractiveness is strongly related to the cost of the ticket, and that can be an important issue to decrease the probability of shifting the travel mode from cars to buses/trams (**EE#1**: *"I usually either walk or take the bus, right? But I found the buses in Manchester extremely expensive for the service they provide… I often make the decision of, like, I can catch the bus, or I can walk, and I usually end up walking because it's spending £2.50 on, you know, a five-minute ride… it's more expensive than in New York…"*) and perceived reliability and comfortability; that is why people tend to use less public transportation.

Deciding whether or not to commute by car not only depends on the perception of travel cost and speed and the convenience of alternative transport modes, it is also related to safety (**EE#1**:*"Safety is probably a concern, I'd imagine people feel safer in cars… also in terms of being* *on public transportation at night"*), comfort (**EE#2**: "*Cars are perceived to be more comfortable and private than public transportation"*), health (**EE#2**: *"If I'm not feeling very well I won't take my bike to come to campus"*), and social norms. For example, more cars in the streets leave less room available for riding a bike, so it creates a feeling of insecurity, which ends up making people avoid riding a bike when they commute (**EE#2**: "*There are so many factors involved in whether a person uses a car or not… so it's really difficult to get people to try alternative transport modes… so when I think about incentivising it or try to get more people to cycle, then there are so many reasons why people might not do that*").

Emotions play an important role to determine people's travel behaviour because some people do not want to deal with the stress of commuting by car when high traffic volumes can affect the commuting experience (**EE#1**: *"…Many of my friends don't have a car… the campus is in the city centre so walking or biking is faster to get to the office than using a car…; I can't imagine driving to the campus because it would be such a nightmare….")*. Furthermore, emotions influence people's mood, so, based on a good trip experience, people can create an attachment to the means of transport, reinforcing their habit of driving, biking, etc. For example, driving is seeing as more comfortable and private than public transportation; those inputs influence people's travel behaviour, and are some of the main reasons that explain why people do not swap so easily between cars and other means of transport. Additionally, experiencing freedom and independence when using a car creates a strong positive feeling that makes people not take into account the negative impact of this means of transport.

Habits are critical to explain car commute: they make the decision to use a car less deliberated and rational, which means that considering an alternative mode of transport to commute does not exist in people's decision-making process (**EE#2**: *"If people always use their car, it is really* *difficult to change that… the more you use your car, the more likely you are to use it"*). People's habits are influenced by social norms because the latter could normalise the fact that cars are the main method of transport.

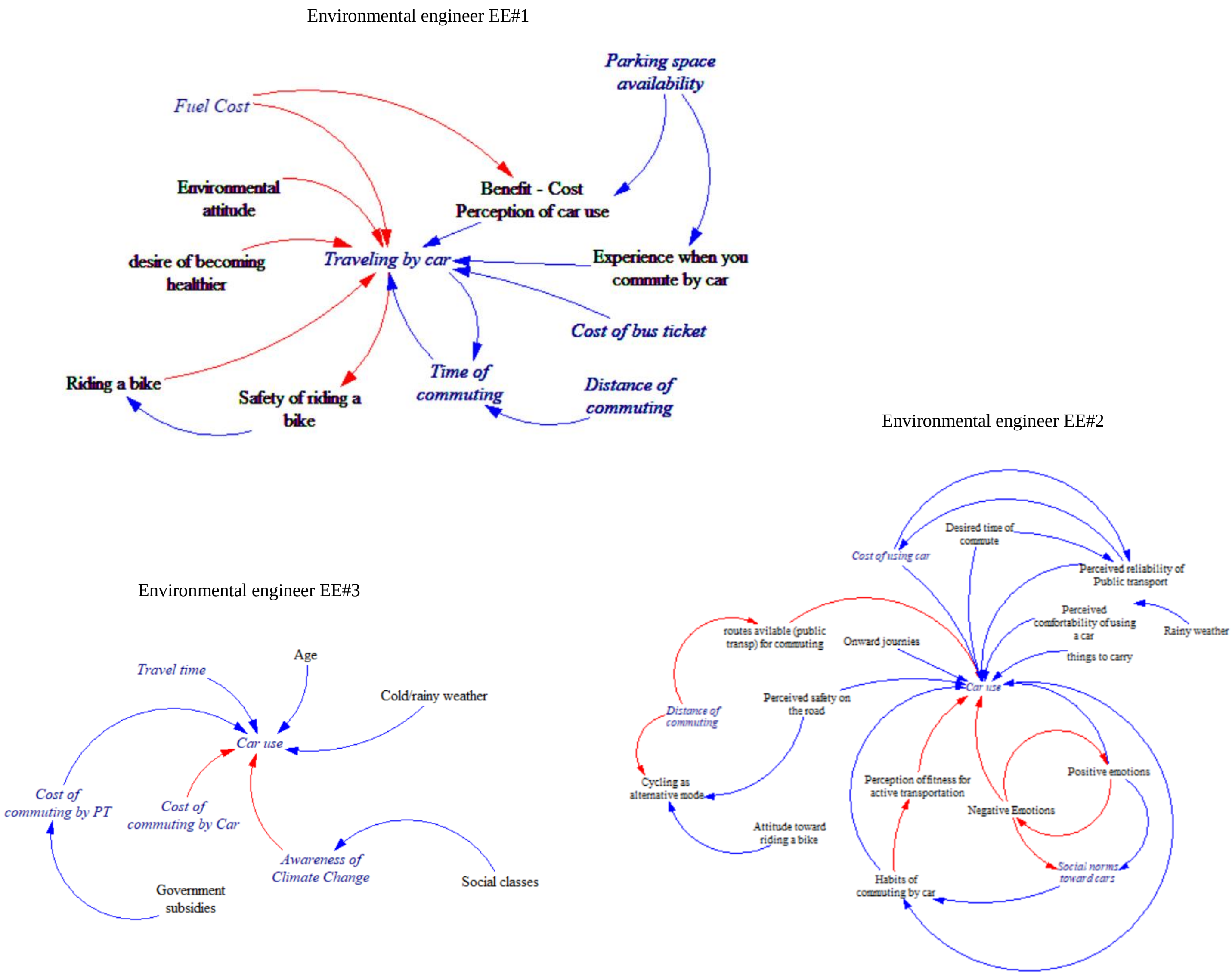
Finally, environmental reasons also influence the decision whether or not to commute by car (**EE#1**: *"I think, around here, many people choose to commute for environmental reasons, so they choose the public transport or ride a bike because they are seen as more environmentally friendly… but again I think that is a really limited population...."*). However, with regard active transportation, even though it could be the most environmentally friendly means of transport, the decision is really restricted to distance and safety. Long commuting distances make riding a bike or walking less attractive as the travel time is out of the boundaries of the desired time to commute and because people might not feel motivated to pedal (or walk) extended distances. In the case of bicycles, the lack of lanes for cyclists creates a bad perception about how safe that means of transport might be, so people prefer to avoid commuting using active transportation. Environmental attitude and a desire to feel healthier could act as factors that can decrease the attractiveness of commuting by car.

Table 7. All **v**ariables mentioned by environmental engineers.

Fuel cost (3 times)	**Experience when people commute**	**Emotions related to using a car**	**Government subsidies**
Commuting time (3 times)	Distance to work (2 times)	**Attitude towards bike**	**Age**
Environmental reasons (2 times)	**Safety of active transportation (2 times)**	Reliability of public transport	**Social classes**
Cost of bus ticket (2 times)	**Residential location**	**Psychological distance**	
Cold/Rainy weather (3 times)	**Feeling of freedom**	Perceived public transport convenience	
Parking space availability	Habits of commuting by car	**Type of work**	
Fitness (2 times)	**Routes of public transport (convenience)**	**Things to carry with you**	
Social norms (what other people do)	**Car comfortability**	**Onward journeys**	

Source: Own elaboration. The variables in bold are the ones that were not included in the original causal loop diagram.

Figure 23. Causal Loop Diagram environmental engineers.



Source: Own elaboration. This map was created on VENSIM according to respondents' draft drawings. Red lines mean a negative relationship, blue lines are positive relations, words in black are the variables that were not considered in the original conceptual model (CLD 0), and words in blue italics are the variables that were already integrated into the original mental model.

After creating the causal loop diagram (Figure 23), respondent **EE#2** proposed that the model should make a distinction between the formation of "pro-environmental values" and "knowledge and belief of car pollution consequences". Moreover, she suggested that pro-environmental values should influence the "acceptance of climate change". Additionally to that, she said that the model should consider the fact that people could have a cognitive separation between the self and the climate change framework because the consequences are not visible in our daily lives. Moreover, she proposed a balancing loop between a "feeling of fear about environmental consequences", "psychological distance" and "acceptance of climate change" to explain how this temporal disinterest in climate change can be progressive across time.

5.5.3.3 Lessons learned from environmental engineers

In conclusion, environmental engineers believe that strict legal restrictions for car use are the most effective and fastest way to produce a significant positive change in the environment, given that cars do not produce any benefit in this respect. These restrictions do not necessarily need to be related to car restrictions; travel behavioural change can be also reinforced by giving incentives to people who walk or cycle.

Environmental engineers identified the seriousness of the problems related to climate change, and they do believe that actions need to be taken in the short term/medium term. They think that changing people's travel behaviour is a combination of psychological determinants (e.g. emotions, stress, attitudes towards cars) and functional determinants (e.g. fare cost, fuel cost, transport alternatives). However, climate change awareness does not seem to be the best way to approach commuters, as **#EE3** explained: "*In general, people do not see the benefits of fighting climate change… therefore, if substitutes for cars remain at a high ticket cost, then people who are struggling with their incomes will not appreciate the idea of travelling on a more friendly transport mode.*" For this reason, diminishing the psychological distance between climate change and people's lives seems to be the key to strengthen climate awareness. **#EE2** stated this point, saying: "*So if you are experiencing it – climate change consequences – like not having any water or whatever, it's a psychological cost… if the Amazon is burning but it's not related to me… then that's distant… but if the Amazon's burning and I can't breathe… then that's psychologically* close *to our perception.*"

Finally, policies and interventions (e.g. propaganda about biking to work) were an important topic in the three interviews as they could change people's travel behaviour faster. Choosing alternative transport modes does not look like a voluntary option under the climate change emergency (**#EE1**: "*I don't think people are gonna drive less by choosing voluntarily [to use] an alternative transport mode… the government plays a key role in regulating car use*"). Therefore, promoting e-cars (**#EE3**: "*In general, we should see a reduction of* CO_2 *emissions as policies in Europe are moving in the right direction… we should expect cleaner cars on the streets*") and framing differently the experience of travelling on public or by active transportation **(#EE2**: *"People don't feel safe on a bike or public transport… or walking*") can help to improve the perception of the benefits when people shift from cars to alternative transport modes (in the short term). For example, governments can either frame public transportation as an opportunity to do things that are not possible to do when people drive or demonstrate that riding a bike (when it is possible) improves people's health immediately. Table 8 shows the variables mentioned by these respondents that were included to improve CLD 0.

Table 8. Variables included (post-interview) in the CLD A (from environmental engineers).

Awareness of environmental emergency	Bicycle trips
Active transportation consideration	Commuting time by bicycle
Perceived safety (bicycle)	Habit of commuting by car
Bicycle attractiveness	

Source: Own elaboration.

5.5.4 Group 3: Transport Engineers and Researchers

5.5.4.1 Recruitment and profile of the transport engineers and researchers

Recruitment of transport planners, transport engineers and transport academics took place during the same period as the other recruitments. Following the same steps as the other groups of experts, 18 emails were sent to invite them to participate in this project. The final sample was a mix between three people working in academia (University of Leeds) and two professionals, one working for ARUP[44] and the other for VECTOS[45]. Table 9 gives more information about each participant in this research project.

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[44] ARUP is a multinational company based in London, which had 13,841 employees and an annual revenue of 1.56 billion GBP in 2018 (https://www.arup.com/perspectives/publications/corporate-reports/section/arup-financial-statements-2018).

[45] Founded in 2011, VECTOS is a transport and design consultancy with offices in London, Cardiff, Manchester, Birmingham, Bristol, Exeter and Leeds (https://www.vectos.co.uk/about).

Table 9. Transport planners/academics' profiles.

Participant number	University/Company	Department	Research focus/Job description
#TPA1	University of Leeds	Management	His research is focused on choice modelling, transport and econometrics.
#TPA2	ARUP	Transport Planning	With more than six years of experience, the respondent has solid knowledge in transport modelling and travel behaviour.
#TPA3	University of Leeds	Institute for Transport Studies	Her research has been developing under the interest of policy making and adoption of low-carbon technologies and sustainable mobility.
#TPA4	VECTOS	Transport planner specialist	This participant has been working for VECTOS for more than four years. His areas of expertise are transport planning, travel demand, travel supply, transport assessments, travel plan development.
#TPA5	University of Leeds	Faculty of Engineering	His areas of expertise related to this project are resilience, infrastructure, transport and climate change.

Source: Own elaboration.

5.5.4.2 List of variables and causal loop diagrams of the transport experts

In general, the view of transport engineers and academics is that working on reducing car use will vary depending on the context or situation in which the travel plans are being developed. Decarbonising cities and rural areas will require tailored travel plans as commuting distances and availability of alternative transport modes differ quite a bit.

TPA#3: "*…It will be completely different in rural and urban areas. In terms of urban areas, when and if the larger cities bring in congestion-type target schemes or residential driving permits, there are many different types of mechanism to restrict car use in cities… I think then car use will go down, decarbonising more in urban areas… particularly, people that live in urban areas might not feel that they need a car… now, on the other hand, in rural areas, there's evidence that people are becoming more car dependent…*"

TPA#4: *"It totally depends on the context… the traffic relationship between the site and how many people are gonna use their cars to get there completely depends on what has been proposed on that site…. So it depends on land use…. For example, in this project… this is another example… the council asked them to produce a travel plan because their site… they've got hardly any car parking… but everybody who works there has to drive to work… now the reason to drive to work is… Lancashire is one of those catchments… if people that work there... within a 2 km catchment, they can't afford a house because it's such an expensive area, so that is a major reason why people need to drive to work. Also, people drive there because it's faster… if you've not got much public transport provision in that area, then travelling by car is gonna be much faster than jumping on the train or if you need to get the train and change somewhere to another service is inconvenient."*

They see that driving involves the accretion of a series of incremental decisions. A typical life-course trajectory might be: Joseph was born in a family that has a car, so from a very early age he experienced the comfort of travelling by car (e.g. when his parents dropped him at school). In a few years, he developed an attachment to cars because every time he needed transportation his parents drove him around. Although he could not drive at that age, he perceived the freedom of being transported in a car every time he requested it. Later on, as a teenager, his parents gave him his first car, which increased his probability of driving because car ownership established the car as the default option in his travel mode choice (**TPA#5**: "*There could be a reduction in car use, when you remove the ownership"*). Sustaining the habit creates that travel mode choice, which becomes a less deliberated decision, which then means that for Joseph it is really hard to consider an alternative transport mode unless an external force or an unexpected situation happens (the car breaks down, road construction, etc.).

TPA#3 and **TPA#5** agreed that younger generations might be the key to control car use in urban areas, where there are more alternatives to commuting.

TPA#3: "*There are other elements to take into account, especially in cities, and especially in younger generations because… there is fair evidence that younger generations are not buying cars or at least not getting them as early as it was in the past… in my generation, you could get your driving licence at 17 and everyone would get a car or borrow the parents' car straight away. But now that's not happening as much… for various reasons… partly because of the cost of ownership, partly because people… you get generations… tend to live with their parents more, they've got their parents to taxi them around… [and] things like Uber, which is much more convenient than getting taxis….*"

TPA#5: "*I assume it's [car pollution] gonna get worse, but there are factors that I think could reduce that, which are the changing trends of demographics… if you are a teenager now you're probably more likely to want the latest iPhone than a car, for instance… particularly with the transport apps as well, they make the public transport a bit easier to use… when I was a kid, at 17, you've got a car whether you like it or not because that was like a status [symbol]. So, I think in urban areas that might change….*"

However, it is not easy to determine if the low interest of car use among younger generations will really be a concrete solution as many new factors are changing the rules of the industry, and that is technology-related to autonomous vehicles.

TPA#2: *"I think it's hard to say what's going to happen because you have different things as well… autonomous vehicles, you have changing working patterns, you've got stuff like… public transport. There are different things happening in the transport sector that would change how* *people travel. For example, with autonomous cars it's not clear if people would want to own their own cars or hire them…."*

TPA#3: "*And then I suppose the other side of car demand is, well, what impact, if anything, automation will have… we've already got sort of level 1 of automation on the roads today, that's very basic… the technology is coming in, and there are so many different predictions about how long it might take for cars to be automated, will be fully automated to level 5… [there have] been a lot of studies looking into that to see how it will actually affect car demand… and the problem is that… there's two very different vision about automated vehicles… some people see them completely as a replacement for individual cars that we have today, and it will be even better because you will have anything you want in the car… you increase the level of comfort, you can work in the car… on the other side, it's seen as an option to increase shared mobility services. With these technologies, attitudes can change towards driving, in some people… so, if we continue as we are now, and car manufacturers push further this technology, more people will be able to use a car… so, if we can get people into shared mobility services, so then actually you are not thinking about, 'Have I got a car for my journey?' You're thinking, 'I'm doing this journey, what's the best mode of transport available to use?' So then we have a potential individual mobility reduction…."*

On the side of climate change, there is a common agreement between them when the topic is introduced to drivers. They think that there is a lot of controversy as people want to help to fight the climate change emergency, but they are not willing to solve intertemporal choices in which they trade off the current comfortable experience of travelling against the future pleasure of living in a clean zone. And the reason behind this is that individuals might not see the benefits of polluting less (**TPA#1**: "*That really depends on what governments do because people are not going to be* *incentivised to take their car less if you don't force them to do it… and by force them that could be via increase the awareness, which is already the case, but more aggressively…"*). People tend to consider more the instant benefits and costs of travelling by car every day than dealing with the immediate unpleasant travel experience that taking alternative transport modes like the bus (e.g. multiple modal shifts) or active transportation (physical effort) could bring. In fact, this overconfidence of drivers to build and foresee an overly simplistic future under climate emergency, creates a difficulty in making them engage in all the actions necessary to decrease the psychological distance to the climate change crisis, and to accept alternative transport modes or to move closer to work, which sometimes is not feasible as the catchment around the work site is expensive, or there is no security about the job in the long run that justifies the investment of moving out.

TPA#1: *"You observe that people want their car more and more. For example, I have data from Germany, where basically people… car availability and use of cars is pretty much steady, so I don't think this is naturally changing."*

TPA#2: *"I'm working on a project called 'cleaner zones', whether it's gonna work or not, I'm not sure… because, this is my personal opinion, I think we haven't still managed to reduce traffic and when you think where money has been spent… basically, we are building more roads and that is still incentivising [us] to continue as we are so far."*

Therefore, this dynamic inconsistency brings an important set of actions to be made between interventions that could increase environmental awareness and legal restrictions that go beyond drivers' desire (**TPA#4**: "*Local authorities recognise that they don't want no parking space at all in every single site because they recognise that people need a car to get to work"*). People are partially aware of car commuting problems because they might recognise the importance of polluting less; nevertheless, they optimistically think that changing the current situation will be because others will change (lack of self-control) and climate change's negative consequences are seen as future costs, so they do not feel it is necessary to revise their travel choices for the environment. Therefore, this tendency that humans have to discount progressively the future benefits, prevents them from accepting a behavioural change as most drivers place significantly more value on their present comfort and freedom. The consequences of this create a tension on how the government's leadership have to act. Decarbonising cities needs to be addressed by disincentivising the use of cars with the restriction of immediate promoters of car commuting (e.g. more roads, more car parks).

TPA#3: "*For the last 50 years, in most countries, the transport policies have been car centric, it's all about infrastructure… build more roads, and then that'll reduce the congestion.*"

TPA4#: "*It depends on the provision of car parking… [For example,] in terms of what Manchester city council wants to do is… existing car parks now… they want us to develop on that piece of land and then not provide any parking… that's the strategy that is being used in Manchester to reduce the number of vehicles travelling to/from the city centre, is by developing on land that's already a car park, and then that development that you've just produced, you don't provide any car parking….*"

However, it is not so simple since politicians have the pressure of keeping their voters happy, which means that, if the vast majority of voters drive, then it is hard to impose strict measures against cars without damaging their political popularity to be re-elected. Additionally, external forces, like car manufacturers, prevent the progressive decrease in the use of cars, so then any reduction in carbon emission looks like more of an effect of technology improvement because of consumer demands, and not as an altruistic action to fight against climate change.

TPA#1: "*In terms of the political state of things, it is hard to predict precisely things are going to evolve… if nothing happens, your business [car industry] continues as usual, I think car demand will increase… but if the political rules change it might be that car demand decreases or shifts to another type of car… if there are the right incentives… again, so far they [people] don't have any reason to change now, but cheaper models [electric cars]… gas now is relatively cheap… so I think the tendency [to use electric cars] is going to increase really slowly…"*; *"also, it will depend on if the government will implement a carbon tax."*

TPA#2: "*People that buy cars are requiring more roads and they are the voters as well, so obviously the politicians don't want to… anger their voters… many documents talk about this death spiral… so* i*t's a political thing, harder measures need to be applied, maybe not only charges, but also they could close some streets, but it would require some government spending…."*

TPA#3: "*The lobbing by vehicle companies is massive because they've got a lot of money behind them… if you look at just the emission reductions in cars, in the EU basis, the actual limits that were originally proposed to be met by the car manufacturers… which [were] arguably not stretching [them], the car manufacturers lobbied down to what was probably gonna happen anyway because it's part of the research. In developing, you want to [make] your cars more efficient anyway because you give a more enjoyable experience to the drivers…. They know that customers value more efficient engines because [the car's] gonna cost less to run, for example."*

TPA#5: *"My feeling is it [car pollution] will get worse; my hope is it will get better… car ownership is increasing, and to some extent we are improving our road networks. It's very case specific, I suppose, depending on your area… so within Leeds there is a lot of expansion going on… if you look at the typical route to relieve congestion, [it] is to expand roads, but of course the trend with that is, if you could create more space on the road you just allow more cars…."*

For that reason, transport engineers and researchers believe that important changes to travel mode behaviour will depend on how local authorities set a cross-sectional work between areas not only related to transport, but also with public health and environment protection and the set of interventions that will be designed to trigger a travel behavioural change. Moreover, giving a complete description of the consequences of car commuting is crucial to disincentivise car use.

TPA#3: "*I think there are gonna be increasing numbers of… major cities [that] are gonna start introducing emission-related congestion schemes…. It's similar to what we have in London. In the UK, it has been discussed for other cities and I think it's probably going in that way… that driving alongside on a local agenda as well we get an increasingly… when [in] a local authority, such as Leeds, the emission agenda is actually being pushed up because more cross-sectoral work is going on between different departments… it's not about transport, it's also about public health and environment together. And, traditionally, they've been working separately… they are working together to reduce emission in big cities, to meet environmental standards that are not [currently] being met… so I think it will gradually decrease….*"

TPA#2: *"You can make it [car pollution] more explicit... because obviously car manufacturers, they always announce just the benefits of owning a car… but maybe it would be helpful to have a calculator that actually estimated the total cost of owning and running a car, and maybe compare it with the times that you need to use the public transportation…."*

TPA#2: *"People tend to think that journey time by car is fixed, but in reality it's very difficult to predict how [long] this journey is going to take you… while, with public transport, it's easier to predict it [journey time] because there is a timetable*."

One respondent added that part of the responsibility has to be internalised by companies. When the option of not driving is not possible, then companies should plan a permit system or a flexible time arrival system for workers that really need it (**TPA#4**: *"[Drivers who] don't think [public transport] is convenient, or they could have a parking permit, which means that they are guaranteed to have a parking space at the university. Now, if you are doing that, you then… you're encouraging people to drive to your site that maybe it's located in an area that they could walk to work… but, because you are providing that free parking space, you're then encouraging vehicle use…. So, with that as a way to manage it… we then produced a parking permit system where we basically said, 'If you live within this catchment or the 5 km catchment of the site, you can't park at the site'. So that basically is forcing people to prove that they live in an area where they have to drive… making sure that those people are the only people driving to the site"*). Finally, the same respondent believed that targeting car comfortability can disincentivise car use. Increasing car inconvenience (e.g. fewer car parks available) and improving public transport networks might impede the ability of individuals to fulfil their own preferences that create negative externalities to the environment (**TPA#4**: "*I've just done a site in Liverpool city centre, and part of that, we aren't providing any car parking at all… so in terms of liaising with the council, the council said to us, 'This site is 32 apartments… and we are not providing any car parking'… so you won't have anyone living there unless you wanna pay… like £10 per day to park"*; *"[for example in this project] if you've got no public transportation provision you can jump on to get to work and you live 15 miles away, the only option is to drive… and this is when we try to start to get the staff into car share"*).

From those interviews, it is possible to summarise commuting happens as follows: commuting by car depends on multiple factors, where distance to work, fuel cost, parking space availability, car ownership, cost of substitutes and road network appear to be the major contributors to decide in favour of the vehicle. Public transportation price in the UK seems to be one of the main reasons why car commuters do not consider travelling by PT (**TPA#1**: *"British transport by train is absolutely unaffordable, so the reason people use their cars is because they can't do it by train… substitutes are expensive, substitutes are ok… but really unreliable… so people have the incentive to use cars"*). Socio-demographic factors could make a different as well. For instance, gender makes a difference in predicting travel mode choice.

Normally people consider journey cost as a breakdown between fuel and parking space cost, so not many people perceive that using a car is much more expensive as car tax, valid MOT, insurance, etc. are required. This creates a problem because people do not take into account the real cost of using a car (and keeping it) to compare it with public transportation on a daily basis. That is why the habit of driving becomes hard to break. This underestimation generates a bias in the selection of the alternative cost of travelling on a bus or tram, so then drivers do not perceive it as a cheaper option that could help them to save money from commuting.

When people buy a car, multiple costs are involved, not only paying for its acquisition, but also in using it. For this reason, car ownership not only directly affects the decision to drive by 'accessibility' to it, but also triggers a 'perceived investment' analysis, which forces people to justify their investment in buying a car by using it more and more (**TPA#3**: *"When you buy a car you pay a lot of money… taxes, car price, MOT check… so somehow you want to justify your investment… that's why people use it more and more"*). Drivers persuade themselves that cars are a more efficient and effective mode of transport than public transportation, but this is because they do not want to pay for bus tickets since they have already invested in a car.

Higher distances to work will make people prefer to commute by car as this transport mode is perceived as more convenient and faster. As more people use a car, politicians have to face two big forces inside society that pressurise them. On the one hand, more pollution results in more public pressure from citizens to governments to reduce CO_2 emissions. On the other hand, more cars on the streets results in more pressure from drivers to governments to build more roads, in order to decrease both traffic levels and travel times.

Social norms towards using a car have become crucial to establish the attractiveness of a mode of transport. There is a reinforcing loop between social norms and mobility culture. As more people use cars, it is more likely that the rule will be accepted on a bigger scale. That explains why, in some countries, the acceptability of bicycles or motorbikes has been emerging in recent years: a small group started the trend, influencing their close social circles (family and friends), and then this new social rule was absorbed by the national culture, which influenced the new urban development to change the perspective of a car-infrastructure to a bike-friendly-infrastructure type. For this reason, public transportation becomes an attractive option when the social norms affect ‘car acceptability’ as the norm for commuting. While it is true that using a car is not enforced by any law, social norms act as an underlying force that impacts on people’s behaviour as they want to be accepted by their social circles. As car acceptability and the investment of buying a car increase, the perception of the availability, reliability and convenience of public transportation decreases.

On the psychological determinants side, drivers feel more control and freedom when they drive (time to commute feels less variable than other trip purposes). It has been documented that people rely more on cars when they travel because they feel that the travel time is more under their control. Also, cars seem to be more comfortable than other modes of transport. Moreover, the door-to-door distance seems to be short (since normally your car is outside your door). Therefore, people have created a symbolic image of cars, which sees the cars as the most reliable and convenient transport mode for commuting. In the UK for example, trains are perceived as unreliable as they cancel many services without notice and they are often delayed, so that creates a bad perception of public transportation in general.

As the numbers of car commuters grow, more cars are running on the streets, which in turn creates more pollution. This pressurises local institutes to look for actions to reduce carbon emissions to meet environmental standards to diminish climate change. That is the first loop (balance loop: environmental standards) created by the interviewees to explain how cities like London have been working on diminishing car use to reduce the indexes of pollution by banning cars in certain areas inside the city centre.

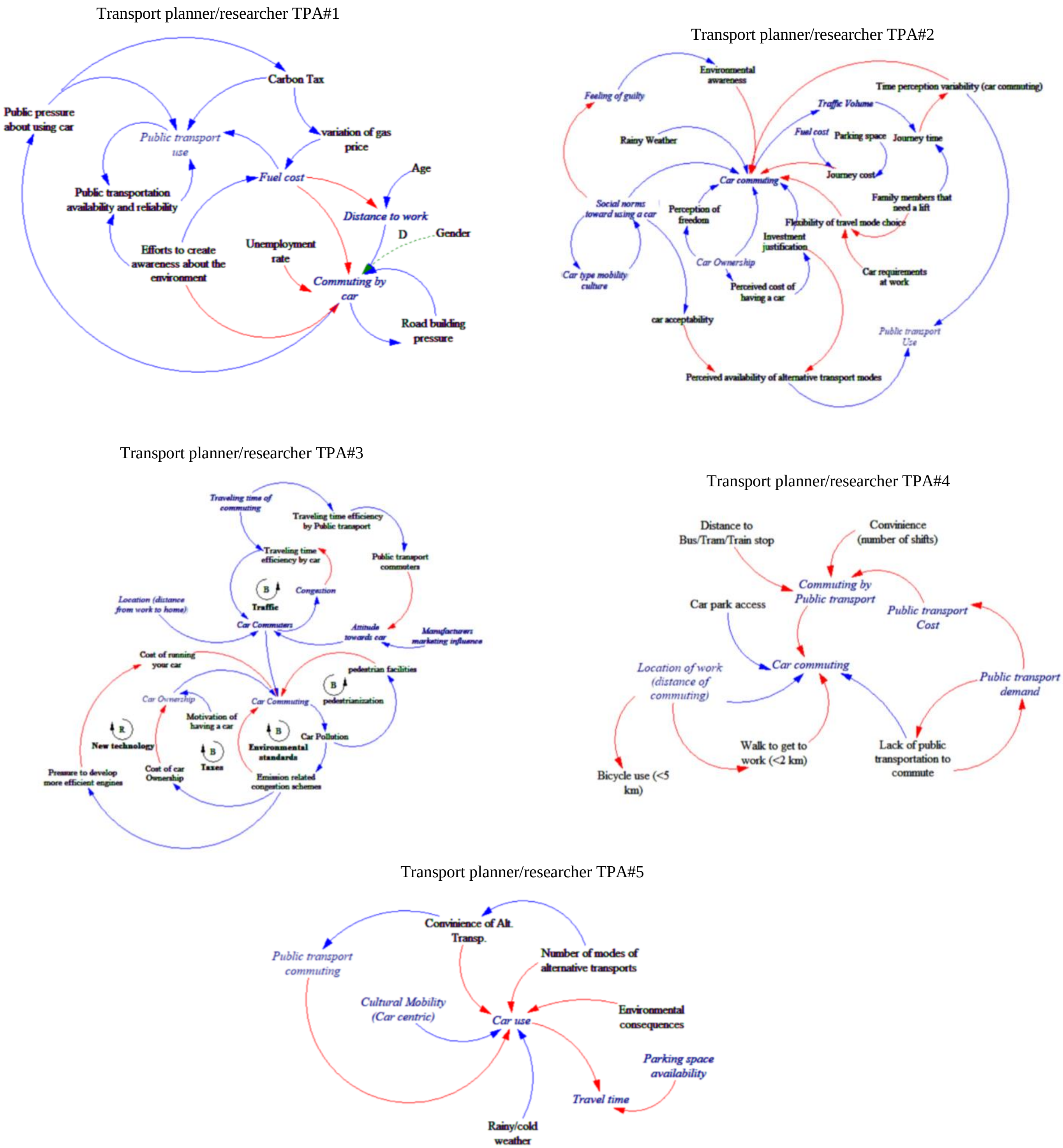
Finally, government efforts to increase awareness of the environment could trigger regulation of fuel availability, which would impact on the fuel cost and the perception of public transportation as a friendlier option for travel. Additionally, local authorities pressurise car manufacturers to adopt cleaner technologies to create car engines. This action emerges from the public pressure to reduce car pollution, in order to decrease the health risks from poor-quality air. In parallel to look for cleaner technologies, governments work on the creation of carbon taxes, which would have a direct impact on fuel cost.

Table 10. All variables mentioned by transport engineers and researchers.

Carbon Tax	**Age**	Public transport use (3 times)	Social norms towards using a car
Fuel Cost (2 times)	**Gender**	**Effort to increase awareness**	Parking space cost (2 times)
Variability of gas price	Unemployment rate	**Feeling guilty**	**Travelling time efficiency by public transportation**
Distance to work (3 times)	**Car acceptability**	**Rainy weather**	**Travelling time efficiency by car**
Car type mobility culture (2 times)	**Perceived availability of alternative transport modes (4 times)**	Perceived cost of having a car	Public transport commuters (2 times)
Environmental awareness	**Mobility requirements at work**	Investment justification	Car commuters
Perception of freedom	Flexibility of travel mode choice	Time perception variability	Attitude towards cars
Car ownership	**Family members that need a lift**	Journey time (2 times)	Manufacturers' marketing influence
Car use (3 times)	Journey cost (public transport vs car) (3 times)	Traffic volume (2 times)	**Pedestrian facilities**
Car pollution	**Emission-related congestion schemes**	**Cost of car ownership (2 times)**	**Distance to bus/tram/train stop**
Pressure to develop better car engines	**Convenience**	Walking to work	Cycling to work

Source: Own elaboration. The variables in bold are the ones that were not included in the original causal loop diagram.

Figure 24. Causal Loop Diagram transport engineers and researchers.



Source: Own elaboration.

5.5.4.3 Lessons learned from transport engineers and researchers

From these interviews, it was possible to validate most of the proposed original causal loop diagram, as well as add new variables related to regulations and local authorities' actions. In general, they see the problem of car pollution as a phenomenon that is difficult to predict as governments' and people's attitudes/behaviours towards cars and the environment play a key role in regulating car use and car ownership. Many agreed that, in the future, governments will have to act to stop car massification and car use because people do not have enough incentives to control themselves against car use. Without direct policy intervention, it is more likely that people's demand for cars will continue to grow. Therefore, taxes and new regulations will be needed to decarbonise our society as the climate change emergency is pressuring us to react faster to decarbonise our cities.

In general, imperfect information was seen as the major contributor to poor decisions. In theory, a society taking decisions under the laws of a free market, should discriminate morally and ethically which products and services represent a threat to humanity, but the lack of self-control dictates the necessity of government actions to diminish market weaknesses. For that reason, some interviewees proposed actions related to design interventions that increase the information about: (1) the alternative options to commute and (2) the lack of consistency when people travel by car. Other opinions were in the sense of economic intervention, like decreasing the cost of substitutes and increasing the cost of running a car (e.g. integration of significant petrol taxes and congestion fee areas), which might help to push back against drivers who want to stick to their cars. Table 11 shows the variables mentioned by these respondents that were included to improve CLD 0.

Table 11. Variables integrated into the CLD A (post-interviews).

Pressure for road construction to satisfy car demand	Economic intervention (carbon tax)	Time variability when commuting by car	PT available to cover the same distance
Road capacity	Feeling of justification for buying a car	Price of petrol per litre	Safety sidewalks
Time of commuting on PT	Parking space cost	PT capacity	Traffic volume (bicycle lanes)
Number of changes in the journey	Convenience	PT speed	Bicycle lane capacity
Pressure to construct more lanes (bicycles)	Commuting time discrepancy on PT	Distance between home-stop-work	Car reliability (time consistency)
Parking space availability for bikers	Average walking speed	Speed of commuting by bike	Monthly budget available to travel
Desired commuting time			

Source: Own elaboration.

5.5.5 Group 4: Environmental psychologists.

5.5.5.1 Recruitment and profile of the environmental psychologists

Recruitment of environmental psychologists took place during the same period as the other recruitments. Following the same steps as the other groups of experts, 20 emails were sent to invite people to participate in this project. Seven decided to participate, who were all academics from universities in the UK apart from one participant that worked for ARUP as a human factor consultant and behavioural specialist.

Table 12. Participants' profiles.

Participant number	University/Company	Department	Research focus/Job description
EP#1	University of Brighton	School of Applied Social Science	His academic career started with working on theorisation of identity. Now, ecological crisis and climate change are part of his research interests.
EP#2	ARUP	Advisory Services	He works as a behavioural psychologist to understand behavioural outcomes in different transport projects that ARUP is leading.
EP#3	University of Surrey	Environmental Psychology Research Group	Her interests are related to topics focused on restorative environments, place experience, and links between environment and wellbeing.
EP#4	University of Cardiff	School of Psychology	She is a professor of environmental psychology and director of the UK Centre for Climate Change and Social Transformations. Her expertise is related to public perceptions, behavioural change, communication and engagement in relation to climate change.
EP#5	University College London	Faculty of the Built Environment	Working on behavioural change, her research is focused on identities, self-determined motivation and other factors that push people to behave in a more environmentally responsible way.
EP#6	The James Hutton Institute	Social, Economic and Geographical Science Department	His expertise lies in people’s attitude towards environmental behaviours. He has participated in different projects related to the protection of the environment: wastewater management, energy consumption, public participation in urban design, among others.
EP#7	University of Sunderland	Faculty of Health Science and Wellbeing	Her worked is based on environmental psychology, which looks to understand how built and natural environments influence behaviour, health and wellbeing.

Source: Own elaboration.

5.5.5.2 List of variables and causal loop diagrams of the transport experts

From those interviews, it is possible to break down car commuting into four key topics that have been found to promote PEB: habits, emotions, social norms and cognitive dissonance. The interviewees agreed that part of the problem is that the right policies can reduce car use and car demand, but only if cultural conventions, habits and transport infrastructure are transformed, in which people can accept that there is another way of living. That is why some of them see electric cars as a short-term solution for a long-term problem.

EP#1: "*My instinct says it's [car pollution] gonna go up. The solutions offered so far are not really solutions to the rise of air pollution… there, governments might push more electric cars, but that doesn't solve the main problem of air pollution, for me… I think electric cars, for example… [they] might reduce air pollution but the attendant issues around mass car use will require an alternative solution…. So, we need to adopt different conventions… which do not involve individual car commuting, that might push the use of public transport… but that will need a radical change in terms of infrastructure… so that might affect the way we work… but that the kind of change, it's required… a cultural change… a social change, material change, and political change to make… to move away from the habit of commuting by car… certainly individually, not the replacement of the car with a more environmental version....*"

EP#2: "*Car demand will remain stable because…. maybe car ownership will decrease, but we will see more and more people adopting shared mobility services… that will compensate the effect of owning [fewer] cars".*

EP#5: *"I think we will see some improvements in the future because more policies will target CO_2 emission… but I think electronic vehicles are not the best for the air quality…. In London, I see some advances since car sharing is becoming more popular… although there is still a lot of work to do to encourage people to drive less… it needs to be in a bigger way."*

For the environmental psychologists, habit response as an important factor to explain car commuting. To acquire a habit, people need to perform the activity frequently in their lifetime, which creates a behaviour based on automatic responses.

EP#1: "*I think there's something around the attractiveness of driving for many people… it's something that we are competent at, we learn how to drive and that becomes… that familiarity… becomes an important variable to explain why people do it…."*

EP#3: *"…So, all of the people I know, who like to drive… started really young… having a car is part of their nature… they grew up outside of London or, you know, in a village or a small town… whereas me and all of my friends, who grew up in the city… we've never really felt the desire to own a car… so currently there is a social perception that owning a car is less important than before."*

In the case of driving, environmental psychologists pointed out that it is not an intentional learning process by itself; instead, people tend to drive because (as the car is one of the fastest ways to commute) more time would be available to deal with different choices existing for them that will require psychological effort, like catching up with colleagues/previous work, or reading the news before starting their duties. For this reason, many experts propose that the interventions to decrease commuting by car need to trigger the reconsideration of an intention to act (e.g. considering commuting by bus) between the other options available for commuting. Habit formation is not only the repeated performance of a behaviour, but also it relies on a stable context. Therefore, in answering the question 'How could the context be changed so car driving is not the default option for commuting?', the environmental psychologists thought that it would be a good starting point to reduce car commuting, thus breaking the car habit (**EP#7**: *"Changing cities' infrastructures, for example, is an essential part of the solution to CO_2 emissions produced by cars"*). Many habits are created unintentionally, so if people are not aware of the factors that trigger the selection of a car (when commuting), then it might be difficult for them to reconsider alternative transport modes.

EP#1: *"As air pollution becomes a more and more visible problem… interrupting our habits, our everyday life…. [It is] more likely people will work collectively… and I think this is important and not just to commute by a car individually, but collectively people will demand alternatives… and again, historically, we have seen those kinds of facts and those kinds of pushes collectively… whether as demands of civil rights or big movements to abolish slavery or restricting smoking areas…."*

These experts also mentioned the importance of social norms and social learning, which has been shown to be a consistent factor influencing people's travel decisions (**EP#2**: *"In London, for example, it's quite normal to use public transportation… it's a social norm"*). Other's people behaviours can be the reference for individuals to understand how to act in a given context. The interpretation of the behaviour is a piece of information that then shapes the form of general norms as people want to act in away where they can match the expected behaviour. If the 'norm' is very strong, it is then integrated into the system of the individual's personal norms.

EP#3: *"And having access to a car… as when it's required, might become more normalised… so you see previous kinds of car-sharing initiatives like Zipcar…."*

Driving is performed within a social context, not only because people see other drivers when they commute, but also because probably many of their relatives or colleagues are also drivers. Historically, cars haven been thought of as an importance reference of success, as well as modern cities have been developed as car centric, so, given that context, the incentives to drive are highly unavoidable as people are influenced by their individual perception of what others might think if they do not drive. This becomes more obvious in a work context, where the type of car can be used to support their career success.

EP#1: "*...and those are hard to separate from an individual's motivation… there's something about the attractiveness of cars that is deeply rooted in our culture as… it's a way of accessing other things that are important to us in our cultural narratives… individuality, autonomy, freedom, respect… those are cultural things that we value.*"

Regarding emotions, these participants think that they are a key factor to explain why environmental interventions might fail or succeed. For example, people might feel frustrated or angry with public transportation because it is unreliable and expensive, so that could make them underestimate the importance of contributing individually to pollute less by using alternative transport modes. Additionally, emotions are involved in the mechanism of behavioural maintenance or habit disruption. For example, experiencing joy or freedom every time a person commutes by car can systematically impact on their travel choice mode, which contributes to patterns of behavioural maintenance.

EP#3: *"…There are increasing problems with… never mind having the car, but when parking the car…. This university, for example… they give us limited parking space access… people now have to… there's one day a week where the university doesn't allow us to drive in… so that's encouraging people to use alternative modes of transport… finding a parking space now sounds really stressful."*

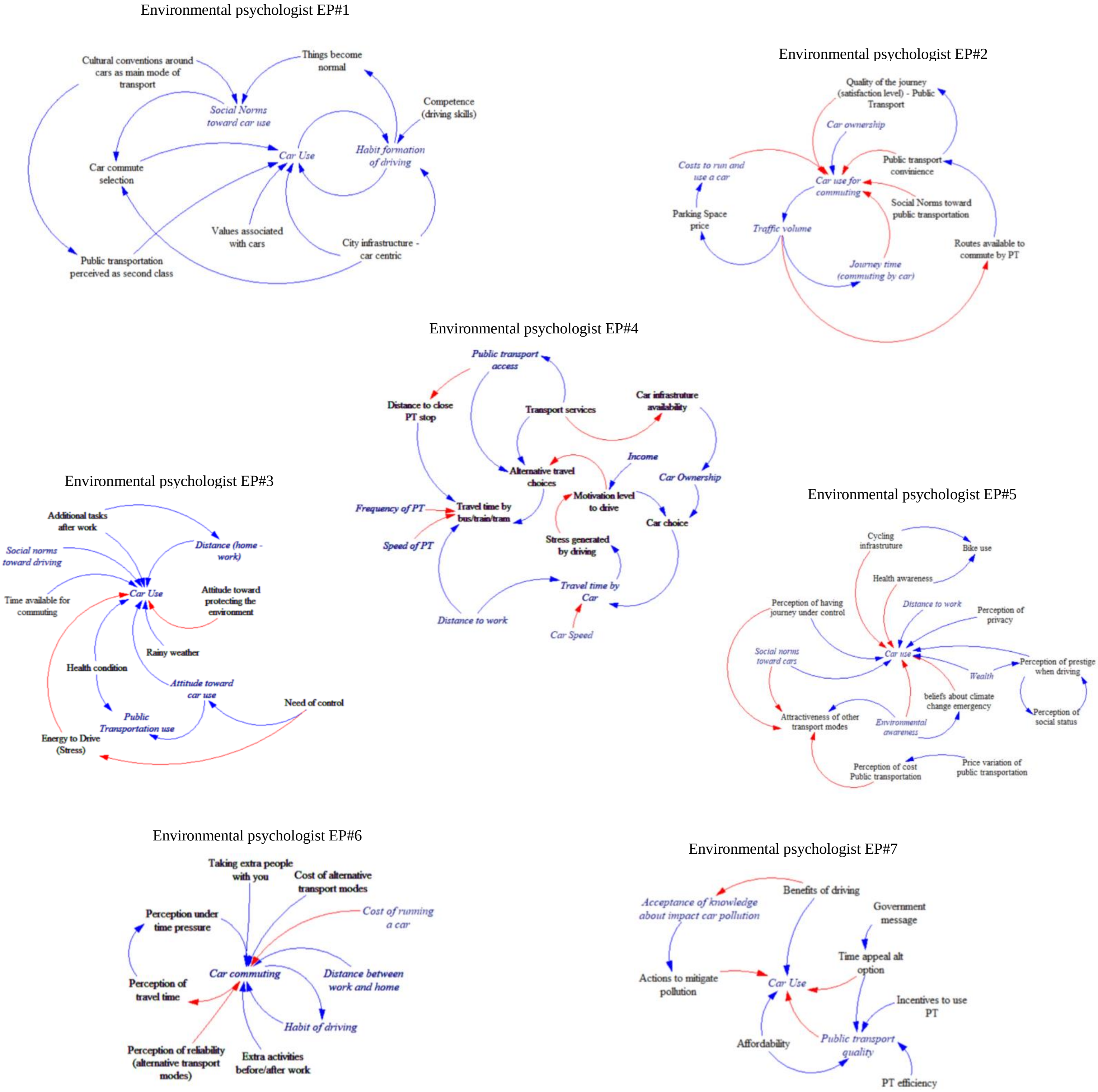
In the domain of cognitive dissonance, they agreed that it is difficult for individuals to internalise environmental-related actions due to the fact that they normally hold contradictory beliefs or values when they take decisions (e.g. transport mode selection) (**EP#3**: *"I feel that people are aware that they should pollute less and have more fuel-efficient cars and switch to other ways of transport… but it's not gonna be easy for people that live out of the cities [to shift to alternative transport modes]…"*). In many cases, people do believe that climate change is a problem and cars are a main source of pollution, but it is still clear that car demand, road construction and car use keep going up. The effects of this contradiction make people decide to either keep the inconsistency or change their attitude towards environmental behaviours to avoid undesirable negative emotional effects. Therefore, a proposal during these interviews was that maybe eliciting and making more evident the inconsistency between what people think and what people do could create an unpleasant mental state that can be used as a pivot to motivate them to reduce their car use. If people do not really accept the inconsistency, it is expectable that they will be less willing to engage in pro-environmental actions since they do not feel responsible for the contradictory decisions.

Table 13. Variables mentioned by environmental psychologists.

Car use (7 times)	Journey time (commuting by car)	**Additional tasks to do after work**	**Stress generated by driving**	**Taking extra people with you**
Habit formation of driving (2 times)	Traffic volume	**Energy to drive (stress)**	**Cycling infrastructure**	**Perception under time pressure**
Things become normal	**Routes available to commute by PT**	**Health condition**	**Bike use**	Perception of time travel
Social norms towards car use (3 times)	Costs to run and use a car	Public transportation use	**Health awareness**	Perception of reliability (PT)
Cultural conventions around car as main mode of transport	**Quality of the journey (satisfaction level) – public transport**	**Need for control (2 times)**	**Perception of privacy**	**Extra activities after/before work**
Public transportation perceived as second class	Social norm towards public transport use	Public transport access	**Perception of prestige when driving**	
Car commute selection	Distance between home and work (3 times)	Distance to bus/tram stop	Social status	
City infrastructure – Car centric (2 times)	Attitude towards protecting the environment	Travel time (public transport and car)	Beliefs about climate change	
Competence (driving skills)	Rainy weather	Car speed and public transport speed	Environmental awareness	
Values associated with cars	**Time available to commute**	Public transport frequency	Perception of cost PT	
Public transport convenience	Attitude towards car use	Income (2 times)	Attractiveness of other transport modes	

Source: Own elaboration. The variables in bold are the ones that were not included in the original causal loop diagram.

Figure 25. Causal Loop Diagram environmental psychologists.



Source: Own elaboration.

5.5.5.3 Lessons learned from environmental psychologists

Respondents observed that human beings have important cognitive constraints, which impede them in processing the future consequences that car pollution brings. In this case, the interviews confirmed that psychological factors, such as attitudes and habits, take a key role in explaining people's travel behaviour. Additionally, important factors were discussed to understand pro-environmental behaviour, in which values and beliefs were identified as key factors to consider in the causal loop diagram. The original CLD vaguely considered the explanation of a pro-environmental behaviour, which was corrected in the final CLD (post-interviews) by extending the cause-effect explanation with new variables regarding values, beliefs and a more complete explanation for social norms.

Additionally, after completing the interviews with the environmental psychologists, more support was found to improve the original causal loop diagram regarding active transportation. They mentioned important aspects to consider when explaining why people tend to avoid cycling to work when the option is doable. Aspects related to emotions, health perception and mood took an important part of the outcomes, demonstrating that it is important to explain car use and the consideration of walking or cycling.

Some interviewees were concerned about e-cars. Overall, they believe that there is a lot of attention on how autonomous and alternative-fuel cars would change future mobility as they seem to pollute less and to be more comfortable. However, some of them argued that there is not enough evidence regarding how quickly this new technology will be adopted and many of the environmental psychologists claimed this it is not sufficient; therefore, they proposed that behavioural approaches are more important (e.g. significant changes in people's lifestyle) than technological ones.

Respondents considered that lifestyle changes are difficult to shift from intervention if there is not a deep understanding of habit formation. They believed that car commuting is a kind of behaviour that will not necessarily change when goals and intentions change. Habits are normally crafted as a response to a stable context (commuting) which increases its strength over time. This incremental nature in habits is extended to behaviours that do not require mental effort to learn a new mental process (e.g. shifting from driving to taking the bus, which would require learning the bus route or reorganising the travel plan). To address breaking those habits, they recommended looking into the factors that promote this habit formation, like action frequency (days of commuting), self-identity, stress, etc. For example, stress has been elicited as a promoter of habitual behaviour: people do not want to be stressed by thinking that the train was cancelled or the tram or bus is crowded or delayed; therefore, driving becomes a more attractive alternative because there are less stimulus and information to mentally process and decreases the chances of feeling frustrated when the decision is based on a goal-directed response (e.g. taking the bus and failing to arrive on time to a meeting because the bus was delayed, something which is out of the person's control.

An additional point discussed during the interviews was related to the formation of cultural conventions. In the case of cars, the strong association to car-centric cities has been pushing back alternative transport modes. Transport infrastructure, values and beliefs, social norms, social status, car manufacturers' marketing actions and individuals' identities have been shown as factors that reinforce those cultural conventions that contribute to a positive perception of car use and ownership, which in turns makes it difficult to overcome the resistance to change. For example, many respondents pointed out that public transportation in the UK has been seen for a long time as a second-class mode of transport, so that creates a detractor for people who are aware about their social status. Table 14 shows the variables mentioned by these respondents that were included to improve CLD 0.

Table 14. Variables integrated into the CLD A (post-interviews/environmental psychologists).

Values towards protecting the environment	Perception of car usefulness for commuting
Social norms towards active transportation	Social acceptance of car as the main method of transport
Level of attitude towards active transportation	Habit (car use)
Walk attractiveness	Psychological distance
Perceived ability to reduce car pollution	

Source: Own elaboration.

5.5.6 Group 5: Policy makers

5.5.6.1 Recruitment and profile of the policy makers

Recruitment of policy makers took place after completing the interviews with commuters, environmental psychologists, transport engineers and environmental engineers. It was decided to include this group as, in many interviews, the lack of intervention and the lack of policies to stop car use were frequently mentioned. Therefore, it was thought that capturing policy makers' views could be helpful to understand the role of institutions in encouraging alternative transport modes, as well as to understand how policy makers see that travel mode choice happens. The theoretical saturation was found after three interviews. The group was composed of three policy makers, two that work for Living Streets and one for Transport for Greater Manchester.

Table 15. Participants' profile.

Participant number	Company	Position	Job description
PM#1	Living Streets	Project Coordinator	He is involved in projects where they look to encourage primary school students to use active transportation, specifically, walking.
PM#2	Living Streets	Project Coordinator and Manager	Working on projects in Sheffield and Manchester that are related to infrastructure development and pedestrian facilities.
PM#3	Transport for Greater Manchester	External Consultant	He is a member of the group of consultants that work for TFGM (working for them fully in the last three years). His personal interest is how societies can make places better from a mobility perspective. Working now on mobility experience.

Source: Own elaboration.

5.5.6.2 List of variables and Causal loop diagrams of the policy makers

For the policy makers, electrification and more hybrid systems as a replacement for private cars are not the solution in the long term (**PM#2**: "*At some point, the government will have to prioritise other modes of transport apart from the car, and that includes electric cars, because electric cars don't solve the problem of congestion… so we need to find more efficient ways of moving people"*; **PM#3**: *"So, even if we change everything to electric vehicles and nothing else changes, you still have all the congestion, noise pollution, you still get 46% of the air pollution that comes from the brakes, tyre use, etc. You don't solve anything of that issue…"*).

They believe that the UK government and councils are making important changes in the infrastructure (**PM#2**: *"There's certainly more money going into cycling and walking infrastructure and making it easier and safer for people to walk and use a bicycle… my only concern is the growing population in Manchester, cause you'll end up with more people that will need transport*"), but there is still a concern that the system is still supporting car ownership and car use (**PM#3**: *"If you move to the centre of London, you will probably not need a car because* *you have the tube to go everywhere… but in Manchester, Glasgow, Leeds, you'll probably live somewhere you can afford that is not necessary close to many public transportation options… so you don't think about how you are gonna get to work because you assume that you are going to drive"*).

Despite the efforts spent on infrastructure to improve bicycle lanes and public transportation networks, and although most people recognise the adverse health effects of pollution, people continue to engage in driving. Policy makers mentioned almost everything that was pointed out by the previous interviewees. However, something new that is important to bring to the analysis is the fact that people have limited willpower (**PM#3**: "…*Without a strong action, I think it [car use] will carry on the same… people make these journeys because it is the easiest way… we are all like that… we want to use the easiest option… once you've invested in a car and it's parked at the entrance of your house, then it becomes your default option… it's easiest to drive than work out what buses or connections you need to move around"*).

To overcome the lack of willpower, policy makers agreed that a behavioural change in the travel domain will depends on three important concepts: (1) possibilities (the choices offered to people to move around and to plan their journeys), (2) communication, how choices are communicated and (3) habits (understanding people's motivations and habit formation).

PM#2: *"…In some parts of Greater Manchester, there's up to 30% of the population don't own a car, but that's not because they don't want to own a car…that's because [of] low income… so then, if you tackle poverty or low income, you'll have then more people that will buy a car… so we need to tackle the desire of wanting a car… so the big question is, [do] people who travel on public transportation do it because they have to or because they choose to?"*

These three layers found in the policy makers' interviews give a path to work into modal shift resistance. Firstly, before expecting a massive change from driving to public transportation, the alternative choices need to be improved. In this point, the proposals were less paternalistic, looking to maintain freedom of choice while alternative options look better (**PM#1**: "*The key thing [for electric cars] will be that cities provide the infrastructure for that, like fast charges for electric cars";* **PM#3***: "We are creating an integrated platform where you can do all your booking payments and get all the info that you need in one app rather than going to multiple sites…. If you have one app to get all the information and plan your journey regardless [of whether] you are getting a bus to a train station, then taking the train to a car club… it'll make it more attractive to plan your journey just with one click*…"). Secondly, to successfully implement interventions, policies need to be communicated in the right way, most importantly understanding how people will process the message and will understand the benefits (**PM#3**: *"I was involved in Mobike coming to Manchester, and it didn't work for many reasons, but we learnt a lot from it and now we're applying those lessons to a new bike programme that we are bringing to Manchester next year"*). Finally, it is essential for transport policies to work on breaking the habit formation of driving. Currently, the interviewees feel that there are more opportunities to reinforce alternative transport modes as generations are changing (**PM#1**: "*I think the environmental movement is growing quite significantly, so there's gonna be new social norms… so more peer pressure to move towards… more sustainable modes of transport"*). Commuting has become an automatic behaviour, without requiring willpower or conscious effort, but there is a significant portion of people that can be attracted by alternative transport modes (**PM#1**: *"We need a shift in investments to provide more sustainable journeys. There's always a percentage of people that is gonna change, as well as a percentage of people who [are] never gonna change, but you have in the middle people* *that you could push in the right direction"*). Younger generations are changing their underlying goals and desires, so, with the right policies, car ownership and car use can be tackled without forcing people through unpopular legal decisions (**PM#3**: "*So, part of the solution will be how to address that opportunity that you see in young people… now people under 30 are looking for more experiences than assets, people do not tend to own things anymore…. Maybe what you'll see in the future is people joining more to car clubs, which will give more options to people to decide what they need for the journey…"*).

Table 16. Variables mentioned by policy makers.

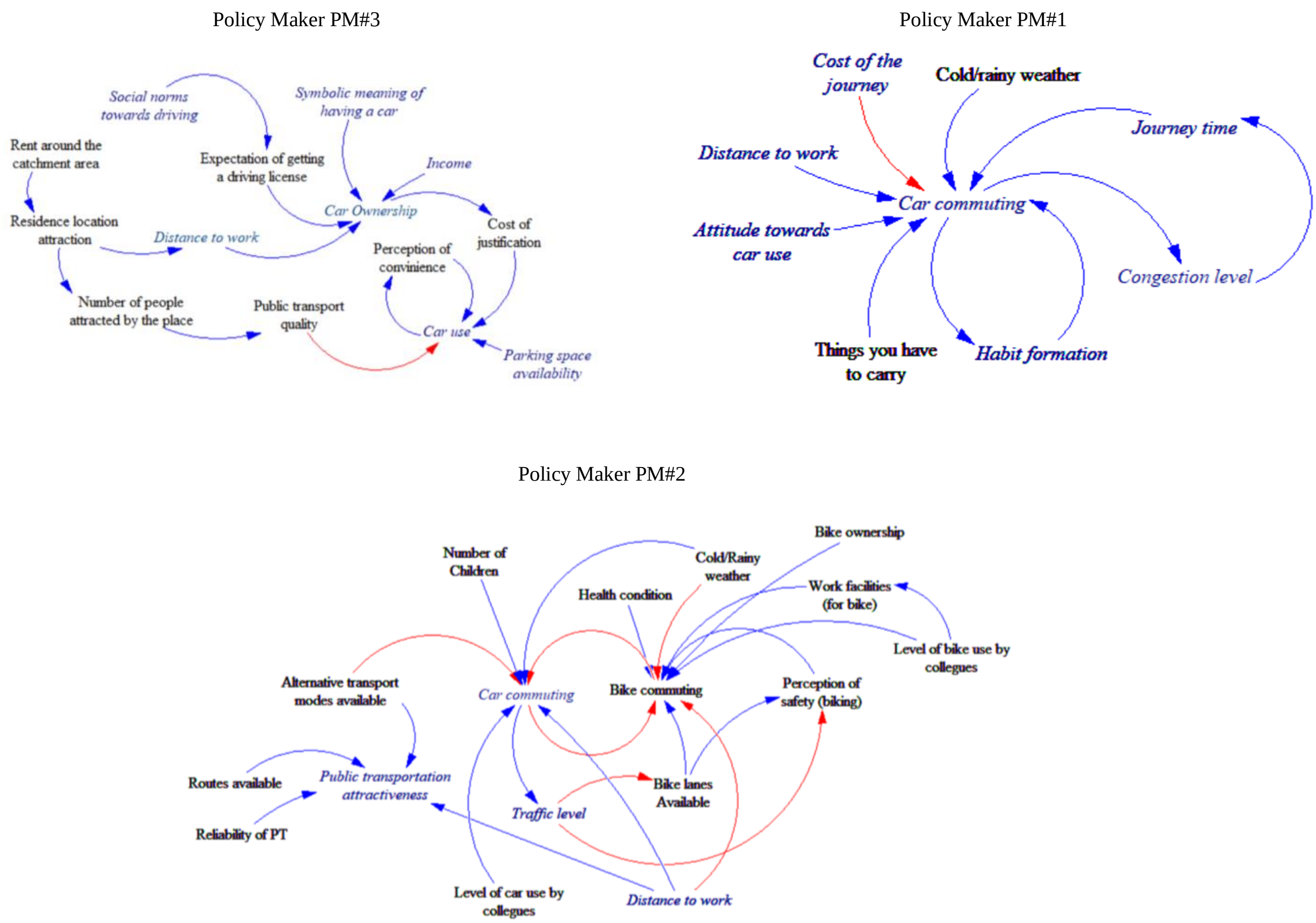
Car use (3 times)	**Rent**	Safety (how you feel, cars feel safer than other modes)	Routes available
Social norms towards car use	Transportation quality	Children	Car ownership/bike ownership
Expectation of getting a driving licence	Parking space availability	Purpose of the journey	
Symbolic meaning of car ownership	**Job location**	Route of your commuting journey	
Income	Attitude towards cars	Alternative modes available	
Car ownership	Time of the journey	**Reliability of other services**	
Perception of car convenience	Level of congestion	Facilities at work (e.g. safe bike park)	
Cost justification	Things you have to carry to work or after work	What you can wear at work	
Previous experience (habits)	Cost of the journey	Environmental conventions	
Distance to work	Weather	Health	
Residence location	Habit of driving	Distance to work	

Source: Own elaboration. The variables in bold are the ones that were not included in the original causal loop diagram.

Policy makers described the process similar to previous interviewees. Car commuting is a process that occurs automatically, where habit, perceived control, income, car ownership, and alternative transport mode availability and reliability play a key role in people deciding whether they prefer to drive or not.

Cars are seen as the most convenient transport mode, so that facilitates the habit formation of driving. This can be justified by the fact that cities have been developed to simplify the use of cars (**PM#3**: *"…in the 1960s, we had a lot of people using public transport, lots of local trains, trams... but all those things were life-time expired…. Instead of renewing them… the decision was made that actually the private car is the future and those things are not worth investing in anymore, they are old fashioned…").* Therefore, now is the opportunity to think again about the factors that are involved in decarbonising the UK transport network. *"It is time to think for the first time in 50 years"* (**PM#3**) how the government and institutions will reconfigure the network and create an efficient system for people to move around (**PM#2**: *"Air quality is the big issue now… it's the big priority. There are some interventions that are helping to decrease air pollution, like charging the most polluting vehicles coming into the city, buses will get cleaner, hybrid public transport…. I'm also optimistic that the public transport will improve in the next few years…"*).

Figure 26. Causal Loop Diagrams - Policy Makers.



Source: Own elaboration.

5.5.6.3 Lessons learned from policy makers

Overall, these interviews confirmed that the whole structure of CLD 0 and the concepts previously mentioned in the other interviews were all relevant to explain travel mode choice. Only six concepts were not found in the original causal loop diagram. However, they were all related to concepts that emerged from the previous interviews. 'Rent' was the only unique concept that was not found in the other interviews, but its effect is similar to the ‘income’ and ‘monthly budget’ effects which were considered by transport engineers and commuters.

In terms of policies, all of them were aware of the importance of understanding people’s travel decisions based on psychological factors. Accepting new policies and persuading people to shift their current transport modes depend on attitudes, habits, norms and beliefs, which are aspects that were highlighted by environmental psychologists as well.

Additionally, there were some concerns about how financial restrictions on car ownership and car use are affecting people’s travel decisions. To own a car and run a car, important monetary investments need to be made (car insurance, MOT tests, car maintenance, petrol, etc.). However, once people can overcome the problems of affordability, they might increase the necessity of justifying their investment, which in turn can reinforce the habit formation of driving and create a counterintuitive effect to limit car use. For this reason, the recommendations from policy makers are aligned with improving the alternative systems available to make people think that the other options are better than driving.

5.6 Next steps: from CLD 0 to CLD A

The outcomes obtained from the interviews allowed the researcher to develop a more comprehensive understanding of travel mode choice, as well as to confirm cause-effect relationships proposed in the original CLD.

Interviews with commuters and transport engineers revealed a number of factors that contributed to improve the original causal loop diagram. These included the explanation of active transportation choice, more functional factors (e.g. transport model availability), economic aspects (fuel cost, travel budget, car ownership cost), and traffic management (road capacity expansion) and its influence (high volumes of traffic decrease the travel speed). The value of the interviews with both groups allowed the researcher to expand the model by including more economic aspects such as parking space cost, cost of having a car and PT ticket prices. Moreover, it was possible to develop more understanding of variables related to speed, convenience, network crowdedness and comfortability, and traffic management. Transport engineers also allowed the researcher to understand factors related to transport network development, and the impact of time reliability in the PT network. Finally, both groups helped to validate the importance of psychological factors, as many of them mentioned variables based on cognitive skills such as perceived comfortability, perceived cost of the journey, car attitude, and feeling of justification for car ownership.

Interviews with environmental psychologists revealed the importance of understanding people's travel behaviour by using psychological factors. Two key findings were discovered: people do not necessarily have a good understanding of the future consequences provoked because of the habit of driving, and people's views about restricting cars might not let policy makers act severely against using cars. Additionally, the environmental psychologists offered a complete background regarding pro-environmental behaviours, making it possible to understand the role of values and beliefs in travel mode choice. The value of these interviews included: the effect of values towards personal norms, the effect of values towards social norms regarding active transportation, the importance of habits, and the effect of psychological distance on car use.

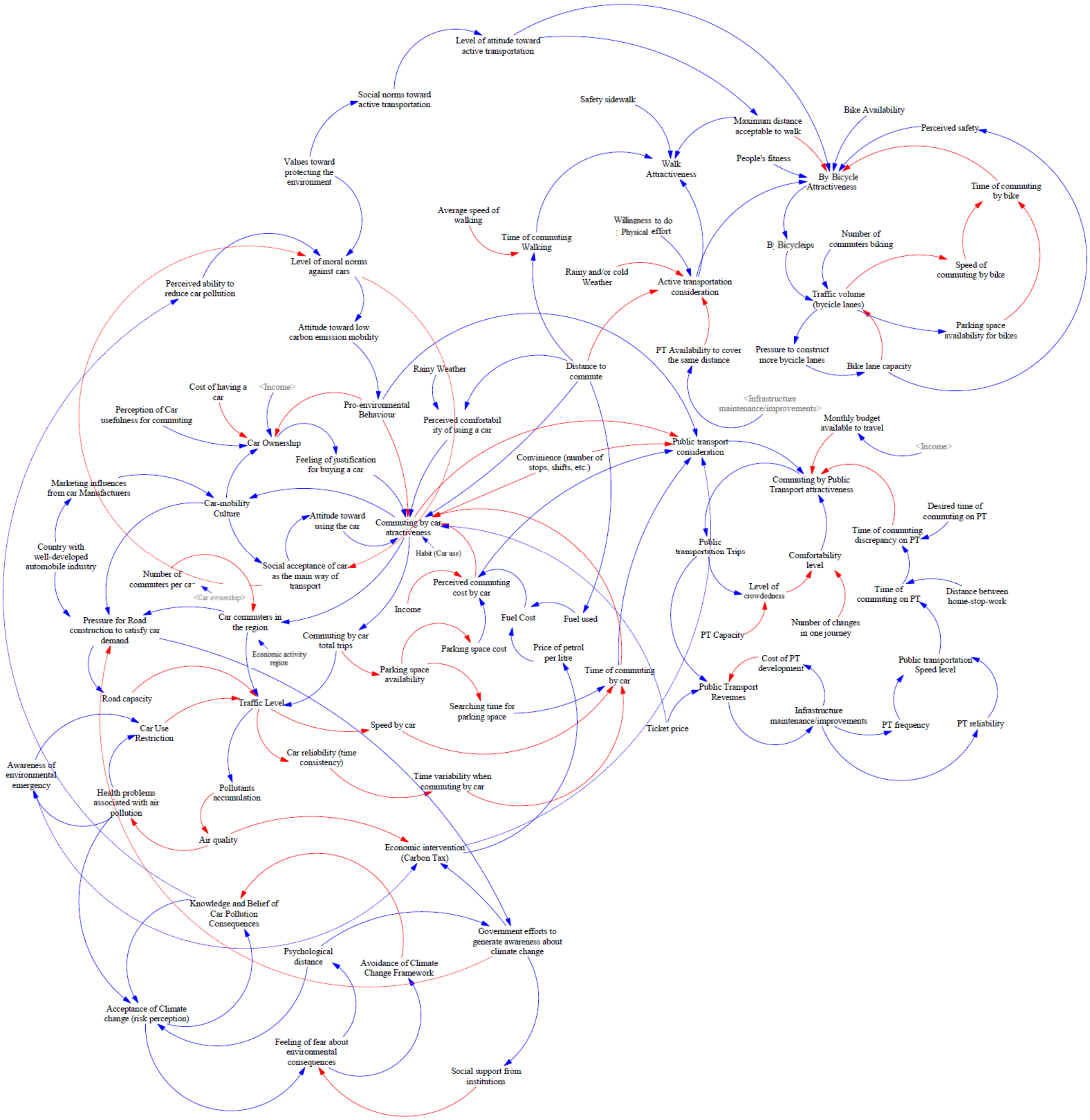
The environmental engineers made several distinctions between people's travel mode choice and their current involvement. This discrepancy led them to express their concern about how societies are handling car pollution. Many of them agree that the seriousness of the problems related to climate change pressures humanity to act immediately. They believed that work on public transportation systems and green interventions targeting psychological factors are the key for long-term solutions. The value of these interviews included: validating the overall structure of car and public transportation use, confirming the loop between traffic volume and air quality, integrating factors related to climate change awareness, and active transport attractiveness.

Policy makers allowed the researcher to validate the overall outcomes obtained from the previous interviews and helped to expand the understanding of how green interventions (to stop cars) are currently being deployed. The results were consistent with what the other experts said, providing reassurance that the new causal loop diagram has a complete view to explain travel mode choice.

From what was discussed with the participants of this study and found in the literature review, a set of changes were applied in order to improve CLD 0. Figure 27 shows a diagram of CLD A which helps to understand the complex dynamics of travel mode choice. As a result, CLD A attempts to explain in which conditions people would consider alternative transport modes. This big picture permits everyone to understand the systematic process of why the car increases its attractiveness, which in turn reinforces the resistance to change to alternative transport modes.

Due to the extension of conceptual model A, CLD A is not fully formalised. There are so many variables and feedback loops involved that it would be impossible to integrate all the parts of CLD A in a simulation model during the developing of this project. Despite the fact that promoting active transportation is the optimum way to fight climate change in transport, incentivising drivers to shift to public transportation still fulfils an important part of the goal. Therefore, the approach of this thesis is first to understand people's desire to drive and why habits take such an important role in commuting before simulating active transportation. Understanding car commuting deeply allows this thesis to offer important insights that might help to decarbonise the transportation network. Governments and policy makers are aware of the proper behaviours needed to develop a sustainable transport system, but, historically, it has been seen that many individuals are reluctant to accept alternative transport modes that do not meet their expectations of comfort, freedom, convenience, etc. In the next chapter, CLD B will be introduced, offering an explanation for its mechanism and the reasons why it was created.

Figure 27. Causal loop diagram A created post-interviews.



Source: Own elaboration.

5.7 Summary

In this chapter, travel mode choice was discussed with experts, focusing on validating and improving causal loop diagram A. This qualitative phase presented a more comprehensive explanation of active, private and public transportation than the one offered in Chapter 4. According to the interviews, travel model choice is influenced by economic aspects and functional factors, as well as cognitive factors and availability regarding the options that a person has to commute. During the interviews, the strong influence that habits have was discussed to explain why people are reluctant to give up driving, establishing a relevant point concerning why it is important to improve the explanation of the dynamics among psychological determinants.

Causal loop diagram A works as a guide to develop a comprehensive simulation model to explain travel mode choice. Despite the fact that the three transport modes (private car, public transport and active transport) are not included in the formalisation of the simulation model, they work as a strong background to understand the dynamics in travel mode behaviour. Additionally, CLD A offers an explanation of how experts in transportation and environmental issues explain commuting; therefore, it helps to support future model developments. Finally, CLD A offers an opportunity to connect different areas in the same topic; in other words, this conceptual model can work as a tool for transport engineers and environmental psychologists to understand why and how cognitive and functional variables influence travel mode behaviour.

The focus of the mathematical model relies on car commuting, but there are many aspects that need to be understood before developing the simulation model. An extensive explanation about this point will be offered later when it is explained why a bi-modal model was developed. The next chapter will focus on the construction of the simulation model, giving the necessary antecedents and reasons why formalising just car commuting is an important step to solve the problem. This does not mean that the other areas included in CLD A are not worth simulating, but, because of the extension of the model, several reference modes are going to be offered to demonstrate how car commuting is the most important part to solve the problem.

6 Simulation model construction: design of a generic structure to simulate alternative transport mode acceptance

Chapter 5 presented the conceptual model that described car use and the basic mechanisms that were understood to discourage it. The aim of this chapter is to clarify how this informal conceptual model becomes a formal simulation model. This chapter gives a complete mathematical description of the causal loop diagram and the simulation model. To facilitate the reading of the simulation model construction, the causal loop diagram will be described first, followed by the basic principles underlying mathematical expression. The explanation of the model elements will be divided into smaller sections to make it easier to describe each equation and the links between them. Each section will represent a sub-system of the model.

6.1 Quantitative phase: system dynamics application (study 2)

After conducting in-depth interviews and analysing the data collected, this second phase aimed to design a generic structure to simulate alternative transport mode acceptance as a second research question was formulated to be answered. The ability to contribute to measuring the impact of different strategies to decrease car choice will depend on the power that the model has to represent people's travel consideration of alternative transport modes. To reach this point, the usefulness of SD will be addressed by using a case study (UK) to explore the behavioural dynamics of people's travel choices.

The decision to build up a generic structure to simulate alternative transport mode acceptance was because during the interviews it was possible to conclude that environmental psychology and transport research were failing to propose a theoretical framework that was able to include both perspectives. Thus, the aim of the simulation model is to provide a solution that enables those from transport or environmental psychology to integrate key variables that are not included in the traditional models proposed. If someone from transport research wants to extend the analysis with variables from environmental psychology, they would need to adapt the generic structure proposed into their model. In the case of a researcher from environmental psychology, the simulation model will help to model the variables that are traditionally measured to understand pro-environmental behaviour through Theory of Planned Behaviour, Norm Activation Model, Value Belief-Norm theory, Comprehensive Action Determination Model, Stage Model of Self-Regulated Behavioural Change, and the CAUSE framework.

6.1.1 Why system dynamics? Method selected

To carry on with the analysis, a system dynamics approach has been selected to complete the quantitative phase of this project. Several reasons led to SD being the proper method for the quantitative phase. Firstly, people's alternative mode consideration choices have been defined as a system composed by multiple causal-effect relationships and time delays (e.g. attitude formation and habits) (Bamberg, 2007; Chng, et al., 2018). Therefore, it is necessary to describe and understand the conditions that create system instability (Davis, et al., 2007), in order to find strategies that can mitigate the expected negative effects in the future, in this particular case, breaking the habit of commuting by car on a daily basis. Secondly, simulation has become an important research method to develop theory as it is possible to run multiple experiments that can provide improved insight into complex theoretical relationships described between multiple factors (Davis, et al., 2007). Thirdly, system dynamics was selected because the methodology can deal with both qualitative and quantitative variables. Finally, while environmental psychology has focused on predicting car use (Abrahamse, et al., 2009; Chng, et al., 2018) and the willingness of car drivers to shift to public transportation (Bamberg, 2002; Bamberg, 2007), their models have not recognised time dependency in the function of predicting people's behaviour. For example, TPB, the most dominant theoretical model to guide research on pro-environmental behaviour (Bamberg, 2007; Unsworth, et al., 2013) and psychology determinants of travel mode choice (Chng, et al., 2018), assumes[46] no fluctuation in the measurement of the constructs (e.g. score punctuation of attitude in a Likert scale) once the model is predicted. However, people might compare new information about the actual and desired states of the real world to correct their errors and take actions (Sterman, 2000; Ulli-Beer, et al., 2010). If that happened, it would make the measurement of some constructs no longer valid because TPB cannot represent people's attitude or perceived behavioural control change with the basic assumptions, unless the model is measured again under the new situational conditions. To some extent, this sounds counterintuitive as some environmental psychologists have already claimed that people's engagement in low carbon activities is based on a learning process that occurs over time (Young & Middlemiss, 2012).

A simple example to explain why dynamism is crucial would be through observing the effect of social norms on public transportation. A social norm is defined as the perceived social pressure that might influence an individual to perform or not perform a certain behaviour (Ajzen, 1991). This means that people develop a social pattern dependency as soon as their behaviour is guided or constrained by this group's rules. Then, when the social norms attain sufficient weight and power, people internalise them as personal norms, so new social perspectives emerge to guide the

[46] First, the constructs in TPB must be compatible, that is, intentions, and PBC must measure a particular behaviour of interest. Second, intention and PBC must remain constant in the interval among evaluation and observation of the behaviour. Finally, PBC increases the prediction of a given behaviour only if it consistently reproduces the person's actual degree of unbiased behavioural control when trying to perform the behaviour (Ajzen, 1991; Bamberg, 2002).

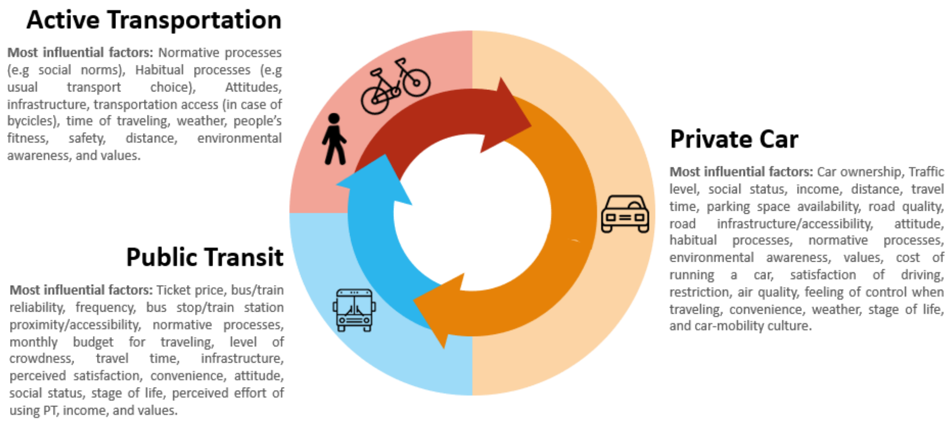
future decision process (e.g. now some people consider it important to commute by public transportation instead of by car because of climate change) (Sterman, 1994; Ulli-Beer, et al., 2010). That is why it is possible to see in the real world how social norms are replaced with new ones. Therefore, the feedback loop between personal norms and social norms means that the social norms emerge as a non-linear process because the modification and adjustment to a changing environment allow the replacement of the old norms and influence the current behaviour patterns by achieving new behavioural patterns (Ulli-Beer, et al., 2010). Hence, a measurement of social norms in TPB is just a picture of what is happening, but it does not allow researchers to learn from the dynamism of the variable itself.

6.2 Specification of the structure and dynamic hypothesis (causal loop diagram B explanation)

6.2.1 Car Use sub-system: main focus of the simulation model

The first step in completing the model was a qualitative analysis (see previous chapter), in which interviews with experts provided the necessary input to understand the dynamic relationships in the transit transportation context. From the interviews, it is possible to see that the transit system can be divided into three main sub-models at the highest level of aggregation: car use, active transportation and public transportation (Figure 28). As the previous sections exhibited (see Figure 27), each of these sub-systems depends on several factors, which prove the complex dynamism in the people's travel mode choice: number of trips, distance travelled, travel time, mode preference, psychological factors (e.g., attitudes), economic restrictions, situational influences (e.g., travel purpose), transport mode satisfaction levels, accessibility and availability, congestion, infrastructure, among many others. All of these findings are in line with what transport and environmental researchers have been discussing in the last 30 years (Bamberg, 2007; Jifeng, et al., 2008; Abrahamse, et al., 2009; Pfaffenbichler, et al., 2010; Shepherd, 2014; Brown, et al., 2016; Krueger, et al., 2018; Abrahamse, et al., 2009; Chng, et al., 2018; Moody & Zhao, 2020).

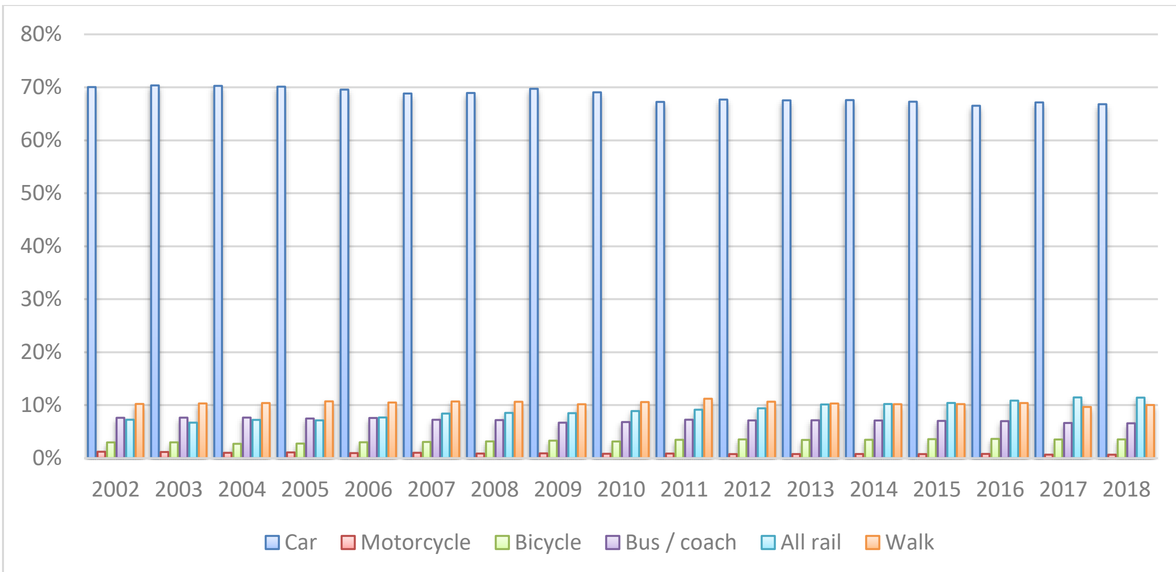
Figure 28. Highest level of sub-system aggregation to explain transport mode choice.



Source: Own elaboration. These are the three main sub-systems found after the interview phase. Each sub-system has a set of factors that can be divided into smaller systems: normative processes, habitual processes, situational influences, functional factors (e.g., road quality), attitudinal processes, values, and beliefs.

Since the complexity of each main sub-system is considerably high, the first decision before proceeding with the simulation model was to focus on the most impactful and harmful of these top-end sub-systems: commuting by car. As was discussed in the literature review, a vast number of researchers, governments and institutions have agreed with the idea that diminishing car use can be the most effective and fastest way to tackle climate change, air pollution and health problems (Bamberg & Schmidt, 2003; Abrahamse, et al., 2009; Chng, et al., 2018). Moreover, Figure 29 shows that the usual method of travel to work in England has been the car, being 70% (on average) of transport mode choice preferences. Therefore, this is clearly a sign to assume that studying in depth the car choice sub-system could lead to promising results to explain why, after so many years of efforts to discourage car use, people keep preferring cars (Abrahamse, et al., 2009; Harich, 2010), even when many studies have reported a high level of people's environmental awareness (Deparment for Transport, 2011).

Figure 29. Usual method of travelling to work (England).



Source: Own elaboration. Data extracted from excel file TSGB 0108, which was downloaded from the Department for Transport (UK) website (https://www.gov.uk/government/organisations/department-for-transport).

6.2.2 Causal Loop diagram B: psychological perspective justification

After understanding the aggregated levels of the transit system, the next step was to construct a second causal loop diagram (CLD B) centred on explaining the dynamics of psychological factors that influence the decision to commute by car. The focus on psychological factors is because of two main reasons.

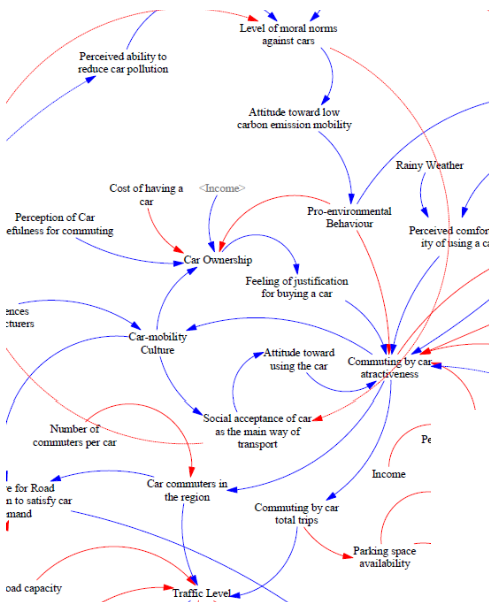
First of all, there are plenty of simulations models that explain travel mode choice (e.g., MARS) (Pfaffenbichler, 2003), especially in system dynamics (Shepherd, 2014). However, looking at these models it is possible to see that there is a preference to explain the dynamic relationship by using functional factors (e.g., traffic congestion), which tend to be easier to measure and simulate than soft/latent variables (Hartgen, 1974; Vij, et al., 2013).

An unappreciated description of the psychological factors, such as behavioural intention or level of cognitive dissonance, led this field of research to re-think how these factors are really taking a role in travel mode choice and its dynamic behaviour in the long term. Car ownership and car use tend to nullify the efforts of technology to produce more environmentally friendly cars, as non-exhaust emissions are still a significant pollutant source among modern cars (Timmers & Achten, 2016). Therefore, it is critical to consider car use behaviour and intentions in an analysis focused on discouraging driving behaviour (Abrahamse, et al., 2009). For this reason, many green interventions (Bamberg & Möser, 2007; Unsworth, et al., 2013), especially in transport (Steg, 2005; Abrahamse, et al., 2009; Gao, et al., 2019), have been targeting the modification of the intentional and/or normative processes, so as to persuade people to drive less. Therefore, if the efforts are normally put into psychological adjustments, then it is crucial to understand psychological determinants dynamicity.

Second of all, despite the efforts to predict behaviour (car use) by using psychological variables in environmental psychology, simulation techniques are not common in the field, so the understanding of the attitude-behaviour gap is normally static and linear (Schröder & Wolf, 2017; Chng, et al., 2018), hiding the potential of simulation methods over traditional forecasting statistical tools (see study Srijariya, et al. (2008)). For those two justifications, then it is reasonable to think that a simulation model of the psychological factors could bring value to and complement the studying of car use.

For the aforementioned reasons, a second causal loop diagram was created, in order to provide a detailed description of the relationships and variables (social norms, personal norms, attitudes, values, beliefs, emotions and perceived behavioural controls) claimed in the interviews. CLD B can be understood as a magnification of Figure 30 (a fraction of CLD A), which can offer a comprehensive sketch of the complexity of the relationship between the psychological factors captured in the construction and analysis of CLD A.

Figure 30. Fraction of CLD A. Most influential and psychological factors involved in the explanation of car use.



Source: Own elaboration.

CLD A (psychological factors section) and CLD B are in line with the most used theories in environmental behaviour and car use/commuting. In both causal loop diagrams it is possible to find: the Theory of Planned Behaviour , the Norm Activation Model, the Stage Model of Self-Regulated Behavioural Change model and the Comprehensive Action Determination Model (Bamberg, 2002; Bamberg & Schmidt, 2003; Bamberg, 2007; Abrahamse, et al., 2009; Bajracharya, 2016; Belgiawan, et al., 2017; Chng, et al., 2018). This can facilitate the construction of the mathematical expression (Srijariya, et al., 2008) as there are many empirical studies to predict car use (Chng, et al., 2018).

6.2.3 Causal loop diagram B: redeveloped dynamic hypothesis

Classical economy proposes that the attractiveness of a good/service normally decreases when the experience/satisfaction does not meet the expected quality (Mankiw, 2011), so then, why do people keep driving their cars when congestion levels are getting worse? According to the Global Traffic Scorecard, British citizens wasted 115 hours in congestion, costing around £894 per driver in 2019 (INRIX, 2019). Part of this answer will be explained with the simulation model constructed from CLD B (see Figure 32).

From a psychological point of view, the behaviour of commuting by car can be predicted from habitual processes, intentional processes, contextual/situational beliefs and normative processes. Starting with the variables in the pre-action phase of the model (social norms, personal norms, attitude, etc.), the higher the attitude towards driving, the higher the behavioural intention to commute by car. The reason behind this rationale is that, because attitudes represent the level of favourable/unfavourable evaluation of the given behaviour (Ajzen, 1991), then it is expected that drivers have a positive attitude towards the behaviour in question. Additionally, perceived behavioural control (PBC) reflects the degree of difficulty/ease to perform a given behaviour (Ajzen, 1991; Bamberg, 2007). In this case, the higher the level of PBC, the higher the intention towards performing the behaviour, which in turn increases the probability of commuting by car. Since PBC represents the self-efficacy belief of performing the behaviour under consideration, then its intensity rises when car-ownership exists (Belgiawan, et al., 2017), and decreases when traffic congestion increases (Sterman, 2000).

In this pre-action phase, social norms play a key role as well in the individual's mobility decisions (Abou-Zeid, et al., 2013), which have been found to be strongly related to commuting behaviour (Thøgersen, 2006). Social norms are defined as the perceived social pressure to engage or not to engage in commuting by car. Social norms act as a guideline or a set of rules that can constrain/control the individual's behaviour (Ulli-Beer, et al., 2010). In the causal loop diagram, there are two perceived social forces influencing car use. On the one hand, the higher the perceived social pressure towards driving, the higher the car commuting behaviour intention. On the other hand, the higher the perceived social norms towards alternative transport modes, the lower the probability of driving. Therefore, car use will be influenced by how the discrepancy between the peer pressures is being resolved, determining the acceptance of one or the other. This way, the model will reflect a social-norm building process (Ulli-Beer, et al., 2010) as a continuous change characterised by the non-linear tension created when a social dilemma emerges from two opposite norms. Depending on external inputs, one force can overcome the other. The acceptance of one or the other social norms is a complex sub-system determined by values, functional factors (e.g., transit infrastructure), beliefs, resistance to change, ascription of responsibility, environmental concern and awareness (see the complete explanation in the section for the sub-system normative processes).

From the interviews and the literature review, it was also possible to recognise that pre-planning one's journey and accessing the complete information about the alternatives, can affect the probability of selecting the car. Thus, in CLD B the assumption is that the higher the public transport consideration, the lower the probability of driving by car. Reasons for that can be because: (1) people do not realise that, in fact, cars are more unreliable in terms of time prediction than public transportation (see interviews with transport engineers/researchers), and (2) an habitual behaviour could mean that the decision-making process is more automatic than deliberate (Nordfjærn, et al., 2014). Therefore, intensifying the pre-planification of the trip (implementation intention) will increase the probability of considering alternatives because people will have an opportunity to recognise that alternatives can be a better option.

Following the pre-action phase, is the action phase, which means the action is being performed. When car use rises, three variables are affected. The first one is the traffic congestion: the more cars on the road, the higher the traffic congestion, which in turn decreases the perceived behavioural control as the control beliefs are affected by the idea that mass transit congestion decreases the speed of free flow, therefore it takes longer to commute by car (balancing loop: *restriction of the perceived difficulty of driving*).

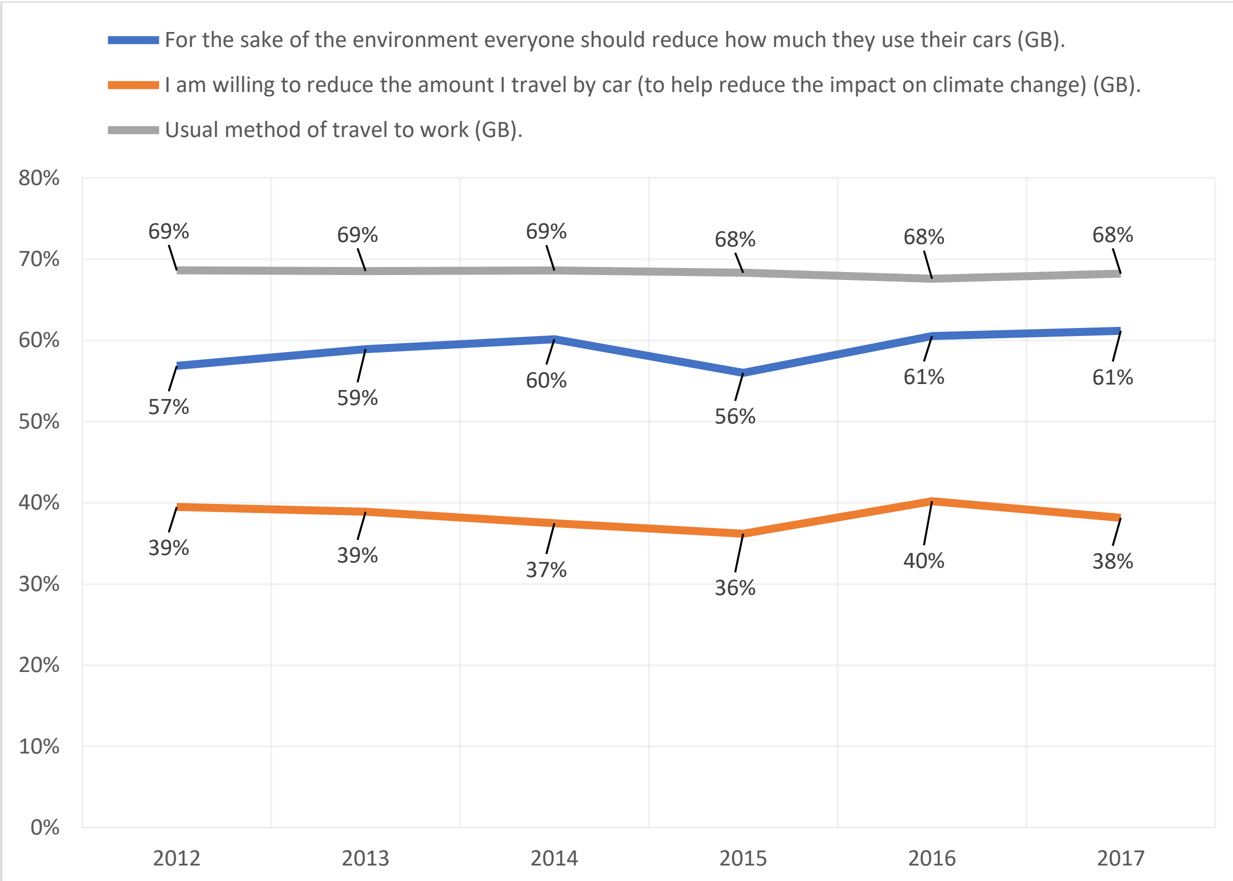
The second one is the pollution accumulation: since cars emit polluting substances, such as CO_2 (Transport & Environment, 2018), the more cars there are on the road, the more pollution is accumulated, which in turn increases the environmental awareness as greenhouse gas emissions contribute to global warming (Abrahamse, et al., 2009). In reality, cars and air pollution have been studied since the 50s (EPA, 2021), and currently more studies have been conducted regarding car ownership, car commuting, electric car adoption and active transportation, as cars account for the largest portion of GHG emission (Abrahamse, et al., 2009; Chng, et al., 2018), and car pollution is linked to many public health issues (Tinch, 2020). Therefore, it is reasonable to think that the increment of car pollution will increase the environmental awareness, which then will decrease people's climate change denial (and the psychological distance ratio) and will accelerate the internalisation and acceptance of green norms into personal norms by moving the perceived social norms towards driving to alternative transport modes. Based on the value-norm theory and the interview results, it is expected that an increment of the level of personal norms towards alternatives will increase the level of green attitudes, which in turn can trigger a realisation of the urgent need for behavioural change in drivers since a conflict emerges between one environmental attitude (low-carbon mobility) and its counter-environmental attitude (car commuting). It is important to note that this model is focused on psychological-basis dynamics, therefore reasons to shift to alternative transport modes, such as transit disruptions, residence reallocation, government restrictions and economic issues (e.g., petrol price), are not considered. There are an important number of models exploring that kind of dynamics (Shepherd, 2014), so, to simplify the functional side of the system, it is accepted that perceived behavioural control (see Ajzen, 1991) can relax these assumptions, and social norms can act as 'internal regulators' when laws are not imposed to change people's behaviour.

If a cognitive dissonance arises (Attitude towards alternatives – Attitude towards car commuting > 0), then people might look for strategies to resolve this uncomfortable state as long as the conflict is salient. However, the conflict might not be perceivable, since transport and psychology research have proved that transport mode choice can be a more automatic process that a deliberated one, thus a difference of attitudes might not be sufficient to encourage a behavioural change development as people can opt for a cognitive restructuring strategy (e.g., trivialisation of pro-environmental attitudes (Lavergne & Pelletier, 2015)). For this reason, car reduction (behavioural change process) is also constrained by habits (automatic vs deliberate thinking process) and the relative propensity of resolving the cognitive conflict (cognitive dissonance elasticity ratio). More details will be provided in the section on attitudinal-behavioural sub-system. This balancing loop is recognised as the 'acceptance of behavioural change'.

If the cognitive dissonance is resolved in favour of green attitudes (acceptance of the behavioural change), then more people will adopt alternative transport modes. In the real world, it is possible to see these dynamics: many ONGs, and governments are constantly deploying interventions to promote public transportation or active transportation, in order to reduce car pollution. Moreover, many reports from the Department for Transport in the UK have shown that British citizens have been reporting high levels of willingness to change their behaviour to limit climate change, as well as a high acceptance of using more public transit instead of cars (47% in 2010) (Deparment for Transport, 2011), and a significant belief that people should reduce car use for the sake of the environment (Department for Transport, 2019). However, the latest report (2019) from the Department for Transport reported that 67% of British commuters normally use cars to commute (see database TSGB 0109, 2019), which is just 1% lower than in 2012 (see Figure 31). Among usual drivers, only 10% of these commuters travel by car as a passenger[47]. Therefore, it is clear that, although high levels of attitudes towards alternative modes/protecting the environment have been reported, they have not been translated into important behavioural changes regarding car reduction in the last 19 years.

[47] See table TSGB0112 on https://www.gov.uk/government/collections/transport-statistics-great-britain.

Figure 31. Comparison of data collected from TSGB0109, NTAS0202, ATT0332.



Source: Own elaboration. Data extracted from reports provided by the Department for Transport UK. The percentages illustrated by the 'usual method to travel to work' are for car use.

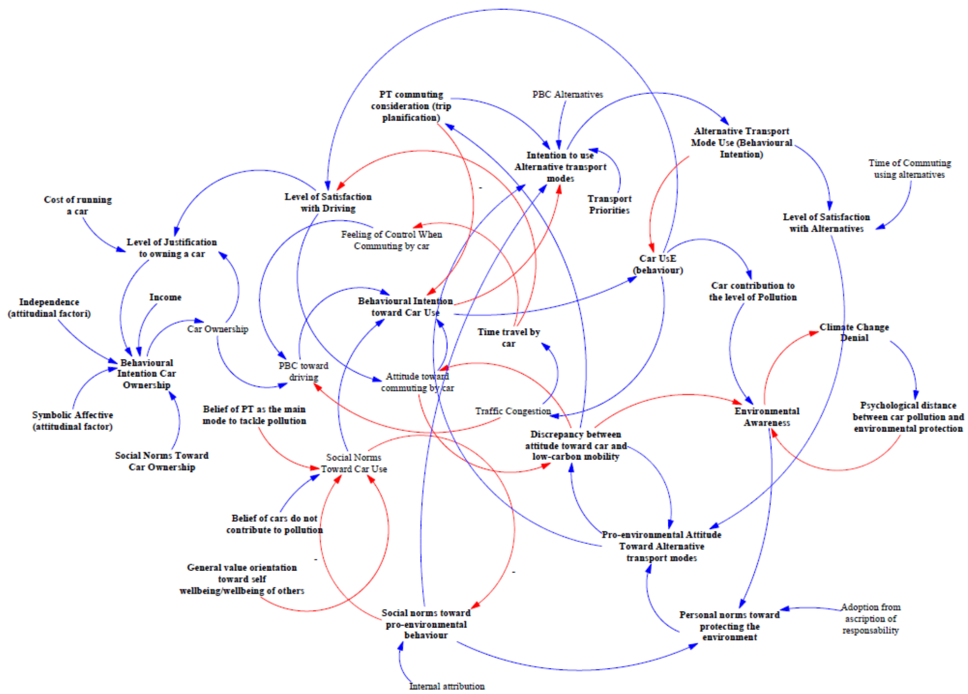
Finally, the third main loop involving car use is the one created with the level of satisfaction: the rationale is, if functional factors allow it (e.g., high road quality), higher levels of perceived satisfaction when driving will increase the level of justification of the need to have/use a car, which in turn will increase the attitude towards the behaviour under consideration. It is assumed that pleasant experiences strengthen the symbolic/affective elements (social status, safety, comfortability, etc.) that explain car possession and car use (Bajracharya, 2016). Therefore, the more people use their cars, the higher the chances are that they will develop satisfactory experiences, which reinforces the relationship between car use and the desire to use it. Researchers believe that the development of a car habit is normally facilitated by pleasant or rewarding experiences in stable contexts (Eriksson, et al., 2008), so, if there is no transit disruption, car satisfaction should encourage driving. This reinforcing loop represents the 'attractiveness of commuting by car'.

The last part of CLD B that needs to be explained is the process of consideration and choice of alternative transport modes. Alternative transport modes that can help to decrease car pollution are: public transportation, walking, cycling, carpool and electric cars. Whichever is the alternative mode chosen, the behaviour process involves the same psychological factors in the procedure of predicting any of these choices. For that reason, CLD B assumes a bi-modal basis. This model assumes the existence of two dominant transit modes, which compete in the commuting preferences. It is believed that specifying more transit modes in the formation of each sub-system will not bring a different conclusion from a bi-modal perspective. While it is thought that the ideal situation is that people prefer active transportation over cars since the emission of GHG can be zero, the aim of this model is to look at understanding how drivers can decrease their behavioural intention score towards driving. Therefore, no matter what people choose, any alternative mode will facilitate the process to decrease car use. So, even when functional variables can take place to make public transportation more attractive than active transportation (especially when people do not feel healthy enough to walk long distances), perceived behavioural control can work as a proxy to capture the effect of how effortful it can be for drivers to shift from cars to a different transport mode, and help to understand the foundations of the decision-making process when drivers consider alternative transport modes.

In CLD B, when behavioural intention to commute by car increases, the intention to use an alternative transport mode decreases. As was defined for the prediction of car behavioural intention, the intention to commute on alternative transport modes depends on attitudes towards the alternative transport mode, perceived behavioural control, trip planification, social norms towards low-carbon mobility and transport priorities (these are the motivations underlying travel mode use that would make the individual prioritise the alternatives over car use). The higher the level of these factors, the higher the level of intention towards the alternative transport mode, which in turn increases the probability of actual use.

In this part of the model, the causal loop diagram also recognised a loop based on satisfaction and the alternative transport choice, which in this case is called attractiveness of commuting by alternative transport modes. The mechanism is the same: the higher the level of satisfaction by using the alternatives, the higher the attitude towards the alternative is expected to be, which in turn decreases the intention to use a car, so then the probability of using the alternative transport mode is higher, and the more it is used, the higher is the construction of satisfactory experiences.

Figure 32. Causal Loop Diagram B. The dynamics of the psychological factors that explain car use.



Source: Own elaboration. Red lines represent that the variables change in opposite directions. Blue lines mean that two nodes change in the same direction.

Table 17 shows a summary of the evolution of the causal loop diagram B. This includes: 1) a brief description of the model; 2) the sources of the data and theory used to generate the model; and 3) the changes made in each version of the model. CLD 0 was mainly used as an input to focus the discussion surrounded car commuting during the interviews. CLD A represents an improved version of CLD 0 as the ideas of the experts were integrated in the initial mental model, in order to offer an extensive and more sophisticated explanation about people's transport behaviour. CLD A can be understood as the highest-level model to explain the overall system of people's commuting decisions. In it, there are factors to explain active transportation, public transportation, and car use. Finally, an extract of CLD A was used to develop CLD B, which is a causal loop diagram focused on the explanation of car commuting and the psychological factors involved in the decision. This decision was made because this project seeks to help understand the incongruencies found between people's opinions about car pollution and people's actual behaviour. Getting insights into how the psychological determinants are embed in a large circular causal system, presents a different and possibly more effective perspective than the currently offered in environmental psychology.

Table 17. Evolution of the final causal loop diagram - From CLD 0 to CLD B.

CLD Name	Description	Source	Changes made between each CLD version
CLD 0	The first causal loop diagram proposed. This CLD contains the main transport factors and psychological determinants, and explains how they are causally interrelated in impacting car and public transportation attractiveness.	**Literature;** main sources: Abrahamse et al., (2009); Bamberg (2002); Bamberg & Schmidt (2003); Shepherd (2014); Pfaffenbichler (2003); Paulley, et al. (2006); Dargay (2001); Chng, et al. (2018); Fiorello et al., (2010); Lanken, et al., (1994); Piattelli et al., (2002); Gärling et al., (2001); Schröder & Wolf (2017); Noonan (2021); Yong-chuan et al., (2011); Şimşekoğlu et al., (2015); Ben-Akiva & Bierlaire (1999); Bouscasse (2018); Klöckner & Blöbaum (2010); Sterman (2000); Struben & Sterman (2008); Liu et al., (2016); Vij & Walker (2016); Vij et al., (2013).	No changes were made as this was the initial CLD.
CLD A	The second CLD presented in this project. This causal loop diagram included the expert knowledge of the explanation of car commuting. Therefore, CLD A is an improved version of CLD 0.	Interviews with experts.	- Active transportation was included. CLD 0 only explains the dynamic behaviour of car commuting and public transport. CLD A included walking and cycling as alternative transport modes. - The explanation of people's acceptance of climate change was extended by including the influence of the government, the effect of the psychological distance towards climate emergency, the effect of carbon tax, and the support of external institutions. - Several new variables were added into the main causal loop: car-mobility culture, time reliability, social norms, car restrictions (when high levels of air pollution are reached), perceived cost of commuting, habit, cost of having a car, feeling

			of justification when buying a car, pressure to increase car infrastructure developments, air quality, and public transport ticket prices. - The importance of considering the weather in transport choices was recognised. - Values and environmentally-driven attitudes were added to explain the moral dilemma between driving and protecting the environment. - Convenience was added as an important factor to justify why car drivers in rural sectors are more difficult to transfer to alternative transport modes. - The public transportation loop was extended by adding variables such as reliability, frequency, cost of development (PT infrastructure), distance between home-stop-work, and comfort levels.
CLD B	The third CLD presented. This CLD is a detailed explanation of a sub-system of CLD A. In this causal loop diagram, only psychological factors were considered to explain car commuting. This way, the simulation outcomes contribute to the aim of the project as well as help with understanding psychological theories in a non-linear and dynamic way. CLD B is an in depth explanation of the behavioural intention towards car commuting, which co-exists with the other parts presented in CLD A. Explaining the economic factors, traffic congestion, transport supply, travel demand, as well as the car-centric infrastructure developments are out of the scope of the thesis because they are not intrinsic characteristics of human behaviour, hence CLD B	CLD A, interviews, and theoretical models in environmental psychology (see chapter 2 for more details).	- Car attractiveness, which was defined in CLD 0, is labelled as the behavioural intention towards car commuting as, it is supposed to reflect the actual behaviour of car commuters. - Social norms, and personal norms sub-systems are extended. - Car ownership is not only explained by costs, but also by symbolic and attitudinal factors. - Values are divided between negative and positive values towards car commuting to represent the theoretical contributions of VBN (Stern, 1999). - Attitudes and behaviours towards car commuting are embedded in a large reinforcing loop. - A discrepancy between attitudes and behaviours is added to reflect the theoretical contributions from cognitive dissonance (Festinger, 1957). - Satisfaction is included as an important factor to shape attitudes and behaviours.

	focuses only on psychological determinants, as they are used to explain behavioural theories.		- Transport priorities are added as the main characteristics that are perceived as important factors in public transportation.

Source: Own elaboration. This table shows the evolution of the 3 CLD presented in this document.

6.3 Mathematical description of each sub-model: estimation of the parameters and initial conditions

In this section, the main variables and relevant equations are described based on the non-linear relationships created by the feedback loops. The proposed model, termed 'The Pro-Environmental Behavioural Change Model' (PEBCM), is broken down into six sub-models, which are all simulated simultaneously to generate a comprehensive analysis of commuting in England between 2002 and 2017. Additionally, the stock-and-flow diagrams from CLD B are exhibited. The stock-and-flow model expresses causal relationships into levels and rates equations, and all the feedback loops (Sterman, 2000).

Before proceeding with the explanation of each sub-model, it is crucial to define that each psychological factor is computing an average score for an individual that the variable would receive in a large population (see Ulli-Beer, et al. (2010) or Bajracharya (2016)). Psychological research often predicts its parameters by aggregating the data obtained from an individual level (Schröder & Wolf, 2017), which means that the betas or lambdas reported in their models represent the aggregated weigh of the sample to predict the dependent variable. Therefore, it is reasonable to think that, following the same pragmatic procedure, the psychological factors of the PEBCM can be seen as the average representation that an individual would have/report/evaluate based on the given simulated context. This allows the thesis to move the problem from an individualistic bias to a societal bias since each factor can be multiplied for the number of people to represent multiple levels. Additionally, solving car reduction requires a societal effort; therefore, this simulation model can be seen as the starting point to understand the dynamics of the psychological factors, to then proceed with a complementary less abstract, more detailed, micro-level simulation model (e.g., agent-based model) (Borshchev & Filippov, 2004).

Finally, before describing each sub-model, it is important to state that the second dominant mode of transport in this bi-modal system is public transportation. The reason behind this decision is because the intention to use public transportation is well documented (Bamberg, 2002; Brown, et al., 2003; Bamberg & Schmidt, 2003; Buehler, 2011; Lind, et al., 2015; Shepherd, 2014; Brown, et al., 2016; Bajracharya, 2016), and there is plenty of data available from the Department for Transport UK.

6.3.1 Intentional process sub-model

The intentional process reflects the developing stage of behavioural formation and behavioural change. As attitudes play a dominating role in predicting behavioural intention and cognitive dissonance, the magnitude of the attitudes determines the intensity of the behavioural intention towards car/alternative transport mode and the latent cognitive dissonance created by the conflict between the attitudes.

The behavioural intention to commute by car at time *t* is a function of seven factors and can be summarised as follows:

(1) $Behavioural\ intention\ toward\ driving\ (BIcc)(t) = \sum_{i=1}^{6}(\beta_i * e_i)$ – IRC

Where $\boldsymbol{e_i}$ is the perceived evaluation of the psychological factor $\boldsymbol{i}$, $\boldsymbol{\beta_i}$ is the perceived strength of this factor to predict the behavioural intention, and IRC is the intention to reduce car use, which is estimated by several other parameters. In this equation, the β were extracted from the following papers: Abrahamse, et al. (2009), Klöckner and Matthies (2009), and Bamberg and Schmidt (2003). The parameters included in the model are shown in Table 18.

Table 18. Parameters to estimate Behavioural Intention towards driving.

Model variable	Parameter	Paper
Habitual frequency car use	β = 0.9	Based on (Bamberg & Schmidt, 2003; Chng, et al., 2018)
Attitude towards commuting by car	β = 0.27	(Abrahamse, et al., 2009)
Perception of how easy it is to reduce car commuting	β = 0.56	(Abrahamse, et al., 2009)
Personal norms towards commuting on alternative modes	β = -0.38	(Bamberg & Schmidt, 2003)
Intention towards driving	β = 0.6	(Bamberg & Schmidt, 2003)
Perceived effort of taking public transportation	β = 0.17	(Klöckner & Matthies, 2009)

Source: Own elaboration. Parameters extracted from empirical studies. All of them were reported to be significant.

The equation to estimate the intention to reduce car use was based on papers by Abrahamse, et al. (2009) and Jakobsson, et al. (2000).

(2) $IRC\ (t) = (ATTC * -022) + (PN * 0.16) + (PHECR * 0.3) + (RWCI * -0.068)$ (score/year)

ATTC is the attitude towards car commuting, ***PN*** is the personal norms towards low-carbon mobility, ***PHECR*** is the perception of how easy it is to reduce car commuting, and ***RWCI*** is the relative weight of the cost of running a car over the median household disposable income.

(3) $$RWCI\ (t) = \frac{CORC}{MHDI}$$

Instead of using income, as in the study by Jakobsson, et al. (2009), this model generated an index to reflect the fact that, more than the income itself, the financial restrictions are associated with the relative cost that running a car involves over the monthly income. The index is computed as *'cost of running a car'* divided by '*household disposable income'*. This way, the model still appreciates the rule that higher incomes will decrease the intention to reduce car use, but it is also recognised that, if the cost of running a car increases but the income does not change, then people have more incentive to reduce car use since it is perceived to be less affordable. Therefore, if RWCI is 1, people feel more incentive to reduce car use; if RWCI is 0, then they have less pressure to reduce car use (if all the other variables remain at the same level). This variation was considered because two respondents in the qualitative phase said that in the UK they have not considered owning a car because it is really expensive to own one and use it in comparison with their previous locations (Chile and the USA), even when they salaries were now higher.

Attitude towards car commuting or public transportation (proxy for alternative transport modes) is estimated as:

(4) $$Attitude\ towards\ car\ commuting\ (ATTC) = (IATT - \Delta ATTchange) + SATC$$

For this equation, it is assumed that people will start with an initial level of the attitude towards driving (*IATT*). The rationale behind this is that, because all the studies reviewed for the construction of the PEBCM have shown that the attitude towards car use is always positive, so, whatever the intensity is, this latent variable seems to be always present in some capacity (average Likert score > 0). The initial value was taken from the paper by Abrahamse, et al. (2009).

In the case of attitudinal change (Δ*ATTchange*), the assumption is that the attitudinal change will emerge as soon as the environmental attitude becomes salient; in other words, attitude towards alternative modes > attitude towards driving. However, the intensity of the change will be restricted by the frequency of driving and the dissonance ratio. As was explained in the CLD B section, multiple studies have shown that habits play an important role in predicting the behavioural intention towards driving (Eriksson, et al., 2008), making the process of travel mode choice less deliberate, which means that, even when an intervention can make a green attitude more salient, it is expected that hard drivers will have lower levels of attitudinal change as cars have become their automatic option. Hence, it is believed that, if a cognitive dissonance changes, the intensity will not only depend on the magnitude of the difference between the attitudes, but also on the ratio that reflects how prone people are regarding resolving the conflict. In other words, resolving the attitudinal conflict will be faster between soft-medium drivers (do not drive to work every day) because the travel mode choice process is less automatic (there is room to consider alternatives), and will be slower among hard drivers (drive to work every day) because they have built a strong habit towards driving, facilitating the perception of cars as the only option available or the most satisfactory (Bamberg & Schmidt, 2003; Eriksson, et al., 2008). These assumptions are in line with the explanation regarding the attitudinal-behavioural gap (Barr, 2006; Lukman, et al., 2013; Lavergne & Pelletier, 2015). The attitudinal change equation is represented as follows:

(5) $$(Attitudinal\ change\ (ATTC)\ (t) = ATTC_0 + \int_{2002}^{2018} ATTCr_{(t)}\, dt$$

(6) $$Attitudinal\ change\ rate\ (ATTCr)(t) = CD_{ratio} * \frac{(ATTlc - ATTcc)}{BIcc}$$

CD_{ratio} = Cognitive dissonance ratio.

ATTlc = Attitude towards low-carbon mobility.

ATTcc = Attitude towards commuting.

BIcc = **Behavioural intention towards driving**. This function is based on habitual transport mode, so car habit is implicitly affecting attitudinal change rate: the more the individual drives, the highest the behavioural intention to drive the next time, then it is less probable for the individual to have a cognitive conflict, hence the person continues to drive and keeps the habit formation.

The attitudinal change is represented as a stock variable since it is affected by the accumulated behaviour of the sub-systems. In other words, the values for this factor are computed based on the sub-systems' previous outputs, reflecting the changes at every new period simulated and adding them to the previous outcomes (Sterman, 2000). This way, the model can capture the effect of the attitudinal-behavioural change as a non-linear change pattern (see Ulli-Beer, et al. (2010) for more details about behavioural change pattern behaviour), and the stock acts as a buffer to affect the intensity of each attitude. The initial conditions for this sub-model are specified in Table 19.

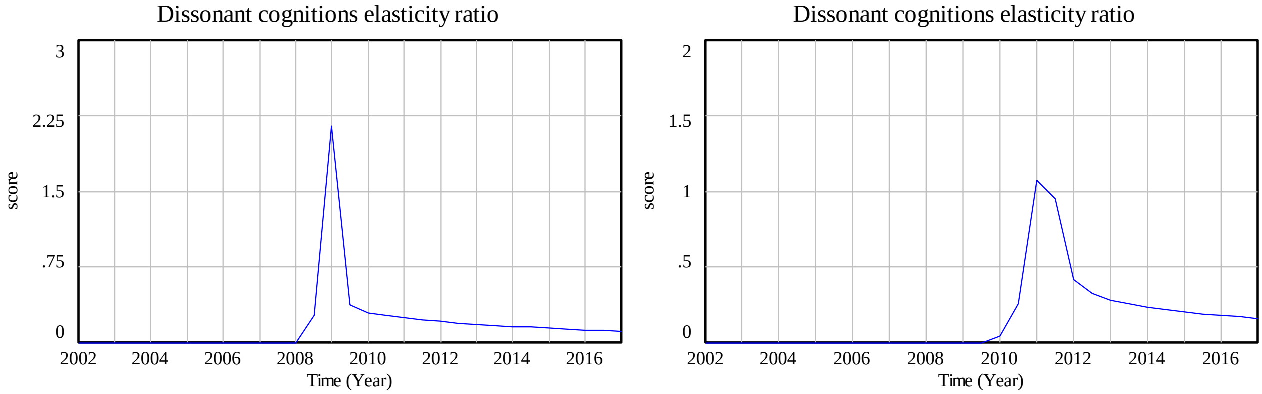
The cognitive dissonance ratio reflects the sensitivity between attitudes over the behavioural intentions. This way, the model represents the state of cognitive discomfort as an overshoot and collapse, which can either boost the behavioural change quickly (attitudinal change grows exponentially, decreasing car use faster) or slowly (see Figure 33). The CDratio is weighted by the intensity of self-relevant pro-environmental belief. The reason for this is based on the hierarchical action-based model of inconsistency compensation in the environmental domain (HABICE) (Lavergne & Pelletier, 2015), in which the strategies to compensate for attitude-behaviour inconsistencies are constrained by people's levels of autonomous and controlled motivation towards the environment.

The PEBCM assumed that the system behaviour is based on an autonomous motivation, which means that people can increase their attitude towards low-carbon mobility as long as they go in line with their values. Consequently, if the level of altruistic value is higher than the level of egoistic value, then the model will assume that people believe in a more integrative tendency to act; in other words, their authentic self-structure is coherent and consistent within their values/beliefs. The model could be adapted to follow a more controlled motivation system; however, there is no sub-model to represent an external actor, which can punish or reward the level of driving. The mathematical expression to define the cognitive dissonance ratio goes as follows:

(7) $$CD_{ratio}(t) = \frac{(ATTcc - ATTlc)}{(BIcc - BIlc)} * SRpeb$$

$$SRpeb \{ \ if \ \ Altruistic \ value > Egoistic \ value, then \ 0.6, otherwise \ 0 \ \}$$

Figure 33. PEBCM simulation results: Dissonant cognition ratio at two different discrepancy levels between attitudes.



Source: Own elaboration. On the left, the graph was made by running a simulation, in which the difference between attitude towards commuting by car and attitude towards commuting by alternatives was at least 7 points on average. On the right is the same variable graph but the difference between attitudes was 3 points on average. The ratio does not only increase its intensity, also, the discomfort happens later in the simulation period.

Table 19. Parameters to estimate the auxiliary variables in the intentional process sub-model.

Model variable	Parameter	Paper
Initial attitude towards commuting by car	Mean = 3.4 (Likert scale)	Abrahamse, et al., 2009
Initial attitude towards commuting by low-carbon mobility	Mean =2.8 (Likert scale)	Deliberated decision since attitudinal change only happens if ATTlc > ATTcc, otherwise ATTC = 0. So, any number below 3.4 can be computed in the model without affecting the initial conditions. The initial condition assumption is that cars are preferred over public transportation among drivers.
Perception of how easy is reducing car commuting	2.7 (Likert Score)	Abrahamse, et al., 2009
Egoistic Value	1.5 (Likert Score)	Based on De Groot & Steg, 2008
Altruistic Value	3.2 (Likert Score)	Based on De Groot & Steg, 2008

Source: Own elaboration.

6.3.2 Normative process sub-model

Pro-environmental behaviour has been defined as a mixture between self-interest (feeling of moral obligations) and pro-social motives (individual's acts can affect others or the ecosystem both present and future) (Bamberg & Möser, 2007). This dual nature in the definition has directed researchers to explain that pro-environmental behaviour depends on moral norms as well as social norms because engaging with this pro-social behaviour is seen by individuals as an obligation based on intrinsic motives (Van der Werff, et al., 2013) that are facilitated by the cognitive, emotional and social factors (Bamberg & Möser, 2007). Personal norms and social norms are relevant for this model as they have been reported as important determinants to predict transit mode choices (Bamberg & Schmidt, 2003; Jansson & Dorrepaal, 2015).

The normative process sub-model represents the effect of the perceived descriptive and subjective norms, and the formation and activation of the personal norms. The PEBCM assumes that the acceptance of reducing car use for the sake of the environment is pushed not only by an intentional process, but also by the strength of the perception of the pressure of external forces (social norms) and the formation and adoption of a moral obligation.

The mathematical equations developed in this simulation model to reflect the normative process are based on the insights obtained from the interviews, the Theory of Planned Behaviour (TPB) (Ajzen, 1991), the norm-activation model (NAM) (Schwartz, 1977), the stage model of self-regulated behavioural change (SSBC) (Bamberg, 2013) and the car use model (CAUSE) (Chng, et al., 2018). This sub-model assumes that personal norms towards using alternative transport modes and a lack of moral obligation towards reducing car use and are two opposite forces, in which their behaviour affects each other in an undesirable way (Harich, 2010).

The norm-activation model (NAM) (Schwartz, 1977) establishes that personal norms are feelings of moral obligation that an individual experiences when pro-social actions are performed (Bamberg & Möser, 2007); thus, the higher the personal norms, the higher the probability for an individual to engage with these actions. NAM assumes that the formation and activation of a personal norm can facilitate the performance of pro-social behaviours, which is facilitated by the influence of cognitive, emotional and social factors (Bamberg & Schmidt, 2003). The model establishes that, for an individual to change a habitual counter-prosocial behaviour, new motives need to be salient, so they can encourage her/him to invest in the cognitive effort required to engage with a new behaviour. This process implies that the individual must recognise that his or her current behaviour has negative consequences for other people or the ecosystem, as well as acknowledge responsibility for causing that harm. This way, the antecedent factors to form a personal norm trigger a feeling of guilt because the individual elicits a feeling of regret associated with the harm done by the old behaviour. This in turn creates the formation of a moral obligation to act differently than before in order to achieve higher goals that are in line with moral standards (Bamberg & Möser, 2007).

Simultaneously to the personal-norm activation, descriptive and subjective norms are also involved in the adoption of moral obligations (Bamberg & Möser, 2007; Chng, et al., 2018). Frequently, the Theory of Planned Behaviour has been commonly used as the model to predict a given behaviour in different fields such as protecting the environment, health-related behaviours, transport choices, among others (Bamberg & Schmidt, 2003; Abrahamse, et al., 2009; Ulli-Beer, et al., 2010; Unsworth, et al., 2013; Chng, et al., 2018; Christensen, et al., 2004). The key assumption of TPB is that people are motivated to act by self-interest, and decisions whether or not to engage in the behaviour rely on a rational way of thinking (Ajzen, 1991); in other words, people would perform a behaviour only if that let them avoid self-punishment or seek self-reward (Bamberg & Möser, 2007). However, TPB only recognises subjective norms as an antecedent to predict intention.

TPB defines subjective norms as the individual's perception of whether a group or a community would approve of them engaging in a given behaviour (Ajzen, 1991), in which the strength of this effect depends on how important the expectations of others about his/her behaviour are for the individual, and the level of his/her motivation to comply with these expectations (Belgiawan, et al., 2017). However, in the field of pro-environmental behaviour and transport, several authors have found that pro-social behaviours such as recycling, car use or energy use require a more complex theoretical framework to explain the normative mechanism (Bamberg & Schmidt, 2003; Bamberg & Möser, 2007; Chng, et al., 2018). Empirical studies in this field have shown that descriptive norms (whether others are engaging with the pro-social behaviour as well) are essential to improve the prediction of a given behaviour (Chng, et al., 2018) since they reflect a moral standard within a group of people that influence the kinds of behaviours that are appropriate to perform within the group context; therefore, descriptive norms work as a source of information about whether a given behaviour is morally right or wrong (Baumeister, 2010). Hence, in line with the suggestions from the interviewees and the literature review, this simulation model includes personal norms, descriptive norms and subjective norms as causes to affect car use since all of them are relevant sources of motivation (Hunecke, et al., 2001; Rivis & Sheeran, 2003; Chng, et al., 2018).

To facilitate the understanding of the simulation model, the normative sub-model will be divided into smaller sections and each one will show figures which are a simplified version of the relationships drawn in the model.

6.3.2.1 Personal norms towards reduce car use

In the context of pro-environmental behaviour, if an individual is not pre-disposed to act pro-socially, norms can take an important role to form this behaviour. This simulation model assumes that the current level of driving is in part because people do not feel morally obligated to reduce car use. Therefore, they would prefer to keep prevailing with their current behaviour as the decision regarding commuting has become automatic, hence they avoid investing in new cognitive effort to choose a different transit mode option (Carrus, et al., 2008). As was explained in the previous section, approximately 70% of UK commuters prefer to drive to work, and this has not changed in the last 20 years[48]. Therefore, to diminish the level of commuting by car, people need to feel more motivated to protect the environment, which can be facilitated by the feeling of moral obligation to protect the environment (Schwartz, 1977).

Following the rationale of NAM, TPB, SSBC and CAUSE, and the interviews, the activation of the personal norm in this model has been divided into two stages (formation and internalisation), which are activated by cognitive, emotional and social factors. To decrease the lack of moral obligation to decrease car use, ascription of responsibility, problem awareness and social norms (descriptive and subjective) have been used as the factors to activate and determine the speed of the internalisation of the personal norm (internalisation). These factors are also seen in the field of transportation research (Bamberg & Schmidt, 2003; Steg, 2005; Bamberg, 2007; Abrahamse, et al., 2009; Chng, et al., 2018).

First, to form a norm, people need to recognise that the current behaviour might be harmful for the eco-system or others. For this to happen, people need to be aware about the negative

[48] See data from https://www.gov.uk/government/statistical-data-sets/tsgb01-modal-comparisons.

consequences that car commuting can produce, so problem awareness (PA) reflects the process of recognition that the outputs of the individual's behaviour are not desirable for the society and the ecosystem in the current context (Bamberg, 2007). Simultaneously, people need to feel responsible as well for the negative consequences that their current behaviour is producing, so ascription of responsibility (AR) plays a key role in forming a moral obligation (Schwartz, 1977). Finally, the process of formation and activation of a personal norm is controlled by descriptive and subjective norms (SNs) as they are the reference of which behaviour is morally right within a group of people (Bamberg & Möser, 2007).

In this case, social norms towards the use of alternative transport mode will accelerate the process of PN formation, and social norms towards car use will decelerate it. This way, the model reflects the tension between two normative processes (Gardner & Abraham, 2010) that can co-exist in reality: an individual interacts in different groups, such as family, friends and colleagues, in which different social forces can pressurise the perception of the social norms (SNs). This means that the model accepts the fact that maybe an individual can be influenced by different external sources to show the morally and accepted behaviour that is expected from them. The strength of each component of the social norm is weighted by external components that determine the commitment to adopt these social norms. Because an individual could perceive two different sources of social norms (towards cars or alternative transport modes), one SN source will deaccelerate PN, while the other one will accelerate the process (Figure 34).

Unlike the traditional model to predict personal norms in psychology, this simulation model assumes that the adoption of a personal norm is the reflection of an evolution process (Gavrilets & Richerson, 2017). Many authors in psychology have used the word 'internalisation' when they describe the interaction of personal norms and social norms (Ulli-Beer, et al., 2010), in order to explain the fact that a personal norm emerges from the strength of a social norm. The higher the peer pressure, the higher the acceptance of the idea that the given behaviour is appropriate to perform in the given context. Therefore, it is reasonable to think that personal norms would emerge after social norms have become strongly influential in the individual’s perception; and the individual had the time to adopt the personal norm. That is why, to capture and reflect this evolutionary dynamic of personal norms, the model has divided the construct into three stock variables, in which an individual would go from feeling a lack of moral obligation to feeling morally obligated to reduce car use. The adoption of the internalisation process has considered a period of time (PN internalisation rate) to compute a delay time between forming and adopting a personal norm. In other words, an individual would first recognise the level of discrepancy between the current behaviour and the morally accepted behaviour (by using AR, SN, and PA), and then he/she would act to internalise the personal norm.

This rate of internalisation is affected by the ratio between positive and negative normative values towards the protection of the ecosystem and/or the wellbeing of others. Environmental psychology has demonstrated that values are part of the norm-activation process (Chng, et al., 2018; Ünal, et al., 2018). Ünal1 et al., (2018) found that values are strongly associated with the prediction of personal norms, having a higher impact on the variable than environmental knowledge. Moreover, Gavrilets and Richerson (2017) found in their simulation model that normative values are initially irrelevant, but they play a key role in the internalisation of a new norm. Therefore, for these reasons, the internalisation rate is affected by the ratio between positive and negative values towards personal norms in the use of alternative transit modes.

Finally, this model recognises an abandonment rate, in order to show that beliefs and values could ultimately affect the adoption of moral obligations. Following the definition of personal norms in Schultz (1999), personal norms are a source of motivation that reflect the feeling of moral obligation to act in a certain way in a given situation. Therefore, if the context changes, it is expected that the beliefs would change as well, hence that would have an impact on the feeling of moral obligation (Pronello & Gaborieau, 2018). Currently, there is a general perception that cars are the main cause of pollution between all the transport mode choices. However, this conception is starting to change as electric engine systems, hybrid fuel systems and more efficient engines have been proposed as options to significantly reduce the pollutant emissions in comparison to petrol-powered cars (Lave, et al., 1995; Abrahamse, et al., 2009). Therefore, these benefits associated with modern cars are changing the current link between car use and pollution: cars are being associated with low or zero emission. This way, it is reasonable to think that personal norms towards reducing car use for the sake of the environment can be relaxed as some people might not feel guilty anymore because their cars would not emit pollution (or would do so at lower levels than conventional cars), hence they would feel that they are not contributing to the problem, leading to more 'freedom' to use cars more (Abrahamse, et al., 2009). For this reason, the model assumes that the ratio between the belief that 'cars do not contribute to air pollution' and 'PT as the solution to tackle air pollution' can accelerate, decelerate or deactivate the abandonment rate as it will reflect the dominance of one belief above the other, which impacts on the adoption of the moral obligation of reducing car use. This way, the belief ratio can act in a way to reflect how an individual can perceive the context around them.

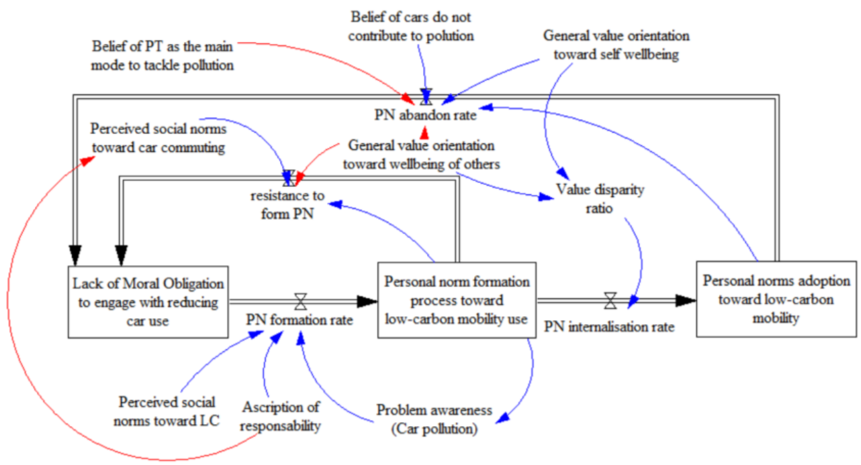
The belief ratio is in line with the findings from interviews and empirical research. In the interviews, transport engineers and policy makers stated that the difficulty of discouraging car use is in fact because people see modern cars as not as harmful as before, so then they feel less guilty when they have to use them for short trips or more times a day. At the same time, empirical research has demonstrated that people believe that car sharing and public transportation are the quickest way to reduce polluting emissions from transportation (Department of Transport, 2017). Therefore, there is a continuous tension between these two opposite beliefs to impact on the feeling of moral obligation to reduce car use for the sake of the environment.

Moreover, several studies in environmental research have concluded that, once the stimuli of green interventions are removed, people tend to go back to the previous behaviour that normally is associated with a counter-environmental behaviour (Abrahamse, et al., 2005; Unsworth, et al., 2013); therefore, this leads to the idea that feeling morally obligated to act and protect the environment can be activated as well as deactivated.

Additionally to the belief ratio, a ratio between negative and positive values towards the protection of the environment is included in order to amplify or decrease the abandonment rate of a moral obligation. Empirical findings have shown that values are part of the formation of personal norms (Chng, et al., 2018), but they covary with beliefs (Pronello & Gaborieau, 2018); therefore, it is reasonable to think that values can also affect the abandonment rate.

Figure 34 shows a simplified stock-and-flow diagram of the three stocks and four flows used in the simulation model to reflect the formation, activation and abandonment of personal norms towards reducing car use for the sake of the environment.

Figure 34. Personal norms dynamic diagram.



Source: Own elaboration. Drawing done on Vensim DS.

The following equations take part in the modelling of personal norm formation and activation towards reducing car use, which lead to adopting alternative transport modes. Table 20 shows the parameters that were set for the initial simulation.

(8) $$\text{LoMO}\ (t) = LoMO_0 + \int_{2002}^{2017} [PNAR_{(t)} + RtFPN_{(t)} - PNFR_{(t)}]\, ds$$

LoMO = Lack of moral obligation to engage with reducing car use

PNAR = Personal norm abandonment rate

RtFPN = Resistance to forming personal norm

PNFR = Personal norm formation rate

(9) $$PNFR\ (t) = \frac{AfAR + AfSN + AfPA}{time\ to\ form\ a\ PN}$$

AfAR = Adoption from ascription of responsibility

AfSN = Adoption from subjective norms towards low-carbon mobility use

AfPA = Adoption from problem awareness

(10) $$SNPEB\ (t) = LoMO * \frac{Alternative\ modes\ users}{(Alt\ modes\ users + Car\ Users)} * MtCPEB * IA$$

SNPEB = Subjective norms towards low-carbon mobility

MtCPEB = Motivation to comply (PEB group)

IA = Internal Attribution[49]

(11) $$AfPA\ (t) = \frac{PNFP * LoMO * AoCP}{\beta_{DP} * DPDCC}$$

AoCP = Awareness of car pollution consequences

DPDCC = Degree of psychological distance of climate change

PNFP = Personal norm formation process towards low-carbon mobility

(12) $$PNFP\ (t) = PNFP_0 + \int_{2002}^{20017} [PNFR_{(t)} - \left(RtFPN_{(t)} + PNIR_{(t)}\right)] ds$$

PNIR = Personal norm internalisation rate

(13) $$RtFPN\ (t) = PNFP * PSNeff * (\frac{BIcc}{GVOtPEB})$$

PSeff = Personal norm effectiveness[50]

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[49] Internal attribution is the concept used to refer to the emotional reactions that are triggered by harmful behaviours (Weiner, 2000; Bamberg & Möser, 2007). In the model, both internal attribution and ascription of responsibility were included and treated differently to accept the possibility that an individual can objectively acknowledge that the causes of the problem could be ascribed to their characteristics, traits or abilities, but that does not necessarily lead them to accept a degree of responsibility for the problem.

[50] This just represents the sum of subjective norms and descriptive norms.

GVOtPEB = General value orientation towards wellbeing of others[51]

(14) $$PNIR\ (t) = \frac{(PNFP * VDr)}{time\ to\ form\ a\ PN}$$

(15) $$VDr\ (t) = \frac{GVOtPEB}{(GVOtPEB + GVOtS)}$$

VDr = Value discrepancy rate[52]

GVOtS = General value orientation towards self-wellbeing

(16) $$PNIR\ (t) = \frac{PNFO * VDr}{time\ to\ internalise\ personal\ norm}$$

(17) $$PNAP\ (t) = PNAP_0 + \int_{2002}^{20017} [PNIR_{(t)} - PNAR_{(t)}] ds$$

(18) $$PNAR\ (t) = PNAP * \frac{(BCC * GVOtS)}{(BPT * GVOtPEB)}$$

PNAP = Personal norm adoption process

BCC = Belief that cars do not contribute to pollution

BPT = Belief that PT is the main mode to tackle pollution

[51] Environmental researchers have found that old behaviours can block the formation of personal norms (Bamberg, 2013); for this reason, behavioural intention is linked to the resistance to form PN rate.

[52] Ratio computed by dividing general value orientation towards wellbeing of others and self-wellbeing.

Table 20. Initial parameters Personal Norms sub-model.

Model variable	Parameter	Paper/source
Initial value $LoMO_0$	3.5 (Likert Score)	Based on a paper by Abrahamse et al. (2009)
Adoption from ascription of responsibility	0.5 (dmnl)	Based on papers by Abrahamse et al. (2009) and Bamberg and Schmidt (2003).
Motivation to comply (PEB group)	1 (dmnl)	Based on Bamberg and Möser (2007) and Chng et al. (2018). Treated as a % and not as a Likert score to reflect the fact that it is an index to weight the influence of SN.
Internal Attribution	0.23 (Likert Score)	Based on Bamberg and Möser (2007).
β_{dp}	0.727 (Likert Score)	Based on Spence et al. (2012)
Initial value PNFP and PNAP	0 (Likert Score)	The model assumes that the individual does not have any level of personal norm formation in the first period of simulation.
General value orientation towards wellbeing of others and self-wellbeing	3.2 (Likert Score) 1.5 (Likert Score)	Based on Schwartz (1977) and Bamberg and Möser (2007).
Delay time personal norm formation and acceptance	2 years	Based on the "Public attitudes to climate change and the impact of transport in 2011"
Belief that PT is the main mode to tackle pollution	0.4 (Likert Score)	Based on the "Public attitudes to climate change and the impact of transport in 2011"
Belief that cars do not contribute to pollution	0.2 (Likert Score)	Based on the "Public attitudes to climate change and the impact of transport in 2011"

Source: Own elaboration.

6.3.3 Social norms towards car use and alternative transit modes

As it was explained in the introductory section for the normative sub-model, social norms have been proposed as guidance for an individual's behaviour (Bamberg & Möser, 2007); this way, individuals can gather information about which behaviours are appropriate. From a dynamic point of view, social norms are seen as important factors to explain societal processes because they can generate system rigidity (the system's behaviour does not change) if the circumstances do not change radically (Ulli-Beer, et al., 2010). In the Pro-Environmental Behavioural Change Model, the social norms' impact is computed by following the rationale of Ulli-Beer, et al.'s (2010) model; the influences of social norms (towards car use and alternative transport modes) are represented by the fraction of people that follow the social norm. This means that the social norms have a higher impact when the groups of adopters (car users vs non-car users) increase. Additionally, each social norm is weighted by an additional factor, which in the case of subjective norms is the motivation to comply and for descriptive norms is social identification. The effects of subjective and descriptive norms have been found to be significant in several studies, improving the explanation of models such as TPB (Rivis & Sheeran, 2003; Gardner & Abraham, 2010; Chng, et al., 2018). Subjective norms are defined as the social pressure perceived by an individual based on whether or not the group will approve one's behaviour (Ajzen, 1991). For this reason, subjective norms are weighted by the motivation to comply as the strength of this perception will depend on whether or not the individual feels motivated to comply with the expectations of others (Belgiawan, et al., 2017).

Descriptive norms are defined as the perception an individual develops regarding whether or not other people are engaging in a given behaviour (Chng, et al., 2018). In other words, it reflects the individual's belief about what others are actually doing (Phua, 2013). Based on this definition, social identity plays an important role to increase or reduce the effect of the descriptive norm. Social identity is defined as the individual's perception of the self, derived from their group membership (Christensen, et al., 2004); thus, the individual can get an idea about what the typical behaviour is. This way, descriptive norms facilitate the adaptation of the individual's behaviour by comparing their self-identity and the social identity within a group. If the individual feels that their identity matches the typical behaviour seen in the group then it is more probable that they will act in the same way as others, which leads to boost the individual's self-esteem (Phua, 2013) and to develop a feeling that they are contributing to a common cause (Van der Werff, et al., 2013). However, researchers have found that descriptive norms can be less effective to guide individuals to identify appropriate behaviours (Christensen, et al., 2004) as they do not include an intrinsic evaluation of the behaviour performed. Additionally, some people in some circumstances may experience surprise rather than negative feelings when descriptive norms are not followed (Snyder & Fromkin, 1977). Therefore, descriptive and subjective norms provide different sources of social pressure to impact on people's behaviour, especially when it is about pro-environmental behaviours (Chng, et al., 2018). That is why both norms have been included in the simulation model.

The following equations describe the variables regarding descriptive and subjective norms:

(19) $$PSNE\ (t) = PDN + PSN$$

PSNE = Perceived social norms' effectiveness

PDN = Perceived descriptive norms

PSN = Perceived subjective norms

(20) $$PDN\ (t) = \frac{Car\ commuters}{(non-car\ commuters + car\ commuters)} * SIwC$$

(21) $$PSN\ (t) = \frac{Car\ commuters}{(non-car\ commuters + car\ commuters)} * MtC$$

SIwC = Social identification with car commuters

MtC = Motivation to comply with car commuting subjective norms

Table 21. Initial parameters Social Norms variables.

Model variable	Parameter	Paper/source
Social identification with car use and commuters	1 (Dmnl)	Based on a paper by Christensen et al. (2004).
Motivation to comply with car commuting subjective norms	1 (Dmnl)	Based on papers by Chng et al. (2018) and Bamberg and Schmidt (2003).

Source: Own elaboration.

6.3.4 Dynamic hypothesis for normative sub-model

The normative sub-system develops the following feedback loop: a car driver is assumed to feel a low level of moral obligation to reduce car use, otherwise he/she would not drive (assuming that there are no financial restrictions to keeping and running a car). To break this pattern, external sources trigger the formation of personal norms; descriptive and subjective norms towards car use reduction, ascription of responsibility and awareness of car pollution can accelerate the formation of personal norms. In parallel with this process, other external and internal sources play a role to decelerate this formation: normative values and the perception of social norms towards car use. Therefore, the PN formation rate and the resistance to form PN rate interact in parallel, determining the speed of formation of a moral obligation before it is adopted. If the psychological determinants are strong enough to form a personal norm, then the time it takes to create a personal norm and the ratio of general value orientation between self-centric values and social-centric values will determine if the moral obligation is adopted. Once the moral obligation is adopted, this psychological determinant will remain relevant as long as the belief about car pollution does not change, and the values towards protecting the environment are significantly higher than values related to self-wellbeing. As was explained before, the PEBCM assumes that there is a possibility in which the moral obligation can be abandoned (partially or totally) if the belief about the harm caused by cars is relaxed.

6.3.5 Car ownership sub-model

The car ownership sub-model represents the effect that car possession has on strengthening the behavioural intention towards driving. In both the literature and the interviews, it was found that there is an important recognition of the reinforcing loop that car ownership creates with car use.

Different approaches have been taken to estimate car ownership. From an economic point of view, income has normally been discussed as a predictor of car ownership (Dargay, 2001). It is believed that, the higher the income, the higher the probability of having and using a car (Paulley, et al., 2006; Jifeng, et al., 2008). From a psychological point of view, attitudinal and normative factors undertake an important part in predicting the probability of future car purchases (Belgiawan, et al., 2017). The rationale goes as follows: private cars have been people’s main choice of travelling in modern urban life (Sterman, 2000; Bajracharya, 2016); thus, if an individual can afford to buy a car, then the choice to be more inclined to drive than alternatives is enabled because there are multiple psychological factors accelerating the habit of driving: safety, convenience, flexibility, feeling of control, social status, emotional attachment, etc. (Hiscock, et al., 2002; Whitmarsh & Xenias, 2015; Gossling, 2017). This way, in car-centric (Abrahamse, et al., 2009) and capitalist societies (Jifeng, et al., 2008), it is possible to find a significant effect of social norms towards purchasing/owning a car as the society strengthens the mental model ‘cars are the main transport mode’ and ‘they give higher social status’. For this reason, ‘People's car purchase intention/owning intention’ is estimated as:

(21) $$CPI\ (t) = (\beta_{sa} * SA) + (\beta_I * I) + (\beta_{snbc} * SNBC) + \left(\alpha_{adjustment} * \beta_{mhi} * MHI\right) + LoJ$$

(22) $$SNBC\ (t) = \frac{1}{n}\sum_{i=1}^{n}(e_i * m_i)$$

(23) $$LoJ\ (t) = LoJ_0 + \int_{2002}^{2017} LoJ_{rate_s}\, ds$$

(24) $$LoJ_{rate}(t) = \frac{CO+SwD}{CoRC}$$

CPI = People's car purchase intention/owning intention

SA = Symbolic affective factors

I = Independence

SNBC = Social norms towards buying a car

MHI = Median household disposable income (α: index to adjust income scale)

LoJ = Level of justification

e_i = Expectations of group i towards buying a car.

m_i = Motivation to comply with the expectations of group i.

CO = Car ownership

SwD = Satisfaction with driving

CoRC = Cost of running a car

Noted that CPI represents the level of buying or owning a car since, once someone buys a car, then the problem becomes an opportunity cost analysis. Having a car can also be seen as a latent loss since it reflects the potential benefit that an individual is missing out on by keeping it. Thus, owning a car can be seen as a ‘repetitive’ car purchase every time it is decided not to sell it. Then, it is expected that, the more often and the longer the car use, the higher the intensity to keep buying/owning a car.

Why does the model follow this reasoning? Because, during the interviews, respondents recognised that car use depends on the construct ‘justification of car ownership’. In other words, people become more dependent on using their car because, once they have invested in it, they feel the necessity of using it to justify the investment. People do not want to feel this negative feeling of leaving a considerable ‘investment’ at home by using alternative transport modes. Based on that, and the opportunity cost perspective, it is reasonable to think that ‘the intention to buy a car’ prevails even when people have already bought one. Individuals are subconsciously thinking that the car needs to be used because it is the way they perceive a positive return (or avoid the feeling of loss). This feedback loop represents the ‘desire to own a car’.

Table 22. Parameters for car ownership sub-model.

Model variable	Parameter	Paper/source
Expectation of family to buy a car	2.22 (Likert score)	Based on results Belgiawan, et al. (2017) [53]
Motivation to comply (e.g. family)	1 (Likert score)	Based on results Belgiawan, et al. (2017)
Expectation of friends to buy a car	2.22 (Likert score)	Based on results Belgiawan, et al. (2017)
Motivation to comply (friends)	1 (Likert score)	Based on results (Belgiawan, et al., 2017)
Expectation of co-workers to buy a car	2.22 (Likert score)	Based on results (Belgiawan, et al., 2017)
Motivation to comply (co-workers)	1 (Likert Score)	Based on results (Belgiawan, et al., 2017)
Median household disposable income	£ 29,400	Value extracted from ONS.GOV.UK (2019)
Cost of running a car	£ 1,944	A report, commissioned by Kwik-Fit[54], has calculated that the average UK motorist spends £162 per month on running their car. That covers things like fuel, insurance, road tax and servicing, and does not include the cost of the car itself.
Symbolic affective (attitudinal factor)	3 (Likert score)	Based on results (Belgiawan, et al., 2017)
Independence (attitudinal factor)	3 (Likert score)	Based on results (Belgiawan, et al., 2017)

Source: Own elaboration.

6.3.6 *Satisfaction sub-model*

As was explained in the previous section, the satisfaction sub-model represents the relationships between car use and the attachment to it because of pleasant experiences. The idea is that such satisfaction will increase the desire to use the car, and, the more frequently this happens,

[53] The results of the paper estimated an average of 2.22 for social norms (e_i * m_i). That is why the assigned score for these variables is the same for all since the model was adapted to match the overall average in the initial condition.

[54] https://www.thecarexpert.co.uk/average-car-costs-more-than-160-per-month-to-run/.

the stronger the relationship between the two. Additionally, the logic behind attractiveness of travelling by car was replicated for alternative transport mode use. The only differences are the sources that increase the level of satisfaction.

Car satisfaction is enhanced by functional attributes such as quality of road and infrastructure, quality of car, and the sense of flexibility and autonomy. Those attributes amplify the satisfaction levels every time drivers drive. That amplification is weighted by the times people drive a year because it is expected that, the more people drive, the more salient their satisfactory experience (expected vs actual evaluation) (Ettema, et al., 2013), and the average score for the perceived satisfaction level per trip. ‘Normal satisfaction per trip’ can be the score associated with the overall perception of all the attributes, while the smooth function can help the ‘external’ sources that can intervene to remove or improve functional factors related to car satisfaction or public transportation satisfaction. For example, public transportation is constantly making improvements, but they are not necessarily perceived since drivers normally have an overall negative perception of the service (Tsirimpa, et al., 2010). This way, the model is capturing the total satisfaction level a year and represents two different perspectives to compute the overall index. Additionally, the satisfaction level is decreased by commuting time. It is assumed that people would enjoy the transport choice less if the commuting time increases. The reason for this is because time is one of the most important variables when it comes to evaluating travel mode choice (Birr, et al., 2014).

In a similar manner, it is expected that public transportation will increase alongside the satisfactory effect reward that people receive every time they take the public transportation. The logic is the same; however, the functional variables to compute satisfaction are perceived overall quality PT, social acceptability and public transportation accessibility. These variables were mentioned in the interviews, and also they can be found in many of the analyses of how public transport can attract more people (Şimşekoğlu, et al., 2015). Perceived overall quality was created from the paper by Fellesson and Friman (2012), which has been adapted to fit the model function of satisfaction with PT.

(25) $$SwD\ (t) = SwD_0 + \int_{2002}^{2017} CwDS_{rate(s)}\, ds$$

(26) $$CwDS\ (t) = \frac{TCY*NDS}{TC} * SMOOTH\ (x) = [RQ, CQ, SFA]$$ [55]

(27) $$SwPT\ (t) = SwPT_0 + \int_{2002}^{2017} CwPT_{rate(s)}\, ds$$

(28) $$CwPT\ (t) = \frac{NPTS*TPTT}{TCPT} * SMOOTH(x) = [\frac{POQ}{TPTT},\ PTACC, SACEP]$$

(29) $$POQ\ (t) = \sum_{i=1}^{5} \beta_i * FQ_i * \alpha_{sensitivity\ factor\ poq}$$

SwD = Satisfaction with driving

CwDS = Change with driving satisfaction rate

TCY = Trips per person per year commuting by car

NDS = Normal driving satisfaction per trip

TC = Time commuting by car

RQ = Road & infrastructure quality

CQ = Quality of car

SFA = Sense of flexibility and autonomy

SwPT = Satisfaction with public transportation

CwPT = Change with public transportation rate

NPTS = Normal public transportation satisfaction

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[55] Smooth function is meant to be a build-in function to help to deal with information delays; therefore, it perfectly reflects expectations, where, in this case, the factors are road quality and car quality (see VENSIM documentation).

TPTT = Trips per person per year public transport

TCPT = Time of commuting on public transportation

POQ = Perceived overall quality with PT service

PTACC = PT accessibility

SACEP = Social acceptability of PT

FQi = Factor of overall quality i

Table 23. Parameters for satisfaction sub-model.

Model variable	Parameter	Paper/source
Normal driving satisfaction	0.8 (Dmnl)	Based on Bajaracharya (2016)
Quality of road & infrastructure	0.8 (Dmnl)	Based on Bajaracharya (2016)
Quality of car	0.8 (Dmnl)	Based on Bajaracharya (2016)
Sense of flexibility & autonomy (car commute)	1.5 (Likert score)	Based on interview results and model adjustment: there is a recognition that the feeling of flexibility is important and affects car satisfaction.
Perceived overall quality with PT service	6.604 (Likert scale)	Based on Fellesson & Friman, 2012
Social acceptability of PT	0.8 (Dmnl)	Based on interviews
PT accessibility	0.7 (Dmnl)	Based on Bajaracharya (2016)
Normal public transportation satisfaction	0.2 (Dmnl)	Based on Bajaracharya (2016)

Source: Own elaboration.

6.3.7 Intentional process towards alternative transport mode

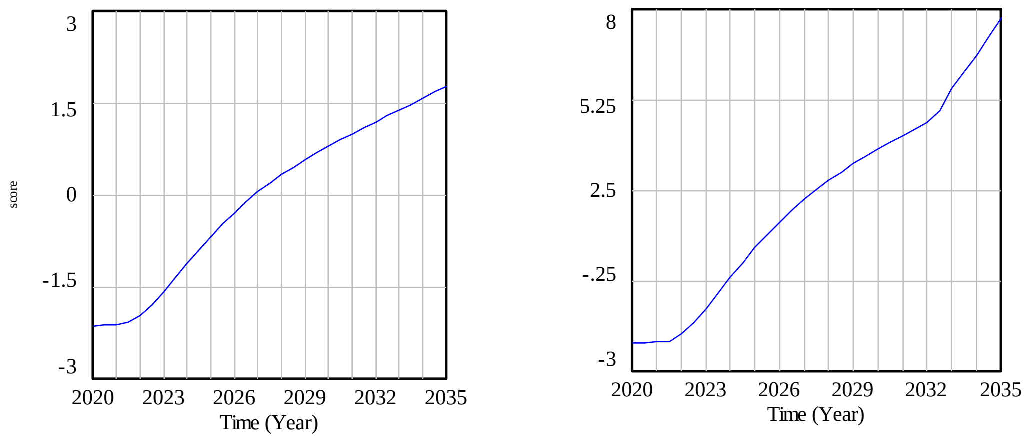
The next sub-model to describe is the one that represents alternative transport mode use. As was explained earlier, the Pro-Environmental Behavioural Change Model is a bi-modal representation of the transit dynamics. Therefore, it will use public transportation literature and interview insights to construct a proxy and represent a section for alternative transport modes.

Following the same logic as the Theory of Planned Behaviour (Ajzen, 1991) and norm-activation model (Schwartz, 1977), it is assumed that the intensity of the behavioural intention to take public transportation depends on intention, perceived behavioural control, social norms towards public transport, personal norms and attitudes. Therefore, this sub-model based its rationale on moral obligations and utility and cost calculations (Bamberg & Schmidt, 2003). The difference here is, instead of assuming a linear behaviour to calculate level of intention (the closest antecedent to predict behaviour), the curve will be represented as an s-shape.

The formulation of intention as an s-shape is intended to reflect a declining marginal sensitivity to changes (see Figure 35). In an initial state, where the intentional and normative processes towards commuting by car are the dominant processes, people would see the modal shift as less attractive than keeping the old behaviour (intention towards PT < 0). The negative outcomes at the beginning of the simulation periods would make the adoption of public transportation slow (and more painful), but, once a critical mass adopts and uses the public transportation more, then the impact of all the normative and intentional sub-models that support car use will decrease, making the intention towards public transportation increase faster (since intention towards public transportation > 0). This way, the model captures the reason behind the temporal dimension of psychological distance: since climate change is about preventing future outcomes, it is difficult for people with lower altruistic values or moral commitment (Schwartz, 1977; Pronello & Gaborieau, 2018) to behave in a way that requires immediate changes. The majority of the people tend to underestimate the negative consequences that are far away in the future (McDonald, et al., 2015). Furthermore, people normally avoid actions that involve purely future rewards, because it is preferable to perform actions that give immediate rewards (Spence, et al., 2012). In the context of driving a car, it is more desirable to have a pleasant experience by driving than decreasing the comfortability today to help decrease future negative consequences for benefits that might not be clear to the individual.

Sources that accelerate shifting from cars to public transportation modes are attitudes and transport priorities. This is another modification from the Theory of Planned Behaviour. Instead of using control beliefs to calculate the intention towards public transportation, the model added the implications of transport priorities as a proxy for control belief. Transport priorities represent the beliefs about what is important to consider in prioritising the public transit (Şimşekoğlu, et al., 2015). Therefore, it makes sense to model the intention towards public transportation by using a set of variables that represent expectations of quality attributes that can encourage modal shifting, since drivers tend to not consider other means of transport (and some may never have even used any). This way, it can be said that priorities will be the facilitators for drivers to shape a control belief about how easy/difficult it is to take public transportation. If the level of those expected values is high, then it will be expected that people will think that it is easy to use public transportation, so then the adoption is accelerated.

Figure 35. PEBCM simulation results: Intention towards public transportation (initial vs modified conditions).



Source: Own elaboration. Graphs extracted from VENSIM. On the left, intention towards taking public transportation when attitude towards car < attitude towards public transportation. On the right, intention towards taking public transportation when attitude towards car > attitude towards public transportation.

The formal mathematical expressions for this part of the model are as follows:

(30) $$PTC\ (t) = ATTC * ImI$$

(31) $$IPT\ (t) = ImI * \sum_{i=1}^{5} \beta_{fpti} * FPT_i$$

(32) $$PTP\ (t) = \sum_{i=1}^{3} \beta_{ptpi} * PTP_i$$

PTC = Public transportation commuting consideration

ImI = Implementation intentions towards public transportation

IPT = Intention towards public transportation

FPT_i = Factor of public transportation (i= car behavioural intention, attitude towards PT, social norms towards PT, resistance to change adoption, transport priorities).

PTPi = Transport priorities i (i= priority of convenience, priority of flexibility, priority of safety and security).

Table 24. Parameters for the initial condition Public Transportation**.**

Model variable	**Parameter**	**Paper/source**
Priority of convenience	5.97 (Likert score)	Based on Şimşekoğlu, et al., 2015
Priority of flexibility	5.06 (Likert Score)	Based on Şimşekoğlu, et al., 2015
Priority of safety and security	2.71 (Likert Score)	Based on Şimşekoğlu, et al., 2015

Source: Own elaboration.

6.3.8 Traffic and environmental pollution sub-model

Finally, the traffic and environmental sub-model is included in the simulation to reflect an organic set of constraints for car use.

Traffic congestion is the result of transport demand and supply. In this model, traffic has been simplified since it is not considering the demand of all methods of transit (cars, taxis, buses, bicycles, motorcycles, etc.) for transportation facilities. Instead, traffic congestion is estimated as the fraction of cars using the capacity available for cars, so basically the assumption is roads are exclusively for only one method of transport. While it is true that this may sound unrealistic, the main goal of the model is not modelling an accurate measurement of traffic congestion; instead, the model is looking at the behavioural intention of car use. Therefore, it only needs a way to acknowledge the fact that: more cars = more traffic, then driving is less attractive, and constrains the preference for cars. This way, the model restricts car use because the capacity is over the maximum, hence a negative feedback loop balances the formation of the satisfaction levels when commuting by car, which in turn decreases the attitude towards driving.

To tackle the problems of car pollution, many countries have been deploying interventions to increase the environmental awareness and decrease the significant impact of driving on climate change. That is why this model has the following loop: the more cars on the road, the higher the emissions of pollution. However, if car pollution goes over the capacity (amount of CO_2 allowed to be emitted), then it is expected that communicational efforts to increase the environmental awareness will take place, in order to meet the goals planned by the government. It is true that, in a scenario where the levels of pollution are unsustainable, it is expected that governments would act by adding new laws that restrict car use severely. However, since these actions are uncertain, the simulation model just added a reasonable logical description of an action-reaction process. In other words, the system will restrict car use through impacting the normative/intentional processes negatively when the pollution levels are over the goals set up by the UK's carbon budget.

(33) $$CCiE\ (t) = CCiE_0 + \int_{2002}^{2017} CADP_s\, ds$$

(34) $$CADP\ (t) = PoD * (\beta_0 + BIcc * \beta_1)$$

(35) $$NoC\ (t) = CCiE * OR$$

(36) $$TCi\ (t) = \frac{current\ vehicle\ per\ km}{capacity\ vehicle\ per\ km}$$

(37) $$TCC\ (t) = ATL * ASFF * TCi$$

(38) $$TKMC\ (t) = ATL * TTCC$$

(39) $$ToCO2\ (t) = ToCO2KM * TKMC$$

(40) $$CPCEFF(t) = \frac{ToCO2}{CO2\ Budget}$$

(41) $$AoCPC\ (t) = AoCPC_0 + \int_{2002}^{2017} AoCPC_{rate(d)}\, ds$$

(42) $$AoCPC_{rate}(t) = ATTClc * RCFSE * AoCPC * (ECT - AoCPC)$$

ECT = Environmental communicational target

RCFSE = Reduction of car use for the sake of the environment

AoCPC = Awareness of car pollution consequences

EACT = Environmental awareness communicational target

CPCEFF = Car pollution communication efforts to decrease global warming

ToCO2KM = Tonnes of CO_2 from car commuting per kilometre

ToCO2 = Tonnes of CO_2 from car commuting

TTCC = Total trips by car commuters

TKMC = Total kilometres travelled by car commuters

ASFF = Average speed by car when commuting (km/hr)

ATL = Average trip length (km)

TCC = Time taken to commute by car

TCi = Traffic congestion index

CCie = Car commuters in England

CADP = Car commuters' adoption rate

BIcc = Behavioural intention towards car commuting

NoC = Number of cars in England

OR = Occupancy rate (%)

Table 25. Parameters for the initial condition environmental & traffic sub-model.

Model variable	**Parameter**	**Paper/source**
Reduction of car use for the sake of the environment	0.0138792 (Dmnl)	Growth rate estimated from ATT0332[56] -Reduction of car use for the sake of the environment.
Score on true EAG	5 (Likert Scale)	Based on Abrahamse, et al., 2009; Bamberg & Schmidt, 2003
Score on false EAG	3.5 (Likert Scale)	Based on Abrahamse, et al., 2009; Bamberg & Schmidt, 2003
Number of lanes per road	2 (roads)	
Average trip	Auxiliary with Lookup[57]	Data extracted from NTS0405
Trip rate growth (car trip)	-0.0161836 (Dmnl)	Estimated from nts0412[58]. TRIPS per person per year when commuting by car between 2002 and 2019
Occupancy rate (%)	0.867 (Dmnl)	According to the data from the Department for Transport, on average 86.7% of people who commute by car, do it as a driver (average estimated 2002 and 2018)

Source: Own elaboration.

6.4 Summary

This chapter presented a complete review of the equations included in the simulation model. Five subsystems were developed to represent how several psychological determinants are involved in explaining car and public transportation in the context of commuting. The intentional sub-model refers to how an individual develops an intention to perform a given behaviour, in this case this is either driving or taking the public transportation. The normative sub-model shows how a person

[56] https://www.gov.uk/government/organisations/department-for-transport/about/statistics.

[57] Historical data was inserted in the computation of the variable.

[58] https://www.gov.uk/government/organisations/department-for-transport/about/statistics.

would evaluate and internalise the necessity of reducing car use or the feeling of social pressure towards driving. The car-ownership sub-model represents the dynamic process about how a person form the desire of acquiring a car, as well as the feeling of car ownership justification. The satisfaction sub-model illustrates the pleasure derived from travel mode choice. Finally, the traffic and environmental pollution sub-model indicates how the use of car can increase the levels of traffic and pollution, and how these issues are the constraints of driving satisfaction and the perceived behavioural control towards car commuting.

Having outlined the background of all the subsystems incorporated and presented the main sources to support the equations and parameters included in the model, the next chapter presents the steps deployed to validate the simulation model.

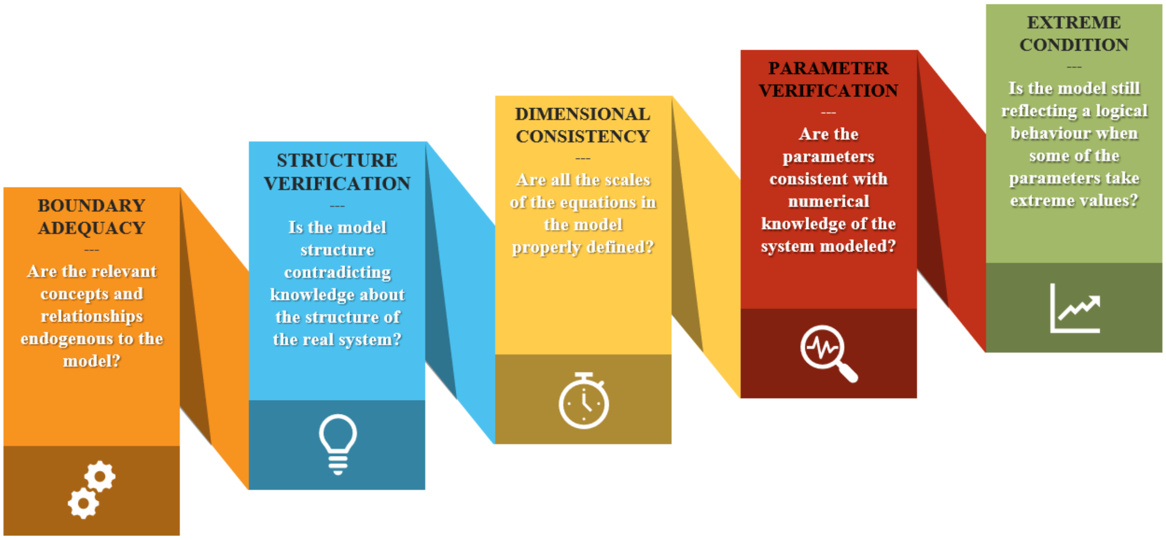
7 Model validation

The aim of this chapter is to consolidate the whole validation process. Some tests of the validation process were part of the formulation and construction of the mathematical model, thus a few of these were already explained in the previous sections. For that reason, this chapter will review the validation assessments completed so far, and then it will continue with the explanation of the remaining tests. The validation process of a system dynamics model can be divided into: (1) structural validity and (2) behavioural validity.

7.1 Validation steps recap: what has been validated so far?

Identification of the appropriate simulation model structure is a multidimensional process that involves several steps to reflect the right logical structures, and mathematical expressions. Forrester and Senge (1980) presented several steps to assess the structural validation of a system dynamics model. In this project, the same steps were followed and discussed. Table 26 shows the tests that correspond to the structural validity test.

Table 26. Tests reviewed in the paper by Forrester and Senge (1980) for structural validity.



Source: Own elaboration based on the paper by Forrester and Senge (1980).

These tests are the most commonly used in SD to validate the structure of a model. Normally, when the development of the conceptual model begins, the **boundary adequacy** and the **structure verification** tests are addressed. When the project moves to the mathematical phase, real data is collected and integrated to create the equations (e.g., coefficients from previous regression models, average obtained from surveys, etc.); therefore, the **dimensional consistency** and **parameter verification tests** are performed. Once the simulation model is fully operational, two more tests are run: **extreme condition test** and **structurally oriented behaviour test** (also known as behavioural sensitivity test). The chapters previously presented have addressed the following two tests:

1. Boundary adequacy test: Chapter 3, Chapter 5 and Chapter 6 have explained the development of the conceptual models and the dynamic hypotheses. These processes implied the selection of which variables were endogenous and exogenous. Chapter 3 introduced the first attempt to construct the conceptual model. By using the literature review and the modeller's knowledge, the first filter to decide the major endogenous and exogenous variables was applied. Then, the interview results (Chapter 5) provided an input to improve the focus and purpose of the model, generating a larger set of endogenous and exogenous variables. The final list of endogenous and exogenous variables has been consolidated during the formalisation of the simulation model. Figure 36 summarises the major endogenous and exogenous variables in the model.

To decide whether or not the level of aggregation of each variable was correct, the variables of the mental model were compared with the level of aggregation of the main theories in environmental psychology (e.g. TPB). In this case, the variables that are internally generated by the model are also endogenous variables in the main models found in environmental psychology (Chng, et al., 2018; Kroesen, et al., 2017; Bamberg, 2013; Klöckner & Blöbaum, 2010).

Other criteria adopted to decide if the variable should be exogenous or endogenous were based on the problem that the model is trying to represent. In this respect, the model is trying to understand how the behavioural intention towards driving is formed and changed; therefore, it is important to set endogenous variables related to cognitive skills and norms. These groups of variables have been stipulated as the principal mechanisms to predict behaviour and travel behaviour (Abrahamse, et al., 2009; Ajzen, 1991; Schwartz, 1977; Klöckner & Blöbaum, 2010; Bamberg & Schmidt, 2003).

Figure 36. Summary of model boundary: exogenous and endogenous variables.

Source: Own elaboration.

The boundary adequacy test is a process that remains active during the whole construction of the simulation model. The modeller is continuously answering the question: is the model considering all the necessary relationships and feedback loop structures to satisfy its purpose? For this reason, it is expected that a system dynamics model changes the definition of the boundaries every time the modeller modifies the model conceptualisation.

2. Structure verification test: the structural verification test is crucial in the overall validation process (Qudrat-Ullah & Seong, 2010; Luna-Reyes & Andersen, 2003). For the structural modification of this model, two main sources were taken in order to validate that the conceptualisation of the relationships and feedback loops was not contradicting relevant knowledge about car use and consideration of alternative transport modes: literature review and modeller's knowledge (see chapters 3 and 6), and experts in the fields of environmental psychology, transportation and environment (see Chapter 5). An additional source of validation relevant to acknowledge is the supervision inputs received during the PhD project. As in every PhD project, supervisors play a key role in the orientation and planning of the development of the theoretical frameworks, the fieldwork and the modelling process; therefore, based on the nature of this project, PhD supervision can also be taken as a validation source.

Similar to the boundary adequacy test, this test requires the question about whether the model structure is consistent with the real system that the model represents to be answered continuously. This thesis constructed three conceptual models and multiple versions for the simulation model. Chapter 6 explained the consolidated causal loop diagram (CLD B) and mathematical model, which is the one used to run the following tests.

7.2 Test: dimensional consistency

Called a mundane analysis, but still an important test (Forrester & Senge, 1980), the dimensional-consistency analysis is necessary to detect any further problems with any model's rate equation. In this thesis, this step was performed by using the feature 'check units' in VENSIM DS, which is a function that reports all the variables which do not have a measurement unit. After checking that all the variables had a unit assigned, the equations were checked again to see if there was any mathematical expression that did not have real-life meaning or contradicted the Likert score estimations according to environmental psychological theories. For instance, the following equation is part of this simulation model:

$$
\begin{aligned}
&Subjective\ norm\ towards\ buying\ a\ car \\
&\qquad = (("Expectation\ of\ Co - workers\ to\ buy\ a\ car" \\
&\qquad * "Motivation\ to\ comply\ (Co - workers)") \\
&\qquad + ("Expectation\ of\ family\ to\ buy\ a\ car\ (ei)" \\
&\qquad * "Motivation\ to\ comply\ (e.g. Family)") \\
&\qquad + (Expectation\ of\ friends\ to\ buy\ a\ car \\
&\qquad * "Motivation\ to\ comply\ (Friends)"))/3
\end{aligned}
$$

This equation describes that the score of the social norm towards buying a car is computed by two factors: (1) the coefficient for the expectations that an individual holds about how the others expect him/her to behave and (2) the individual’s motivation to comply with these expectations. In psychology, these kinds of factors are normally measured with Likert scores. Following the paper by Belgiawan et al. (2017), motivation to comply and expectations can be multiplied to compute an overall score (in a Likert scale). Thus, it is accepted in psychology that the multiplication of two Likert scores corresponds to a weighted score in the same measurement. The same process and rationale were performed for all the equations in this model (following several papers in environmental psychology such as Abrahamse, et al., 2009; Bamberg & Schmidt, 2003; Bamberg and Möser, 2007; Kroesen, et al., 2017; Klöckner & Blöbaum, 2010; thus, it is fair to conclude that this test was passed.

7.3 Test: parameter verification

The parameter verification test was conducted during the development of the mathematical model. Chapter 6 showed a set of tables to specify the sources used for the auxiliary variables and parameters that weighted the influence of some factors. An auxiliary variable in system dynamics is a variable that is part of a rate equation, or an auxiliary equation connected to a rate that determines a flow equation. In this case, many of the parameters are either constants or constants with look-up (a graph is attached to the auxiliary variable to determine the value in each period) that were computed based on the papers reviewed for this thesis. More details about the parameter verification test can be found in the previous chapter.

7.4 Test: extreme condition analysis

In this test, the modeler assigns extreme values to selected variables in the model, in order to compare the model outcomes to the expected or observed behaviour of the real system (Qudrat-Ullah & Seong, 2010). To decide whether or not the model passes this test, the outcomes obtained from the simulation during the test, should not contradict these observed or expected behaviour of the real system under similar extreme conditions. Ideally, these conditions are tested one by one, meaning that the manipulation of each exogenous variable is done separately.

In this case, the extreme condition tests were carried out by contrasting the simulation behaviour against the expected behaviour of the real system. The limited data in environmental psychology impede the comparison of the tests against observed behaviours of the real system.

Because this thesis is focused on cognitive dissonance, habits, and the formation of a moral obligation, the extreme condition values were applied in the variables that are relevant in the topic of pro-environmental behaviour and car use: Frequency of car use, personal norm formation (done via ‘Resistance to Form PN’), environmental concern, environmental attitude towards low-carbon mobility, perception of how easy is reducing car commuting, attitude towards car use, general values orientation towards wellbeing of others, adoption from ascription of responsibility, belief of cars do not contribute to pollution, and internal attribution of a harmful behaviour. Therefore, 10 extreme conditions were analysed.

7.4.1 Model configuration: extreme condition test

In PEBCM, there are more than 40 exogenous variables which can be modified to generate a new simulation scenario. Table 27 specifies the values selected for the exogenous variables in each simulated test. The table shows the base model (BM) and the test value. For example, in the first extreme condition test, the frequency of car use was modified from 5 (base model value) to 0 (test value), while the other 42 variables remained unchanged, meaning that their values were set exactly the same as they were in the base model (BM value = Test value).

After modifying the value and running the model, the resulting behaviour of four endogenous variables was analysed and compared against the expected behaviour described by the literature review (Abrahamse, et al., 2009; Ardeshiri & Vij, 2019; Bamberg & Schmidt, 2003; Carrus, et al., 2008; Kitamura, 2009; Chng, et al., 2018; Lo, et al., 2016; Belgiawan, et al., 2017; Klöckner & Blöbaum, 2010; Møller, et al., 2018; Nordfjærn, et al., 2014). The simulation outcomes of the endogenous variables were individually interpreted as if the simulated behaviour had been observed in the real system under the same extreme conditions. If reasonable outputs were observed in the model after manipulating the endogenous variables, then an extreme condition validity can be concluded. The endogenous variables that were selected for the analysis are: behavioural intention towards car commuting, population of car commuters, personal norms adoption towards low-carbon mobility, attitude towards car commuting, and attitude towards low-carbon mobility. This selection was based on the relevance of these variables in fulfilling the purpose of the model.

Table 27. Model configuration for the extreme value tests.

	Test 1	**Test 2**	**Test 3**	**Test 4**	**Test 5**	**Test 6**	**Test 7**	**Test 8**	**Test 9**	**Test 10**
Exogenous variables (values specified before running the simulation)										
Frequency of car use [Days a week]	**BM: 5** **Test: 0**	BM: 5 Test: 5	BM: 5 Test: 5	BM: 5 Test: 5	BM: 5 Test: 5	BM: 5 Test: 5	BM: 5 Test: 5	BM: 5 Test: 5	BM: 5 Test: 5	BM: 5 Test: 5
RI [Dmnl]	BM: 1 Test: 1	**BM: 1** **Test: 0**	BM: 1 Test: 1	BM: 1 Test: 1	BM: 1 Test: 1	BM: 1 Test: 1	BM: 1 Test: 1	BM: 1 Test: 1	BM: 1 Test: 1	BM: 1 Test: 1
Environmental concern [Score]	BM: 1 Test: 1	BM: 1 Test: 1	**BM: 1** **Test: 0**	BM: 1 Test: 1	BM: 1 Test: 1	BM: 1 Test: 1	BM: 1 Test: 1	BM: 1 Test: 1	BM: 1 Test: 1	BM: 1 Test: 1
Environmental Attitude towards carbon mobility [Score]	BM: 2.8 Test: 2.8	BM: 2.8 Test: 2.8	BM: 2.8 Test: 2.8	**BM: 2.8** **Test: 10**	BM: 2.8 Test: 2.8	BM: 2.8 Test: 2.8	BM: 2.8 Test: 2.8	BM: 2.8 Test: 2.8	BM: 2.8 Test: 2.8	BM: 2.8 Test: 2.8
Perception of how easy is reducing car commuting [Score]	BM: 2.7 Test: 2.7	BM: 2.7 Test: 2.7	BM: 2.7 Test: 2.7	BM: 2.7 Test: 2.7	**BM: 2.7** **Test: 6**	BM: 2.7 Test: 2.7	BM: 2.7 Test: 2.7	BM: 2.7 Test: 2.7	BM: 2.7 Test: 2.7	BM: 2.7 Test: 2.7
Attitude towards car use [Score]	BM: 3.4 Test: 3.4	BM: 3.4 Test: 3.4	BM: 3.4 Test: 3.4	BM: 3.4 Test: 3.4	BM: 3.4 Test: 3.4	**BM: 3.4** **Test: 10**	BM: 3.4 Test: 3.4	BM: 3.4 Test: 3.4	BM: 3.4 Test: 3.4	BM: 3.4 Test: 3.4
Values: wellbeing of others [Score]	BM: 3.2 Test: 3.2	BM: 3.2 Test: 3.2	BM: 3.2 Test: 3.2	BM: 3.2 Test: 3.2	BM: 3.2 Test: 3.2	BM: 3.2 Test: 3.2	**BM: 3.2** **Test: 10**	BM: 3.2 Test: 3.2	BM: 3.2 Test: 3.2	BM: 3.2 Test: 3.2
Adoption from Ascription of Responsibility [Score]	BM: 0.1 Test: 0.1	BM: 0.1 Test: 0.1	BM: 0.1 Test: 0.1	BM: 0.1 Test: 0.1	BM: 0.1 Test: 0.1	BM: 0.1 Test: 0.1	BM: 0.1 Test: 0.1	**BM: 0.1** **Test: 1**	BM: 0.1 Test: 0.1	BM: 0.1 Test: 0.1
Belief of cars do not contribute to pollution [Score]	BM: 0.2 Test: 0.2	BM: 0.2 Test: 0.2	BM: 0.2 Test: 0.2	BM: 0.2 Test: 0.2	BM: 0.2 Test: 0.2	BM: 0.2 Test: 0.2	BM: 0.2 Test: 0.2	BM: 0.2 Test: 0.2	**BM: 0.2** **Test: 3**	BM: 0.2 Test: 0.2
Internal attribution [Score]	BM: 0.6 Test: 0.6	BM: 0.6 Test: 0.6	BM: 0.6 Test: 0.6	BM: 0.6 Test: 0.6	BM: 0.6 Test: 0.6	BM: 0.6 Test: 0.6	BM: 0.6 Test: 0.6	BM: 0.6 Test: 0.6	BM: 0.6 Test: 0.6	**BM: 0.6** **Test: 4.5**
Belief of PT as the main mode to tackle pollution [Score]	BM: 0.4 Test: 0.4	BM: 0.4 Test: 0.4	BM: 0.4 Test: 0.4	BM: 0.4 Test: 0.4	BM: 0.4 Test: 0.4	BM: 0.4 Test: 0.4	BM: 0.4 Test: 0.4	BM: 0.4 Test: 0.4	BM: 0.4 Test: 0.4	BM: 0.4 Test: 0.4
value orientation toward self-wellbeing [Score]	BM: 1.5 Test: 1.5	BM: 1.5 Test: 1.5	BM: 1.5 Test: 1.5	BM: 1.5 Test: 1.5	BM: 1.5 Test: 1.5	BM: 1.5 Test: 1.5	BM: 1.5 Test: 1.5	BM: 1.5 Test: 1.5	BM: 1.5 Test: 1.5	BM: 1.5 Test: 1.5
Motivation to comply toward subjective norm PEB [Score]	BM: 1 Test: 1	BM: 1 Test: 1	BM: 1 Test: 1	BM: 1 Test: 1	BM: 1 Test: 1	BM: 1 Test: 1	BM: 1 Test: 1	BM: 1 Test: 1	BM: 1 Test: 1	BM: 1 Test: 1

Social identification with pro-environmental actions [Score]	BM: 1 Test: 1	BM: 1 Test: 1	BM: 1 Test: 1	BM: 1 Test: 1	BM: 1 Test: 1	BM: 1 Test: 1	BM: 1 Test: 1	BM: 1 Test: 1	BM: 1 Test: 1	BM: 1 Test: 1
Temporal Distance [Score]	BM: 5 Test: 5	BM: 5 Test: 5	BM: 5 Test: 5	BM: 5 Test: 5	BM: 5 Test: 5	BM: 5 Test: 5	BM: 5 Test: 5	BM: 5 Test: 5	BM: 5 Test: 5	BM: 5 Test: 5
Motivation to comply toward subjective norm toward driving [Score]	BM: 1 Test: 1	BM: 1 Test: 1	BM: 1 Test: 1	BM: 1 Test: 1	BM: 1 Test: 1	BM: 1 Test: 1	BM: 1 Test: 1	BM: 1 Test: 1	BM: 1 Test: 1	BM: 1 Test: 1
Average Speed [km/hr]	BM: 33.7 Test: 33.7	BM: 33.7 Test: 33.7	BM: 33.7 Test: 33.7	BM: 33.7 Test: 33.7	BM: 33.7 Test: 33.7	BM: 33.7 Test: 33.7	BM: 33.7 Test: 33.7	BM: 33.7 Test: 33.7	BM: 33.7 Test: 33.7	BM: 33.7 Test: 33.7
Social identification with car use and commuters [Score]	BM: 1 Test: 1	BM: 1 Test: 1	BM: 1 Test: 1	BM: 1 Test: 1	BM: 1 Test: 1	BM: 1 Test: 1	BM: 1 Test: 1	BM: 1 Test: 1	BM: 1 Test: 1	BM: 1 Test: 1
Symbolic Affective: Car ownership [Score]	BM: 3 Test: 3	BM: 3 Test: 3	BM: 3 Test: 3	BM: 3 Test: 3	BM: 3 Test: 3	BM: 3 Test: 3	BM: 3 Test: 3	BM: 3 Test: 3	BM: 3 Test: 3	BM: 3 Test: 3
Independence [Score]	BM: 3 Test: 3	BM: 3 Test: 3	BM: 3 Test: 3	BM: 3 Test: 3	BM: 3 Test: 3	BM: 3 Test: 3	BM: 3 Test: 3	BM: 3 Test: 3	BM: 3 Test: 3	BM: 3 Test: 3
Cost of running a car [Pounds]	BM: £ 1,944 Test: £ 1,944	BM: £ 1,944 Test: £ 1,944	BM: £ 1,944 Test: £ 1,944	BM: £ 1,944 Test: £ 1,944	BM: £ 1,944 Test: £ 1,944	BM: £ 1,944 Test: £ 1,944	BM: £ 1,944 Test: £ 1,944	BM: £ 1,944 Test: £ 1,944	BM: £ 1,944 Test: £ 1,944	BM: £ 1,944 Test: £ 1,944
Median household disposable income [Pounds]	BM: £ 29,400 Test: £ 29,400	BM: £ 29,400 Test: £ 29,400	BM: £ 29,400 Test: £ 29,400	BM: £ 29,400 Test: £ 29,400	BM: £ 29,400 Test: £ 29,400	BM: £ 29,400 Test: £ 29,400	BM: £ 29,400 Test: £ 29,400	BM: £ 29,400 Test: £ 29,400	BM: £ 29,400 Test: £ 29,400	BM: £ 29,400 Test: £ 29,400
Quality of Car [Score]	BM: 0.8 Test: 0.8	BM: 0.8 Test: 0.8	BM: 0.8 Test: 0.8	BM: 0.8 Test: 0.8	BM: 0.8 Test: 0.8	BM: 0.8 Test: 0.8	BM: 0.8 Test: 0.8	BM: 0.8 Test: 0.8	BM: 0.8 Test: 0.8	BM: 0.8 Test: 0.8
Quality of Road Infrastructure [Score]	BM: 0.8 Test: 0.8	BM: 0.8 Test: 0.8	BM: 0.8 Test: 0.8	BM: 0.8 Test: 0.8	BM: 0.8 Test: 0.8	BM: 0.8 Test: 0.8	BM: 0.8 Test: 0.8	BM: 0.8 Test: 0.8	BM: 0.8 Test: 0.8	BM: 0.8 Test: 0.8
Sense of flexibility & autonomy [Score]	BM: 1 Test: 1	BM: 1 Test: 1	BM: 1 Test: 1	BM: 1 Test: 1	BM: 1 Test: 1	BM: 1 Test: 1	BM: 1 Test: 1	BM: 1 Test: 1	BM: 1 Test: 1	BM: 1 Test: 1
Normal Driving Satisfaction per trip [Score]	BM: 0.8 Test: 0.8	BM: 0.8 Test: 0.8	BM: 0.8 Test: 0.8	BM: 0.8 Test: 0.8	BM: 0.8 Test: 0.8	BM: 0.8 Test: 0.8	BM: 0.8 Test: 0.8	BM: 0.8 Test: 0.8	BM: 0.8 Test: 0.8	BM: 0.8 Test: 0.8
Subjective Norms towards buying a car [Score]	BM: 5.6 Test: 5.6	BM: 5.6 Test: 5.6	BM: 5.6 Test: 5.6	BM: 5.6 Test: 5.6	BM: 5.6 Test: 5.6	BM: 5.6 Test: 5.6	BM: 5.6 Test: 5.6	BM: 5.6 Test: 5.6	BM: 5.6 Test: 5.6	BM: 5.6 Test: 5.6
time threshold (commuting by car) [Minutes]	BM: 35 Test: 35	BM: 35 Test: 35	BM: 35 Test: 35	BM: 35 Test: 35	BM: 35 Test: 35	BM: 35 Test: 35	BM: 35 Test: 35	BM: 35 Test: 35	BM: 35 Test: 35	BM: 35 Test: 35
delay time personal norms acceptance [Years]	BM: 2 Test: 2	BM: 2 Test: 2	BM: 2 Test: 2	BM: 2 Test: 2	BM: 2 Test: 2	BM: 2 Test: 2	BM: 2 Test: 2	BM: 2 Test: 2	BM: 2 Test: 2	BM: 2 Test: 2
Reduction of car use for the sake of the environment [Score]	BM: 0.014 Test:0.014	BM: 0.014 Test:0.014	BM: 0.014 Test:0.014	BM: 0.014 Test:0.014	BM: 0.014 Test:0.014	BM: 0.014 Test:0.014	BM: 0.014 Test:0.014	BM: 0.014 Test:0.014	BM: 0.014 Test:0.014	BM: 0.014 Test:0.014
Co2 Budget [Tonnes of Co2]	BM: 9.7e+006 Test: 9.7e+006	BM: 9.7e+006 Test: 9.7e+006	BM: 9.7e+006 Test: 9.7e+006	BM: 9.7e+006 Test: 9.7e+006	BM: 9.7e+006 Test: 9.7e+006	BM: 9.7e+006 Test: 9.7e+006	BM: 9.7e+006 Test: 9.7e+006	BM: 9.7e+006 Test: 9.7e+006	BM: 9.7e+006 Test: 9.7e+006	BM: 9.7e+006 Test: 9.7e+006

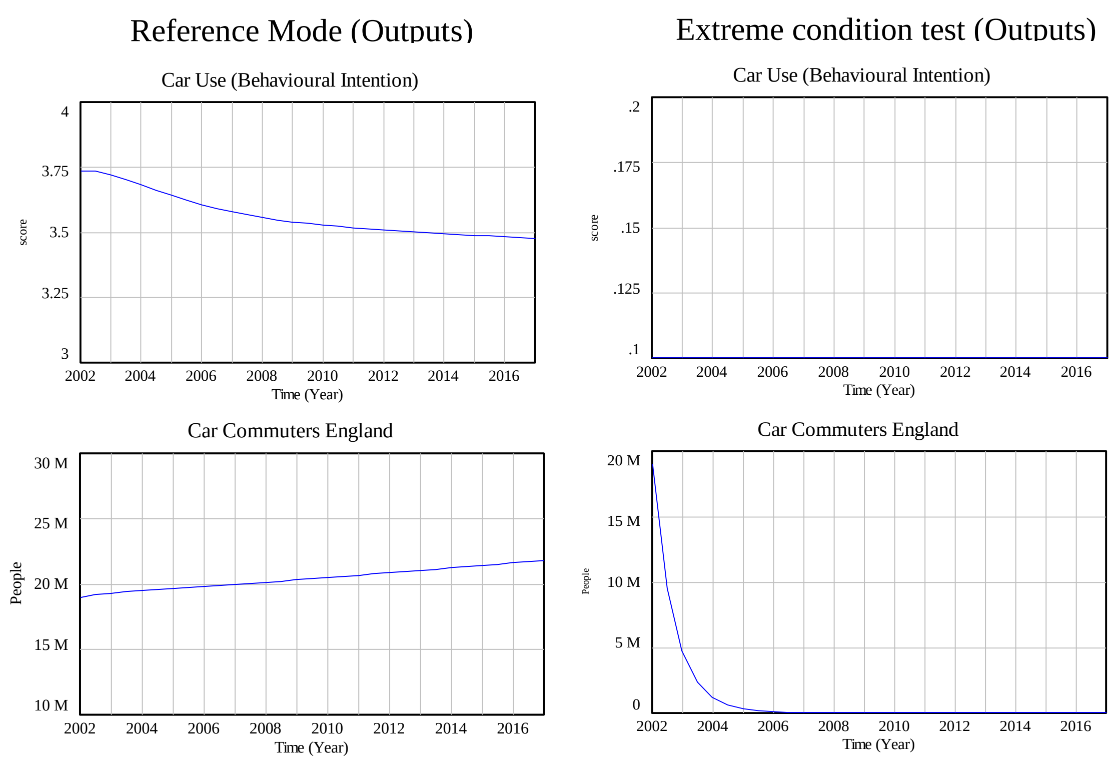
Trip rate growth (car trip) [Dmnl]	BM: -0.01442 Test: -0.01442	BM: -0.01442 Test: -0.01442	BM: -0.01442 Test: -0.01442	BM: -0.01442 Test: -0.01442	BM: -0.01442 Test: -0.01442	BM: -0.01442 Test: -0.01442	BM: -0.01442 Test: -0.01442	BM: -0.01442 Test: -0.01442	BM: -0.01442 Test: -0.01442	BM: -0.01442 Test: -0.01442
Number of Lanes [Lanes pre road]	BM: 2 Test: 2	BM: 2 Test: 2	BM: 2 Test: 2	BM: 2 Test: 2	BM: 2 Test: 2	BM: 2 Test: 2	BM: 2 Test: 2	BM: 2 Test: 2	BM: 2 Test: 2	BM: 2 Test: 2
Occupancy rate [Dmnl]	BM: 0.867 Test: 0.867	BM: 0.867 Test: 0.867	BM: 0.867 Test: 0.867	BM: 0.867 Test: 0.867	BM: 0.867 Test: 0.867	BM: 0.867 Test: 0.867	BM: 0.867 Test: 0.867	BM: 0.867 Test: 0.867	BM: 0.867 Test: 0.867	BM: 0.867 Test: 0.867
Perceived effort to take PT [Score]	BM: 3 Test: 3	BM: 3 Test: 3	BM: 3 Test: 3	BM: 3 Test: 3	BM: 3 Test: 3	BM: 3 Test: 3	BM: 3 Test: 3	BM: 3 Test: 3	BM: 3 Test: 3	BM: 3 Test: 3
Transport priorities [Score]	BM: 0.7162 Test: 0.7162	BM: 0.7162 Test: 0.7162	BM: 0.7162 Test: 0.7162	BM: 0.7162 Test: 0.7162	BM: 0.7162 Test: 0.7162	BM: 0.7162 Test: 0.7162	BM: 0.7162 Test: 0.7162	BM: 0.7162 Test: 0.7162	BM: 0.7162 Test: 0.7162	BM: 0.7162 Test: 0.7162
Trip rate growth (AT trip) [Dmnl]	BM: 0.00315233 Test: 0.00315233	BM: 0.00315233 Test: 0.00315233	BM: 0.00315233 Test: 0.00315233	BM: 0.00315233 Test: 0.00315233	BM: 0.00315233 Test: 0.00315233	BM: 0.00315233 Test: 0.00315233	BM: 0.00315233 Test: 0.00315233	BM: 0.00315233 Test: 0.00315233	BM: 0.00315233 Test: 0.00315233	BM: 0.00315233 Test: 0.00315233
PT accessibility [Score]	BM: 0.7 Test: 0.7	BM: 0.7 Test: 0.7	BM: 0.7 Test: 0.7	BM: 0.7 Test: 0.7	BM: 0.7 Test: 0.7	BM: 0.7 Test: 0.7	BM: 0.7 Test: 0.7	BM: 0.7 Test: 0.7	BM: 0.7 Test: 0.7	BM: 0.7 Test: 0.7
Normal AT satisfation per trip [Score]	BM: 0.2 Test: 0.2	BM: 0.2 Test: 0.2	BM: 0.2 Test: 0.2	BM: 0.2 Test: 0.2	BM: 0.2 Test: 0.2	BM: 0.2 Test: 0.2	BM: 0.2 Test: 0.2	BM: 0.2 Test: 0.2	BM: 0.2 Test: 0.2	BM: 0.2 Test: 0.2
Social Acceptability of PT [Score]	BM: 0.8 Test: 0.8	BM: 0.8 Test: 0.8	BM: 0.8 Test: 0.8	BM: 0.8 Test: 0.8	BM: 0.8 Test: 0.8	BM: 0.8 Test: 0.8	BM: 0.8 Test: 0.8	BM: 0.8 Test: 0.8	BM: 0.8 Test: 0.8	BM: 0.8 Test: 0.8
Time of commuting on PT [Minutes]	BM: [35.22 – 39.37] Test: [35.22 – 39.37]	BM: [35.22 – 39.37] Test: [35.22 – 39.37]	BM: [35.22 – 39.37] Test: [35.22 – 39.37]	BM: [35.22 – 39.37] Test: [35.22 – 39.37]	BM: [35.22 – 39.37] Test: [35.22 – 39.37]	BM: [35.22 – 39.37] Test: [35.22 – 39.37]	BM: [35.22 – 39.37] Test: [35.22 – 39.37]	BM: [35.22 – 39.37] Test: [35.22 – 39.37]	BM: [35.22 – 39.37] Test: [35.22 – 39.37]	BM: [35.22 – 39.37] Test: [35.22 – 39.37]
Growth Rate Employee Population [Dmnl]	BM: 0.9176 Test: 0.9176	BM: 0.9176 Test: 0.9176	BM: 0.9176 Test: 0.9176	BM: 0.9176 Test: 0.9176	BM: 0.9176 Test: 0.9176	BM: 0.9176 Test: 0.9176	BM: 0.9176 Test: 0.9176	BM: 0.9176 Test: 0.9176	BM: 0.9176 Test: 0.9176	BM: 0.9176 Test: 0.9176
Perceived uncertainty surrounding climate change [Score]	BM: 5 Test: 5	BM: 5 Test: 5	BM: 5 Test: 5	BM: 5 Test: 5	BM: 5 Test: 5	BM: 5 Test: 5	BM: 5 Test: 5	BM: 5 Test: 5	BM: 5 Test: 5	BM: 5 Test: 5

Source: Own elaboration. BM means ‘Base Model’. The BM values are the initial values of the base model.

7.4.2 Results extreme condition tests

As an extreme condition (test 1), the frequency of commuting by car was decreased to 0. As expected, if for any reason an individual is not allowed to drive or an intervention is effective enough to persuade people not to drive, then the average behavioural intention towards commuting by car would be close to 0. It is believed that, in this scenario, the person would not form a motive to perform the action. This means that the model should not compute a high level of car commuters in the population. Figure 37 shows the outputs: if the simulation model restricts driving to 0, the level of commuters would plunge to almost zero, exhibiting the fact that driving would decrease completely. This behaviour pattern of the model is justified as it is expected that people would have a positive behavioural intention to perform a given behaviour as long as the behaviour is available to perform, or it is considered to be performed. By failing with satisfying this condition (Frequency of driving > 0), then the outcomes should show zero people driving.

Figure 37. PEBCM simulation results: Extreme condition test 1.

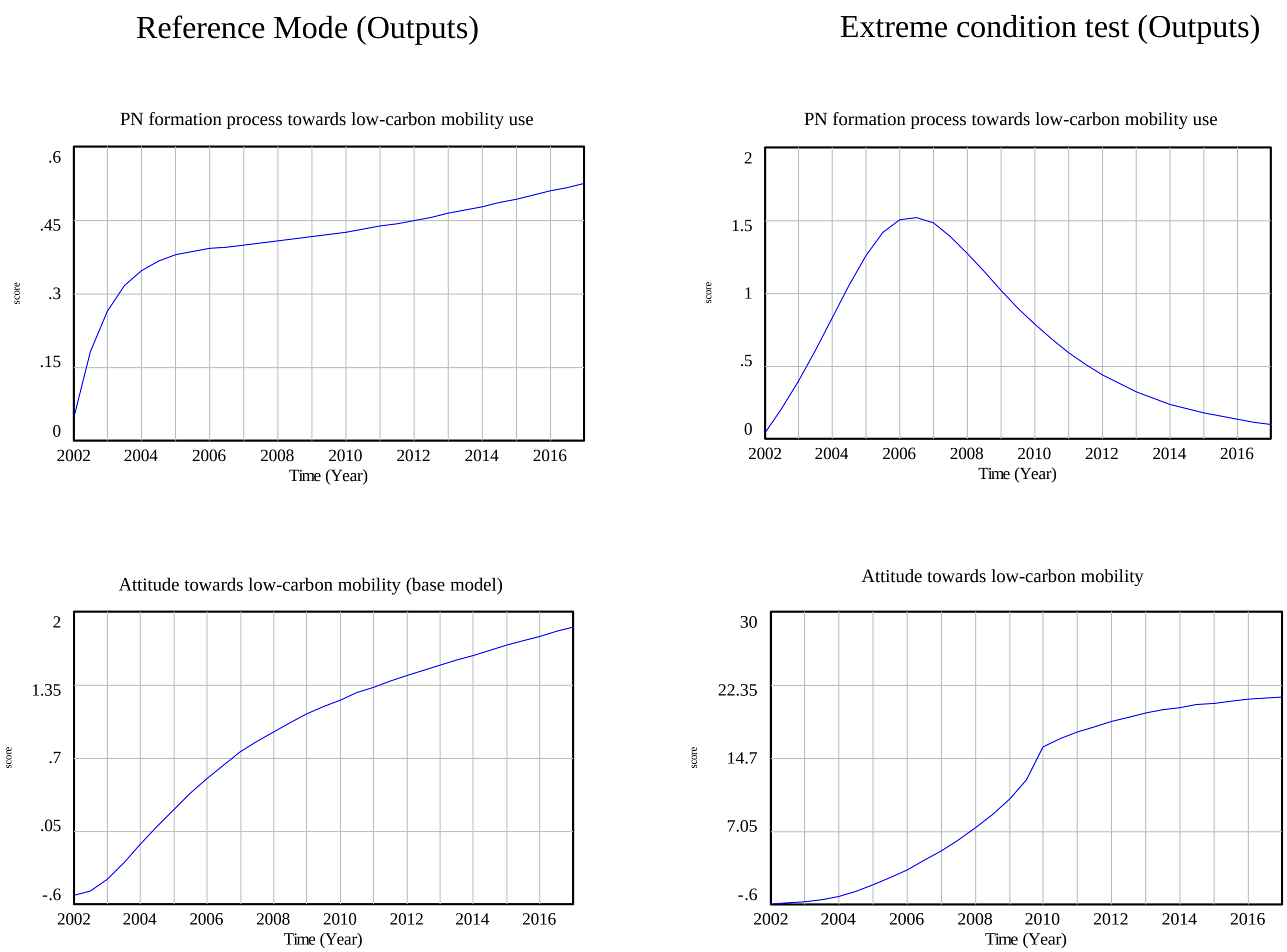


Source: Own elaboration with VENSIM DS. The comparison between the reference mode (on the left: people commute on average 5 days a week by car) and the extreme condition scenario (on the right: people commute on average 0 days a week by car).

Another extreme condition tested was limiting the 'resistance to forming a personal norm' and 'the personal norm abandonment rate' (test 2); both rates were set up at zero. In this case, the model is assuming that a person would not be affected by counter-environmental subjective norms, such as subjective norm towards driving by car. In theory, if the personal norm formation and activation process towards reducing car use (or using an alternative transit mode) do not have an opposite force to restrict the process (e.g., subjective norms towards car use), then it is expected that the internalisation rate of a subjective norm associated with a moral obligation will grow faster, reflecting an overshoot and collapse behaviour pattern (see Figure 38), once the moral norm is internalised the formation process stops, and only the activation process works).

This behaviour pattern can be justified from theory, as many studies in environmental psychology and car use have predicted the behaviour in question by using the norm-activation model: when subjective and descriptive norms towards restricting car use (or using public transport) for the sake of protecting the environment are the salient norms (plus other factors promoting personal norms are active, such as ascription of responsibility), then it is expected that a person would internalise this norm faster than in other contexts, which means that the individual would overcome the lack of motivation to create a moral obligation about decreasing car use. This extreme condition is, in fact, in line with recommendations proposed by many studies (Schwartz, 1977; Bamberg & Schmidt, 2003; Klöckner & Matthies, 2009; Abrahamse, et al., 2009; Klöckner & Blöbaum, 2010; Bamberg, 2013).

Figure 38. PEBCM simulation results: Extreme condition test 2.



Source: Own elaboration.

These two examples are an illustration of the procedure carried out in this project to detect problems regarding extreme conditions. The same rationale was applied to the other 10 extreme condition tests, in order to ensure that the outcomes are consistent with what would be expected in reality. Table 28 summarises the results of the 10 extreme conditions with the conclusion of each test. In all the extreme condition tests, the resulting behaviour of the model matched the expected behaviour of the real system under the same extreme conditions. These tests helped to improve some of the mathematical equations by adding arguments such as ‘IF THEN ELSE’ (e.g.

‘behavioural intention towards car commuting’) to avoid any software crashes and undetermined mathematical expressions.

Table 28. Summary of extreme condition tests.

	Test 1	Test 2	Test 3	Test 4	Test 5	Test 6	Test 7	Test 8	Test 9	Test 10
Endogenous variables (Test outcomes)										
Behavioural intention towards car commuting	Value = 0	Exponential decay	Gradual growth	Exponential decay	Exponential decay	Constant = 4 score	Exponential decay	Exponential decay	Slow growth	Exponential decay
Population of car commuters	Exponential decay	Exponential decay	Gradual growth	Goal seeking.	Exponential decay	Gradual growth	Exponential decay	Exponential decay	Fast growth	Exponential decay
Personal Norms Adoption towards carbon Mobility	S-shape growth	S-shape growth	Overshoot and collapse	Exponential growth	S-shape growth	S-shape growth	Fast growth	S-shape growth	Value close to 0	S-shape growth
Attitude toward Car Commuting	Exponential decay	Exponential decay	Gradual growth	Exponential decay	Exponential decay	Slow growth	Exponential decay	Exponential decay	Slow Growth	Exponential decay
Attitude towards low-carbon mobility	S-shape growth	Exponential growth	Exponential decay. Value = 0 from 2002	Exponential growth	Exponential growth	Fast growth	Exponential growth	Exponential growth	Value = 0	Exponential growth
Do these results contradict the expected outcomes in real-life?	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO
TEST DECISION	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass

Source: Own elaboration.

7.5 Test: sensitivity test

Sensitivity analysis was performed to test the model’s behaviour under the initial condition (see Chapter 6) and how this one responds when the parameters are changed. This is an overall view to evaluate how the model’s behaviour changes over time as auxiliary variables are changed one at a time (Breierova, 1996; Sterman, 2000). This latest test dictated the last reports to evaluate whether or not there are problems in the definition of the model boundary, feedback structure and other structural assumptions (Sterman, 2000). There is no formal protocol to follow for the sensitivity analysis because it is impossible to perform an extensive test for all the variables in the simulation model (Breierova, 1996). Therefore, the modeller needs to use their expertise to pick the parameters that have the most influence on the behaviour of the model. However, the more tests the model passes, the higher the confidence that the model is well defined, and is logically acceptable according to its assumptions.

7.5.1 Model configuration: sensitivity analysis

As explained in the previous section, this simulation models more than 40 exogenous variables that can be modified. In this case, the modifications were as follows: a base scenario was set as the reference mode (see Table 28 for detailed information about the values of the base scenario), and then each exogenous variable that was relevant to respond to the research question was modified. The modifications were the result of a percentual increment from the base model value. For example, 'Belief that cars do not contribute to pollution' is equal to a 0.2 Likert score in the base scenario (reference mode). For the sensitivity analysis, this value was incremented by 25%, 50%, 75%, 100% and 150% to test its impact on the targeted variable. In this test, the modifications were performed per variable, meaning that, when an exogenous variable was modified according to the percentual variation, all the other variables remained unchanged (values = BM, see Table 28). Therefore, to avoid redundancy, Table 29 only shows the values calculated for the exogenous variables to perform the sensitivity analysis.

Table 29. Values selected for each percent variation (exogenous variables).

% variation	Belief of cars do not contribute to pollution	Belief of PT as the main mode to tackle pollution	General value orientation toward wellbeing of others	Social identification with pro-environmental actions	Sense of flexibility & autonomy (Car commute)
Base	0.2000	0.4000	3.2000	1.0000	1.0000
25%	0.2500	0.5000	4.0000	1.2500	1.2500
50%	0.3000	0.6000	4.8000	1.5000	1.5000
75%	0.3500	0.7000	5.6000	1.7500	1.7500
100%	0.4000	0.8000	6.4000	2.0000	2.0000
150%	0.5000	1.0000	8.0000	2.5000	2.5000
	Adoption from Ascription of Responsibility	Motivation to comply toward subjective norm PEB	Internal attribution	Temporal Distance	Quality of Road Infrastructure
Base	0.1000	1.0000	0.2300	4.9500	0.8000
25%	0.1250	1.2500	0.2875	6.1875	1.0000
50%	0.1500	1.5000	0.3450	7.4250	1.2000
75%	0.1750	1.7500	0.4025	8.6625	1.4000
100%	0.2000	2.0000	0.4600	9.9000	1.6000
150%	0.2500	2.5000	0.5750	12.3750	2.0000
	Perceived uncertainty and skepticism surrounding climate change	Reduction of car use for the sake of the environment	Symbolic Affective (attitudinal towards buying a car)	Social identification with car use and commuters	Quality of Car
Base	5.0000	0.0139	3.0000	1	0.8000
25%	6.2500	0.0173	3.7500	1.2500	1.0000
50%	7.5000	0.0208	4.5000	1.5000	1.2000
75%	8.7500	0.0243	5.2500	1.7500	1.4000
100%	10.0000	0.0278	6.0000	2.0000	1.6000
150%	12.5000	0.0347	7.5000	2.5000	2.0000
	Motivation to comply toward subjective norm toward driving	Independence (attitudinal factor)	Subjective Norms towards buying a car	Cost of running a car	Normal Driving Satisfaction per trip
Base	1	3.0000	2.2500	1944.0000	0.8000
25%	1.2500	3.7500	2.8125	2430.0000	1.0000
50%	1.5000	4.5000	3.3750	2916.0000	1.2000
75%	1.7500	5.2500	3.9375	3402.0000	1.4000
100%	2.0000	6.0000	4.5000	3888.0000	1.6000
150%	2.5000	7.5000	5.6250	4860.0000	2.0000
	Implementation intention (toward PT)	Transport priorities (beliefs of what's important to be considered)	Perceived effort to take PT (aux variable)	Occupancy rate	Social acceptability of PT
Base	2.7900	0.7162	3.0000	0.8670	0.8000
25%	3.4875	0.8953	3.7500	1.0838	1.0000
50%	4.1850	1.0743	4.5000	1.3005	1.2000
75%	4.8825	1.2534	5.2500	1.5173	1.4000

100%	5.5800	1.4324	6.0000	1.7340	1.6000
150%	6.9750	1.7905	7.5000	2.1675	2.0000
	PT accesibility	Normal AT satisfation per trip	Perception of how easy is reducing car commuting	Attitude towards car commuting	Attitude towards low-carbon mobility
Base	0.7000	0.2000	0.8000	3.4000	
25%	0.8750	0.2500	1.0000	4.2500	3.5
50%	1.0500	0.3000	1.2000	5.1000	4.2
75%	1.2250	0.3500	1.4000	5.9500	4.4
100%	1.4000	0.4000	1.6000	6.8000	5.6
150%	1.7500	0.5000	2.0000	8.5000	7

Source: Own elaboration.

7.5.2 Results sensitivity analysis

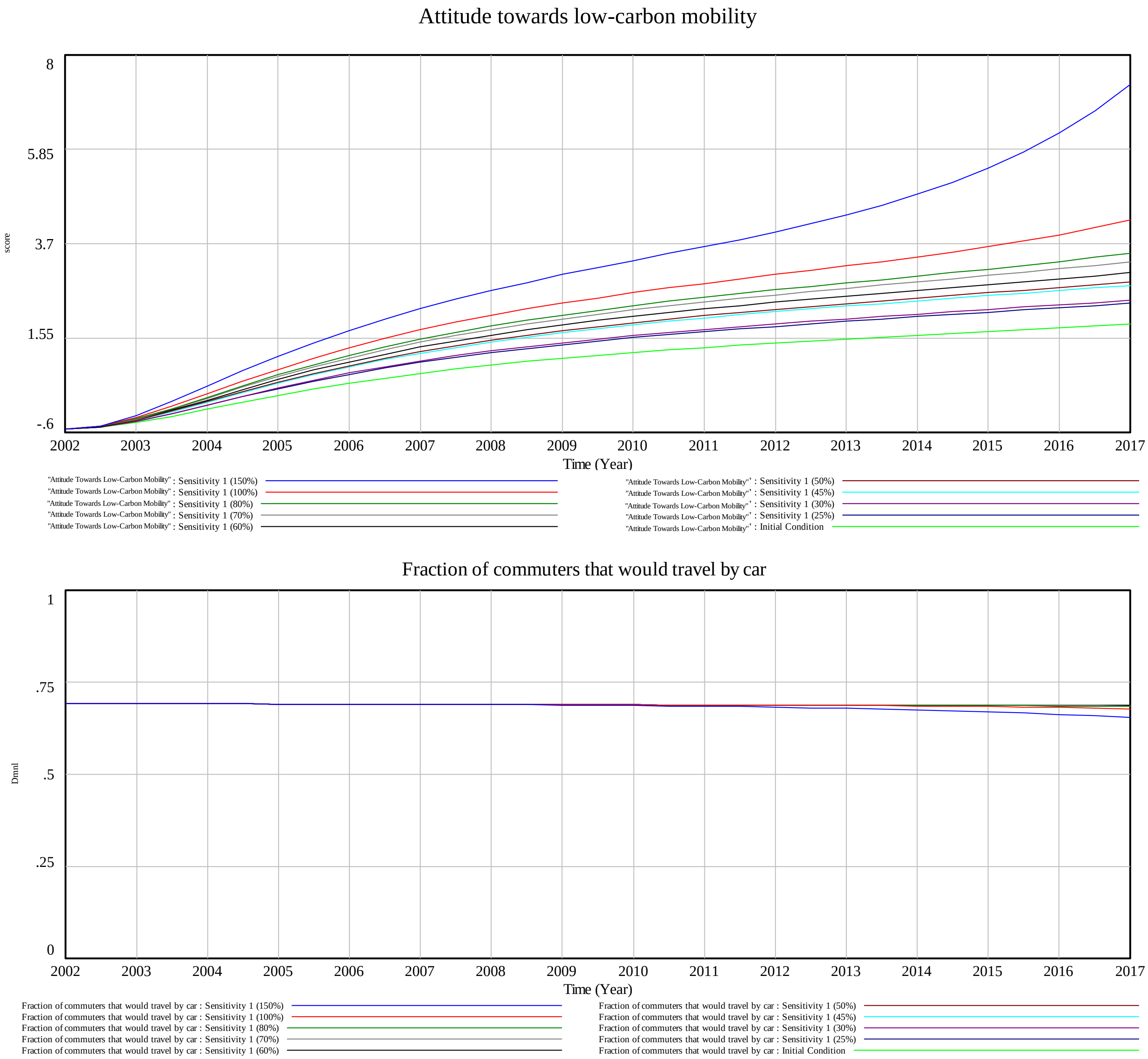
The behaviour patterns under interest in this thesis are produced by the intentional sub-system and the norm-activation sub-system; therefore, the variables to run the sensitivity test were selected from the set of these sub-systems. Two examples of the rationale used in this test are described below.

In the intentional sub-system, the variable ‘initial attitude towards alternative transport modes’ was tested with an increase of different percentual variations to its base value. As Figure 39 shows, increasing the attitude towards alternative transport modes does not significantly affect the fraction of commuters that would select car use. This is in line with the observed pattern in real life. As was discussed in Chapter 6, even when people have reported high levels of attitude towards reducing car use to protect the environment from pollution, there is still an important fraction of the commuters that use a car as the main mode to go to work[59]. This way, the model shows the fact that important changes in attitude will not necessarily bring the outcomes expected from policy

[59] Table TSGB0112: https://www.gov.uk/government/statistical-data-sets/tsgb01-modal-comparisons.

makers to stop car use. In fact, the fraction of people that would drive starts to decrease significantly only when the attitude towards low-carbon mobility is increased by 150%. If nothing else but the attitude towards low-carbon mobility is positively affected to that level, it would take 64 years to make an important reduction in car use and decrease the fraction of car commuters to lower than 50%, which is not hard to believe as real data from the Department for Transport in the UK has shown that, between 2002 and 2017, the fraction of commuters that usually drive decreased by 2.47% (from 70.50% to 68.03%).

Figure 39. PEBCM simulation results: Graphs of sensitivity analysis – Attitude towards alternative transport mode.



Source: Own elaboration. Ten different values were tested to evaluate the sensitivity of these changes on the target variable: behavioural intention towards car use.

Another variable tested to observe any potential issue of sensitivity was the general value orientation towards the wellbeing of others. In the same way as attitude towards alternative transport modes, this variable was changed 10 times to test the impact of different levels on the behavioural intention towards car use. Table 30 shows all the values adopted for the test.

Table 30. Different levels for General value orientation towards wellbeing of others.

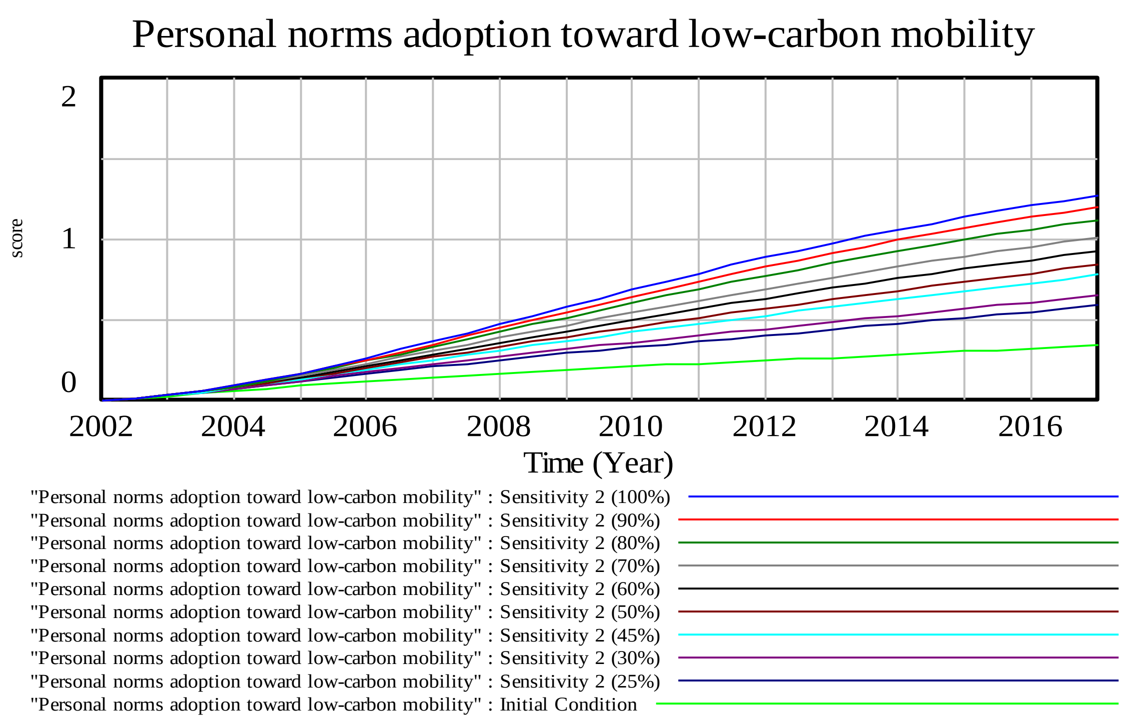
% variation	Value
Base	3.2
25%	4.0
30%	4.2
45%	4.6
50%	4.8
60%	5.1
70%	5.4
80%	5.8
90%	6.1
100%	6.4
150%	8.0

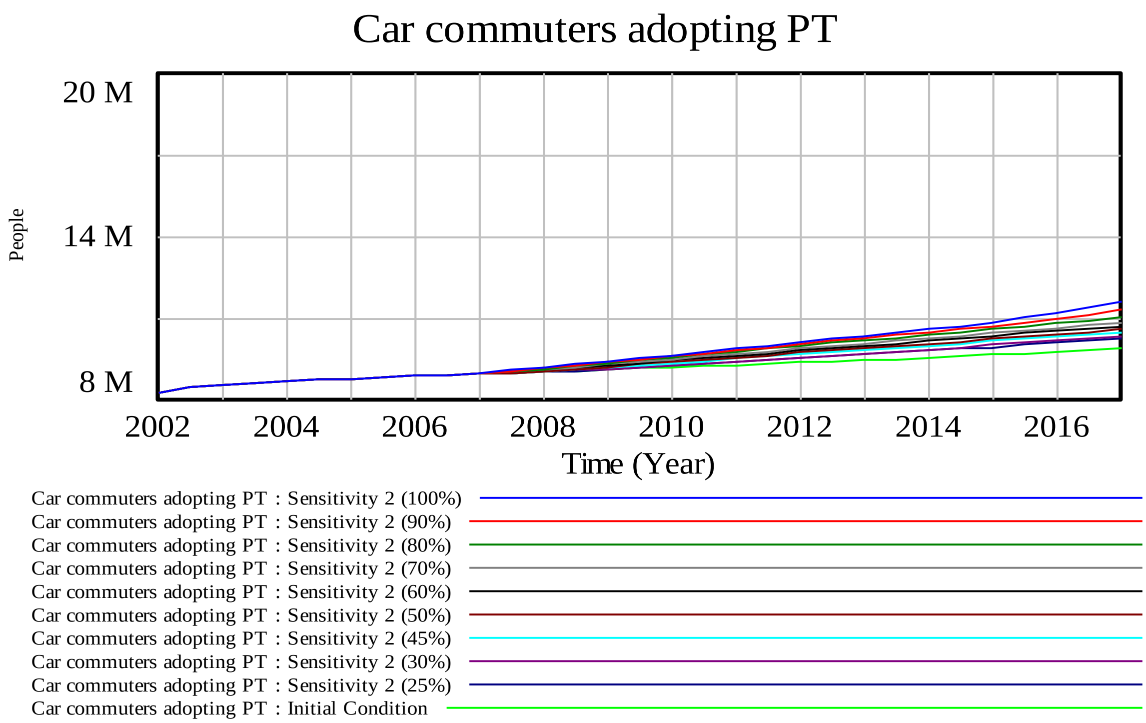
Source: Own elaboration. The initial value for the initial simulation scenario was 3.2 Likert score. For each simulation, the values were increased by the percentage on the left. In other words, 8 represents an increment of 150% from 3.2.

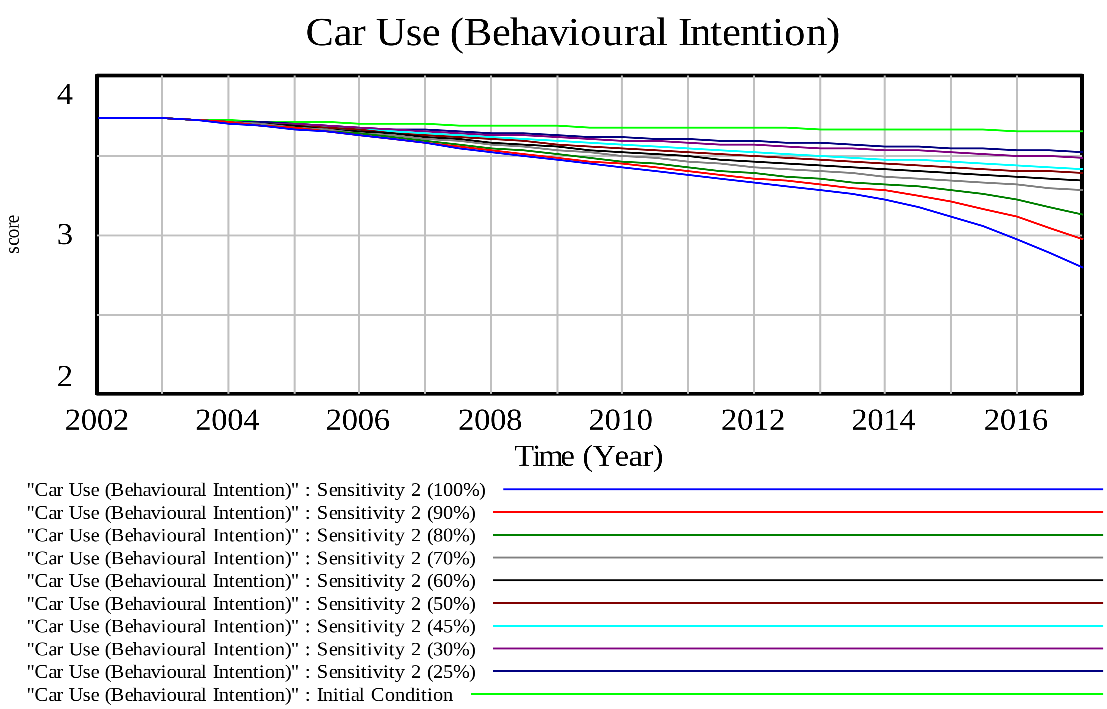
As Figure 40 shows, increments on the general value orientation score (towards the wellbeing of others) create positive changes on personal norm activation and the behavioural intention towards car use, which is something expected from the results reported in empirical studies in environmental psychology (Carrus, et al., 2008; Kollmuss & Agyeman, 2002; Heath & Gifford, 2002). If people are more inclined to develop values that are aligned to protect the environment and the wellbeing of others, then it is expected that personal norms will positively change, accelerating the formation of a moral obligation (De Groot, et al., 2012), which in turn increases the attitude towards and the adoption of an alternative transport mode (Jakovcevic & Steg, 2013).

As it is possible to observe in the simulation model graphs, increasing the positive value orientation by double can increase the adoption of alternative transport modes by 18% (approximately). In fact, increasing the general orientation by 1 Likert point increases the adoption of alternative transit modes by 4%, which is something close to the values of betas predicted in the study by Heath and Gifford (2002) (betas of environmental values towards public transport use). Therefore, changing the inputs of positive values can deliver significant changes within the expected outcome.

Figure 40. PEBCM simulation results: Sensitivity analysis 2: Outputs obtained from the different scenarios.





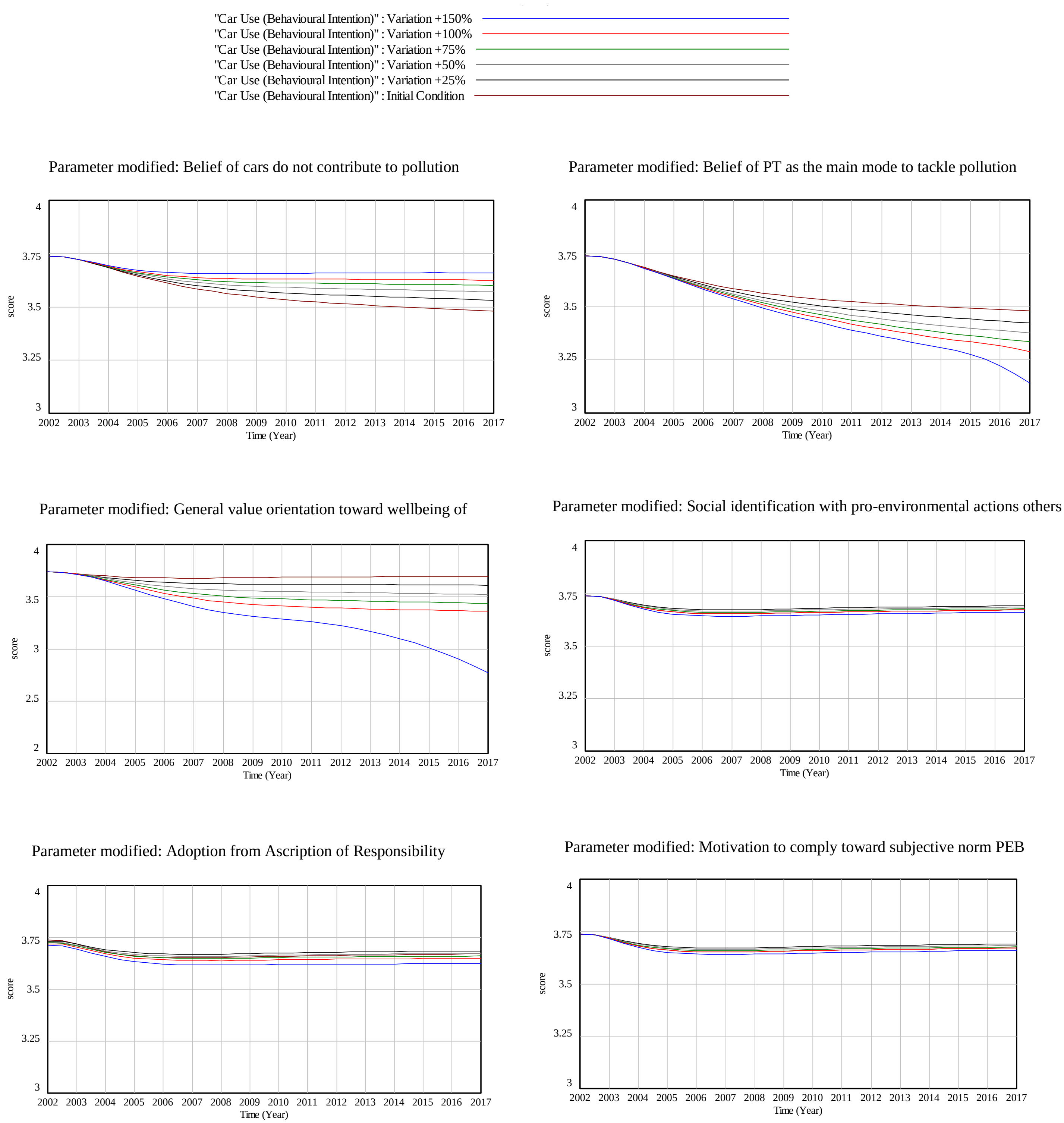


Source: Own elaboration. Graphs obtained from VENSIM DSS.

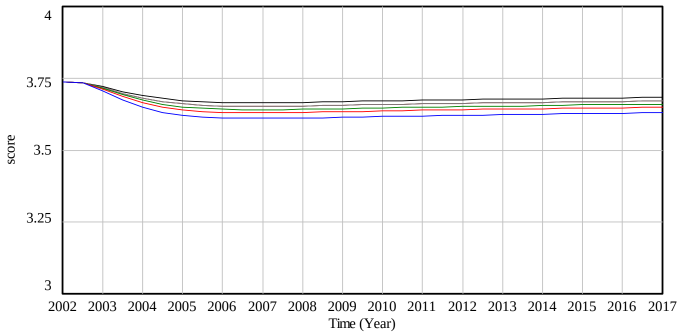
Figure 41 shows all the changes applied to all the other parameters in the model to test their impact on the behavioural intention towards car commuting. In the rest of the tests, the changes were tested by increasing each parameter (one at a time) by 25%, 50%, 75%, 100% and 150%. Each graph in the figure shows how these changes impacted on the behaviour of the most important variable to explain why people commute by car: the behavioural intention towards car commuting.

The sensitivity analysis again showed that changing the value of different parameters (one at a time) makes some changes in the behaviour of the variable called "behavioural intention towards car commuting"; however, the changes do not change the general behaviour of the model abruptly: the behavioural intention towards car commuting only fluctuated between 2.77 and 4.47 Likert score points (see Appendix 4 for more details on the results of each simulation). Some parameters have demonstrated a bigger impact on the targeted variable than others, affecting the status quo of the model to a larger extent. Using a variation between 25% and 150% (extreme values) demonstrates that it is an excellent model to use in the understanding of car use in the context of commuting, as the analysis is suggesting that deeper changes in the overall model require a combination of parameters instead of affecting the system by modifying only one parameter. This is in line with most of the suggestions made by the integrative theories presented in environmental psychology, in which researchers have concluded that multiple variables are involved in the determination of car use (Bamberg, 2002; Bamberg & Schmidt, 2003; Abrahamse, et al., 2009; Carrus, et al., 2008; Klöckner & Blöbaum, 2010; Noonan, 2021; Kroesen, et al., 2017; Ben-Akiva & Bierlaire, 1999; Bolduc, et al., 2008; Chng, et al., 2018).

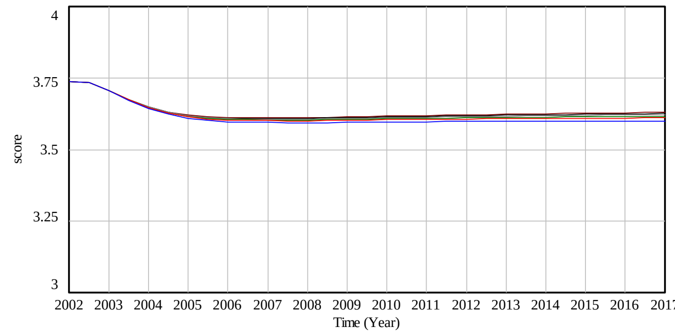
Figure 41. PEBCM simulation results: Sensitivity analysis: Testing the impact of modifying other parameters on the behavioural intention towards car commuting.



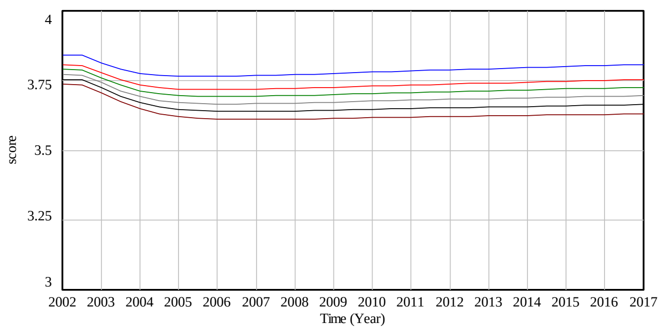
Parameter modified: Internal attribution



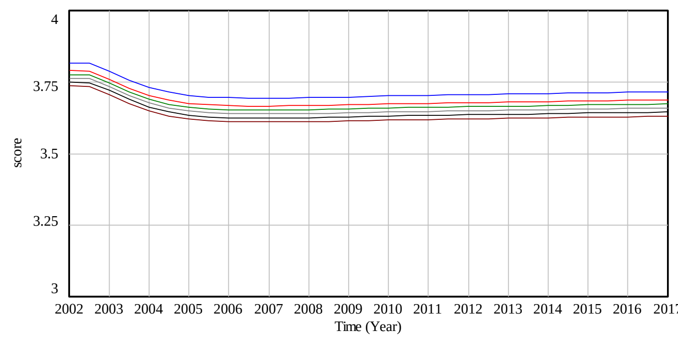
Parameter modified: Temporal Distance



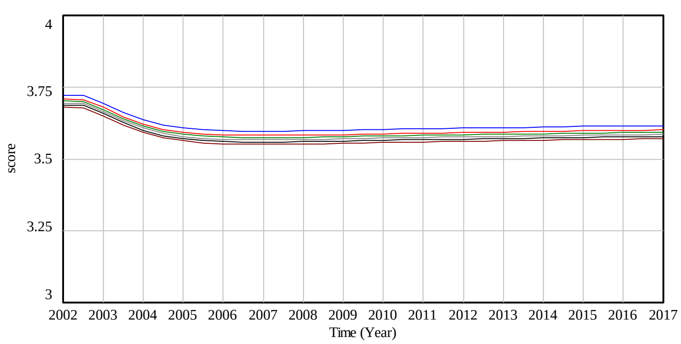
Parameter modified: Motivation to comply toward subjective norm toward driving



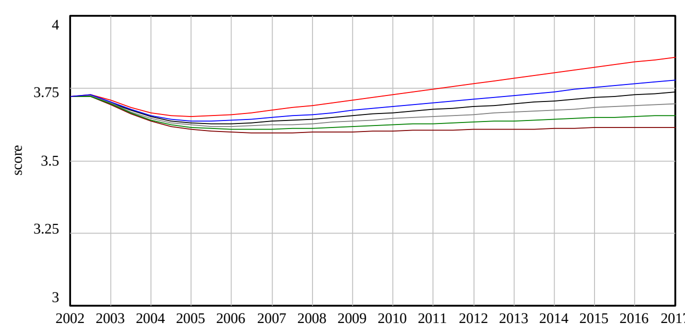
Parameter modified: Independence (attitudinal factor)



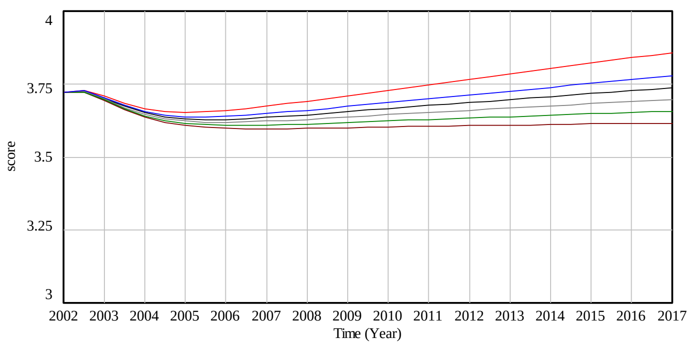
Parameter modified: Subjective Norms towards buying a car



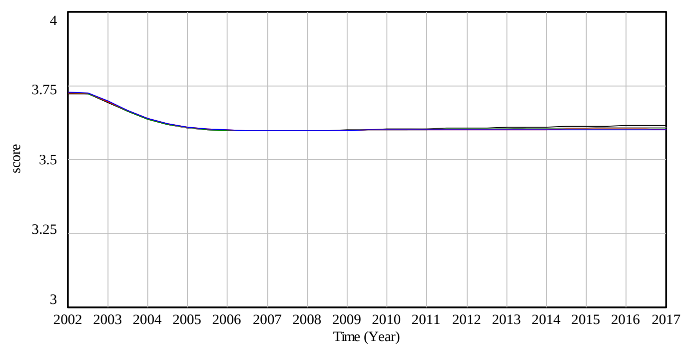
Parameter modified: Sense of flexibility & autonomy (Car commute)



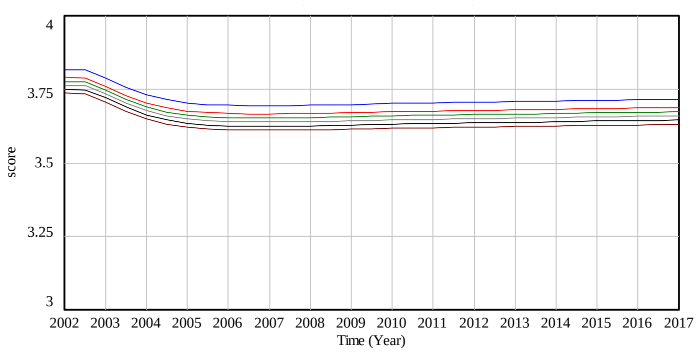
Parameter modified: Normal Driving Satisfaction per trip



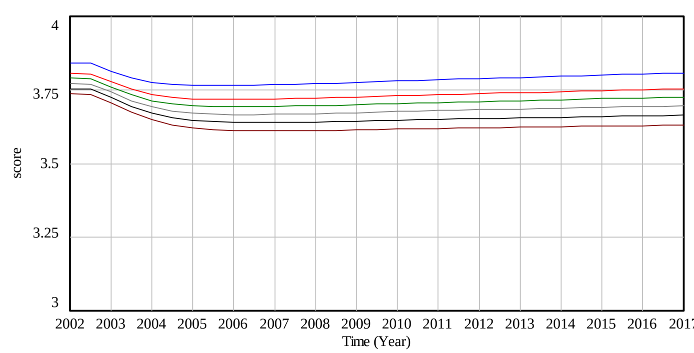
Parameter modified: Cost of Running a Car



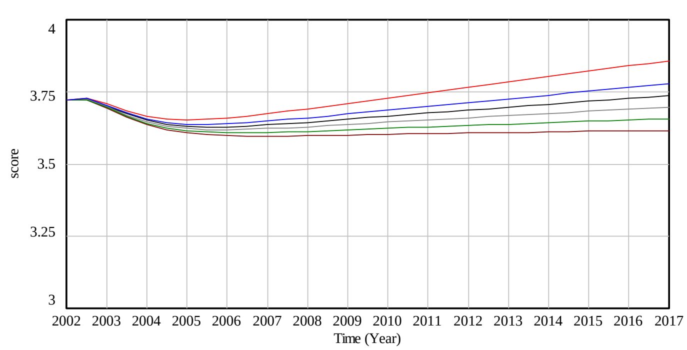
Parameter modified: Symbolic Affective (attitudinal towards buying a car)



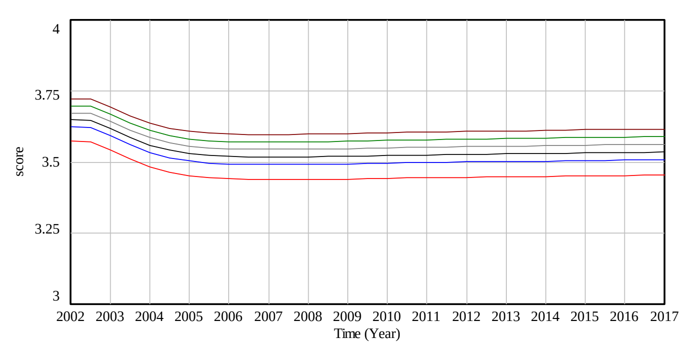
Parameter modified: Social identification with car use and commuters



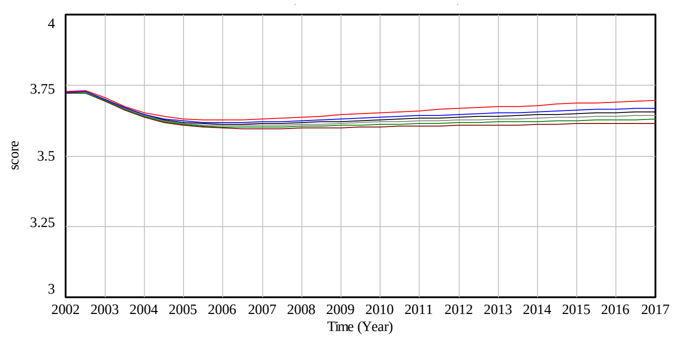
Parameter modified: Quality of Car



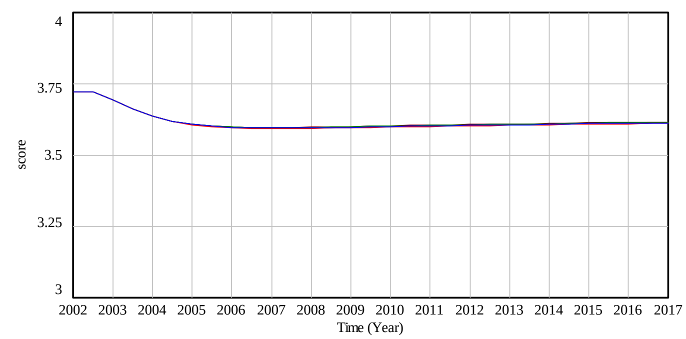
Parameter modified: Implementation intention (toward PT)



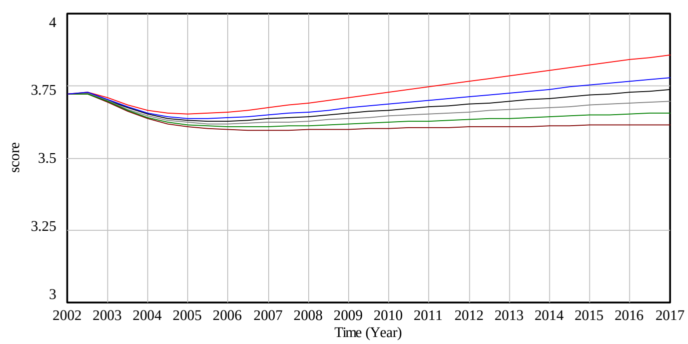
Parameter modified: Perceived effort to take PT



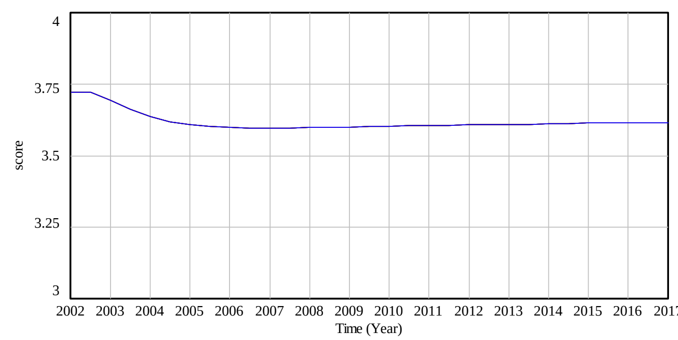
Parameter modified: Transport priorities



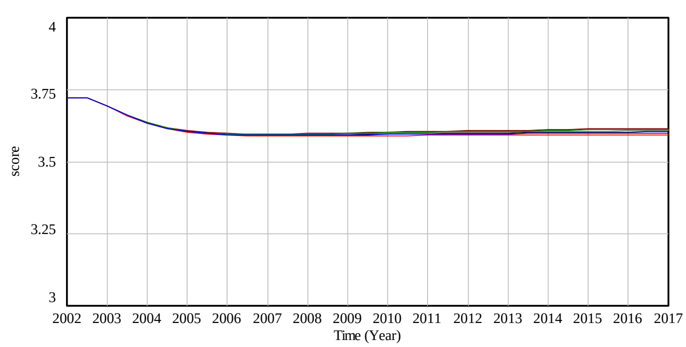
Parameter modified: Quality of Road Infrastructure



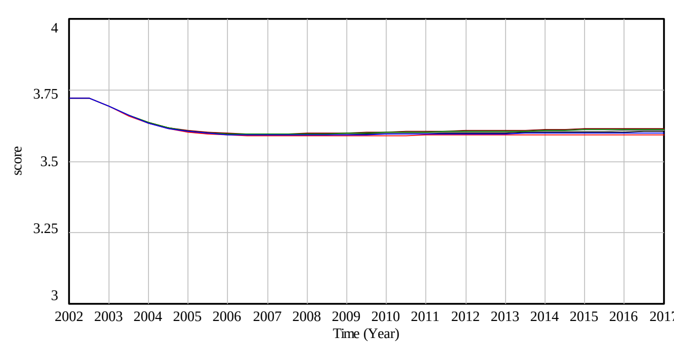
Parameter modified: Occupancy rate

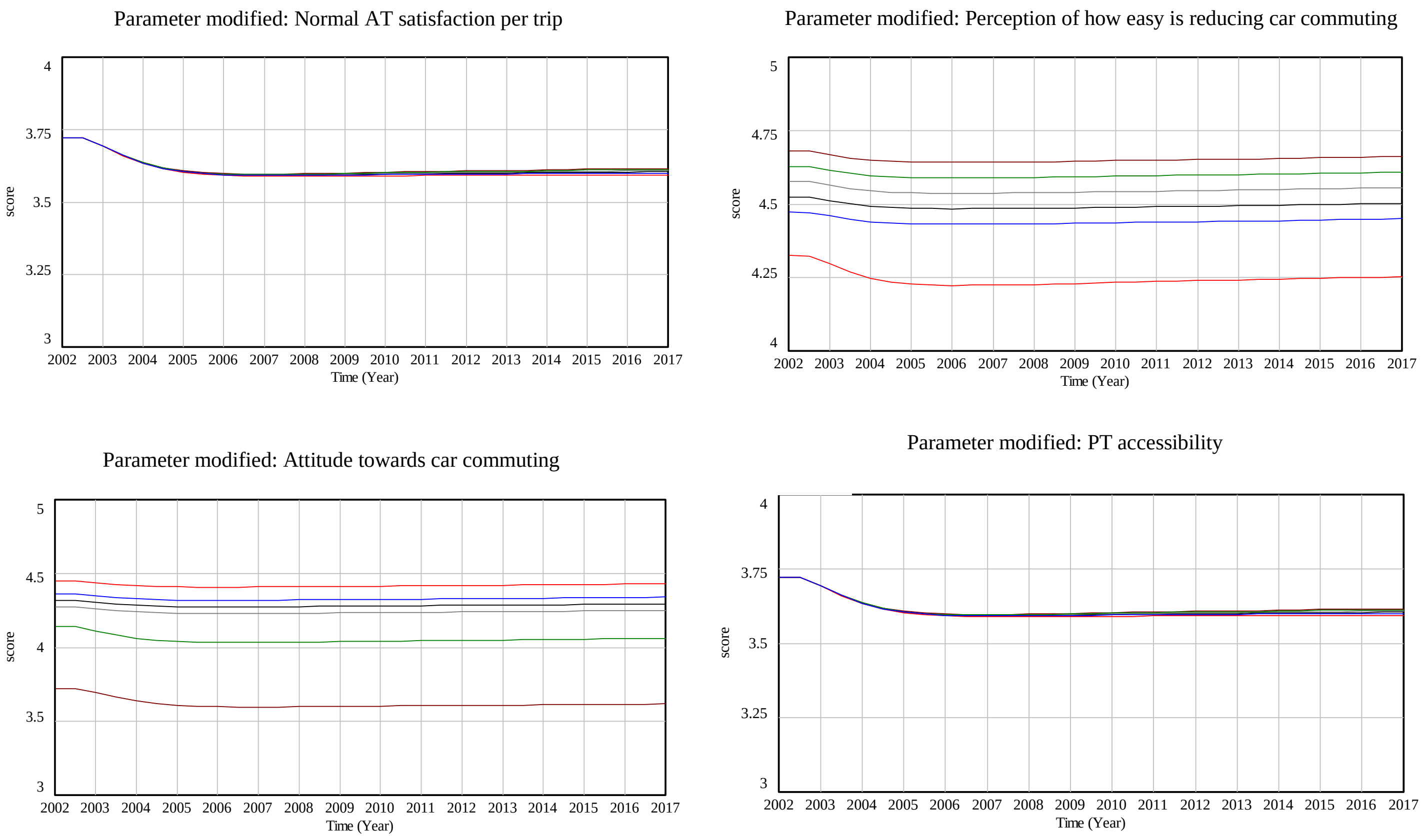


Parameter modified: Social acceptability of PT



Parameter modified: PT accessibility





Source: Own elaboration.

7.6 Behavioural validity of the simulation model

The aim of the behavioural validity is to compare the model outcomes with the observed behaviour of the real system. In this stage, the last step of validation is regarding the accuracy that the simulation model has to reproduce the real-life system's behaviour. This is not a test to evaluate the accuracy of statistical outcomes (e.g., average, standard deviation), but the behaviour pattern (Qudrat-Ullah & Seong, 2010). To address this test, the variables selected to run the comparison were: car commuters, non-car commuters[60], and commuting time. Two reasons justify this decision. First of all, these sets of variables are endogenously generated by the model and they address the purpose of the model: "to observe the impact of an attitudinal discrepancy (attitude towards driving vs using alternative transport modes) and a moral dilemma (the feeling of moral obligation towards reducing car use) on car use, over the long term". If an attitudinal discrepancy or moral dilemma generates a significant tension (the discrepancy is large enough to change the model's behavioural pattern), then it is expected that the probability of commuting by car would decrease, which in turn would decrease the number of commuters in a given context and would increase the number of car commuters adopting an alternative transport mode. Second of all, there is no real data about the evolution of attitudes towards car commuting and public transportation, but there is plenty of data about the actual behaviour of driving in the real system. Therefore, as the car commuters' population is estimated endogenously, it can also be used to support the existence of good fit between the model and the historical data. If the goodness-of-fit measurement fails, it would lead to the model needing to be reviewed and some of its parameters adjusted. It is important to acknowledge that good levels of fit are necessary but far from sufficient, as a good system dynamics model is expected to reproduce the historical behaviour. Therefore, large measures of errors between model and historical data do not necessarily compromise the validity

[60] This model reflects a bi-modal system and assumes that the non-car commuters are every commuter that would use public transportation. It is important to acknowledge that this level of aggregation might be biased because the alternative transport mode is just considering the behavioural intention to use public transportation, but, in reality, a non-car commuter can also use other types of transport (e.g., bicycle). This assumption was taken as the % of other transportation does not exceed 3% by itself. Therefore, all these commuters are treated as one large group that uses only public transportation as an alternative to cars. This model is looking for ways to discourage car use; therefore, even if that means just using public transportation, the purpose of the model is fulfilled as public transport pollutes less per person than driving.

of the system dynamics or imply a lack of confidence in the outcomes, because the behaviour patterns might follow the same trends (Sterman, 1984).

Regression modelling uses historical data to estimate the parameters, which is why the coefficient of determination (R^2) plays an important role, because the quality of predictions from the regression model will depend on how well the observation matches the estimates predicted from the model proposed. The higher the R^2, the greater the confidence the statisticians gain to predict forecast data. In contrast, system dynamics fulfils a purpose, which means the model is evaluated by its capacity to reproduce the behaviour expected endogenously. For that reason, SD does not apply a goodness-of-fit index; instead, the confidence is gained by confirming with experts, literature, aim of the model and size of the problem that the conceptualisation created to simulate the historical behaviour has a reasonable cause-effect explanation (Sterman, 1984). Good models can show a large total measurement error, but that is acceptable as long as the variables included offer a conceptualisation that does not compromise the quality of the explanation. Matching historical data cannot become the main goal itself, because omitting variables for the sake of goodness-of-fit can misguide the comprehension of why and how an observed behaviour emerges (Sterman, 1984; Qudrat-Ullah & Seong, 2010). For that reason, an SD modeller should prioritise the inclusion of variables when it helps to understand how behavioural patterns, feedback loops and delays affect the targeted variables, and not omit variables to minimise some measure of error (Sterman, 1984).

Figure 42. Discrepancy between real and simulated data (in million) UK vs model.

Source: Own elaboration. ‘O’ is the data gathered from the databases and ‘S’ is the data gathered from PEBCM (simulation results).

To properly test the adjustment of the model to the observed data, the mean-square error (MSE), the root-mean-square percent error (RMSPE) and inequality statistics were used to evaluate the accuracy of the simulation model (Sterman, 2000; Qudrat-Ullah & Seong, 2010):

$MSE = \frac{1}{n} * \sum(\hat{Y}_s - \hat{Y}_o)^2$

$RMSPE = SQRT(\frac{1}{n} * \sum(\hat{Y}_s - \hat{Y}_o)^2)$ (SQRT stands for square root)

$$U^M = \frac{(\bar{Y}_s - \bar{Y}_o)^2}{MSE}$$

$$U^S = \frac{(S_s - S_o)^2}{MSE}$$

$U^C = \frac{2(1-r)S_s S_o}{MSE}$; or alternatively $U^c = 1 - (U^M + U^s)$

The 'S' symbol represents the outcomes obtained from the model, while 'o' is for real data. MSE is the mean-square-error, which computes the difference between 'n' data points of the model and the real data; '**$\bar{Y}$**' is the average; '**S**' is the standard deviation and '**r**' represents the covariation between data from the model and the real system. U^M, U^S, and U^C are indexes to break down the total error calculated between bias, unequal variation, and unequal co-variation, respectively (Sterman, 1984). Table 31 shows the indicators estimated for each variable in the model.

Table 31. Error analysis of the model.

	MSE (units)	RMSPE (%)	U^M	U^S	U^C
Car commuters	0.089621	1.476%	0.012275599	0.019311606	0.968412795
Alternative transport mode commuters	0.037014	2.117%	0.124653768	0.003237125	0.872109107
Travel time	0.996721	4.018%	0.041120478	0.844843382	0.11403614

Source: Own elaboration.

MSE and RMSPE show the size of the error, in which the latter is common and easy to interpret as it is a dimensionless measure (Sterman, 1984). In this case, the RMSPE is lower than 5% in the three cases, which means that the variables are able to replicate the real behaviour accurately (Qudrat-Ullah & Seong, 2010). Car commuters and non-car commuters mainly explain this small magnitude error by unequal co-variation (87.2%). This means that the simulated variables do not match the point-by-point values of historical data, but the model is able to capture the average values and dominant trends properly. A large U^C indicates that one of the explanatory variables contains a large component of randomness or cyclical modes (Sterman, 1984), the noise of which is not being captured by the model. For this reason, models might not be rejected due to unsystematic error as the purpose of the study can still be fulfilled by the representation of the model outcomes.

In the case of travel time, the small error is mostly accumulated in the unequal variance index. This is another way to show that the model is not able to capture random noise; however, this index reflects that there is systematic error by comparing both simulated and historical data. This is something that would be expected, as there has been vast research in travel time prediction (Simroth & Zähle, 2010), creating complex models based on current transit, which is not available in this simulation model. In fact, the average speed that a car commuter travels was fixed to a constant value for all the periods; therefore, correcting the systematic value would not be difficult to fix, but accurately predicting the average speed year by year is beyond the aim of this project.

The recommendation to continue is based on the purpose of the model: if the model has been built to investigate the randomness of the travel time, then this is an issue that should be solved, which means the modeller should review the model again. However, if the aim of the model relies on understanding the long-term behaviour pattern that does not depends on the cyclic mode (or noise), then it becomes unimportant (Sterman, 1984; Qudrat-Ullah & Seong, 2010). In other words, if the model is not looking to forecast the travel time when people commute by car, then what only matters is if the model can capture the average value and long-run trend (hence, U^M & U^C are small). In conclusion, it is fair to say that this simulation model used for policy analysis accurately replicates the actual data as the errors are unsystematic and concentrated in U^C and U^S.

7.7 Summary

The purpose of the model is to act as a guide to evaluate whether a model is acceptable or not. For that reason, modellers in SD work on developing a strong conceptualisation of the problem observed. In this chapter, a series of tests were performed, in order to extend the level of confidence of the model presented in this project. The results obtained are satisfactory, offering a good level of confidence to use this model to understand the dynamics observed among psychological determinants in the contexts of travel behaviour. This does not mean that, because of these results, the model is assumed to be completed. The model can still be improved. However, the outcomes obtained in the structural and behavioural validity tests provide reassurance that this model is a strong version to explain behavioural intention towards car use. By accepting the conceptualisation offered by the model, the following chapter will use it to understand why car commuting in England has not changed drastically in 20 years.

8 Case study. Commuters' travel choice in England

Chapters 6 and 7 presented the simulation model and the last steps to validate it. Additionally, the dynamic hypotheses were explained for each sub-system, which suggested that a more desirable system behaviour can be achieved. Furthermore, the sensitivity analysis showed that there is still room to discourage car use. Running different scenarios by adjusting multiple psychological determinants can give valuable insights to understand the underlying dynamic structures that keep the behavioural intention towards car commuting unchangeable in the long term.

In this chapter, a series of model-based policy experiments (policy analysis) are performed in order to try different combinations of variables that can discourage car use significantly. The recommendations obtained from these analyses will be discussed in Chapter 9. However, some reflections about simulation experiments are shared at the end of this chapter.

The chapter is divided as follows: first, general data about people's travel behaviour in England is presented. This way, historical data can help to understand the common transport trends in England, as well as how they have evolved between 2000 and 2017. Second, the scenario specification is described. In this section, the initial parameters of each scenario are chosen. Only four parameters were selected to run the experimentations. This decision was based on the results that previous authors presented (Klöckner & Blöbaum, 2010; Abrahamse, et al., 2009; Bamberg, 2013; Kroesen, et al., 2017; Lanzini & Khan, 2017; Chng, et al., 2018). It has been found that the most important factors to promote an alternative transport mode are related to attitudes, environmental concern, habits and ascription of responsibility. Finally, this chapter presents four scenarios in which different strategies are shown to illustrate the consequences of modifying the initial conditions.

8.1 Case study – commuters in England

Choosing a case study[61] to address the research question helps when undeveloped theory exists to describe the phenomenon (Davis, et al., 2007). In the case of environmental psychology, theories to explain car choice are still works in progress as multiple authors have claimed lately that integrative theoretical frameworks can still improve the understanding in predicting behavioural intention towards transport mode choices (Gärling, et al., 2001; Klöckner & Blöbaum, 2010; Bamberg, 2013; Chng, et al., 2018). Therefore, using a case study and a simulation model can be a great strategy (Davis, et al., 2007) to help to evaluate the current integrative theoretical works dynamically. Running different scenarios can reveal relevant considerations to improve/modify the current theory surrounding the prediction of the behavioural intention towards car use.

The choice of England was based on pragmatic considerations. The Department for Transport has a lot of data available for this country, which makes it easier to contrast the model's behaviour in the initial condition with the real-life reference mode. The comparison and calibration of the model to the England data were made in the previous chapter.

8.2 Introduction to the England context

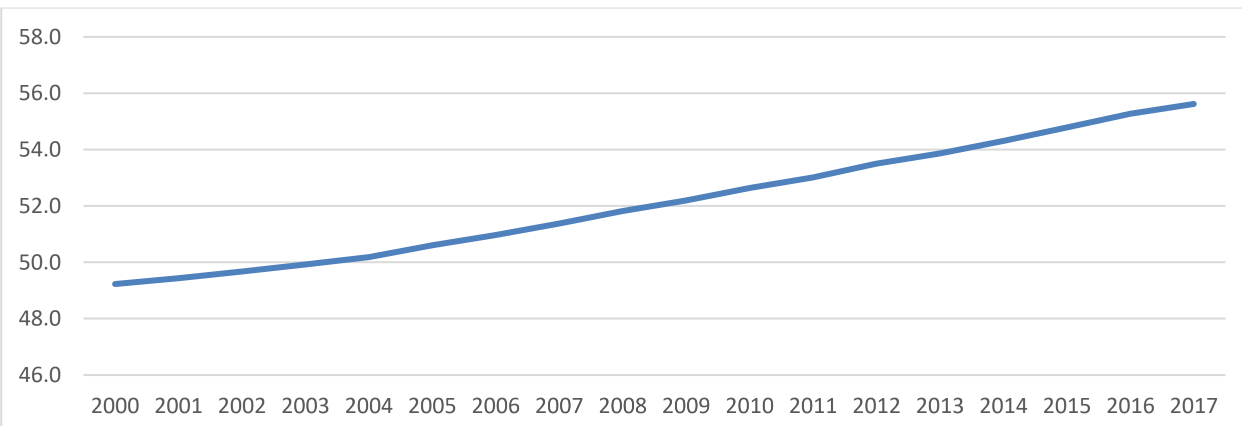
In system dynamics, reference modes play a key role as they help to visualise an unambiguous graphical description of the targeted behaviour. For that reason, this section will show a series of graphs and statistics to indicate what factors are of interest, and therefore what should be the main

[61] It has been defined as an empirical research approach that allows the researchers to explore a phenomenon in a real-life context as there is a lack of evidence to claim a complete understanding (Yin, 2017).

focus of policy makers when it comes to behavioural intention towards car use. Having the historical behaviour of the target variable can help to visualise the desirable behaviour policy makers are looking for. Ideally, these reference modes are built based on numerical data.

England is a nation which is part of the United Kingdom, alongside Wales, Scotland, and Northern Ireland. According to a report by the Office for National Statistics (2021), its population was estimated to be 56.3 million in 2019 (UK: 66.8) and it is expected to keep growing, but at a slower rate (see Figure 43). If this trend continues, England could reach over 60 million people by 2040.

Figure 43. England's population (in million).



Source: Own elaboration. Using a database from ONS[62].

Figure 44 shows how the number of commuters has evolved in England between 2002 and 2017. Notice that this graph only contains information about the people who have declared cars as

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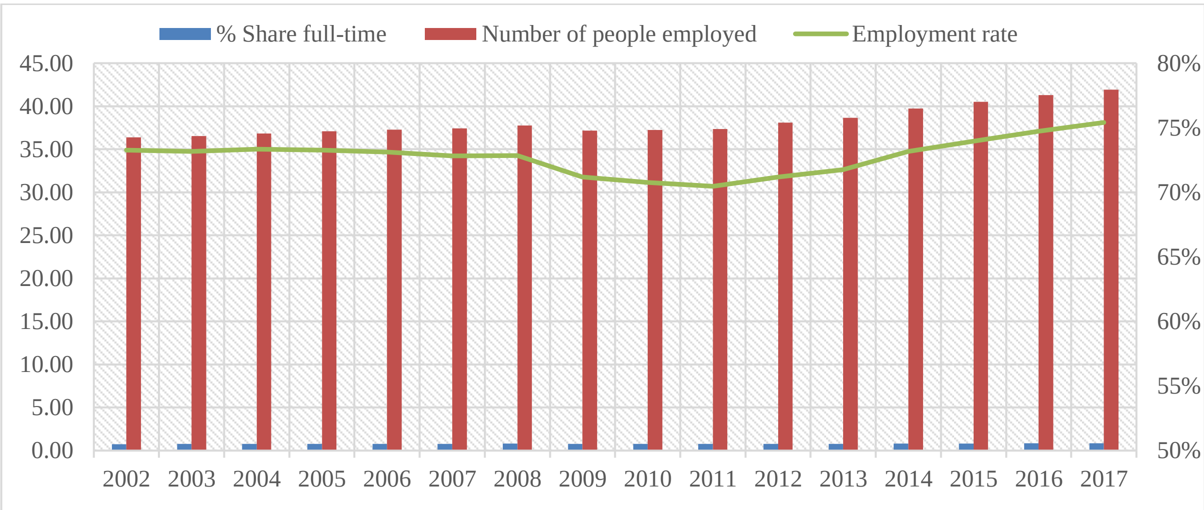
62 https://www.ons.gov.uk/peoplepopulationandcommunity/populationandmigration/populationestimates/articles/overviewoftheukpopulation/january2021.

the main transport mode to go to work; therefore, this does not consider people that might go to work by using two modes of transport or people that travel as a passenger in a car (e.g., taxis).

Figure 44. Number of employees (millions), car commuters (millions) and employment rate in England (%).



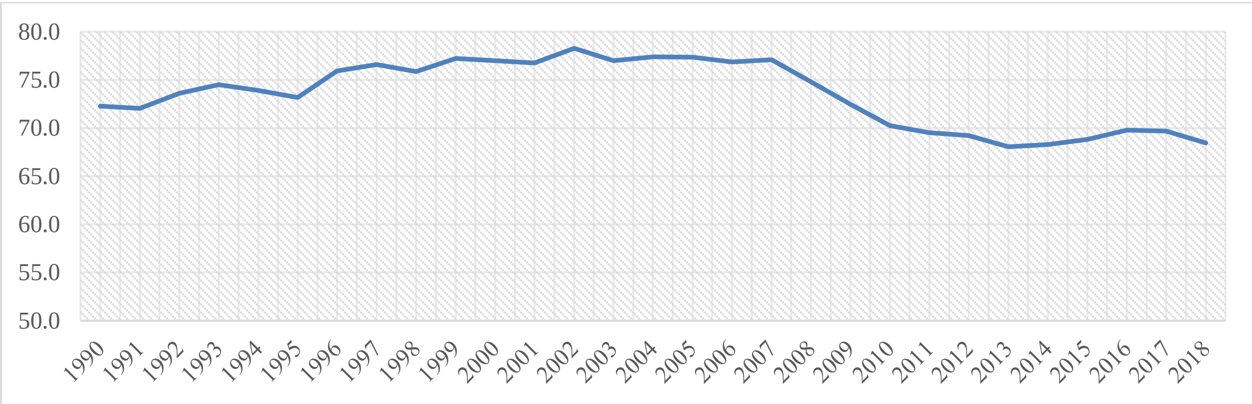
Source: Own elaboration by using data from the ONS, UK. Population is in millions. The data was calculated by using the regional labour market report, population data and tsgb0108. All data was collected from the Office for National Statistics and the Department for Transport (UK).

Based on the previous figure, it is possible to observe that the number of car commuters keeps growing alongside the population. The percentage of people that declared car use as their main mode of transport to work dropped from 70.05% to 67.15% (between 2002 and 2017), but, since the population has grown at a higher rate, 0.74% yearly on average, the actual number of car commuters increased from 25.49 million to 28.17 million people in the same period. To have seen a true improvement in 2017 in comparison to 2002, the fraction of people that mainly commute by car needed to have been 45%, therefore, 25.1 million people.

In transportation, different sources can contribute to the emission of greenhouse gases (cars, taxis, buses, coaches, motorcycles, airplanes, etc.). Whichever is the source, the total amount of pollution emitted is the result of the amount of greenhouse gas a transport mode emits times the frequency of use. For example, in 2017 a car emitted 121g of CO_2 per kilometre (SMMT, 2018); that means, if a person commutes to work in a car that emits a similar amount of pollution, a distance equal to 10 km (home to work), twice a day, and five days a week, then its contribution to the monthly amount of CO_2 would be 48,400 grams of CO_2. Hence, controlling the amount of pollution becomes an issue related to technology (car engine efficiency), frequency of use, distance travelled, number of commuters and fuel source.

In term of technology, positive changes have happened in the last 20 years. In 2017, for example, the average new car CO_2 emissions remained 33.1% lower than 2000 levels (SMMT, 2018). However, as Figure 45 shows, the total emissions of carbon dioxide in the UK from taxis and cars have been barely reduced, by 5% between 1990 and 2018 (data from the Department for Transport, UK). Another report (SMMT, 2018) indicated that the total emissions from all cars fell 7.4% between 2000 and 2016. However, at these rates it seems difficult for transportation to contribute to achieving the net zero target by 2050. The problem here is: the markets for the most efficient cars (AFVs) are growing, but such cars did not represent more than 5% of the market of new cars registered in 2017, so even when more AFVs are adopted they are a tiny part of the market. And the average emission of CO_2 from the most pollutant and popular type of car (petrol) increased from 123.70 g/km to 125 g/km (see Table 32).

Figure 45. Cars and taxis: million tonnes of carbon dioxide equivalent between 1990 and 2018 (U.K.).



Source: Own elaboration from data gathered from env0201 (Department for Transport, UK). Even though this data does not correspond to England, its population represents 84.3% of the U.K., so a similar trend can be expected.

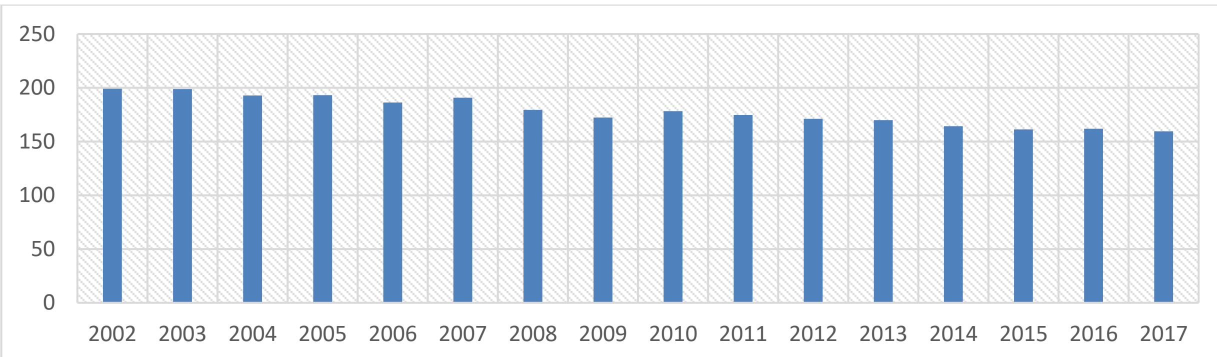
Table 32. New car registration and average CO_2 emission by type of car.

		2000	2007	2016	2017	var 2000-2017
Total Market	CO_2 g/Km	181.00	164.90	120.10	121.00	-33%
	Registrations (thousands)	2222	2404	2693	2541	14%
Diesel	CO_2 g/Km	167.70	164.30	120.10	122.00	-27%
	Registrations (thousands)	313	967	1285	1066	241%
Petrol	CO_2 g/Km	183.20	165.70	123.70	125.00	-32%
	Registrations (thousands)	1908	1420	1319	1355	-29%
AFV	CO_2 g/Km	127.30	127.00	66.80	67.50	-47%
	Registrations (thousands)	0	17	89	120	N.A

Source: Own elaboration by using date reported in the New Car Report 2018 (SMMT, 2018).

In terms of trips, the average trip per person (when commuting) in England fell at a rate of 1.44% on average per year, ending with a variation of -20% between 2002 and 2017. The variation is more pronounced among full-time workers, with the average number of trips per year decreasing from 227 to 186 (-1.28% yearly variation) in the same period. In the case of part-time workers, the average was mostly steady during the same period, decreasing from 125 to 111 trips per year (-0.59% on average a year). Figure 46 shows the evolution of the trips per person per year when commuting estimated from all employment status.

Figure 46. Trips per person per year in England.



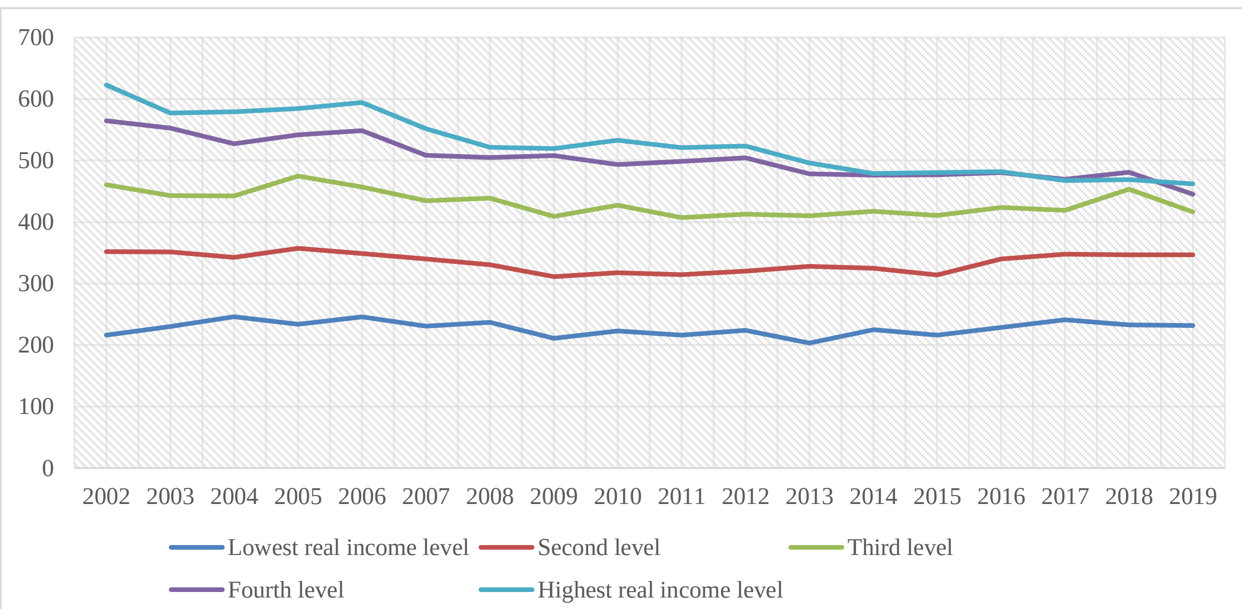
Source: Own elaboration using data gathered from NTS 0412.

This can be considered as a relevant improvement, especially because the average trips per person kept dropping until 2019[63]. However, it might not be clear if this trend remains the same when the average number of trips per person is disaggregated by travel by household income. Unfortunately, the Department for Transport does not show this information by purpose and main mode, but, if the portion of trips made to commute follows the same pattern, it is possible to observe from Figure 47 that the average trips per household might not fall at the same rate when the population is divided by income. In the lowest quintile groups, the average trips rate did not change in the same way as for the general population. In fact, the lowest real income level quintile

[63] See: https://www.gov.uk/government/statistical-data-sets/nts04-purpose-of-trips.

increased the average number of trips per year between 2002 and 2019 by 7.16% (from 216 to 231 trips per year), while the second level quintile decreased the trips by only 1.51% (from 351 to 346 trips per year). This is more concerning when accessibility to cars has been easier in the last 20 years. For example, the lowest real income households have increased the percentage of car accessibility by 23.1% among main drivers[64], increasing the number of adults who can access a car to drive to 41% in 2019. Important changes can be seen among the highest income levels, in which the number of trips have decreased more than the average of the general population. Table 33 shows that on average the number of trips per household income quintile have been decreasing by over 1% per year.

Figure 47. Travel by household income quintile and main mode.



Source: Own elaboration.

[64] The main driver is defined as the person that reported driving the most mileage in a vehicle.

Table 33. Variation of travel by household income quintile and main mode (between 2002 and 2019**).**

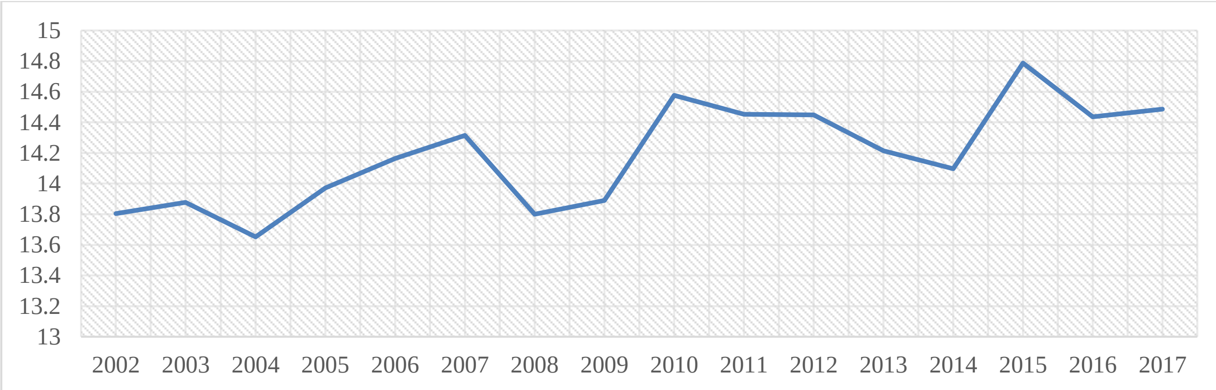
	Low Income	Second	Third	Forth	High Income
Average yearly variation	0.60%	-0.04%	-0.49%	-1.34%	-1.69%
Variation 2002-2019	7.16%	-1.51%	-9.63%	-21.16%	-25.80%

Source: Own elaboration.

Finally, in terms of distance travelled, data from the Department for Transport has shown that the average trip length when people are commuting has been increasing since 2002. When the average kilometres per year are evaluated by households, the yearly variation among all groups fluctuates between -2% and 2%, in which the lowest, second and forth income level have positive changes and the third and highest income have shown a drop.

Another important issue related to distance travelled was mentioned during the interviews. One of the transport engineers said that important concerns they have to deal with are associated with the population distribution. People that live out of the cities are less connected to public transportation, hence reducing car use outside the urban areas is much more challenging than in cities, making longer trips more problematic to control.

Figure 48. Average trip length when commuting (km).



Source: Own elaboration from NTS 0705.

Unfortunately, at the time this chapter was being written, it was not possible to find the evolution per trip per length when people commute by car to quantify the previous point. However, the Department for Transport offers access to information about the number of trips per length and main mode. From this table, it is possible to partially support the fact that short trips are decreasing at higher rates than long trips (which is pretty much steady between 2015 and 2016).

Table 34. Average number of trips by trip length and main mode: England, from 2002.

Year	Under 1 mile	1 to under 2 miles	2 to under 5 miles	5 to under 10 miles	10 to under 25 miles	25 to under 50 miles
2002	31.6	76.3	145.6	90.8	66.0	17.8
2003	27.4	69.8	143.6	90.6	67.6	17.3
2004	27.7	68.9	141.9	89.7	64.8	17.7
2005	28.8	71.3	145.2	95.8	65.6	17.3
2006	26.3	70.8	148.2	92.5	66.1	18.0
2007	22.7	62.9	136.6	89.3	69.5	18.5
2008	23.4	67.0	136.4	89.6	68.1	16.3
2009	23.0	63.2	133.1	86.8	62.9	15.7
2010	23.2	64.1	138.1	87.5	63.0	17.2
2011	22.0	65.7	131.4	83.8	63.8	16.8

2012	24.1	63.7	133.3	87.6	63.4	16.0
2013	20.6	63.3	131.7	80.2	60.4	15.1
2014	22.5	64.9	127.9	82.5	61.5	16.0
2015	22.1	63.7	125.2	81.4	63.3	16.9
2016	24.0	64.8	130.7	82.7	61.8	16.9
2002-2016 % variation	-24.05%	-15.07%	-10.23%	-8.92%	-6.36%	-5.06%

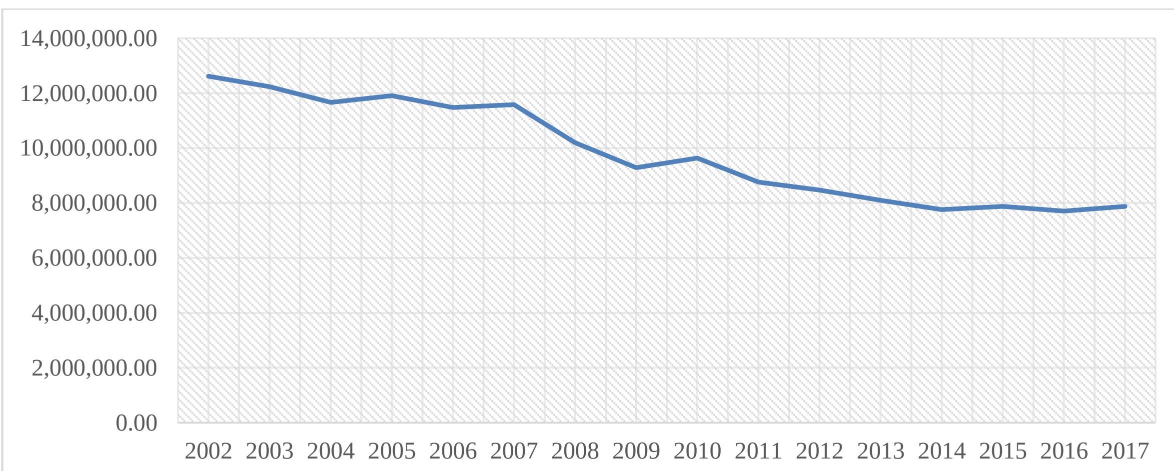
Source: Table extracted from data nts0308 (Table NTS0308a).

By putting all the relevant variables together and using the averages (fraction of people that commute by car, trips, average length per trip, average gas emissions), the total tonnes of CO_2 produced between 2002 and 2017 in England are shown in Figure 49. As can be seen, the CO_2 emissions were decreasing significantly until 2014, where the yearly variation was over 4% in the majority of the years. However, between 2015 and 2017, the yearly variation dropped to levels lower than 3%, which demonstrates that controlling car pollution needs a structural change that goes beyond the efficiency of new engines if significant changes are needed. The fact that longer trips are being taken on average, and the population is increasing at a rate that overcomes the reduction of the fraction of drivers (when commuting) shows that decreasing car use to commute needs a deeper intervention that affects individuals' preferences in travel mode choice and does not depend significantly on new technology or laws. If people become more environmentally concerned about car pollution, green attitudes are more accepted, and the feeling of moral obligation to contribute to the good cause is relevant to the individual, then it will not be necessary to wait for technology to meet the efficiency needed or the application of several laws to decrease car use for the net zero emissions plan.

Cars not only pollute by emitting greenhouse gases, non-exhaust emissions are also relevant, and they will not decrease with better engines as they are related to brakes, clutch or tyre wear.

Therefore, electric cars cannot be seen as the long-term solution. Governments are promoting electric cars more than ever, but the positive impact on reducing greenhouse gas emission can be counteracted as there is evidence that electric cars are heavier than equivalent internal combustion engine vehicles and the weight has been linked to more emissions of particulate matter (PM) (Timmers & Achten, 2016). Hence, the definite solution is encouraging people to commute by active transportation or public transport to at least decrease the total greenhouse gas emission per capita.

Figure 49. Tonnes of CO2 produced by commuters in England.



Source: Own elaboration by using NTS 0405, NTS 0412 and SMMT report (SMMT, 2018).

Based on the current restrictions and policies, the CO_2 is not falling at the rate needed to meet the carbon targets. To achieve the current government goals, the UK would need to cut another 31% of CO_2 by 2030. However, expert's projections are expecting just a 10% cut by the end of that period (Evans, 2020). Therefore, this opens the question: what is required to change from a psychological point of view to decrease the behavioural intention to commute by car in England? The following section will develop the explanation for the different scenarios that will be tested.

8.3 Methodology of analysis: variable configurations and scenario specifications

To analyse the case of England, a series of parameter changes were decided from the case study. For these experimentations, four exogenous variables were manipulated, in order to create different simulated scenarios. Generally, environmental psychologists in transport studies have concluded that environmental attitudes, habits, individuals' ascription of responsibility and people's environmental concern are key variables to encourage the formation of a pro-environmental behaviour (Klöckner & Blöbaum, 2010; Abrahamse, et al., 2009; Bamberg, 2013; Kroesen, et al., 2017; Lanzini & Khan, 2017; Chng, et al., 2018).

The goal is to investigate how much impact on the targeted exogenous variables is required to change the tendency of the car use loop dominance within the system and investigate whether there are substantial differences between the scenarios, in the decrease of the individual's behavioural intention towards car commuting. To achieve this, four scenarios were formulated, in which different combinations of the selected exogenous variables were made to generate different starting conditions for the PEBCM model system. Variables which were not selected in the scenario specification were kept at their values from the base model scenario (see Table 35). Each new set of starting conditions (see Table 36) generated different model outputs and model conditions. It is important to note that this model is a deterministic model, which means that the simulations do not involve elements of randomness. In other words, each time a simulation is run, the outputs are the same unless changes in the exogenous variables are applied. Each of these scenarios is then analysed in order to find the leverage points in the system.

The process went as follows: after computing the base scenario, the four targeted variables were changed according to the values of Table 36. Once a scenario was computed, the process continued with extracting a line graph created by the software, to observe and evaluate the evolution of the behavioural intention towards car commuting, as well as comparing it with the reference mode (base scenario). Additionally, the numerical data was analysed to estimate the percentage of variations between each year of simulation to appreciate the deceleration of the endogenous-target variable when changes were applied in the exogenous variables.

Table 35. Initial condition of the exogenous variables in the base model scenario.

Exogenous variables (values specified before running the simulation)					
Frequency of car use [Days a week]	5	Resistance Rate (RI) [Dmnl]	1	Environmental concern [Score]	1
Attitude towards car use [Score]	3.4	Adoption from Ascription of Responsibility [Score]	0.1	Environmental Attitude towards carbon mobility [Score]	2.8
Values: wellbeing of others [Score]	3.2	Belief of cars do not contribute to pollution [Score]	0.2	Perception of how easy is reducing car commuting [Score]	2.7
Internal attribution [Score]	0.6	Motivation to comply toward subjective norm toward driving [Score]	1	Cost of running a car [Pounds]	£1,944
Belief of PT as the main mode to tackle pollution [Score]	0.4	Average Speed [km/hr]	33.7	Median household disposable income [Pounds]	£29,400
value orientation toward self-wellbeing [Score]	1.5	Social identification with car use and commuters [Score]	1	Quality of Car [Score]	0.8
Motivation to comply toward subjective norm PEB [Score]	1	Symbolic Affective: Car ownership [Score]	3	Quality of Road Infrastructure [Score]	0.8
Social identification with pro-environmental actions [Score]	1	Independence [Score]	3	Sense of flexibility & autonomy [Score]	1
Temporal Distance [Score]	5	Transport priorities [Score]	0.7162	Normal Driving Satisfaction per trip [Score]	0.8
Co2 Budget [Tonnes of Co2]	9.70E+06	Trip rate growth (AT trip) [Dmnl]	0.00315233	Subjective Norms towards buying a car [Score]	5.6
Trip rate growth (car trip) [Dmnl]	-0.01442	PT accessibility [Score]	0.7	time threshold (commuting by car) [Minutes]	35
Number of Lanes [Lanes pre road]	2	Normal AT satisfation per trip [Score]	0.2	delay time personal norms acceptance [Years]	2
Occupancy rate [Dmnl]	0.867	Social Acceptability of PT [Score]	0.8	Reduction of car use for the sake of the environment [Score]	0.014
Perceived effort to take PT [Score]	3	Growth Rate Employee Population [Dmnl]	0.9176	Perceived uncertainty surrounding climate change [Score]	5
Time of commuting on PT [Minutes]	Look up graph [35.22 – 39.37]				

Source: Own elaboration.

Table 36. Scenario specifications – starting conditions for targeted exogenous variables.

Scenario (#)	Attitude towards an alternative transport mode	Environmental concern	Ascription of responsibility	Habit
0	0	1	1	5
1	3.4	1	1	5 & 4
2	5.1	1 & 0	1 & 2	5 & 3
3	8	1	1	5
4	6.3	1	1	2

Source: Own elaboration. All the variables are measured in Likert-scale points (from 1 to 5) apart from environmental concern, which in this model is treated as a binary Likert-point variable (1= high level of environmental concern, 0= low level of environmental concern) and habits, which is measured as 5 = 'regularly use of car to commute' and 0 = 'no car use'.

Scenario 0 corresponds to the base model, which closely mimics the case of England. In 20 years, the percentage of car commuters has barely changed, being over 60% of the employee population. Scenario 1 aims to compare the effect of habits on the behavioural intention towards car commuting, when the frequency of driving is modified. In this scenario, the model starts with a low attitude towards low-carbon mobility. Scenario 2 evaluates the effect of a high level of an environmental attitude, but it also tests the impact on car commuting when high and low levels of car use frequency are selected, as well as when people have (and do not have) an environmental concern and different levels of ascription of responsibility. In this scenario, the model wants to test the power of an environmental attitude in changing a non-environmental behaviour in the long run based on high and low levels of car commuting. Scenario 3 is more exaggerated in terms of forming an environmental attitude. In this scenario, ascription of responsibility, car habit and environmental concern are kept constant, in order to test the impact of only encouraging people to develop an environmental attitude. Finally, scenario 4 evaluates the impact of a low level of habits when high levels of environmental attitudes and ascription of responsibility are in place. The following sections will explain the different scenarios regarding how these factors will dynamically affect the formation of a behavioural intention towards car use (endogenous variable).

8.4 Policy evaluation: attitudinal tension

8.4.1 Scenario 0: initial condition (reference mode)

Since the 1970s, studies in transportation have been studying the attitude-behaviour relationship and its link to travel mode choice (Dobson, et al., 1978; Tardiff, 1977; Tischer & Phillips, 1979). Since then, many theoretical frameworks have been introduced in transportation in order to fully understand how attitudes affect behaviours (as well as the other way around), and then the implications for future research and policy design (Bamberg & Schmidt, 2003; Carrus, et al., 2008; Ajzen, 2015; Kroesen, et al., 2017; Chng, et al., 2018). In this model, the relationship between attitude and behaviour is bi-directional, as attitude directly affect behavioural intention and the balancing/reinforcing loops created through attitude change and satisfaction affect the level of attitude when the level of behaviour towards car commuting changes (see Chapter 6 for more details).

Financial incentives, mass media advertising and transit structure improvements have been normally taken to influence people's travel choice (Tertoolen, et al., 1998), but those actions have not worked as expected. Researchers have found that actual behaviour and attitudes are not normally consistent in the field of climate change and travel behaviour (Kroesen, et al., 2017), which can be observed when attitudinal surveys are contrasted to the actual commuting levels by car. For example, in 2019 the National Travel Attitude Study found that 85% of people in England believed that climate change is currently taking place, and people's actions are responsible for it[65]. However, in the same year, the Department for Transport reported that 67% of commuters in England normally travelled by car, of which 90% of them did so as the driver[66].

Cognitive dissonance theory has clarified this situation (Cooper & Fazio, 1984; Aronson, 1997; Tertoolen, et al., 1998). When an individual feels psychologically uncomfortable with an inconsistency between attitudes or attitudes and behaviour, two strategies are possible: if the attitude towards using alternative transport modes is higher than the attitude towards driving, then the person can follow a behavioural change process (in this case, reduce car use) or, if the individual

[65] Table NTAS0201d: https://www.gov.uk/government/statistical-data-sets/national-travel-attitudes-study-ntas

[66] Table tsgb0112: https://www.gov.uk/government/statistical-data-sets/tsgb01-modal-comparisons

holds a low level of environmental concern, then the cognitive discrepancy will encourage the person to mask this salient green attitude by perceiving the undesirable effects of car use as less negative as they actually are (attitudinal change).

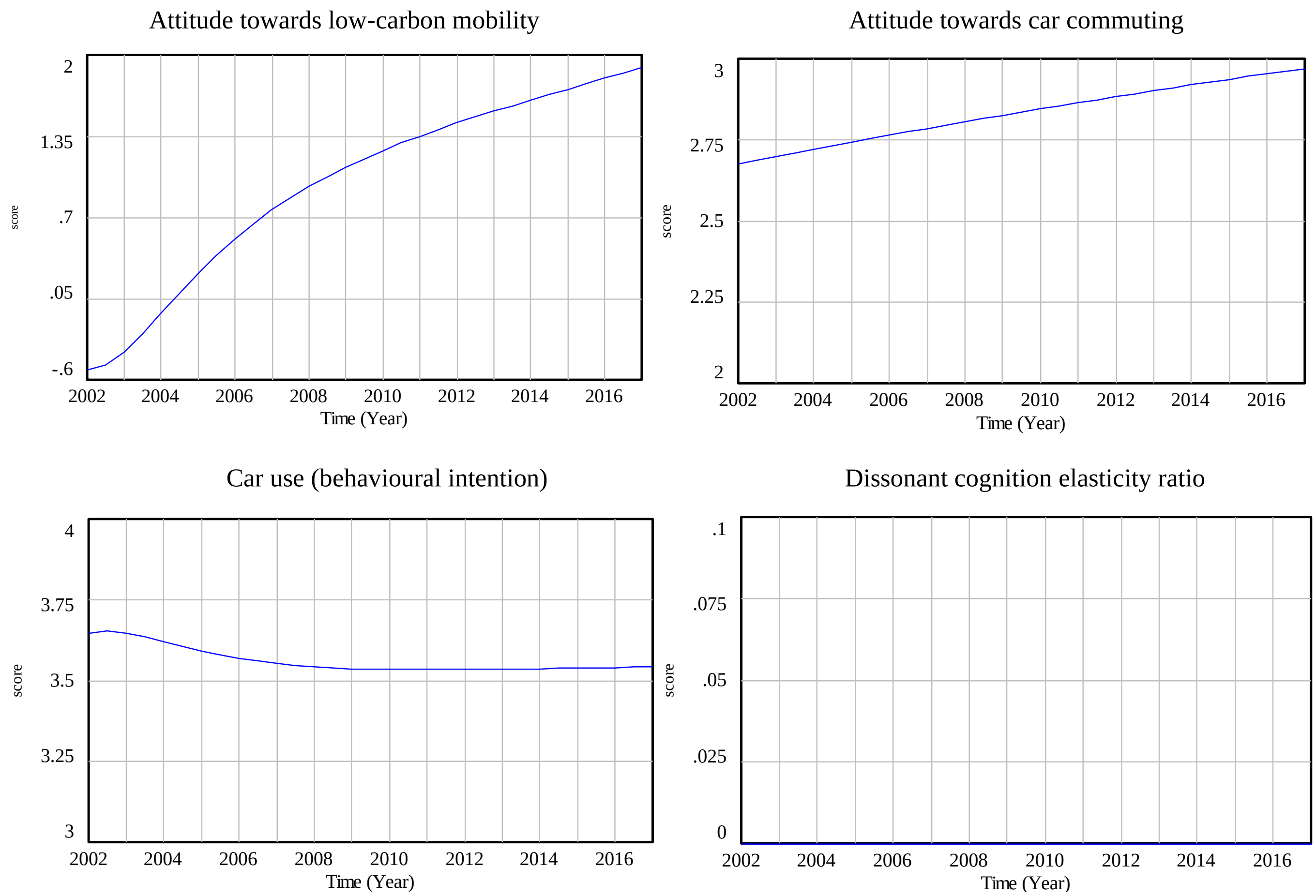
For this reason, the experiment in this chapter will explore how a cognitive discrepancy between the attitude towards commuting by car or an alternative transport mode emerges and is resolved. Additionally, it will show the consequences on the behavioural intention towards driving and how that decreases the probability of driving.

Before exploring changes on the initial level of attitude towards alternative transport modes, scenario 0 is presented to set the reference model and to observe how some of the variables in the simulation model evolve without any intervention (see Figure 50). On the one hand, the formation of the green attitude starts to be positive after two years of simulation, showing an s-shaped behavioural pattern. The values fluctuate between 0 and 1.90 Likert scores, and the most explosive change comes between years 2004 and 2006, where the annual change rate is over 30%. By the end of the simulated periods, the level of attitude towards alternative transport modes changes at a rate around 2% per year. Even though the attitude towards alternative transport modes becomes positive, it is not higher than the attitude towards car commuting in any period of the simulation model. Therefore, it is expected that there is no attitudinal conflict that could initiate a behavioural change. This is reflected in the dissonance cognitions elasticity ratio (DCE ratio). The DCE ratio measures how likely the person is to develop a change in behaviour based on the differential of one attitude in relation to the opposite and how impactful is that difference on the actual behaviour (which is based on habits). As was explained before, habits play an important role in reinforcing routines; therefore, a driver is expected to keep driving as the decision-making process of travelling becomes more automatic than deliberated (no room to think of taking the bus or using a bicycle).

This way, the ratio can be seen as the pricing value between resolving the dissonance between the attitudes, the current behaviour and habits. If the attitude towards the alternative transport mode is higher than the attitude towards driving, then the cognitive dissonance will be activated, relevant and resolved when the person performs the second behaviour available. If the relative weight of the cognitive dissonance is low, then it is expected that it will not be a factor to initiate a behavioural change. In other words, when a person is strongly performing behaviour A (driving), the "price of changing" to stop doing it become extremely high, reflecting that there are no reasons to change the current behaviour. On the other hand, the attitude towards car use is constantly growing at rates over 0.25%, showing important changes at the beginning of this scenario. If, in the following years, this behavioural pattern remains unchangeable, it is expected that the attitude towards an alternative transport mode would overcome the attitude towards car commuting in 2040.

Since the attitude towards car commuting is stronger than the green attitude, the behavioural intention towards car use remains steady during almost all the periods. There is a significant reduction at the beginning of the simulated scenario, and that is because there is a behavioural intention process (the intention to reduce car use) occurring in parallel with the intention to use alternative transport modes. The reduction of the attitude lasts until year 2005, after that period the yearly variation rate is close to zero.

Figure 50. PEBCM simulation results: Average level of attitude and behavioural intention towards car driving.



Source: Own elaboration based on initial conditions.

Before considering the effect of the level of attitude increments, a few simulations considered the comparison of the existence or not of environmental concern levels. The reason for comparing two different possibilities during the simulations is because the theory of cognitive dissonance assumes that there is no dominance between attitudinal or behavioural change when a cognitive conflict emerges (Festinger & Carlsmith, 1959; Kroesen, et al., 2017). However, based on studies investigating the attitude-behaviour relationship in transportation and environmental psychology, it is possible to assume that environmental concern (EC) can play a role in determining which strategy can be followed. EC refers to the attitude towards environmental issues (Fransson & Gärling, 1999; Schultz & Zelezny, 1999; Hansla, et al., 2008), and, because an attitude is determined by beliefs regarding consequences of the behaviour and evaluations of these consequences (Fransson & Gärling, 1999), then the existence of EC should reflect the fact that a person would be able to resolve the cognitive dissonance towards protecting the environment behaviourally because he/she can understand the future problem and accept that there is a proximity between car commuting and its negative consequences for the ecosystem (e.g., reducing car use). Contrary to that, if an individual does not have any level of EC, the model assumes that the person would modify the level of the green attitude (attitudinal change), as research has demonstrated that car users normally stick to their cars especially when high levels of driving are reported (Thøgersen & Møller, 2008).

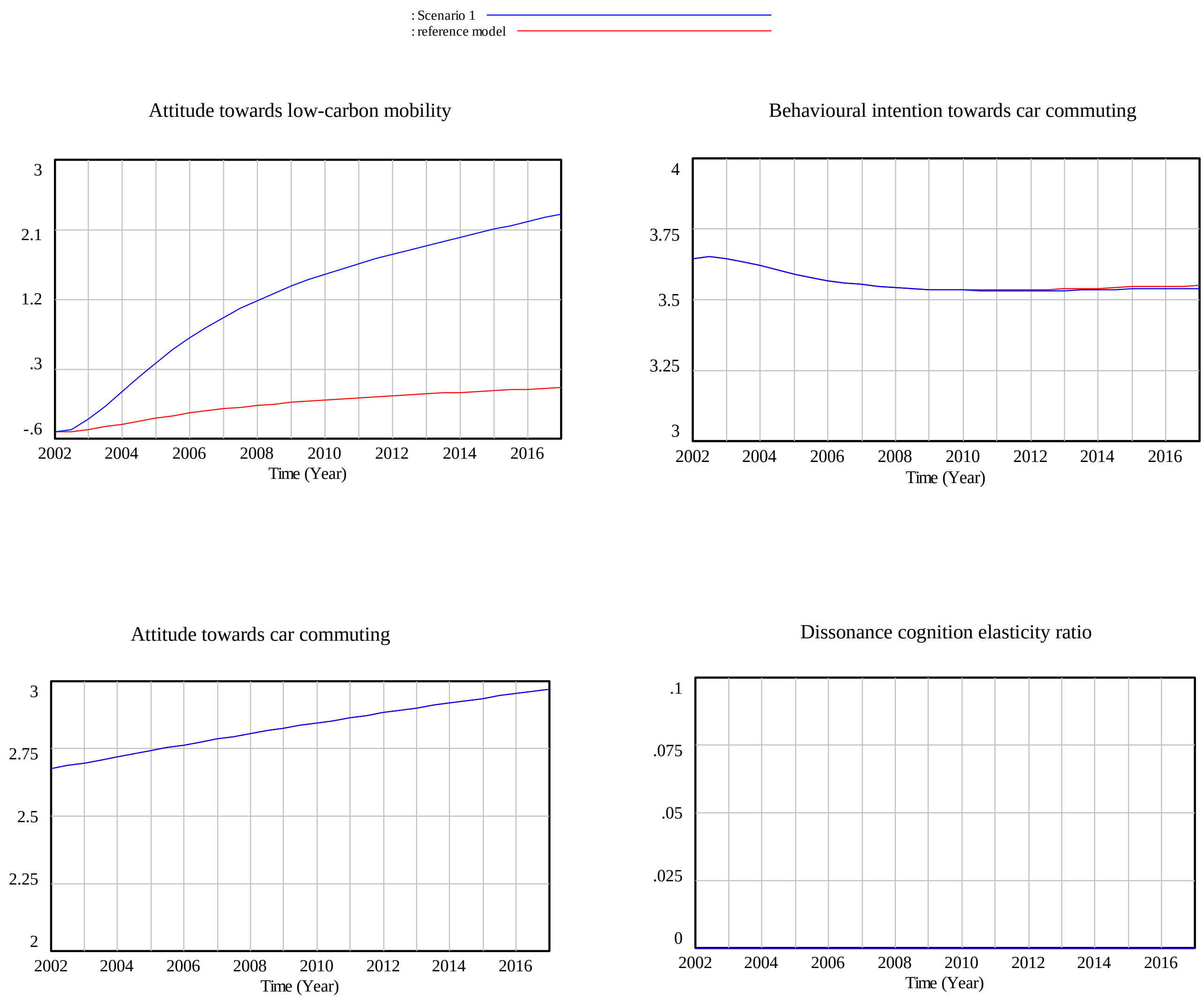
8.4.2 Scenario 1

For scenario 1, the initial attitude level towards alternatives was changed. In the previous scenario this number was set equal to zero, but in this new simulation, this attitudinal value was set equal to 3.4 (Likert score). By doing this, the scenario assumes that drivers would start with a cognitive dissonance issue as the attitude towards alternatives is higher than the attitude towards driving. The simulated scenario is shown in

Figure 51. A significant increment can be observed for the green attitude: at the end of the simulation period, this attitude grew by 3608.94% in comparison to the reference mode. However, it is possible to note that this significant change is not enough to generate a cognitive dissonance problem. The cognitive dissonance ratio (CDR) remains equal to zero during the whole simulated

period. This small impact on behavioural change can be seen as the behavioural intention towards car commuting decreased by 0.25% at the end of the 16 periods.

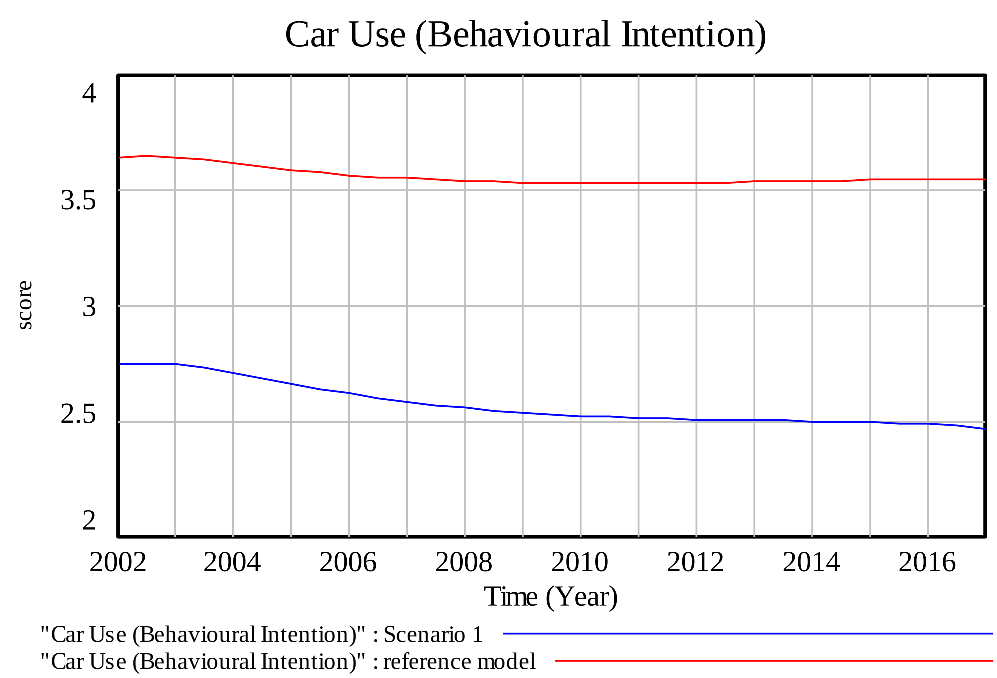
Figure 51. PEBCM simulation results: Scenario 1 outputs.

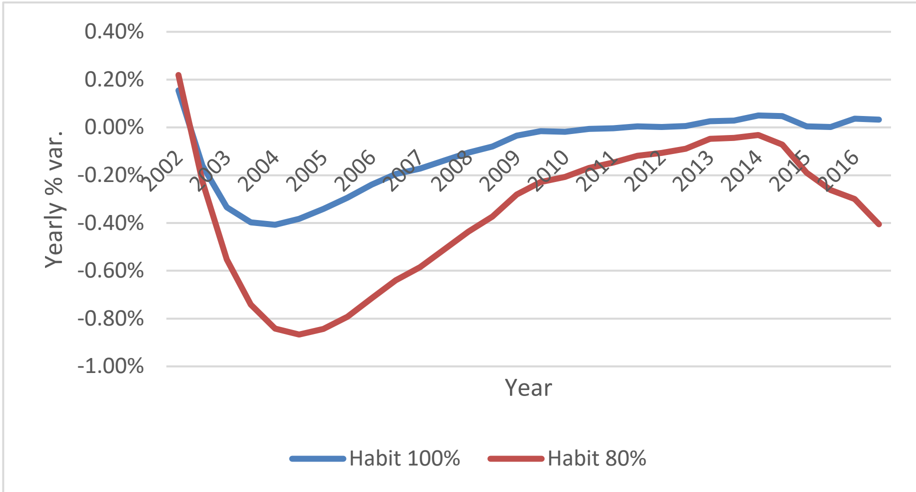


Source: Own elaboration.

Compared to the base case, the behavioural intention towards cars remains around the same levels in the new scenario, which means that the parameter increment did not alter the levels of driving in the simulated population. Greater changes can be observed when the level of habit is decreased by 20% (score equal to 4) (see Figure 52). In this case, not only did the behavioural intention decrease its initial level by 24.68%, it also constantly decreased its levels across all the simulated periods at negative rates. This demonstrates how important it is to break the habit of car driving to negatively impact its selection for commuting (Thøgersen & Møller, 2008; Klöckner & Matthies, 2009), and the fact that promoting a pro-environmental behaviour among people who perform high levels of commuting (e.g., five days a week) might not work as it is expected, to reduce car use.

Figure 52. PEBCM simulation results: Comparison of behavioural intention when habit is decreased by 20%.



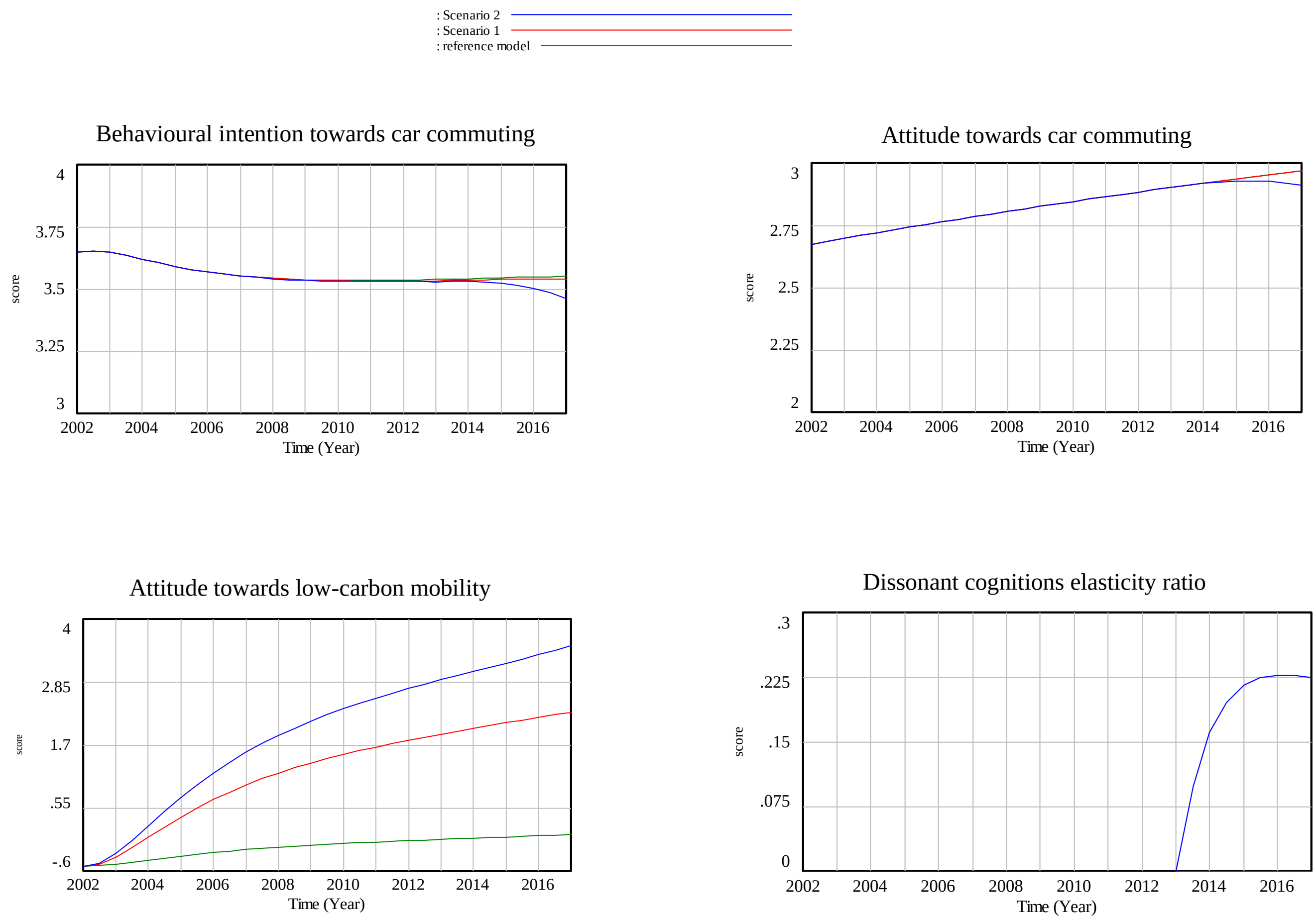


Source: Own elaboration. In this case, even when the cognitive discrepancy was equal to zero at the beginning, cutting the habit levels by 20% demonstrated that decreasing the behavioural intention is a joint effort between attitude and behaviour modifications.

8.4.3 Scenario 2

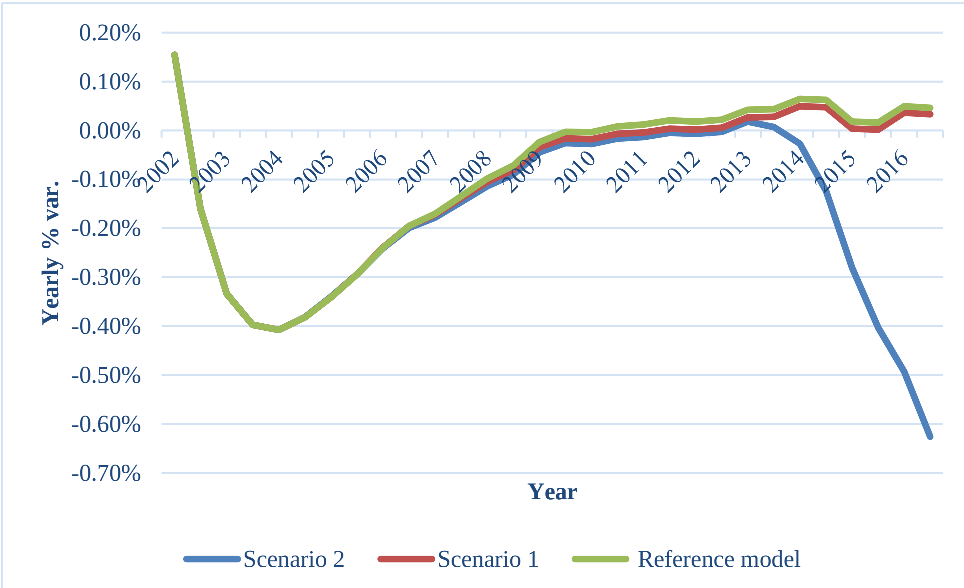
In this scenario, the attitude towards using the alternative transport was increased by 50% in the first period of simulation. Important changes can be observed in Figure 53, where the behavioural intention towards car decreased on an average of -0.18% during the 16 periods. Additionally, it is possible to see the effect of the attitude-behaviour and the cognitive dissonance loop: the accumulative effect of 'behavioural change' (see Chapter 6 for detailed information about the model) accelerated the growth of the attitude towards the alternative transport mode, which in turn rapidly decreased the behavioural intention towards cars at the end of the periods (see Figure 54). Moreover, the cognitive dissonance state becomes salient after seven periods of simulation, in which there is an exponential growth that last two periods and then starts to collapse as the green attitude overcomes the counter-environmental attitude (in this simulation, the environmental concern level = 1).

Figure 53. PEBCM simulation results: Scenario 2: Attitude towards alternative transport mode > 50%.



Source: Own elaboration.

Figure 54. PEBCM simulation results: Yearly variation of behavioural intention towards car use (%).



Source: Own elaboration.

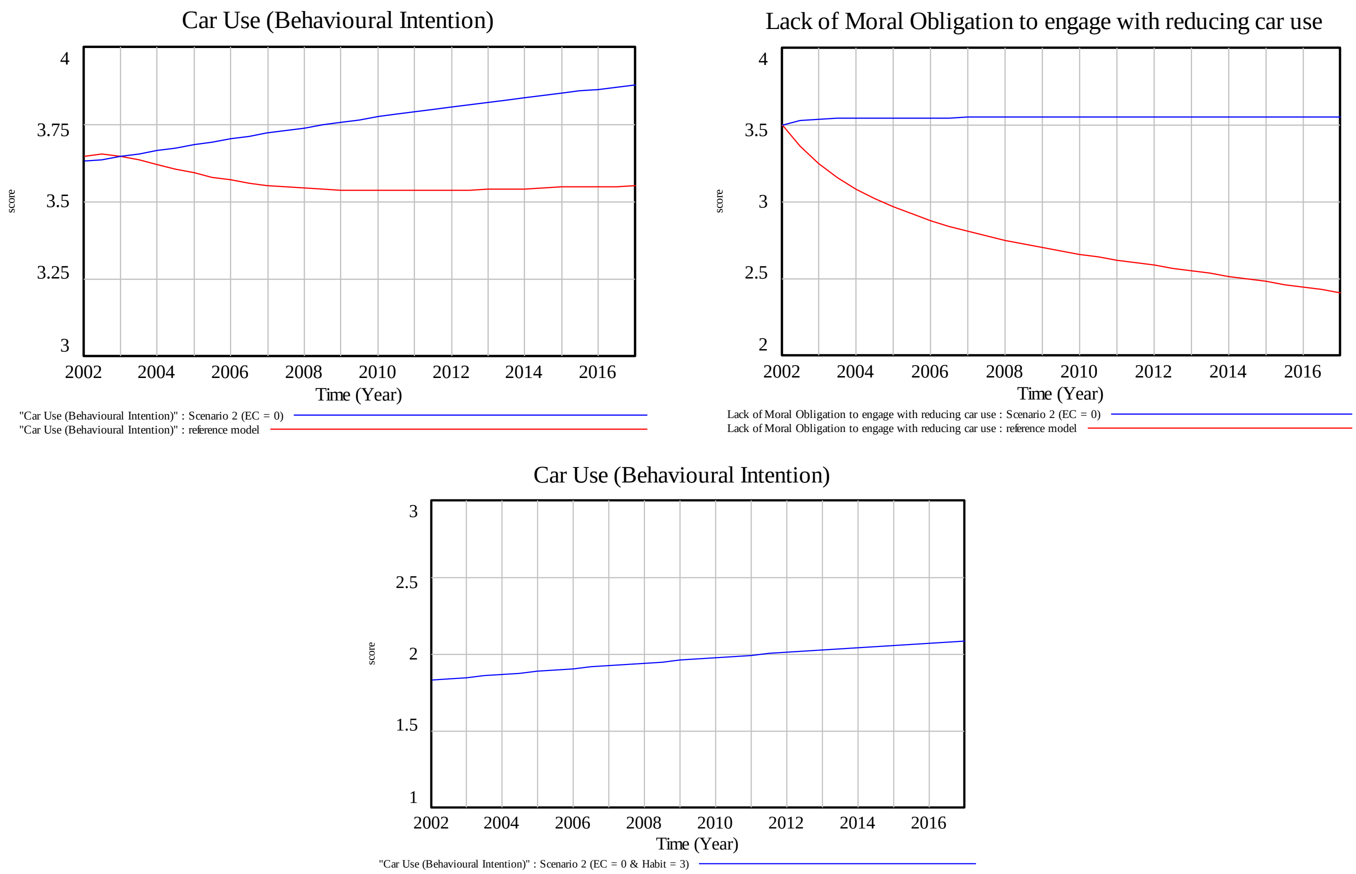
Contrary to the previous cognitive dissonance strategy, when the model assumes that the average individual has a low level of environmental concern then the green attitude shrinks, changing the course of the behavioural intention towards car commuting. As Figure 55 shows, in a scenario where EC = 0, the behavioural intention increases progressively. This suggests that, if a person is not concern about environmental issues, then the level of attitude towards alternative transport modes becomes irrelevant, not making an impact to promote a behavioural change.

The low level of environmental concern also affects the norm-activation process. The behavioural pattern of the lack of moral obligation (LoMO) to engage with reducing car use stayed stable during the 16 periods of simulations, which means that the personal norms internalisation did not exist. As Figure 55 demonstrates, the level of LoMO became steady, following a different pattern than the reference mode, in which it is assumed that, on average, an individual has a level of environmental concern. These results are in line with the integrative model CAUSE proposed by Chng et al. (2018), because it is possible to observe that the level of environmental concern determines the strength and direction in the formation of a personal norm and a green attitude, which are necessary to decrease the probability of choosing a car when commuting. If a personal norm is not formed, then the level of a green attitude does not have strong increments over time, and it is diminished by the reinforcing loop formed between driving, attitude, satisfaction with driving and habits. This is in line as well with most of the literature in environmental psychology and pro-environmental behaviour, where researchers have proposed that, in the absence of both variables (attitude & personal norms), a pro-environmental behaviour is unlikely to happen as the individual would not have the cognitive, motivational and emotional capacity (Bamberg & Schmidt, 2003; Bamberg & Möser, 2007; Bissing-Olson, et al., 2013; Coelho, et al., 2017; Chng, et al., 2018; Carrus, et al., 2008) to determine that reducing car use is necessary when humankind is facing several problems related to climate change.

Therefore, even when levels of habitual performance of a given behaviour are reduced[67] and there is a significant discrepancy between two attitudes, it is expected that an individual would not change their current behaviour if there were no (or low levels of) environmental concern.

[67] When the simulated scenario reduced the habitual frequency of driving at the beginning of the simulation exercise, it was possible to observe that the behavioural intention score was lower than the reference mode, which is in line with the literature regarding habit formation and behavioural intention (Thøgersen & Møller, 2008; Thogersen, 2012). However, it is still possible to see that the behavioural pattern of the behavioural intention towards driving is similar between the two scenarios (EC = 1 vs EC = 0): the behavioural intention grows constantly across time.

Figure 55. PEBCM simulation results: Scenario 2 (Environmental Concern = 0 & habit = 3 days a week).

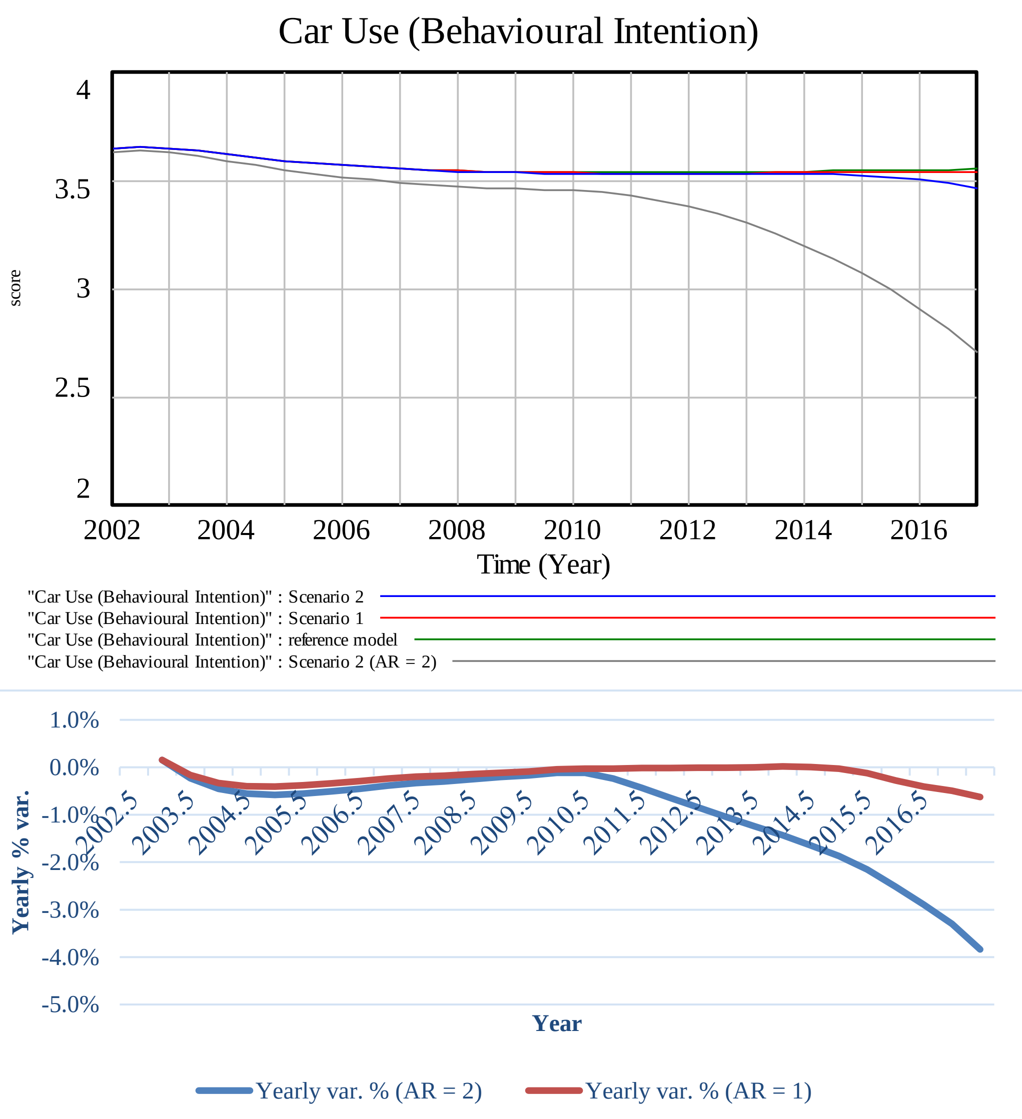


Source: Own elaboration.

Following the same analysis, another output was produced from the simulation model: the initial parameters of this scenario (green attitude = 5.1; habits = 5; environmental concern = 1) were tested when the ascription of responsibility is increased by double. The ascription of responsibility reflects the person's belief about the level of responsibility regarding the negative consequences that their act could cause. In this case, people with a low level of ascription of responsibility do not feel responsible for the pollution they are causing when they drive. Figure 56 shows that, by increasing the AR by 100%, there are important decreases at the end of the period.

After period 11, the behavioural intention towards commuting by car decreases at a rate of over 2% (average: 2.19%) when the AR is set at 2 Likert-score at the beginning of the simulation, while, in the previous scenario, when the AR was set to 1 Likert-score, the average rate of decrease was lower than 1% (average: -0.2% a year).

Figure 56. PEBCM simulation results: Scenario 2 (AR is increased a 100%).



Source: Own elaboration.

8.4.4 Scenario 3

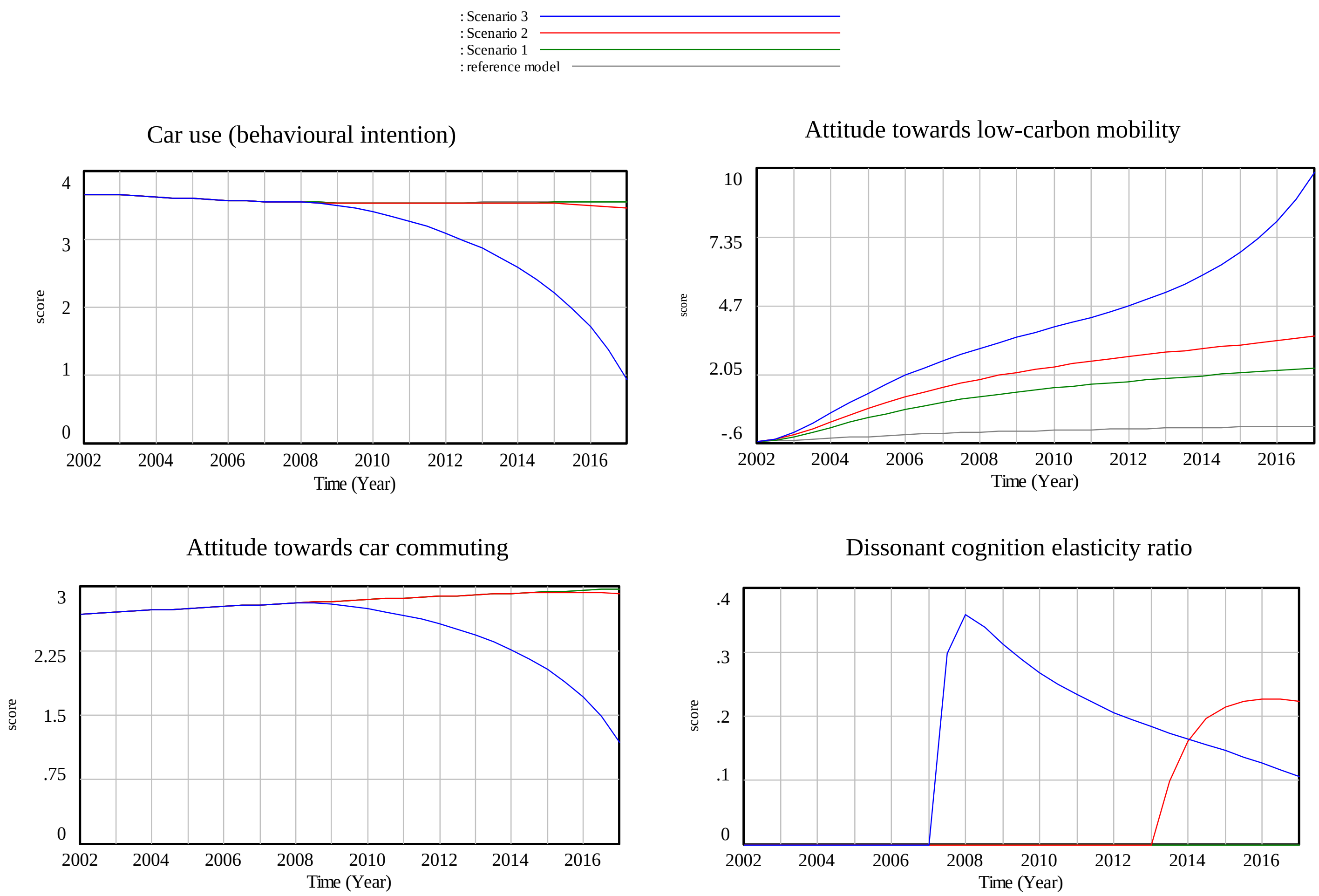
In this scenario, the attitude towards car commuting was increased by 50% compared to the previous scenario (initial attitude to low-carbon commuting = 8). Everything else was kept as it was set in the reference mode (initial condition). As Figure 57 shows, scenario 3 reveals substantial changes in terms of behavioural intention, attitude and cognitive dissonance.

In terms of attitude, it is possible to see that the attitude towards low-carbon commuting exceeds the attitude towards car use much earlier than in other scenarios. In this scenario, the attitude towards alternative transport modes grows moderately until 2008, when the slope changes to an exponential growth, creating substantial differences between the two attitudes. Moreover, in the same year, the behavioural intention towards car commuting exhibits an exponential decay, a level that ends close to zero at the completion of the simulated periods. The drastic change in both slopes matches the overshoot and collapse behaviour of the cognitive dissonance ratio. Overshoot and collapse behaviour are a behavioural pattern that exhibits an exponential growth at the beginning, followed by an asymptotic growth, an exponential decline and an asymptotic decline. It is important to note that the peak of the cognitive dissonance ratio occurs much earlier than in the other scenarios.

At the beginning, the strong levels of an attitude towards car commuting are satisfactory for the individual – the discrepancies between the two attitudes are not relevant (attitude towards car > attitude towards alternatives). However, the constant increment of the green attitude makes the dissonant cognition not sustainable, pushing the individual to resolve it quickly. It is understood that a cognitive dissonance brings discomfort to the person, so it is expected that a resolution is needed to decrease this psychological distress (maximum point in the graph).

After 2008, because in this scenario an environmental concern exists, the significant levels of discrepancy have substantial impacts on changing the behaviour. This means that the attitude towards low-carbon mobility will prevail, which in turn decreases the attitude towards car commuting. This will lead to boost the reinforcing loop of increasing the green attitude, which overcomes the reinforcing loop of habits, which is the result of solving the dissonant cognition (discrepancy between attitudes). This led to the conclusion that the individual successfully adopts a new attitude.

Figure 57. PEBCM simulation results: Scenario 3 - Attitude towards commuting on a low-carbon mode is increased by 50%.



Source: Own Elaboration.

8.4.5 Scenario 4

The previous simulation experiments showed that decreasing levels of behavioural intention towards car commuting is a complex problem that required multiple adjustments for effective changes: habits, personal norms, attitudes and environmental concern. This reinforces the idea that travel mode behaviour is a multidisciplinary effort, in which environmental psychology, transport, marketing and sociology should be involved (Kollmuss & Agyeman, 2002).

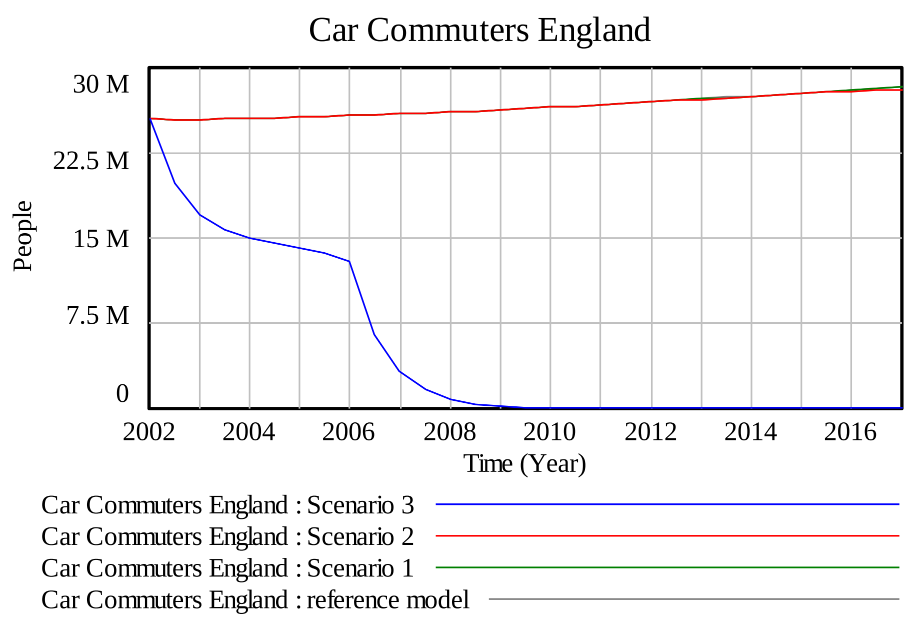
This last scenario will run a series of modifications to show under which conditions substantial changes can be seen. In this case, habits, ascription of responsibility (AR) and attitude towards alternative transport mode were modified as they have been demonstrated to be important factors to initiate a behavioural change. Habit and AR were set up equal to 2 and the initial attitude towards alternative transport modes was modified, adjusting the initial condition to 125% higher than the attitude towards driving.

As the previous experiments showed, modifications in only one variable at a time did not lead to significant changes in decreasing the behavioural intention towards car commuting. The reinforcing loop associated with car habits demonstrated that the behavioural intention is pretty much stable unless large changes occur in terms of attitudes, emotions and beliefs. For example, when the attitude towards environmental commuting was increased over 100% in comparison to the counter-environmental attitude, the model showed a significant impact on the given behaviour; however, its level did not change until the 7^{th} period of simulation. Therefore, changes that are focused on one variable are unlikely to see great results in the short term. This suggests that, as long as people develop strong habits about car commuting, it will be hard to see important improvements in reducing car use in the short term when only one variable is influenced.

An important insight obtained from the model was the fact that small changes in a set of variables are more effective to discourage car use in the short/middle term. This is important to highlight because it enables policy makers to focus their efforts by targeting specific variables with specific goals: promotional and information campaigns can focus on adapting attitudinal levels, but that has to come along with an intervention that decreases the average frequency of commuting by car per week, as well as activities that make drivers feel that they are contributing to the good cause by reducing car use for the sake of nature. If these variables are targeted together, important changes should be seen in the short term.

Figure 58 shows how the total number of car commuters can be decreased exponentially: within six periods, the number of car commuters decreased exponentially when the frequency of car use of an average driver is reduced to two days a week, their AR is increased to 2, and also the green attitude is increased by 125%. These extremes changes can be seen as unrealistic, but there are plenty of other variables in the model that can help to explore more feasible strategies such as: (1) cost of running a car (e.g., governments can increase the cost of using a car), (2) the perception of time control when commuting (e.g., institutions can make visible that in fact car commuting time is more unreliable than public transportation), (3) public transportation attributes (e.g., institutions can communicate more the levels of user satisfaction), (4) quality of road when commuting (e.g., it can be communicated that public transportation has better infrastructure to make quicker journeys in the city centre), (5) belief that cars do not contribute to pollution (e.g., communicating the whole carbon footprint of cars, therefore the myth that electric cars are the definitive solution is demolished), (6) environmental awareness (e.g., providing friendly apps that help people to correctly estimate their pollution emissions), etc. There are plenty of other variables in the model that can be set to find an approach that can decelerate car commuting faster.

Figure 58. PEBCM simulation results: Targeting Attitude, habits and personal norms (Habit = 2; green attitude = 125%; AR = 2; PN = no resistance rate).



Source: Own elaboration.

8.5 Summary

This chapter reported and explained the results of the policy experiments for England when psychological determinants are changed. Structural changes were investigated and explained according to what was found in the literature review and previous empirical studies. Experiments demonstrated the importance of planning interventions that have to influence multiple parts of the model: habits, personal norms (ARs) and attitudes.

During the simulated cases, this model demonstrated how insensitive behavioural intention towards car use can become on a number of occasions. Important changes were observed in small modifications in several parameters to diminish the level of the given behaviour. This is not surprising, given the current literature, in which many authors have stressed the importance of modifying attitudes, emotions, beliefs and habits to discourage car use (Bamberg, 2013; Abrahamse, et al., 2009; Bamberg & Möser, 2007; Chng, et al., 2018). However, the relevant learning points here are related to the fact that the simulations showed the different rates at which the behavioural intention towards car use can change. Therefore, the model can help to plan ahead for a green intervention by setting specific goals to a set of variables. This way, the simulation model can provide guidelines to reconfigure the effort towards discouraging car use and promoting public transportation.

The next chapter will conclude the research. As part of this process, a series of reflections and recommendations will be offered.

9 Implications: discussion and conclusion

The aims of this chapter are to draw the main research contribution regarding the study of car use from a dynamic-based psychological framework, and, finally, to conclude this thesis.

This chapter starts by discussing the recommendations and policy implications from the learning outcomes obtained from this project. Four key areas are presented. The first one is regarding habit and its power to keep unchanged the preference to commute by car. The second one is a comparison between the main theoretical frameworks in environmental psychology. The results obtained are in line with previous authors' contributions (Bamberg & Schmidt, 2003; Abrahamse, et al., 2009). The third one is the effect that habits have on the evolution of attitude towards car use and alternative transport mode, which illustrates the dynamics involved in the driver's resistance to change. The final one discusses the importance of analysing psychological theories under feedback loop system thinking.

After explaining the main insights obtained from this simulation model, the chapter continues with the demonstration of the usefulness of the model. As was discussed in Chapter 3, demonstrating that the model fulfils the purpose of the project is essential to conclude whether or not the outcomes are satisfactory. In this case, the model is seen as a reasonable option to accomplish the main goal of the project as several aspects are answered from the simulated experiments.

To finalise this chapter, reflections and the weaknesses of the model are reviewed to serve as a guideline for future research. Methodological as well as model extensions are reviewed. Additionally, some comments are made regarding the current world situation and the limits of the model to reflect what is happening with COVID-19 and lockdowns. The last section is the final conclusion to wrap up the learning outcomes obtained from this project.

9.1 Discussion about recommendations and policy implications

In Chapter 7, it was demonstrated that the simulation model can mimic the case study data in terms of car commuters and non-car commuters. In Chapter 8, the model used data from England to make multiple comparisons against other parameter settings. All these simulations were looking for decreasing car use in the long term. Assuming that the simulation model can provide a reasonable reflection of the behavioural structures observed in the real world, and the modelling iterations are aligned with the purpose of the project, these outcomes portray valuable information about 'what would have happened' questions, which enables a reassessment of car-reduction interventions. Accepting this degree of confidence, a series of lessons and recommendations can be derived for the case study and the comparison with alternative scenarios. From the previous chapter, four lessons and recommendation will be analysed and assessed.

9.1.1 Habits: the block of behavioural change

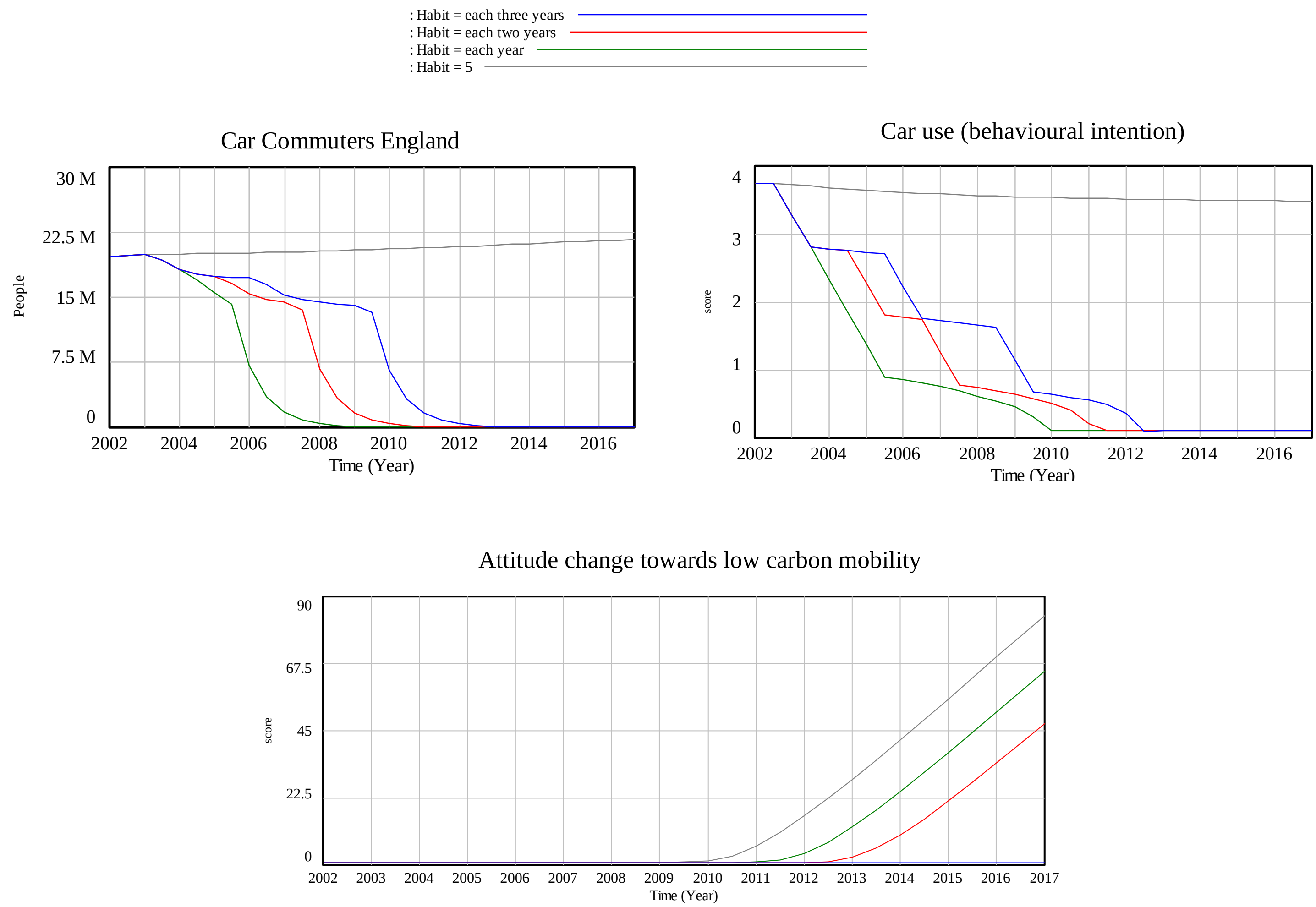
Habit has been well recognised as one of the main barriers to activate modal shift (Verplanken & Orbell, 2003; Bamberg & Schmidt, 2003; Klöckner & Blöbaum, 2010; Şimşekoğlu, et al., 2015; Chng, et al., 2018). However, psychological theories have not appreciated its effect from a feedback loop structure in the context of behavioural change. Figure 59 shows three scenarios in which the model base line (initial conditions) was contrasted against three more scenarios in which only habit was reduced.

In this model-based experiment, the condition was based on the following question: what if car frequency is decreased from five days a week to four days a week, then three days a week? This scenario can illustrate the power of habits, which can make policy makers think about how green interventions can go beyond increasing environmental awareness or boosting environmental attitude. Habits are understood as one of the main reasons why car use becomes a less deliberated decision. Researchers in transportation believe that, when people are inserted in a commuting routine, it is unlikely that they would consider alternative transport modes (Klöckner & Matthies, 2009; Thøgersen & Møller, 2008). Therefore, observing different levels of commuting will help to understand how fast people can develop a new attitude towards an alternative transport mode.

Interrupting car habits is not a new proposal, and it has been studied under real-life experimentation. For example, Eriksson et al. (2008) studied the effect of reassessing travel possibilities in advance. In the experiment, the authors asked people to complete a diary with all the trips that were meant to be by car during the following week. After completing the diary, the respondents had to review a list of different strategies to reduce car frequency (e.g., changing the destination, considering an alternative mode, cancelling the trip), and then they had to think again about whether or not any of the planned car trips could be changed. The results showed that weakening the association between car use and habit strongly reduced car use. In the same topic, Fujii and Kitamura (2003) offered a one-month free bus ticket to see the effect in considering alternative transport modes post-intervention. The results showed that the attitude towards taking the bus increased, as well as the frequency of use. Therefore, the value of breaking habits is not under question; however, experimenting with different levels of restrictions can illustrate how different strategies can modify habits in the long run.

In the model experimentation, the frequency of car use was restricted from five to three days. Whether or not this interruption is forced or voluntary, the model assumed three systematic frequency reductions. In the first scenario (M1), car use was decreased one day a week every year until reaching three days a week. In the second scenario (M2), the same measure was taken, but every two years. Finally, the third scenario (M3) restricted car frequency every three years.

Figure 59. PEBCM simulation results: Restricting car use from 5 days a week to 3 days a week.



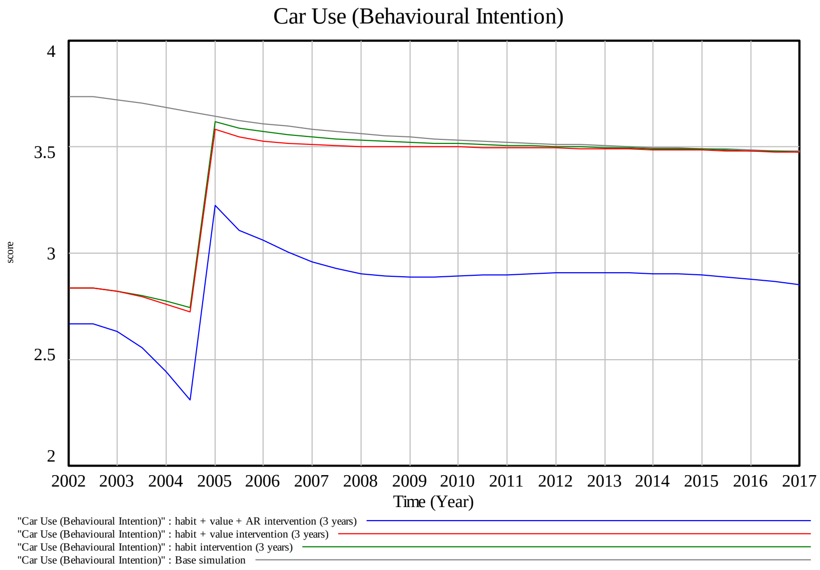
Source: Own elaboration. In this simulation, car use was restricted from 5 days a week to 4 and 3 days a week. The simulation referring to 'habit=each year' represents a scenario in which the restriction is taken year by year; in other words, in 2003 cars can be used 4 days a week and in 2004 cars can be used 3 days a week.

The impact of this experimentation on behavioural intention towards car use is not surprising. However, it is interesting to discuss the progressive acceleration that the different scenarios showed. Restricting car frequency every year by one day has a more progressive and abrupt impact on behavioural intention, as well as in attitudinal change. By the end of period 2, in M1 the behavioural intention plunged by 62%, whereas M2 and M3 dropped it by 37% and 25%, respectively. Therefore, systematic changes in terms of habits tend to be more impactful when interruptions are more frequent than spread over longer periods. This might explain the heterogeneity obtained in terms of post-intervention outcomes regarding previous studies in real life. The frequency of the interruptions and the time that these interventions were applied varied in each study, leading to different conclusions being obtained based on the weakening of the habit-behaviour relationship. This suggests that future research in the field should work on conducting a meta-analysis study to compare cross-sectional studies, in order to understand how the length of the intervention applied affects the evolution of cognitive aspects such as attitudes or perceived behavioural control.

This demonstration has extremely valuable contributions as it demonstrates that car habit really matters as it is embedded in extremely powerful reinforcing loops that make it really difficult for car-oriented people to consider alternative transport modes, nullifying attitudinal change towards alternative transport modes when drivers drive on a daily basis. By decreasing car frequency to three days a week, frequent car users dropped to levels lower than 1000 people after 10 years.

This is one of the main contributions found in this project: breaking habits can be a powerful tool to re-shape behavioural intention towards car use, as long as consistent interventions are deployed. This opens the possibility for car-oriented individuals to consider alternatives more easily, which in turn impacts on important levels of car reduction. These habit changes have to be systematic and be spread among short windows of time if important changes are to be sustained in the long term. Otherwise, if the interruptions are removed, a rebound effect is expected to happen in terms of behavioural intention towards car use (see Figure 60), reinforcing again travel preferences in the direction of cars. This conclusion is in line with Thøgersen and Møller (2008), who ran an experiment in which they offered a one-month travel card for public transportation. In this study, the authors observed similar results to Fujii and Kitamura's (2003). However, in the long run (when the free card was withdrawn), experimental subjects did not use public transport more than the control group, suggesting that interrupting car use has to be supported by modifying other components if the intervention is not permanent. To decrease the rebound effect, the intervention needs to target the modification of additional psychological determinants such as ascription of responsibility and values towards protecting the environment. As Figure 60 shows, when habits, values and ascription of responsibility are modified (and then returned to the original levels), the behavioural intention increases but not up to the levels of the base model, nor to the levels of a scenario in which only habits are modified.

Figure 60. PEBCM simulation results: Rebound effect when the interruption is removed after 3 periods.

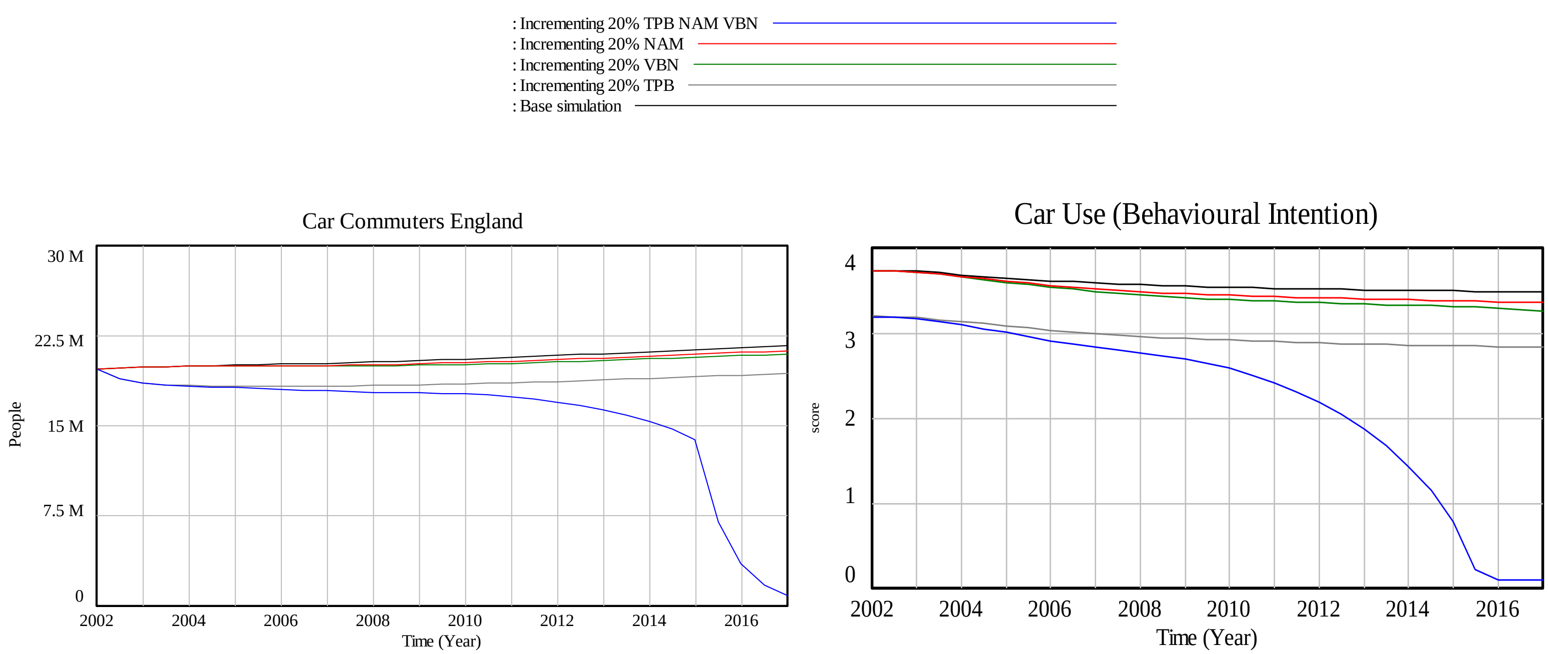


Source: Own elaboration.

9.1.2 Interventions must act across the overall chain of TPB, NAM and VBN

In the last 30 years, environmental psychologists have not only been polishing the assumptions of their model, but also searching for more variables that can improve the understanding of pro-environmental behaviour. Independent of which model has had better results in terms of empirical applications, most of the conclusions point to one common direction: the explanation of adopting pro-environmental behaviours is a multi-factorial problem. All the models based upon psychometric variables have proved a degree of validity and explanation in the prediction of PEB, as well as integrative frameworks (e.g., TPB + NAM) in transportation (Abrahamse, et al., 2009; Bamberg & Schmidt, 2003; Carrus, et al., 2008; Klöckner & Blöbaum, 2010; Belgiawan, et al., 2017; Lanzini & Khan, 2017; Ünal, et al., 2018; Chng, et al., 2018). Therefore, it is reasonable to think that encouraging the adoption of a pro-environmental behaviour is a multi-layered model. However, authors tend to recommend green interventions that imply the modification of the latent variable which had the higher power explanation in their model. Figure 61 shows another policy-type analysis. Under the assumption Pareto principle (80% of the consequences are explained by 20% of the causes), a new intervention was applied. The psychometric variables normally included in TPB, NAM and VBN (see Chapter 2 for a detailed explanation of each model and variables) were increased by 20% at the beginning of the periods of simulation.

Figure 61. PEBCM simulation results: Experimentation: isolated models vs multi-layered analysis.



Source: own elaboration.

The results are clear: applying a multi-layered intervention has much more impactful outcomes than isolated-model applications. In order, affecting NAM variables is the intervention with the lowest performance, decreasing behavioural intention by 2.22% on average during the 16 periods of simulation. This model's outcomes are followed by VBN, averaging a change of 3.55% in the same periods. Then, TPB shows the highest outcomes related to isolated-model interventions, in which the variables of this model dropped behavioural intention by 20.47% on average. The reasons to explain this difference are based on how the cause-effect relationship structure is distributed, as well as the number of feedback loops. TPB antecedents are immediately related to the behaviour in question (Bamberg & Schmidt, 2003; Lanzini & Khan, 2017); therefore, any change in one of these variables creates an instant behavioural modification. In contrast, NAM and VBN variables are at the back of the cause-effect chain of the model. This kind of cause-effect relationship chain has been supported in many other studies in transportation (Abrahamse, et al., 2009; Bamberg, 2013; Klöckner & Blöbaum, 2010; Chng, et al., 2018). The rationale behind this is based on the nature of each construct. Values and beliefs are understood as the fundamentals of behaviour and worldviews (Kollmuss & Agyeman, 2002). They are the principles that shape moral meaning, establishing a general conception and orientation to construct the sense of rightness. They are formed by people's personal experiences and cultural roots, and they are normally considered stable and long-term guides (Stern, et al., 1999). For these reasons, values are the first-line predictors of behaviours. Then, closer to the action, cognitive and emotional constructs take place, being defined as the aspects that people consider, in order to evaluate which action to select. That is why perceptions about personal capabilities, attitudes and emotions are normally targeted to see immediate behavioural changes (Bamberg, 2013), because they can explain volitional behaviours and cognitive dissonances. In the middle, the formation of personal norms can drive behavioural changes, as people interact in a social context, therefore, modifications about what is right can come and go depending on the subjective and descriptive norms (Chng, et al., 2018).

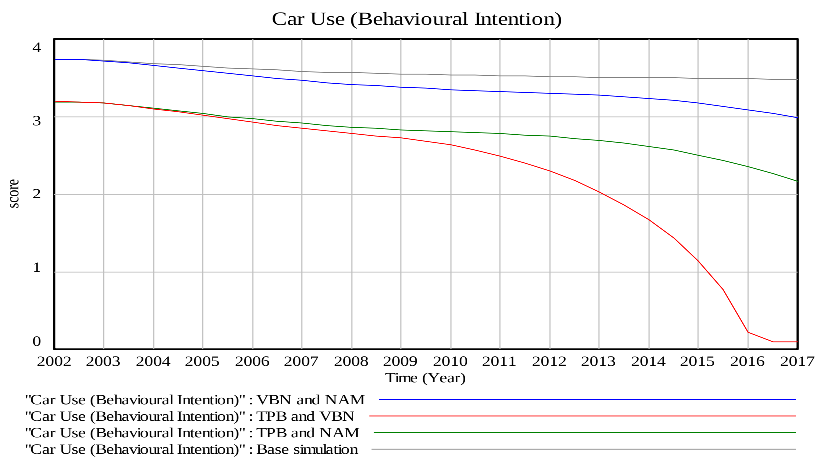
Testing different combinations between TPB, NAM and VBN, it is possible to see that TPB drives the quickest changes in the results (see Figure 62). These findings might explain why interventions have questionable effectiveness and TPB is so popular. First of all, the TPB combined with VBN model was shown to be the strategy that delivers the fastest reduction of the behavioural intention towards car commuting. TPB + NAM illustrated substantial improvements in comparison to the original model, but important discrepancies can be observed between TPB + NAM and TPB + VBN. After 2005, both strategies increase their discrepancy as time in the simulation model elapses, showing that, when values are involved[68], the reinforcing loops related to VBN can greatly boost the intention to reduce car commuting. VBN + NAM were demonstrated to be a better strategy than the base model. However, the reduction of the behavioural intention towards car it is less than the other two combinations (TPB + NAM and TPB + VBN).

Finally, the results show that TPB can bring significant improvements in the short term. However, it is possible to observe that TPB-driven interventions are more sensitive to changes when they are withdrawn. As Figure 63 shows, once the intervention is removed, the behavioural intention towards car commuting increases almost to the same levels as the base simulation, demonstrating that a larger rebound effect is more likely to happen in a TPB context. In contrast, NAM + VBN were demonstrated to have a smoother rebound effect, matching the same levels of the simulation base scenario by almost the end of the periods. The explanation for this is in line with what researchers have discussed before (Bamberg & Schmidt, 2003; Stern, 1999; De Groot & Steg, 2008). TPB does not include values and personal norms in its conceptualisation, hence also does not modify more stable antecedents such as values or beliefs. Researchers have previously discussed the rebound effect in green interventions (Abrahamse & Steg, 2011; Steg & Vlek, 2009; Ünal, et al., 2018; Kollmuss & Agyeman, 2002; Unsworth, et al., 2013), concluding that, once the

[68] VBN and NAM share a great number of variables in the conceptualisation of each model. However, one of the biggest discrepancies is that VBN includes values in the model, which affect not only the behaviour, but also the rate of formation of personal norms.

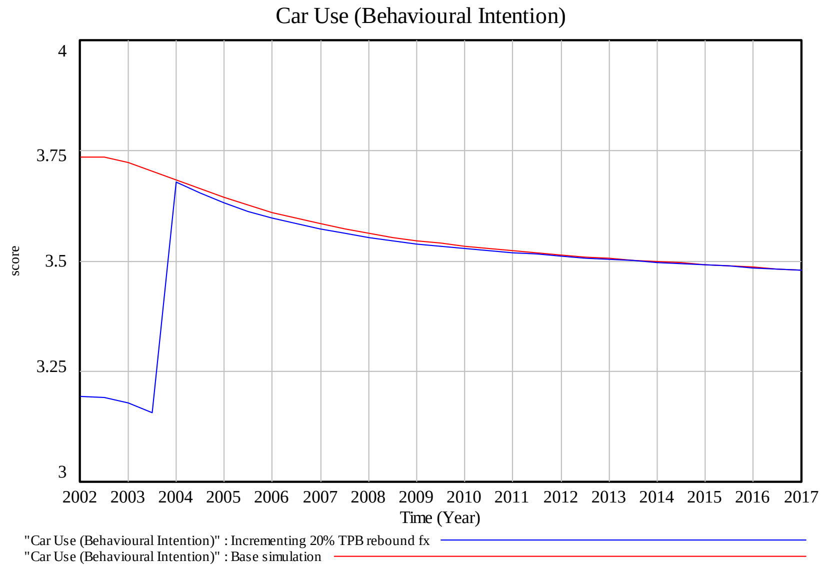
intervention is removed, the outcomes are either minimal or null as habits, identities, values and self-concordance can reinforce the attitudinal and intentional processes towards old behaviours. While it is true that the levels did not rise to the same levels as the base scenario, the average individual's scores for the behavioural intention in both scenarios are almost the same at the beginning, and they match their scores after 11 years of simulation. These results are in line with the popularity of TPB in transport and car choice (Chng, et al., 2018; Lanzini & Khan, 2017), as well as with the research motivations to improve the TPB framework with NAM or VBN (Chng, et al., 2018; Bamberg & Schmidt, 2003).

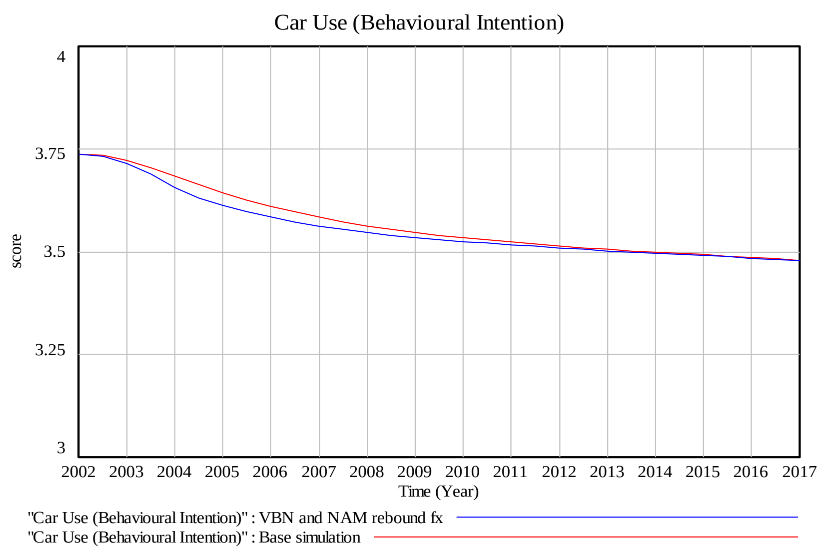
Figure 62. PEBCM simulation results: TPB + NAM, TPB + VBN, and NAM + VBN.



Source: Own elaboration.

Figure 63. PEBCM simulation results: TPB rebound effect and NAM + VBN rebound effect[69].



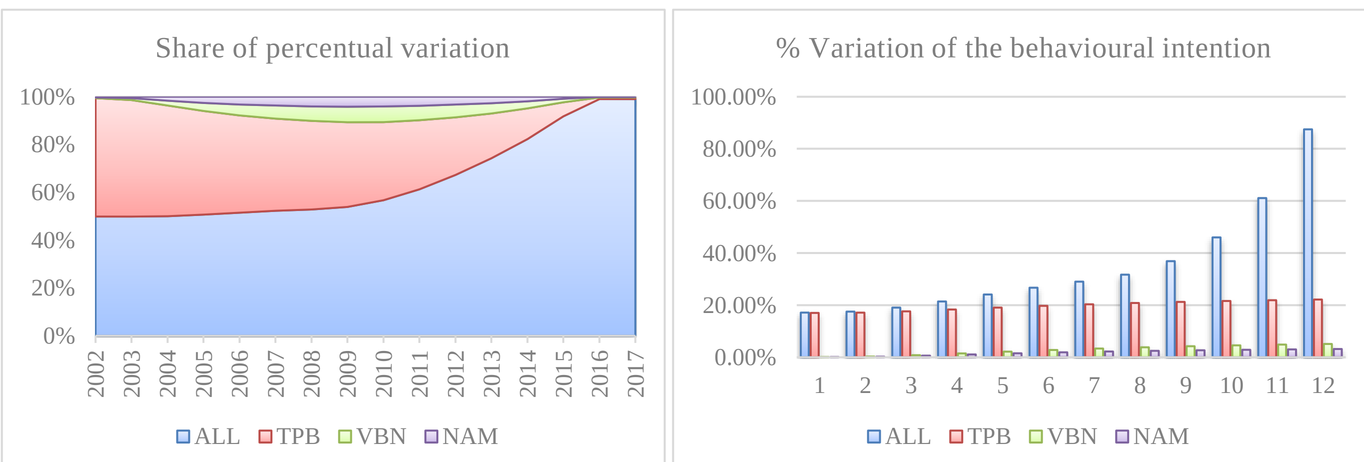


Source: Own elaboration.

[69] In this case, the rebound effect was tested by combining VBN and NAM as both have in their conceptualisation personal norms, ascription of responsibility and awareness (which are three out of four of the constructs modified).

The best outcomes were obtained when the intervention was applied across the three theoretical models. Figure 64 shows the variation (%) of the behavioural intention of each model in comparison with the base model, and the variation share (%). An example to read the latter is the following: in 2002, when all the factors of all the models were modified, the behavioural intention dropped by 17%, whereas TPB, VBN and NAM decreased by 17%, 0.09% and 0.09%, respectively. In 2017, the modifications of all factors decreased the behavioural intention by 87.49%, whereas TPB did it by 22.15%, VBN by 5.09% and NAM by 3.15%. By estimating the variation share, it can be easier to appreciate why an integrated intervention has better results (graph on the left).

Figure 64. PEBCM simulation results: Share of percentual variation of behavioural intention regarding the base scenario.



Source: Own elaboration. The % variation of the behavioural intention shows the percentage in which the modifications of the intervention decreased the behavioural intention in comparison to the first model. Therefore, a 17% decrease means that the behavioural intention is 17% lower than the base scenario.

A joint-model intervention showed a better performance, for two main reasons. First, the impact of the modification of variables related to TPB can create an immediate negative effect in the behavioural intention level. This is because TPB is a model based on rationality, in which the first antecedent to predict the behaviour is the intention; therefore, if an intention is modified, then the process of travel mode choice becomes more deliberate. Second, as values and beliefs are long-term and more stable factors, the behavioural intention changes its slope when NAM and VBN factors have been increased by the double in comparison to their initial values. As the variation share graph shows, in 2009 NAM and VBN accumulated an important level of change of the latent variable; in fact, after that period, the slope of the all-in intervention changed massively, shifting the trend from a gradual-linear increment to a more exponential growth.

This experimentation evidenced another contribution in the field of environmental psychology. Interventions have to be seen as multi-layered applications as pro-social factors (NAM and VBN) take more time to accumulate significant modifications than self-interest variables (TPB), but, when they are internalised, the average of the behavioural intention decreases exponentially. Therefore, a successful green intervention has to be seen as a continuing and balanced intermediation across the three models to cause deeper changes in an individual's car preference. A model-isolated recommendation impedes the understanding of long-term changes as pro-environmental behaviours are spread across the spectrum of pro-social and self-interest motives, and theoretical models are in a complex dynamism led by feedback structures that might be the missing piece required to maximise the potential of the insights found so far by TPB, NAM, VBN and any other model born from either one or the three of them.

9.1.3 Attitudinal change is limited by habits

Another contribution is related to attitudinal change and habits. Relying only on attitudinal changes is not enough for long-term changes in the context of car use. This is important to highlight because one of the main approaches seen in environmental psychology is based on providing information to change attitudes. Attitudinal change has been demonstrated by the model to be overrated as the silver bullet to cause a long-term behavioural change. In the context of transportation, habit modifications as well as attitudinal change have to be activated if car reduction wants to be seen in the short/middle term.

As was shown in section 9.1.2, habits can provoke important changes in car reduction, as well as in the initiation of an attitudinal change, but, when car-oriented commuters keep driving every day, attitudinal changes tend to be inert. Moreover, Chapter 8 showed that, to impact negatively on the behavioural intention towards car use through the activation of an attitudinal discrepancy, attitudes have to be on average 100% higher than the attitude towards car use, when an environmental concern exists. In reality, the efforts for that to happen are unrealistic. Data from England and previous studies showed that high levels of attitudes towards alternative transport modes or reducing car use for the sake of the environment are not necessarily translated into actions. Therefore, keeping the efforts focused on promoting the benefits of reducing cars to have an impact on attitudes or personal norms, will not have the outcomes society needs under the climate emergency. This is simply because people do not have the capacity to really evaluate long-term outcomes coming from environmental actions; therefore, this cognitive impediment makes the process of evaluation (attitudes) less powerful than it should be.

9.1.4 The necessity of studying psychological theories under feedback loop structures

This is the main contribution of this thesis. The comprehensive revision of psychometric relationships of the literature in transport, environmental psychology, cognitive dissonance, system dynamics, and the interviews led the model to create multiple feedback loop structures to simulate latent variables dynamically. The inclusion of feedback loops in the analysis uncovers important issues such as the attitudinal change inertia, the habit supremacy, and the barrier of activation and internalising a moral obligation.

To verify the dynamic complexity of the model, one can review the number of feedback loops included in the model. For example, the behavioural intention is embedded in 1302 feedback loops, which is why small changes spread across the model are more effective than focusing on only one part of the cause-effect relationships chain. The conflict between so many feedback loops means that the changes obtained from modifying a few variables in the model are quickly compensated from the other parts of the systems that remain as the base model. Another example is the adoption of a moral norm, which is integrated in 1017 loops.

Feedback loops play an important role in real-life systems, and, if researchers miss them, then policies are destined to fail. One great example is the underrated importance of the feedback loop between pollution and climate change. In the 90s, people were promised that using cars with a catalytic converter would avoid further and deeper car restrictions as this measure was proposed as the solution to defeat greenhouse emissions problems. However, in the analysis feedback loop authorities missed structures between car demand, population growth, car emissions and pollution accumulation, which is now showing the negative impacts of this feedback-loop-myopia. Many countries around the world are dealing with important problems related to car pollution, up to the point that, during winter, in some countries (e.g., Chile) cars with catalytic converters are also banned some days in the week, whilst urban centres in other countries (e.g., the UK) have limited the speed to decrease emissions.

9.2 Model usefulness

Having reviewed the contributions of the SD model and understood its ability to support the policy-making process, it is necessary to discuss the usefulness of this model. Demonstrating its modelling power will give researchers confidence in using this SD model for future research and new policy creation.

As stated in the methodological chapter, a model's usefulness is based on its ability to explain the system under study; in this case, this SD should provide a plausible explanation of how psychological determinants affect the behavioural intention towards car use. Chapter 8 and the previous section demonstrated that the revision of feedback loops in the analysis can provide relevant insights associated with behavioural and attitudinal change processes. If feedback loop structures had not been included in the discussion of the interviews and recent papers such as Klöckner and Blöbaum (2010) and Kroesen, et al. (2017), SD would have been inappropriate and limited to support any policy-making process. However, the contribution discussed in the previous section proved that the integration of the traditional behavioural models from psychology in an SD provided insightful outcomes that can offer new approaches to future green interventions. Chapter 8 provided a step-by-step systematic review of the model, demonstrating that SD is a practical way to simulate different scenarios. This SD model showed how important it is to include habits in a feedback loop, instead of a linear analysis. Furthermore, the revision of this SD helped to highlight the importance of creating integral interventions that aim to modify values, beliefs, attitudes and perceptions, as the focus on only one group of variables ends with lower or null outcomes in the long term.

To assess the simulation power and usefulness of this SD model, multiple areas are discussed:

1. Quality of the analysis: despite the criticism around the area of simulation and SD (see Chapter 3 for further details), this study was based on a strong modelling procedure and revision. In constructing the model, the literature review, the interviews with experts, the model validation checks and the PhD supervision meetings provided a wide range of sources to gather enough data during the conceptualisation and mathematic formalisation of the model. More importantly, this SD was subjected to a series of rigorous tests established in the SD community, in order to gain confidence and validity. All these points can be considered enough to conclude that this study presented quality outcomes.

2. The significance of the analysis: the contribution demonstrated the importance of shifting from static analysis to dynamic analysis, where the power of simulation was made clear with the numerous iterations provided. This SD was used to tackle the inertia of car reduction in England, in which an integral solution was offered to proceed with in the near future. Furthermore, the model demonstrated how sustainable improvements can be achieved in the short term and middle term. In the case of England, the analysis showed a way to understand why actual car commuting is not closely related to attitudinal measurements. This discrepancy was assessed and solved with multiple scenarios, proving that there are feasible strategies to discourage car use.

3. The completeness of the analysis: to assess this point, the question to answer is based on whether or not this SD model provides enough details to translate theoretical insights into actionable recommendations that can generate positive outcomes in restricting car use. In this case, modifications to the variables were easy to apply in theory; however, the operationalisation of this action is not fully clear. For example, in the experiments, the increment of TPB variables by 20%

can decrease the behavioural intention towards car use by 17% when the modifications take place. However, the model cannot provide the actions that can be made for TPB to be modified.

To overcome this weakness, the model's development should continue by linking situational variables (e.g., ticket fares) and latent variables, such as the reliability of public transportation and the attitude towards PT. In this way, modifying variables that are under the control of policy makers can allow the analysis to set out a complete actionable plan. One feasible suggestion to improve the completeness of the analysis can be through integrating this simulation model with other transport models developed in SD such as MARS. Another important point to continue to complete the analysis is by integrating other transport modes, such as bicycles. In the near future, cycling is expected to be more common; therefore, linking behavioural models related to bicycle use can bring new insights to more quickly overcome the high preferences for cars.

4. The originality of the insights: this is an important aspect to asses usefulness. Providing or confirming what is already known does not justify the construction of a simulation model, hence finding original insights can determine whether or not the model is useful. To some extent, the PEBCM corroborates the existing knowledge regarding car use, and the influence of psychometric variables to determine it, as well as providing a number of new insights that challenge the existing understanding. For example, the model demonstrated the importance of car frequency to speed or slow down the resolution of an attitudinal conflict. This insight developed a more enhanced understanding of feedback loops underlying the formation of a behavioural intention. Furthermore, the model demonstrated why integrated theory-driven studies provide a comprehensive long-term analysis, as many psychological determinants are incorporated in long and many feedback loops. Determining those modifications in the TPB model bring higher improvements than NAM and VBN is not new, but what is new is the fact that, when more stable variables are modified, TPB variables change their variation from gradual to exponential increments. Therefore, this prompts a mindset shift regarding the creation of green interventions. With these insights, the question is no longer about whether or not an intervention takes either a pro-social or self-interest perspective; instead, the model demonstrated that approaching a behavioural modification by altering both can produce much better results with lower modifications.

To sum up, several steps were carefully carried out in the construction of the simulation model. Many sources were involved in the conceptualisation and mathematical development to address the problems of car use; hence it is believed that the model can be part of the interests of many researchers and fields. The results led to the conclusion that, when psychological theories in the behavioural field are put into a dynamic perspective, new valuable insights are obtained. Moreover, these experimentations expanded the comprehension about the current understanding held in environmental psychology, opening new areas of future research such as how the evolution of routines affects the activation and internalisation of personal norms and environmental values or how the integration of identities can influence the feedback loop structures regarding attitudinal change and behaviours.

9.3 Reflections

A wide range of considerations can be shared from the outputs obtained from this project. To ease the comprehension of the reflections, this section will be divided into three parts: theoretical, computational and practical reflections.

The capability of transferability of the learning outcomes is essential in SD dynamics to justify its existence and contribution to policy-making and learning processes. Therefore, reflecting on these three areas provides a wider comprehension of the outcomes and implications, assigning the project results to tangible matters that can be considered by other researchers or policy makers in future research. Theoretical reflections will help to elucidate relevant considerations in the conceptualisation of car use and car reduction, whereas computational reflections will help to understand the weaknesses that the model could have based on the modeller experience with the software. Finally, practical reflections are meant to contribute to the debate of climate change and the impact of overusing cars.

9.3.1 Theoretical reflections

In terms of theoretical reflections, the construction of a non-linear system in a psychological theoretical context has demonstrated the challenges involved in changing a behaviour, specifically car use. For an average car-oriented individual, the model showed that, when all the relationships and feedback loops proposed in environmental psychology and transportation are considered, the intentional, normative, behavioural, habitual and attitudinal processes are multiplicative combinations of inputs rather than linear weighted averages. Moreover, as drivers' cognitive aspects are inserted into a multi-factor setting, the results of a human behaviour are the reflection of the circular interaction between internal processes and social systems, which balances or reinforces certain types of identities, ideas, moral obligations, values, beliefs and social commitments. Therefore, it is fundamental to extend the current research practices in behavioural theories with the advantages of non-linear modelling.

For that reason, this thesis has value in complementing the understanding of the complex configurations and ambiguities detected in human behaviour and rational thinking. Whereas environmental psychology has been demonstrated to be familiarised with the acceptance of feedback loop structures and time-oriented models, as their models have theoretically addressed circular causality of a few cause-effect relationships (Klöckner & Blöbaum, 2010; Chng, et al., 2018), the application of these assumptions has not been demonstrated in the models so far. Instead, the practical model application in the field has been more focused on extending the set of psychometric variables and/or changing the direction of cause-effect paths; for example, when TPB was integrated with NAM (Lanzini & Khan, 2017), or when personal norm was proposed as an antecedent for intentions instead of behaviour (Bamberg & Schmidt, 2003). Nevertheless, decision making, social interactions and benefit-maximisation thinking have been proved to be inherent non-linear processes (Tversky & Kahneman, 1974; Schröder & Wolf, 2017; Ulli-Beer, et al., 2010); thus, the traditional direction in developing static models based on linear thinking has to be reconsidered in improving future theories regarding human behaviour.

In this particular case, the non-linearity inclusions captured the propensity of behavioural intention towards car use to be a multi-layered stable state, meaning that, if there are no changes in multiple factors, significant changes are unlikely to happen. For instance, if attitudes, values, personal norms and beliefs do not change altogether, the reinforcing loop between behaviour and habits overcomes any cognitive dissonance state in the short term, requesting extreme increments of the attitude towards alternatives to decrease the behavioural intention in the middle term. This example encapsulates the time-evolving implications that could emerge in non-linear mathematical models. Furthermore, if attitudes are meant to change across time, then cross-sectional data is insufficient. And, even if time-series data is used, the mere sum of positive or negative Likert statements can only capture proportional changes, which do not accurately reflect the reality. Therefore, simulation can be key for progressing in more deeply understanding the dynamics in psychological processes.

Some researchers have critiqued the use of simulation as a scientific method as it does not follow the rigour of statistical techniques (Barlas, 1996; Davis, et al., 2007). However, by reviewing multiple studies in environmental psychology regarding car use, one can conclude that this is nothing less than a contradiction as the main linear-modelling techniques have implicitly accepted the same rationale that a modeller holds in simulation. For example, structural equation modelling (SEM), which is the statistical technique widely (and mostly) used in environmental psychology (Abrahamse, et al., 2009; Bamberg & Möser, 2007; Lanzini & Khan, 2017; Hoffmann, et al., 2017), is a multivariate statistical analysis, which employs linear relationships to explain the data. The method bases its success on the level of fit by evaluating how well the estimated model can model the data. Therefore, SEM and simulation answer the same question: given the observed data, what are the equations that best represent it? Based on this, one can claim that, in fact, it is less scientific to recognise the existence of circular causality in the theory (e.g. habits and behaviour (Chng, et al., 2018)) and not include them in the modelling process (e.g., path analysis), than to invent equations (in extreme cases from a non-theoretical basis) for a simulation model to capture non-linear behavioural patterns and match the observed data.

A critical challenge for policy makers is identifying the boundaries and the range of uncertainties coming from the available information to produce a reliable and effective solution (Nair & Howlett, 2017). Because of these characteristics, problems are sharply shaped by chaos and randomness, requiring better approximations to understand behavioural patterns through a clear thinking based on dynamic principles. In many of these cases, there are no guidelines to determine an equation from the observed data, hence the criteria to deduce the mathematical representation of the psychometric constructs converge to the same starting point in both statistics and simulation. For this reason, it is believed that simulation is beneficial rather than useless in the development of theories and empirical testing.

This thesis is not looking to persuade the reader that simulation has to replace SEM or any other technique. However, there are few models in history that have run with a vast range of data series to feed large regression models and create satisfactory theories (Morrison, 2012). Therefore, this thesis calls for developing good modelling practices based on the proper representation of the theoretical assumptions and data, instead of battling for the model that captures the largest amount of variance. For instance, Kroesen, et al. (2017) was one of the few papers found that challenged linear thinking by using SEM, proving the existence of a feedback loop between attitudes and behaviour in the context of transportation. This proves to be a great example of testing cause-effect relationships proposed in theory, but has never been tested before in the transport context. Thus, the critique debated here is more about the human thinking system, rather than how the technique is used. For these reasons, more balanced and integrative procedures between linear and non-linear thinking need to be developed in the near future.

Finally, it is important to acknowledge that this project presented an extended development of current theories in psychology in the context of car use and simulation, which is a demonstration that soft variables can be implemented in transport models. The generic structures developed in this thesis can serve as sub-systems that can be integrated into larger models utilised in the transportation-policy-making process. Since the 80s, a significant number of researchers in transport studies have proposed the inclusion of psychometric variables (Hartgen, 1974; Stokols, et al., 1978), but only a few models have been found that properly developed simulation models by including formal psychological theories (Bajracharya, 2016; Ulli-Beer, et al., 2010; Schröder & Wolf, 2017; Feola, et al., 2011; Levine, 2000; Levine, 2003). Therefore, it is undoubtable the contributions of this thesis in explaining TPB, NAM, VBN and other theoretical frameworks dynamically for both transportation and environmental psychology.

9.3.2 Computational reflections

The explosive growth of computational-based resources has significantly decreased the barriers and complexities of creating non-linear models. This opens a wide range of possibilities to study human behaviour under the prism of more complex models, which gives the opportunity to plot and analyse unpredictable dynamical systems.

For a long time, cognitive psychology has demonstrated that people's cognitive abilities fail to understand non-linear system (Sterman, 2000; Morecroft, 2015). The reason is because people's minds have limited resources to run multiple iterations between multiple variables, feedback loops, and resolving advanced maths mentally. Instead, human analytical thinking is naturally straightforward, establishing linear relationships to solve problems (Sterman, 2000; Morecroft, 2015). However, this is not a barrier anymore as various software packages are available for experts and non-experts in advanced mathematics to run complex mathematical problems (e.g., solving differential equations), helping them to expand their understanding of the world as better descriptions of the phenomena can be offered. With the current computational capacity, modellers can render complex systems in computers built on multiple relationships, external databases, advanced mathematical expressions and stochastic computational algorithms (e.g., Monte Carlo). These are enormous advantages to shift from linear to non-linear thinking. These benefits, however, are restricted to user proficiency with the software.

For example, Vensim, the software used in this thesis, has more than 50 build-in functions to choose from. Therefore, to make the most of the software's potential, it is important to read the documentation and have a decent understanding of almost all the functions, in order to know which ones are the best ones for recreating a smoother representation of the data. Furthermore, nicer interventions can be designed in the model to prepare scenarios. For example, Vensim has the function 'STEP', which computes a 0 in the model until the model's time achieves the {stime}, returning a value set in {sheight}. As well as 'STEP', 'PULSE' is available, returning a value equal to 1 starting at time sets in {start} and lasting for the interval configured in {duration}. Both equations can be used for similar purposes[70], as well as more specific cases. This simple illustration shows that the decision which one to use is probably a matter of how well the modeller knows the functions and their creativity to design the mathematical expressions and restrictions.

The reflection here is that computational tools can definitely support more complex thinking systems (linear vs non-linear), but it should always be considered that better results are restricted to how well the software is known because there are many functions and settings available that can determine how well the model can mimic the data. Moreover, knowing all the potential tools available in the software can lead to create complex scenarios and interventions that normally depend on many 'IF THEN ELSE' situations in real life.

9.3.3 Practical reflections

This work has produced several contributions, from which practical reflections can be discussed. The current project attempted to explain car commuting by using an extensive environmental psychology and transport literature exploring people's travel behaviour, as well as experts' knowledge, which aimed to add a holistic perspective of the topic. Combining several

[70] A function using 'STEP (1,2) + STEP (-1,4)' is equal to a function using 'PULSE (2,2)'.

psychological determinants from the main theories, this model has demonstrated that changing people's behavioural intention towards car commuting requires a multi-level strategy when long-term changes are necessary. TPB, NAM and VBN differ in their impact on the behavioural intention towards car commuting, showing a significant discrepancy in the intention development. Overall, TPB is more effective in making changes in the short term, and more consistent than the other models. The simulated scenarios confirmed that car use is rooted in a routine-driven behavioural intention, making it less probable that people will consider alternative transport modes once it has become a habitual (and satisfactory) choice. Therefore, encouraging a pro-environmental behaviour requires a multi-level strategy, which means that several psychological layers of the individual have to be modified in order to persuade car commuters to drive less in the long run.

Another contribution lies in the effect of habits in the intentional process. The model has demonstrated the importance of the strength of the positive feedback loop in the intentional process, and how this impedes people from expressing a pro-environmental behaviour even when a positive environmental attitude is reported (cognitive dissonance). Based upon the detailed outputs presented in the previous chapters, habits are one of the main barriers that stop people from resolving an environmental conflict. In this case, they are not able to express the attitude towards low-carbon mobility (translated into a pro-environmental behaviour) as the reinforcing loop between the old habit (driving) and the current behaviour (car use) diminishes any positive level of attitude towards low-carbon mobility.

Habitual behaviours have been found difficult to stop or change due to the level of complexity behind the cognitive process. A habitual behaviour emerges from a cognitive structure that is learned, saved in a person's mind and available to be recalled from their memory when a particular context is perceived (Verplanken, et al., 1998). This human capability leads choices to be more driven by old behaviours than new, because people tend to choose options in which the information is already available or the outcomes have already been experienced, rather than ones that require the analysis of new information which might not be aligned with their habitual behaviour (Steg & Vlek, 2009).

In the model, car habit was artificially modified, demonstrating that forcing car drivers to reduce car use induced long-term acceptance of alternative low-carbon transport modes. The impact of such a measure was particularly successful when the changes were imposed between shorter temporary restrictions, suggesting that the rate of decay of car commuting is highly adaptable under severe restrictions on expressing the old behaviour. Based on these results, it is advisable to impose a gradual restriction of car use, in order to induce a significant long-term reduction of car commuting. By enforcing several interventions between short periods, policy makers can accelerate the unlearning curve of car commuting up to the levels needed to fight this climate emergency, and avoid shocking changes that can lead to a rebound effect, making the current situation worse.

Transport policies have always challenged several issues of acceptance and implementation due to high societal inequality, lobbying, high political risk (restriction to cars are unpopular) and governance (Gössling & Cohen, 2014), creating important difficulties in the effort to develop sustainable transport policies. Nevertheless, by making people learn how to break their car commuting habit, these so-called transport taboos reduce their importance in the equation of creating social acceptance of low-carbon transport modes because individuals would be guided by a different cognitive structure that would be embedded in their values, beliefs and personal norms.

Up to the present, transport policies have focused on limiting the scope of car benefits in urban areas, by imposing speed restrictions, increasing car park prices, reducing car park availability, raising costs to run a car, forbidding cars in certain city centre areas and improving public transportation. However, no one has implemented restrictions that limit the right to use cars. In approximately 20 years, England has only managed to decrease car commuters from 70.047% (2002) to 67.119% (2019)[71], and car commuting distance by 14.6%[72]. This demonstrates that the current transport policies are insufficient to achieve the current zero-emission goal by 2050. Based on this, another relevant contribution can be noted. The design of a tool to study the modification of habits and its impact on the targeted behaviour can help to plan ahead for pro-environmental behavioural interventions as this simulation model elucidates several leverage points to intervene in people's behavioural intention towards car commuting. To understand habitual behaviours, it is important to recognise how habits are constructed, reinforced and sustained (Steg & Vlek, 2009). In this case, this simulation model has formalised the behavioural determinants and processes in car commuting.

Finally, another practical contribution acknowledged is the fact that these findings and the construction of this model can be transferable to other pro-environmental behaviours. The theories and psychological determinants in the model have been widely described in environmental psychology, in order to understand water consumption, recycling, energy use and food waste (Abrahamse, et al., 2005; Bamberg & Möser, 2007; Carrus, et al., 2008; Ayob, et al., 2017; Aliabadi, et al., 2020; Islam, 2021). The simulation model presented here serves as a generic

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[71] See dataset: https://www.gov.uk/government/statistical-data-sets/tsgb01-modal-comparisons

[72] See nts0409: https://www.gov.uk/government/statistical-data-sets/tsgb01-modal-comparisons

structure to study other non-environmental behaviours which are triggered by inaccurate perceptions of the advantages and contributions of performing an alternative behaviour, as well as strong habitual behaviours that impede the expression of environmental attitudes that conflict with non-environmental attitudes.

9.3.4 Considerations for the future of car use

Multiple solutions have been offered in transportation to reduce car use. Apart from the efforts to improve the public transportation networks, replacing diesel and petrol vehicles with electric cars (Bjerkan, et al., 2016; Yang, et al., 2017), and adding a carbon tax (Parry, et al., 2007) have been the main policies suggested to deal with car use and its environmental impact. These policy proposals have not only been claimed by the literature, but also by the interviewees in this project. Nevertheless, reflecting on the learnings outcomes of this thesis, and the fundamental idea of system dynamics, they might not necessarily act as sustainable solutions. Incentivising the demand for electric cars or integrating more taxes can lead societies to other policy resistance issues, as they are only transferring the problem to a different industrial sector, activity of the value chain, or socio-economic groups.

The implications of changing 31.5 million petrol and diesel vehicles to e-cars (Amos, 2021) are devastating in terms of resource depletion and car pollution coming from production. Undoubtedly, encouraging the demand for more electric cars means expanding the production capacity of electric cars, which is not guaranteed to be free of environmental externalities. In the process, e-cars require the construction of lithium batteries, which use multiple minerals including lithium, copper, cobalt and aluminium. The extraction of minerals brings negative impacts to the environment such as the loss of biodiversity[73], resource depletion[74], water overconsumption[75] and chemical emissions (e.g., if minerals extracted in the process leak to aquifers or rivers) (Denisova , 1977; Azcue, 2012). Moreover, by considering non-exhaust PM emissions (Timmers & Achten, 2016) and the origin of the electricity use to charge the batteries, the massive replacement of petrol and diesel cars to e-cars is likely to overcompensate the potential benefits of electric engines. Conventional cars are not exempt from the same problems, and are much worse to the environment, but incentivising electric cars is only transferring the problem from the roads to the production and recycling chain, which eventually can become worse if the demand for and use of e-cars increases at higher rates than the improvements of procedures towards a more environmentally friendly production.

On the other range of solutions, policy makers and researchers have proposed the inclusion of carbon taxes to control the use of and demand for cars. Generally, taxes have been promoted by governments as an alternative for individuals and businesses to internalise the costs derived from negative externalities. Based on this nature, taxes are seen as self-regulation mechanisms for individuals and societies to weight the importance of the negative externalities in the decision-making process. However, multiple studies in carbon tax and inequality have shown that imposing tax restrictions in societies with high levels of income inequality is more likely to be regressive than progressive (Oueslati, et al., 2017; Fremstad & Paul, 2019; Speck, 1999; Andersson & Atkinson, 2020), because low-income households tend to spend more of their income on carbon-

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[73] The jaguar's habits in Mexico are expected to be in danger when the 100,000 hectares of the lithium plant are constructed (Castañeda, 2020)

[74] Additionally, the extraction of raw materials might result in a considerable loss of resource-efficiency. For example, producing 10 tons of lithium requires the extraction of 250 tons of the mineral ore spodumene (Harper, et al., 2019)

[75] 65% of the water in the region of Atacama (Chile) is used for mining activities (Katwala, 2010).

intensive goods (e.g. non-renewable energy, petrol) (Fremstad & Paul, 2019), as well as income inequality has been increasing in some developed countries during the last decade (Andersson & Atkinson, 2020). This undoubtedly enhances problems of social inequality. Lower-economic classes face a challenging social-economic development, as normally they live in places where there are limited job and educational opportunities, being forced to travel long distances to increase their chances of getting a job and accessing educational/training programmes (Gates, et al., 2019).

Effectiveness and implementation of both policies mentioned previously are in fact highly dependent on the political view and leadership of a country, which might not necessarily promote engaging with environmental activities. An example of a lack of commitment to protecting the environment was Donald Trump's presidency, as he publicly admitted his doubts about climate change, as well as prioritising a series of policies that encouraged fossil fuel-based energies. At the end of his administration, the government revoked more than 100 environmental rules (Popovich, et al., 2019). Relying on political leadership becomes more complicated when lobbying takes place. Lobbying has become essential in recent years as strong regulatory demands have been required. Many examples can be found in mining, metal and agriculture industries. Transportation has not been exempt from this either. For example, during the revision of the restriction to reduce greenhouse gas emissions from vans by 2020 in the EU, many car manufacturers and car associations got to lobby the European Parliament (Rasmussen, 2015), in order to weaken the restrictions imposed. Surprisingly, the lobbying actions worked, making the EP[76] agree with the

[76] An EP is a policy entrepreneur who looks after the interests of environmental groups, taking a stronger position than the government institutions when environmental issues are addressed (Rasmussen, 2015).

Council's proposal, which not only decreased the target levels of CO_2, but also decreased the penalties to car manufactures which had not achieved the targets (Rasmussen, 2015).

For the reasons aforementioned, this thesis calls for keeping and strengthening the work on behavioural change interventions regarding car use by modifying values, beliefs, attitudes and norms. The most effective strategy to reduce car use is by avoiding its usage in the first place, which was the aim of the simulation model. The SD model demonstrated that important behavioural changes can be achieved by focusing on multiple structures in the chain of the behavioural process, reducing car use in the long term. That is, modifying more stable directional guidance (value or norm changes regarding environment protection) can encourage the internalisation of the responsibility for car pollution, decreasing habits and cognitive dissonances that promote car use.

Purely relying on taxes or technology can still be detrimental for the environment or social equality. Car demand and usage seems to be a growing problem in many countries, and so, even if technology offsets emissions on the road, its production and recycling are still an important concern among the environmental community. Furthermore, the richest 10% of the world's population were responsible for 52% of the carbon pollution between 1990 and 2015 (Gore, 2020); thus, taxes are more likely to be a measure that would control a lower fraction of pollution than in the whole society. When carbon inequality exists, economic interventions in countries with severe income inequality can exacerbate the real problem.

For these reasons, it is believed that the outcomes of behavioural change interventions would be more efficient in the long term as the new behavioural outcomes will not be dependent upon resource depletion and income inequality. Behavioural change strategies could bring better outcomes than restricting car use by taxes as they will not create a sort of social discomfort as the freedom of choice would be still preserved regardless of the social economic backgrounds. This is the nature of 'libertarian paternalism' (Thaler & Sunstein, 2003), which looks for strategies that affect behavioural patterns without restricting freedom in the decision-making process. This way, the internalisation of moral obligations based on intrinsic motivations can create a positive feeling of contributing to the good cause, making car reduction the right thing to do. Research has already found strong foundations to demonstrate that people who feel strongly about moral issues have more chances to get involved in collective goals (Van der Werff, et al., 2013). Moreover, previous studies have also demonstrated that attitude towards car use among car users, significantly (and negatively) affects the acceptance of driving restrictions, in contrast to public transport commuters, who are more inclined for those changes to be implemented (Liu, et al., 2016; Rienstra & Rietveld, 1996). Therefore, if radical changes are needed to limit global warming effectively, it makes more sense to boost interventions that gently decrease psychological factors attached to car use, in order to decrease any political crisis and to increase the acceptability of imposing more radical policies such as banning petrol cars or increasing petrol prices, which target no car use at all.

9.4 Model weaknesses and future research

9.4.1 Model weaknesses

The simulation model presents weaknesses that are important to acknowledge. These weaknesses include limited application of psychological frameworks regarding alternative transport modes, absence of demographic aspects, unrealistic representation of the current situation (COVID-19 and lockdowns), lack of endogeneity to represent important aspects such as values, methodology aspects, and clarity regarding the occurrence of the changes.

First of all, the model lacks a deep representation of NAM and VBN to explain public transportation behavioural intention, thus there are several assumptions that the model is not dealing with. For example, the model is not considering how personal norms can boost the adoption of public transport use. The fact that personal norms affect ‘the reduction of car use’ does not necessarily mean that the individual would then be encouraged to take the bus. Moreover, habits were not integrated in the explanation of public transportation use in the long term, which makes that side of the model really sensitive when aspects related to PT are modified.

This model also lacks the capability to explain travel behaviour from a more demographic point of view. The simulations cannot offer any insight regarding full-time or part-time workers. Moreover, the model does not have the capacity to explain the differences of commuting by car across ages, gender and commuting distance. This can be problematic when strategies to reduce car commuting are targeting different population clusters. For example, the model cannot reflect on the differences between people with a large family vs a household with two members, nor in understanding how distance can create restrictions to considering an alternative transport mode.

The model cannot offer any behavioural understanding for the current situation. COVID-19 and the several lockdowns have changed workers’ routines, which represents an interesting context to see how this kind of disruption could impose travel behavioural changes among drivers. Moreover, the fact that people are more concerned about sharing indoor places with others might be the major drawback to discourage people from taking public transportation. Private cars offer a safe environment to commute as they are not expected to be shared with many people. This perception of safety can then give more confidence to drive more, and everywhere. In this case, the simulation model cannot present any experimentation to find insights regarding the current pandemic.

Another concern is the fact that the model has not included in the conceptualisation an explanation to represent values endogenously. This is a disadvantage to fully understand people's travel behaviour because it shows a limited application to represent feedback loops in this area. Instead, the model keeps constant the representation of values; however, it is believed that values and beliefs can evolve across time. This weakness leads to the assumption that values and beliefs are rigid, and the dynamics of the model cannot affect them, concluding that, for values to make a major impact in the model, they have to be set up at the beginning of the simulated experiment. This way, how cultural changes can affect an individual's values cannot be observed.

Methodology aspects can also be considered a weakness of this project. The interviews tried to be as clear as possible in reflecting what was the role of each respondent in the conversation. However, all respondents were commuters as well, hence sometimes it was hard to discern if the answers from transport engineers or environmental psychologists were coming from personal experiences or from their expertise in the field. This is important to acknowledge because the role of the experts was to capture the understanding of the average commuter, but the degree to which personal experiences are involved in the topic might have restricted an unbiased opinion of commuting. Another problem with the methodology was that not everyone had the same quality to deliver a mental model. Many of them did not understand what a causal loop diagram meant, and that is possible to see when all the mental models are compared. This creates a disadvantage in the conceptualisation of the model as, because of the method, the interviewees did not explain themselves completely, not giving a comprehensive explanation of their ideas due to the restrictions of not understanding what a causal loop diagram was for.

Finally, the major weakness of the model is the assumption regarding behavioural change. The model assumes that changes occur immediately after one variable has been affected. Therefore, a change of 5% in attitude would immediately affect the following period. In empirical studies, the shape of the curve regarding the evolution of psychological determinants is not clear. In fact, long-time series studies are not common in environmental psychology. For these reasons, this model lacks confidence in the representation of how quickly (or slowly) changes affect the behavioural intention towards car use.

9.4.2 Future research

Different ways can be taken to improve the work presented here, therefore many possibilities can be advised for future research. The wide range of possibilities include continuing the model development, generating further insight into car use in the UK and other countries, comparing policies from different nations, considering this SD model to explain other behaviours beyond car use, and adding other stakeholders that can bring more insights to the mental model (e.g. city planners).

In the current project, many simple assumptions were taken in order to elaborate this model. That is why future research can focus on extending and refining the current model. For example, the model boundary can be extended to endogenise the motivations to comply with subjective norms or the factors that determine the degree of psychological distance, so as to boost the decrease of car use in the middle term. Another example would be integrating self-identities (Van der Werff, et al., 2013) and self-concordance (Unsworth, et al., 2013), as they can improve the conceptualisation regarding pro-environmental behaviour engagement. Individuals generally engage with pro-social actions that are visible to others (Brick, et al., 2017), as well as when the pro-environmental actions are self-concordant with other goals (Unsworth, et al., 2013). These two factors are not captured by the model dynamics, thus disaggregating goals and groups (motorists vs pedestrians, or cyclists vs public transport users) can increase the explanation of car reduction in different settings and contexts.

Although this project presented various experiments, they were not exhaustive as there are many other variables that can be adjusted. For example, future research can explore the effect of decreasing the desire to own a car, and how that dynamically affects the behavioural intention towards car use. Additionally, the simulation model did not explore any alteration regarding the satisfaction with driving, which can also be modified in order to decrease the attitude towards car use. In terms of the case study, the current model only tested the data from England, hence there is plenty of room for future research to test the model by using data from different countries. In fact, research effort can focus on comparing the differences between decreasing the behavioural intention towards car use in developed and developing countries.

In terms of policy testing, different approaches can be tested to provide behavioural changes. So far, multiple actions have been proposed to encourage using public transport (PT) over private cars. For example, fare-free travel on PT has been largely discussed as an excellent measure to increase PT attractiveness (Cats, et al., 2017). Hence, this policy design can be tested to see its impact on behavioural intention towards car use. Furthermore, it is believed that more information about alternative transport modes could result in a shift mode, especially when this information helps to decrease the level of uncertainty regarding ‘estimated time of arrival’. However, authors have found that habits are a strong force to stop people acquiring new information to plan their future travel or to consider alternative transport modes (Eriksson, et al., 2008; Şimşekoğlu, et al., 2015); thus, this model could help to understand dynamically how providing information can be more effective. Finally, the model could test the potential effect of time compensation. People who travel to work by public transportation can have the benefit of arriving 10 minutes later and leaving

10 minutes earlier than the official work hours, in order to reward workers that do not use cars. To test all these applications, the current model would need to be modified and expended in order to be able to capture the effect of these new contexts.

This simulation model contemplated psychological theories that have been applied in the prediction of other behaviours. Therefore, future research could take the generic structure of this model and use it to explain other pro-environmental behaviours including food wasting, water consumption, energy consumption, recycling, airplane travel and consumerism. All of these behaviours are detrimental to the future; hence, researchers still have a big challenge to reverse the current crisis and provide more insights that can help to encourage the whole society towards more efficient and acceptable behaviours.

Finally, the inclusion of more actors regarding urban planification and transportation can improve the mental model used to construct the simulation model. For example, city planners play a key role in creating more sustainable urban development. They tend to work on creating policies regarding land use, business location, transportation and leisure; hence, they have a relevant understanding about what modern cities that support alternative transport modes will look like. Moreover, they can add a wide perspective about policy acceptance, and how the development of city centres will redefine the concept of transportation. In a similar vein, car manufacturers can be added to the conversation. They are the main input in travel demand and car use; therefore, it would be interesting to capture their vision about the future of cars and how they are working on encouraging people to use more environmentally friendly transport modes. Additionally, they would have great insights regarding the impact of automated cars from a psychological perspective. Automated cars are meant to be the next generation of private transportation, in which people would not need to drive. This opens the opportunity for drivers to re-conceptualise ‘commuting by car', leading to a new concept that might reinforce the use of private mobility as new routines are going to be able to be adopted (e.g. reading emails or preparing presentations on the way to work).

9.5 Final notes

It is clear that the transportation network needs adjustments from an individual and a social perspective. People's travel decisions are affecting the behaviour of the environment in an undesirable manner as a large contribution from CO_2 emissions and non-exhaust emission sources (e.g. brake dust) is exacerbating the poor air quality and climate change. Theoretically, classical economists have argued (Timmer, 1989) that, when individuals are incapable of achieving an optimum behaviour, governments are meant to intervene as they are seen as better judges to decide what is best for societies (Meier, 1994; Schwartz & Cheek, 2017). Unfortunately, there is an evident sign that the car market and the transportation infrastructures in the UK (and many other part of the world) have failed in tackling these environmental issues as there has not been any significant support for sustainable transport modes or encouragement to reduce car use.

Drivers have limited cognitive skills to acknowledge that their current travel decisions can impose negative externalities to future generations. Instead, they prefer to maximise their own comfort, without considering future environmental costs. For that reason, deep changes in making policies are needed, in order to stop supporting car use, so as to achieve the international targets towards zero emissions. This means that society's leadership must shift the fundamental aspects related to a country's economic development and growth towards a system more integrated with socio-ecological practices to reassure people that there will be sustainable eco-systems on Earth. In this sense, important work to do today is related to understanding public adoption and acceptance of behavioural changes forced by new regulations related to the environment.

In democratic societies, policy makers have been adopting different perspectives to change people's behaviour, through taxation, information and regulation. However, because transport policies deal with the tension between improving people's freedom (in terms of choices) and society's wellbeing, complex unanticipated side effects are found. The more restrictive an action plan, the more tension created between politicians, voters, car manufacturers, drivers and environmental supporters. For this reason, new interventions towards car reduction should capitalise on its value by modifying psychological aspects as they play an important role in making people develop long-term changes towards desirable outcomes, and creating the feeling that transport shift is based on an individual's own decision rather than a restriction of transport freedom.

It is believed that the following steps by governments and institutions that are tackling the problems of pollution must go towards the creation of interventions that reframe the way in which people see the immediate benefits from travelling on an alternative transport mode. That is, creating a new perception of how beneficial it can be to use alternative transport modes can impact on the behavioural intention towards car use. Additionally, finding ways that can disrupt drivers' habits can open an opportunity to decrease car use significantly. In fact, these opportunities can create new routines to which people can develop a habit, creating a quick reinforcing loop for the new behaviour. For example, travelling by train can be seen as a relaxing time to read a book or play a game before and after going to work, or cycling can see as the minimum amount of exercise to keep a healthy condition. If these goals can be apparent for the commuters, then the aspects to create a new routine are more likely to be evident, increasing the chances of creating a new habit. However, this cannot go ahead without implementing proper infrastructures that support the necessity of pedestrians, passengers and cyclists. That is why solving environmental issues in transportation cannot solely be solved by nudging people; it has to come as well with the provision of high standards to make alternatives more attractive than private cars.

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Appendices

Appendix 1

Target:

a) Transport planners who are selecting and developing plans to organise mass transit.

b) Environmental engineers who work on developing solutions to environmental problems related to air pollution and transportation.

c) Researchers who are experts in the area of environmental psychology, transport planification and/or air pollution.

d) Commuters.

1. Knowledge and Experience

TARGET A B C

a. Description of his/her role in the area (work experience, number of years working in the area, etc.)

TARGET D E F

a. What kind of transport modes do you use to commute? (in case there is more than one) Which one do you use more?

Car Users/Soft Car Users

b. How often do you commute by car during the week?

c. How long is the distance between your work and home?

d. Do you think that cars are an important source of air pollution? (If the person says yes… follow with: Have you ever considered stopping using cars? Why?)

Non-Car Users

b. Why don’t you use a car to commute?

c. How long is the distance between your work and home?

d. Do you think that commuting on [INSERT TRANS MODE] is a good way to decrease the levels of air pollution?

ALL TARGETS

What do you think is going to happen with the tendency of…

e. …air pollution produced by car,
…car demand,
…car use,
…eco-friendly transport modes?

2. Exploratory Variable Analysis

b. Could you tell me what are the main factors that impact on the decision to use a car for commuting?

c. Could you tell me what are the most important factors that lead people to decide to commute in other low-carbon mobility modes?

3. Conceptual Map

a. With the factors mentioned above, I would like that we could relate them to each other to obtain a causal scheme of the proposed variables. What variables explain the behaviour of the others? (Pair the Post-Its.)

b. How do you think that these factors can be related to explain the process of car ownership and car use?

4. Proposed Model

a. With the model proposed by you, I would like to contrast my causal model for the adoption of car use and car ownership and obtain your opinion regarding the relationships and variables proposed in my thesis.

Appendix 2

Travel demand forecasting aims to calculate spatial distribution of travel in a given zone (e.g. city centre) by predicting people's travel mode choice given a series of variables to consider in the decision-making process. The process has been documented as a four-stage model which includes trip generation, trip distribution, modal split and trip assignment (Modi, et al., 2011). Each stage estimates a part of the process of travel demand (sequenced-stage model) by using different forecasting techniques with combining the individual's and household's socio-demographic characteristics, trip data, transport priorities or modal attributes, and land use distribution (see Table 37). Modern software packages have reworked this sequential algorithm by adding land-use modelling, as it has been demonstrated that urban development is closely related to travel demand, and vice versa (Pfaffenbichler, et al., 2010).

Table 37. The process of travel demand forecasting.

Decision travel stage	**Description**	**Forecasting technique**
Trip Generation	First step in the modelling process, which computes the number of trips originating in or destined for a specific area.	• Regression methods • Category analysis • Trip rate methods • Expansion factor methods
Trip Distribution	Second step in the modelling process, which aims to distribute the trips generated in the previous phase, displaying the number of trips going from zone-*i* to zone-*j*.	• Growth factor models • Interaction models • Opportunity models
Modal Split	Third step in the modelling process, which computes the number of trips made in each transport mode available (e.g. car).	• Probit method • Logit method
Trip Assignment	Final phase of modelling travel demand, in which the route for each trip is computed based on minimising travel time, and travel distance, which depend on traffic volume.	• All-or-nothing assignment model • Multiple route assignment model • Capacity restraint assignment model • Capacity restraint multipath route assignment model • Diversion curves technique model

Source: Own elaboration based on Modi, et al. (2011).

Appendix 3

Table 38. Key papers reviewed for the construction of the simulation model.

Author(s)	Paper title	Findings
Nilsson & Küller (2000)	Travel behaviour and environmental concern	• Environmental attitudes have a stronger impact than knowledge on encouraging PEB. • Environmental concern and car affection strongly affect the acceptance of car restrictions. • It seems that journeys on PT are more affected by the lack of positive attitudes towards cars than attitudes towards PT as such. • Personal concern did not show a significant result to explain travel behaviour or policy acceptance.
Dargay (2001)	The effect of income on car ownership: evidence of asymmetry	• The elasticity regarding declining incomes is significantly lower than the elasticity observed in rising incomes; therefore, people are less willing to dispose of their cars in older age even though their incomes have reduced significantly.
Moody and Zhao (2020)	Travel behavior as a driver of attitude: Car use and car pride in U.S. cities	• Car use, car ownership and car pride are closely related through a reinforcing loop, making it harder to encourage alternative transport modes among drivers as the social construction of car ownership shapes individual attributes and social status. • Individuals that reported a high level of car pride were more inclined to car ownership, enabling frequent car use.
Ünal et al., (2018)	Values versus environmental knowledge as triggers of a process of activation of personal norms for eco-driving	• Values work as a stronger motivational factor to encourage eco-driving in comparison to environmental knowledge. • Values strongly affect the activation of personal norms, especially biospheric values.
Noonan (2021)	Family income matters! Tracking of habitual car use for school journeys and associations with overweight/obesity in UK youth	• High levels of income were associated with a high level of car use to take children to school. • Children living in households with the highest income reported the lowest rate of overweight/obesity.
Abrahamse et al. (2009)	Factors influencing car use for commuting and the intention to reduce it: A question of self-interest or morality?	• The intention to reduce car use depends more on the existence of a feeling of moral obligation, while car use (in the context of commuting) was more explained by self-interest determinants (attitudes and perceived behavioural control). • The intention towards reducing car use is strongly affected by personal norms, but when perceived behavioural control towards driving is low.

Dogan et al. (2014)	Making small numbers count: Environmental and financial feedback in promoting eco-driving behaviors	• Reporting feedback regarding environmental gains is more meaningful to engage with eco-driving practices than observing financial savings.
Hunecke et al. (2001)	Responsibility and environment: Ecological norm orientation and external factors in the domain of travel mode choice behavior	• High levels of moral norms contribute significantly in approaching integrative interventions such as external economic incentives.
Bamberg & Schmidt (2003)	Incentives, morality, or habit? Predicting students' car use for university routes with the models of Ajzen, Schwartz, and Triandis	• In the context of students' car use, the authors empirically confirmed the structures of the TPB and TIB models to predict car use. • NAM model has a lower explanation power than TPB and TIB to predict car use. • Personal norms are suggested to act as a predictor of intention, rejecting their original proposition as a direct predictor of the behaviour. • After testing TPB and TIB, the results suggest that car use is strongly associated with a less deliberated behaviour, as habit explains more behavioural variance than intention. Once the person analyses the pros and cons of driving, the process follows an automatic routine.
Eriksson et al. (2006)	Acceptability of travel demand management measures: The importance of problem awareness, personal norm, freedom, and fairness	• Personal norms and problem awareness play a key role in predicting the acceptability of travel demand management actions. • Moral considerations and perceived fairness are linked to increasing the probability of accepting tax on fuel, whereas freedom aspects and problem of awareness are relevant to predict the acceptability of public transportation improvements.
Møller, et al. (2018)	Adolescents' associations between travel behaviour and environmental impact: A qualitative study based on the Norm-Activation Model	• Relevant sub-groups can be found among adolescent based on their level of moral obligation: Environmentalists, Pragmatics, Indifferent, De-emphasisers, and Deniers. Based on these groups, different strategies of engagement in reducing driving have to be taken.
Lo et al., (2016)	Commuting travel mode choice among office workers: Comparing an Extended Theory of Planned Behavior model between regions and organizational sectors	• Intention is strongly associated with intention towards commuting by car. • Attitudes are more relevant in PT commuting among long-distance commuters. • Habits did not play an important role in predicting intention. • In commuting, industrial sector and region may influence the effect of attitude towards intention. Workers from the public sector are less inclined towards car commuting.

Chen & Chao (2011)	Habitual or reasoned? Using the theory of planned behavior, technology acceptance model, and habit to examine switching intentions toward public transit	• Habits play a key part in determining whether or not an individual is willing to shift to PT. The study found that motorcyclists are less motivated to shift from their current transport mode to PT than car commuters.
Heath & Gifford (2002)	Extending the theory of planned behavior: Predicting the use of public transportation	• TPB improves the behavioural prediction when personal norms and the interaction between intention and PBC are considered.
Lind, et al. (2015)	The value-belief-norm theory, personal norms and sustainable travel mode choice in urban areas	• VBN framework proved to be appropriate to understand the choice mechanism of sustainable travel mode in urban areas. • The researchers quantified the effect of personal norms and situational factors on three different sub-groups of travellers (PT users, car users and active transportation users). • Personal norms variance was explained in 58% by value and belief constructs.
Klöckner and Blöbaum (2010)	A comprehensive action determination model: Toward a broader understanding of ecological behaviour using the example of travel mode choice	• A new model is presented to explain pro-environmental behaviours. This new theoretical framework was contrasted against established models that explain PEBs, finding that CADM explained the greatest proportion of variance regarding travel mode choices.
Nayum & Klöckner (2014)	A comprehensive socio-psychological approach to car type choice	• Choosing more fuel-efficient cars is strongly influenced by intentions. • Consumers that reported lower levels of brand loyalty were more inclined to buy more fuel-efficient cars. • Car symbolic meanings play an important role in car purchasing process.
Bamberg (2013)	Changing environmentally harmful behaviors: A stage model of self-regulated behavioral change	• A time-oriented model is proposed to improve the explanation of the 'intention-behaviour' relationship. By using NAM, TPB and MAP, the author proposed a more detailed mechanism about how intentional process should be estimated to explain a pro-environmental behaviour.
Chng et al. (2018)	Psychological theories of car use: An integrative review and conceptual framework	• A new theoretical framework is proposed as the authors found that previous models were not satisfactory to explain car use as they missed the inclusion of a wider range of potential mechanisms that affect travel behaviour.

Recker & Golob (1976)	An attitudinal modal choice model	• The so-called behavioural model demonstrated a great model fit, concluding that conventional logit models can improve their explanatory power. • Attitudinal models proved to bring important insights to transportation research as new factors are included in understanding travel mode choice, revealing underlying mechanisms that were never explained before in choice decision-making research.
Hartgen (1976)	Attitudinal and situational variables influencing urban mode choice: some empirical findings	• Situational factors explained greater variance of mode choice than attitudinal factors. • The author concluded that the implication of a low attitudinal explanation might be because governmental policies and infrastructure development in transportation have supported the rapid acceptance of automobiles. However, these changes implicitly required attitudinal changes; therefore, future modelling should be based on both groups of factors.
Gilbert & Foerster (1977)	The importance of attitudes in the decision to use mass transit	• The inclusion of attitudinal data improved the power of prediction of models that use network-based mode choice data.
Temme et al. (2008)	Incorporating latent variables into discrete choice models – A simultaneous estimation approach using SEM software	• The integration of latent variables to understand the process of travel mode choice reported promising results, which led the authors to propose that future discrete choice models in transportation should add latent variables.
Chorus & Kroesen (2014)	On the (im-)possibility of deriving transport policy implications from hybrid choice models	• The authors critiqued the use of latent variables in discrete choice models. The arguments were based on problems of endogeneity and measurement methodologies. • They proposed that latent variables can still be helpful.
Vij et al. (2013)	Incorporating the influence of latent modal preferences on travel mode choice behavior	• The authors proposed a methodology to operationalise the measurement of modality styles. • They found that there is a group that presents a strong auto-oriented bias, as well as there is an important group of people defined as multi-modal passengers. • There are some mobility styles in which subjects are not affect by time uncertainty.
Keskisaari et al. (2017)	Greenhouse gas impacts of different modality style classes using latent class travel behavior model	• Authors found seven different mobility styles. • Car drivers might be easier to be persuaded by encouraging them to adopt more fuel-efficient cars, whereas multimodal passengers might be more receptive to adopting alternative transport modes such as walking or cycling.

Moody and Zhao (2020)	Travel behavior as a driver of attitude: Car use and car pride in U.S. cities	• The authors tested the existence of a feedback loop between car use, car pride and car ownership. • They recognised the difficulty of reducing car use as attitudes are embedded in a reinforcing loop with car use and car pride.
Jakobsson et al. (2000)	Determinants of private car users' acceptance of road pricing	• The study found that, the lower the income, the higher the probability of reducing car use when the cost of using it increases. Therefore, this affects the perception of how fair it is to implement road pricing schemes. • Reducing car use because of the environment was not relevant to boosting the acceptance of road pricing. • Social norms play a key role in reducing the intention towards car use.
Jifeng et al. (2008)	System dynamics model of urban transportation system and its application	• The authors tested a system dynamics model, which included six sub-models: population, economic development, environmental aspects, travel demand, travel supply, and congestion. • The authors tested the implications of restricting car ownership to study the impact on urban development, and environmental aspects.
Pucher & Buehler (2006)	Why Canadians cycle more than Americans: A comparative analysis of bicycling trends and policies	• The authors made a comparison between the USA and Canada in terms of bicycle levels. The cultural differences are mostly explained by transport and land-use policies, and not from cultural or economic aspects.
Buehler (2011)	Determinants of transport mode choice: a comparison of Germany and the USA	• The author compared the level of motorisation in the USA and Germany, finding the most important factors that explain why Germans walk more, use public transportation more frequently and drive less. • A key conclusion of the study is that, even when both countries share many of the explanations for why people drive less, North Americans are more car-dependent than Germans. • Policies that make cars go slower than PT might explain why Germans tend to drive less than North Americans.
Bamberg et al. (2007)	Social context, personal norms and the use of public transportation; two field studies	• The authors found that 'personal norms' are a significant predictor of the intention towards public transport • Personal norms are triggered by two related but different processes: anticipated feeling of guilt and the perception of social norms. This demonstrates that the intention to use public transport is strongly affected by social contexts.
Steg et al. (2001)	The effects of motivational factors on car use: a multidisciplinary modelling approach	• The explicit inclusion of motivational factors to explain car use was demonstrated to be key to improving the prediction of car use. • If motivational changes are taken into account, the forecasting of car use can change significantly.

Kitamura (2009)	Life-style and travel demand	• Forecasting life-style clusters can be a useful approximation to understand people's travel behaviour. • The study found relevant trends that go beyond the explanation of demographic data such as age, gender and income.
Scheiner & Holz-Rau (2010)	Travel mode choice: affected by objective or subjective determinants?	• The influence of life situation has a higher predictive power than the influence of lifestyle on mode choice. • The main conclusion of the study is that objective and subjective factors are equally important to predict travel mode choice.
Walker et al. (2014)	Old habits die hard: travel habit formation and decay during an office relocation	• Behavioural change tends to be difficult because habits impede old behaviours from disappearing immediately, making travel mode choice more automatic and less deliberative.
Raux et al. (2015)	Would personal carbon trading reduce travel emissions more effectively than a carbon tax?	• The study was unable to demonstrate if personal carbon trading (PCT) can be more effective than carbon tax. However, the authors found that there is still an important contribution to reduce car use. Further research should be applied regarding social norms and see how that can influence PCT.
Han & Hayashi (2008)	A system dynamics model of CO_2 mitigation in China's inter-city passenger transport	• An SD was created, in which the authors found that the best way to mitigate CO_2 emission is by increasing the construction of a rail network, as well as decreasing the plans for future construction regarding highways. This can also be boosted by adding a carbon tax.
Prato et al. (2017)	Latent lifestyle and mode choice decisions when travelling short distances	• The authors found that encouraging people to shift from car use to alternative transport modes is not so easy as they found a car-oriented cluster, which use cars as a reflection of their lifestyle decisions. • The four clusters found were: car oriented, bicycle oriented, public transport oriented and public transport averse.
Lanzini & Khan (2017)	Shedding light on the psychological and behavioral determinants of travel mode choice: A meta-analysis	• Habits, intentions and past use are the psychological constructs most important in the prediction of travel mode choice. • Environmental variables such as values, environmental concern and personal norms have been found to be relevant predictors for the behavioural intention, which was not the case to explain actual behaviour. • The heterogeneity of the paper's results is mostly explained by behaviours' operationalisation and scale measurement.

Collins & Chambers (2005)	Psychological and situational influences on commuter-transport-mode choice	• The authors found that values play a key role to predict travel mode choice. • Increasing public transportation preferences is a joint effort that should be focused on both psychological and situational factors.
Idris, et al. (2015)	Investigating the effects of psychological factors on commuting mode choice behaviour	• The authors identified a strong influence of habits in the choice of a car for commuting. • The authors found that emotions play a key role in evoking positive outcomes towards their habitual modal choice.

Appendix 4

Table 39. Simulation Outputs (Sensitivity Analysis).

	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017
Initial Condition	**3.74**	**3.72**	**3.68**	**3.64**	**3.61**	**3.58**	**3.56**	**3.55**	**3.53**	**3.52**	**3.51**	**3.51**	**3.50**	**3.49**	**3.49**	**3.48**
Belief of cars do not contribute to pollution	**2002**	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**
: Variation +150%	3.74	3.72	3.69	3.67	3.66	3.66	3.65	3.65	3.66	3.66	3.66	3.66	3.66	3.66	3.66	3.66
: Variation +100%	3.74	3.72	3.69	3.66	3.65	3.64	3.63	3.63	3.63	3.63	3.63	3.63	3.63	3.63	3.63	3.62
: Variation +75%	3.74	3.72	3.69	3.66	3.64	3.63	3.62	3.61	3.61	3.61	3.61	3.61	3.61	3.61	3.60	3.60
: Variation +50%	3.74	3.72	3.69	3.65	3.63	3.61	3.60	3.60	3.59	3.59	3.58	3.58	3.58	3.58	3.57	3.57
: Variation +25%	3.74	3.72	3.68	3.63	3.58	3.54	3.50	3.46	3.42	3.39	3.36	3.34	3.31	3.28	3.23	3.16
Belief of PT as the main mode to tackle pollution	**2002**	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**
: Variation +150%	3.74	3.72	3.68	3.63	3.58	3.54	3.49	3.46	3.42	3.39	3.36	3.33	3.31	3.28	3.22	3.14
: Variation +100%	3.74	3.72	3.68	3.63	3.59	3.54	3.51	3.47	3.45	3.42	3.39	3.37	3.35	3.33	3.32	3.29
: Variation +75%	3.74	3.72	3.68	3.63	3.59	3.55	3.52	3.49	3.46	3.44	3.42	3.40	3.38	3.36	3.35	3.34
: Variation +50%	3.74	3.72	3.68	3.64	3.59	3.56	3.53	3.50	3.48	3.46	3.44	3.43	3.41	3.40	3.39	3.38
: Variation +25%	3.74	3.72	3.68	3.64	3.60	3.57	3.54	3.52	3.50	3.49	3.47	3.46	3.45	3.44	3.43	3.42

Gral. value orient. toward wellbeing of others	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017
: Variation +150%	3.74	3.72	3.65	3.56	3.48	3.41	3.35	3.31	3.29	3.26	3.22	3.17	3.10	3.01	2.90	2.77
: Variation +100%	3.74	3.72	3.66	3.59	3.53	3.48	3.45	3.43	3.41	3.40	3.39	3.38	3.38	3.37	3.36	3.36
: Variation +75%	3.74	3.72	3.67	3.61	3.56	3.53	3.50	3.49	3.48	3.47	3.46	3.46	3.45	3.45	3.44	3.44
: Variation +50%	3.74	3.72	3.67	3.63	3.60	3.58	3.56	3.55	3.55	3.55	3.54	3.54	3.53	3.53	3.52	3.52
: Variation +25%	3.74	3.72	3.69	3.66	3.64	3.63	3.62	3.62	3.62	3.62	3.62	3.62	3.62	3.61	3.61	3.61

Social identification with PEB actions	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017
: Variation +150%	3.74	3.72	3.67	3.65	3.64	3.64	3.64	3.64	3.65	3.65	3.65	3.65	3.65	3.66	3.66	3.66
: Variation +100%	3.74	3.72	3.68	3.66	3.65	3.65	3.65	3.66	3.66	3.66	3.66	3.66	3.67	3.67	3.67	3.67
: Variation +75%	3.74	3.72	3.69	3.67	3.66	3.66	3.66	3.66	3.67	3.67	3.67	3.67	3.67	3.67	3.68	3.68
: Variation +50%	3.74	3.72	3.69	3.67	3.67	3.67	3.67	3.67	3.67	3.67	3.68	3.68	3.68	3.68	3.68	3.68
: Variation +25%	3.74	3.72	3.69	3.68	3.67	3.67	3.67	3.68	3.68	3.68	3.68	3.68	3.69	3.69	3.69	3.69

Adoption from AR	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017
: Variation +150%	3.71	3.69	3.66	3.63	3.62	3.62	3.62	3.62	3.62	3.62	3.62	3.62	3.62	3.62	3.62	3.62
: Variation +100%	3.72	3.70	3.67	3.65	3.64	3.64	3.64	3.64	3.64	3.64	3.64	3.65	3.65	3.65	3.65	3.65

: Variation +75%	3.72	3.71	3.68	3.66	3.65	3.65	3.65	3.65	3.65	3.65	3.66	3.66	3.66	3.66	3.66	3.66
: Variation +50%	3.73	3.71	3.68	3.67	3.66	3.66	3.66	3.66	3.66	3.67	3.67	3.67	3.67	3.67	3.67	3.67
: Variation +25%	3.73	3.72	3.69	3.68	3.67	3.67	3.67	3.67	3.68	3.68	3.68	3.68	3.68	3.68	3.68	3.68
Motivation to comply toward subjective norm PEB	**2002**	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**
: Variation +150%	3.74	3.72	3.67	3.65	3.64	3.64	3.64	3.64	3.65	3.65	3.65	3.65	3.65	3.66	3.66	3.66
: Variation +100%	3.74	3.72	3.68	3.66	3.65	3.65	3.65	3.66	3.66	3.66	3.66	3.66	3.67	3.67	3.67	3.67
: Variation +75%	3.74	3.72	3.69	3.67	3.66	3.66	3.66	3.66	3.67	3.67	3.67	3.67	3.67	3.67	3.68	3.68
: Variation +50%	3.74	3.72	3.69	3.67	3.67	3.67	3.67	3.67	3.67	3.67	3.68	3.68	3.68	3.68	3.68	3.68
: Variation +25%	3.74	3.72	3.69	3.68	3.67	3.67	3.67	3.68	3.68	3.68	3.68	3.68	3.69	3.69	3.69	3.69
Internal attribution	**2002**	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**
: Variation +150%	3.74	3.71	3.65	3.62	3.61	3.61	3.61	3.61	3.62	3.62	3.62	3.62	3.62	3.63	3.63	3.63
: Variation +100%	3.74	3.71	3.66	3.64	3.63	3.63	3.63	3.63	3.64	3.64	3.64	3.64	3.64	3.65	3.65	3.65
: Variation +75%	3.74	3.72	3.67	3.65	3.64	3.64	3.64	3.64	3.65	3.65	3.65	3.65	3.65	3.66	3.66	3.66
: Variation +50%	3.74	3.72	3.68	3.66	3.65	3.65	3.65	3.66	3.66	3.66	3.66	3.66	3.67	3.67	3.67	3.67
: Variation +25%	3.74	3.72	3.69	3.67	3.67	3.67	3.67	3.67	3.67	3.67	3.68	3.68	3.68	3.68	3.68	3.68

Temporal Distance	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017
: Variation +150%	3.74	3.71	3.64	3.61	3.60	3.59	3.59	3.59	3.60	3.60	3.60	3.60	3.60	3.60	3.60	3.60
: Variation +100%	3.74	3.71	3.65	3.61	3.60	3.60	3.60	3.60	3.60	3.61	3.61	3.61	3.61	3.61	3.61	3.61
: Variation +75%	3.74	3.71	3.65	3.62	3.61	3.60	3.60	3.61	3.61	3.61	3.61	3.61	3.61	3.61	3.62	3.62
: Variation +50%	3.74	3.71	3.65	3.62	3.61	3.61	3.61	3.61	3.61	3.61	3.61	3.62	3.62	3.62	3.62	3.62
: Variation +25%	3.74	3.71	3.65	3.62	3.61	3.61	3.61	3.61	3.61	3.62	3.62	3.62	3.62	3.62	3.62	3.63

Perceived uncertainty climate change	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017
: Variation +150%	3.74	3.71	3.66	3.64	3.63	3.64	3.64	3.64	3.65	3.65	3.66	3.66	3.67	3.67	3.67	3.68
: Variation +100%	3.74	3.71	3.66	3.63	3.63	3.63	3.63	3.64	3.64	3.64	3.65	3.65	3.66	3.66	3.66	3.67
: Variation +75%	3.74	3.71	3.65	3.63	3.63	3.63	3.63	3.63	3.64	3.64	3.64	3.65	3.65	3.65	3.66	3.66
: Variation +50%	3.74	3.71	3.65	3.63	3.62	3.62	3.62	3.63	3.63	3.63	3.64	3.64	3.64	3.65	3.65	3.65
: Variation +25%	3.74	3.71	3.65	3.63	3.62	3.62	3.62	3.62	3.62	3.63	3.63	3.63	3.63	3.64	3.64	3.64

Red. of car use for the sake of the env.	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017
: Variation +150%	3.74	3.71	3.65	3.61	3.60	3.59	3.58	3.58	3.57	3.56	3.55	3.54	3.53	3.53	3.52	3.52
: Variation +100%	3.74	3.71	3.65	3.62	3.60	3.60	3.59	3.59	3.59	3.58	3.58	3.57	3.57	3.56	3.56	3.55

: Variation +75%	3.74	3.71	3.65	3.62	3.61	3.60	3.60	3.60	3.60	3.59	3.59	3.59	3.58	3.58	3.57	3.57
: Variation +50%	3.74	3.71	3.65	3.62	3.61	3.60	3.60	3.60	3.60	3.60	3.60	3.60	3.60	3.60	3.59	3.59
: Variation +25%	3.74	3.71	3.65	3.62	3.61	3.61	3.61	3.61	3.61	3.61	3.61	3.61	3.61	3.61	3.61	3.61

Symbolic Affective (att. towards buying a car)	**2002**	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**
: Variation +150%	3.82	3.79	3.73	3.70	3.70	3.69	3.70	3.70	3.70	3.70	3.71	3.71	3.71	3.71	3.71	3.72
: Variation +100%	3.79	3.76	3.70	3.68	3.67	3.67	3.67	3.67	3.67	3.68	3.68	3.68	3.68	3.68	3.69	3.69
: Variation +75%	3.78	3.75	3.69	3.66	3.65	3.65	3.65	3.66	3.66	3.66	3.66	3.67	3.67	3.67	3.67	3.67
: Variation +50%	3.76	3.73	3.68	3.65	3.64	3.64	3.64	3.64	3.65	3.65	3.65	3.65	3.65	3.66	3.66	3.66
: Variation +25%	3.75	3.72	3.66	3.63	3.63	3.62	3.63	3.63	3.63	3.63	3.64	3.64	3.64	3.64	3.64	3.64

Social identification with car use and commuters	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017
: Variation +150%	3.84	3.81	3.78	3.77	3.76	3.77	3.77	3.78	3.78	3.78	3.79	3.79	3.80	3.80	3.80	3.81
: Variation +100%	3.81	3.78	3.73	3.72	3.72	3.72	3.72	3.73	3.73	3.73	3.74	3.74	3.74	3.75	3.75	3.75
: Variation +75%	3.79	3.76	3.71	3.70	3.69	3.69	3.70	3.70	3.70	3.71	3.71	3.71	3.72	3.72	3.72	3.73
: Variation +50%	3.77	3.74	3.69	3.67	3.67	3.67	3.67	3.67	3.68	3.68	3.68	3.68	3.69	3.69	3.69	3.70
: Variation +25%	3.75	3.72	3.67	3.65	3.64	3.64	3.64	3.64	3.65	3.65	3.65	3.65	3.66	3.66	3.66	3.66

Motivation to comply toward SN toward driving	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017
: Variation +150%	3.84	3.81	3.78	3.77	3.76	3.77	3.77	3.78	3.78	3.78	3.79	3.79	3.80	3.80	3.80	3.81
: Variation +100%	3.81	3.78	3.73	3.72	3.72	3.72	3.72	3.73	3.73	3.73	3.74	3.74	3.74	3.75	3.75	3.75
: Variation +75%	3.79	3.76	3.71	3.70	3.69	3.69	3.70	3.70	3.70	3.71	3.71	3.71	3.72	3.72	3.72	3.73
: Variation +50%	3.77	3.74	3.69	3.67	3.67	3.67	3.67	3.67	3.68	3.68	3.68	3.68	3.69	3.69	3.69	3.70
: Variation +25%	3.75	3.72	3.67	3.65	3.64	3.64	3.64	3.64	3.65	3.65	3.65	3.65	3.66	3.66	3.66	3.66

Independence (attitudinal factor)	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017
: Variation +150%	3.82	3.79	3.73	3.70	3.70	3.69	3.70	3.70	3.70	3.70	3.71	3.71	3.71	3.71	3.71	3.72
: Variation +100%	3.79	3.76	3.70	3.68	3.67	3.67	3.67	3.67	3.67	3.68	3.68	3.68	3.68	3.68	3.69	3.69
: Variation +75%	3.78	3.75	3.69	3.66	3.65	3.65	3.65	3.66	3.66	3.66	3.66	3.67	3.67	3.67	3.67	3.67
: Variation +50%	3.76	3.73	3.68	3.65	3.64	3.64	3.64	3.64	3.65	3.65	3.65	3.65	3.65	3.66	3.66	3.66
: Variation +25%	3.75	3.72	3.66	3.63	3.63	3.62	3.63	3.63	3.63	3.63	3.64	3.64	3.64	3.64	3.64	3.64

Subjective Norms towards buying a car	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017
: Variation +150%	3.72	3.69	3.64	3.61	3.60	3.60	3.60	3.60	3.60	3.61	3.61	3.61	3.61	3.61	3.61	3.62
: Variation +100%	3.71	3.68	3.62	3.59	3.58	3.58	3.58	3.58	3.59	3.59	3.59	3.59	3.60	3.60	3.60	3.60

: Variation +75%	3.70	3.67	3.61	3.59	3.58	3.57	3.57	3.58	3.58	3.58	3.58	3.59	3.59	3.59	3.59	3.59
: Variation +50%	3.69	3.66	3.61	3.58	3.57	3.57	3.57	3.57	3.57	3.57	3.58	3.58	3.58	3.58	3.58	3.59
: Variation +25%	3.69	3.66	3.60	3.57	3.56	3.56	3.56	3.56	3.57	3.57	3.57	3.57	3.57	3.58	3.58	3.58
Cost of running a car	**2002**	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**
: Variation +150%	3.73	3.70	3.64	3.61	3.60	3.60	3.60	3.60	3.60	3.60	3.60	3.60	3.60	3.60	3.60	3.60
: Variation +75%	3.73	3.70	3.64	3.61	3.60	3.60	3.60	3.60	3.60	3.60	3.60	3.60	3.60	3.60	3.60	3.60
: Variation +50%	3.73	3.70	3.64	3.61	3.60	3.60	3.60	3.60	3.60	3.60	3.60	3.60	3.60	3.61	3.60	3.60
: Variation +25%	3.72	3.69	3.64	3.61	3.60	3.60	3.60	3.60	3.60	3.60	3.60	3.61	3.61	3.61	3.61	3.61
Normal Driving Satisfaction per trip	**2002**	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**
: Variation +150%	3.72	3.71	3.67	3.65	3.66	3.67	3.69	3.71	3.73	3.75	3.77	3.78	3.80	3.82	3.84	3.86
: Variation +100%	3.72	3.70	3.66	3.64	3.64	3.65	3.66	3.67	3.69	3.70	3.71	3.73	3.74	3.75	3.76	3.78
: Variation +75%	3.72	3.70	3.65	3.63	3.63	3.64	3.64	3.65	3.67	3.68	3.69	3.70	3.71	3.72	3.73	3.74
: Variation +50%	3.72	3.70	3.65	3.62	3.62	3.62	3.63	3.64	3.65	3.65	3.66	3.67	3.67	3.68	3.69	3.70
: Variation +25%	3.72	3.7	3.64	3.61	3.61	3.61	3.61	3.62	3.62	3.63	3.63	3.64	3.64	3.65	3.65	3.66
Quality of Car	**2002**	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**

: Variation +150%	3.72	3.71	3.67	3.65	3.66	3.67	3.69	3.71	3.73	3.75	3.77	3.78	3.80	3.82	3.84	3.86
: Variation +100%	3.72	3.70	3.66	3.64	3.64	3.65	3.66	3.67	3.69	3.70	3.71	3.73	3.74	3.75	3.76	3.78
: Variation +75%	3.72	3.70	3.65	3.63	3.63	3.64	3.64	3.65	3.67	3.68	3.69	3.70	3.71	3.72	3.73	3.74
: Variation +50%	3.72	3.70	3.65	3.62	3.62	3.62	3.63	3.64	3.65	3.65	3.66	3.67	3.67	3.68	3.69	3.70
: Variation +25%	3.72	3.7	3.64	3.61	3.61	3.61	3.61	3.62	3.62	3.63	3.63	3.64	3.64	3.65	3.65	3.66

Quality of Road Infrastructure	**2002**	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**
: Variation +150%	3.72	3.71	3.67	3.65	3.66	3.67	3.69	3.71	3.73	3.75	3.77	3.78	3.80	3.82	3.84	3.86
: Variation +100%	3.72	3.70	3.66	3.64	3.64	3.65	3.66	3.67	3.69	3.70	3.71	3.73	3.74	3.75	3.76	3.78
: Variation +75%	3.72	3.70	3.65	3.63	3.63	3.64	3.64	3.65	3.67	3.68	3.69	3.70	3.71	3.72	3.73	3.74
: Variation +50%	3.72	3.70	3.65	3.62	3.62	3.62	3.63	3.64	3.65	3.65	3.66	3.67	3.67	3.68	3.69	3.70
: Variation +25%	3.72	3.7	3.64	3.61	3.61	3.61	3.61	3.62	3.62	3.63	3.63	3.64	3.64	3.65	3.65	3.66

Sense of flexibility & autonomy (Car commute)	**2002**	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**
: Variation +150%	3.72	3.71	3.67	3.65	3.66	3.67	3.69	3.71	3.73	3.75	3.77	3.78	3.80	3.82	3.84	3.86
: Variation +100%	3.72	3.70	3.66	3.64	3.64	3.65	3.66	3.67	3.69	3.70	3.71	3.73	3.74	3.75	3.76	3.78
: Variation +25%	3.72	3.70	3.64	3.61	3.61	3.61	3.61	3.62	3.62	3.63	3.63	3.64	3.64	3.65	3.65	3.66

: Variation +50%	3.72	3.70	3.65	3.62	3.62	3.62	3.63	3.64	3.65	3.65	3.66	3.67	3.67	3.68	3.69	3.70
: Variation +75%	3.72	3.70	3.65	3.63	3.63	3.64	3.64	3.65	3.67	3.68	3.69	3.70	3.71	3.72	3.73	3.74
Implementation intention (toward PT)	**2002**	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**
: Variation +150%	3.57	3.54	3.48	3.45	3.44	3.44	3.44	3.44	3.44	3.44	3.45	3.45	3.45	3.45	3.45	3.45
: Variation +100%	3.62	3.59	3.53	3.50	3.49	3.49	3.49	3.49	3.50	3.50	3.50	3.50	3.50	3.51	3.51	3.51
: Variation +75%	3.65	3.62	3.56	3.53	3.52	3.52	3.52	3.52	3.52	3.52	3.53	3.53	3.53	3.53	3.53	3.54
: Variation +50%	3.67	3.64	3.59	3.56	3.55	3.54	3.54	3.55	3.55	3.55	3.55	3.56	3.56	3.56	3.56	3.56
: Variation +25%	3.7	3.67	3.61	3.58	3.57	3.57	3.57	3.57	3.58	3.58	3.58	3.58	3.58	3.59	3.59	3.59
Transport priorities	**2002**	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**
: Variation +150%	3.72	3.69	3.64	3.61	3.60	3.59	3.59	3.60	3.60	3.60	3.60	3.60	3.61	3.61	3.61	3.61
: Variation +100%	3.72	3.69	3.64	3.61	3.60	3.60	3.60	3.60	3.60	3.60	3.60	3.61	3.61	3.61	3.61	3.61
: Variation +25%	3.72	3.69	3.64	3.61	3.60	3.60	3.60	3.60	3.60	3.60	3.61	3.61	3.61	3.61	3.61	3.62
: Variation +50%	3.72	3.69	3.64	3.61	3.60	3.60	3.60	3.60	3.60	3.60	3.61	3.61	3.61	3.61	3.61	3.61
: Variation +75%	3.72	3.69	3.64	3.61	3.60	3.60	3.60	3.60	3.60	3.60	3.60	3.61	3.61	3.61	3.61	3.61
Perceived effort to take PT	**2002**	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**

: Variation +150%	3.73	3.70	3.65	3.63	3.63	3.63	3.64	3.64	3.65	3.66	3.67	3.67	3.68	3.69	3.69	3.70
: Variation +100%	3.73	3.70	3.65	3.62	3.62	3.62	3.62	3.63	3.64	3.64	3.65	3.65	3.66	3.66	3.67	3.67
: Variation +75%	3.73	3.70	3.64	3.62	3.61	3.61	3.62	3.62	3.63	3.63	3.64	3.64	3.64	3.65	3.65	3.66
: Variation +50%	3.72	3.70	3.64	3.62	3.61	3.61	3.61	3.61	3.62	3.62	3.63	3.63	3.63	3.64	3.64	3.64
: Variation +25%	3.72	3.7	3.64	3.61	3.6	3.6	3.6	3.61	3.61	3.61	3.62	3.62	3.62	3.63	3.63	3.59
Occupancy rate	**2002**	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**
: Variation +100%	3.72	3.69	3.64	3.61	3.60	3.60	3.60	3.60	3.60	3.61	3.61	3.61	3.61	3.61	3.61	3.62
: Variation +150%	3.72	3.69	3.64	3.61	3.60	3.60	3.60	3.60	3.60	3.61	3.61	3.61	3.61	3.61	3.61	3.62
: Variation +25%	3.72	3.69	3.64	3.61	3.60	3.60	3.60	3.60	3.60	3.61	3.61	3.61	3.61	3.61	3.61	3.62
: Variation +50%	3.72	3.69	3.64	3.61	3.60	3.60	3.60	3.60	3.60	3.61	3.61	3.61	3.61	3.61	3.61	3.62
: Variation +75%	3.72	3.69	3.64	3.61	3.60	3.60	3.60	3.60	3.60	3.61	3.61	3.61	3.61	3.61	3.61	3.62
Social acceptability of PT	**2002**	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**
: Variation +100%	3.72	3.69	3.63	3.60	3.59	3.59	3.59	3.59	3.59	3.60	3.60	3.60	3.60	3.60	3.60	3.60
: Variation +150%	3.72	3.69	3.63	3.60	3.59	3.59	3.59	3.59	3.59	3.59	3.59	3.59	3.59	3.59	3.59	3.59
: Variation +25%	3.72	3.69	3.64	3.61	3.60	3.60	3.60	3.60	3.60	3.60	3.60	3.61	3.61	3.61	3.61	3.61

: Variation +50%	3.72	3.69	3.64	3.61	3.60	3.59	3.59	3.60	3.60	3.60	3.60	3.60	3.60	3.61	3.61	3.61
: Variation +75%	3.72	3.69	3.63	3.61	3.59	3.59	3.59	3.59	3.60	3.60	3.60	3.60	3.60	3.60	3.60	3.60
PT accessibility	**2002**	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**
: Variation +150%	3.72	3.69	3.63	3.60	3.59	3.59	3.59	3.59	3.59	3.59	3.59	3.59	3.59	3.59	3.59	3.59
: Variation +100%	3.72	3.69	3.63	3.6	3.59	3.59	3.59	3.59	3.59	3.6	3.6	3.6	3.6	3.6	3.6	3.6
: Variation +75%	3.72	3.69	3.63	3.61	3.59	3.59	3.59	3.59	3.60	3.60	3.60	3.60	3.60	3.60	3.60	3.60
: Variation +50%	3.72	3.69	3.64	3.61	3.60	3.59	3.59	3.60	3.60	3.60	3.60	3.60	3.60	3.61	3.61	3.61
: Variation +25%	3.72	3.69	3.64	3.61	3.6	3.6	3.6	3.6	3.6	3.6	3.6	3.61	3.61	3.61	3.61	3.61
Normal AT satisfaction per trip	**2002**	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**
: Variation +150%	3.72	3.69	3.63	3.6	3.59	3.59	3.59	3.59	3.59	3.59	3.59	3.59	3.59	3.59	3.59	3.59
: Variation +100%	3.72	3.69	3.63	3.60	3.59	3.59	3.59	3.59	3.59	3.60	3.60	3.60	3.60	3.60	3.60	3.60
: Variation +75%	3.72	3.69	3.63	3.61	3.59	3.59	3.59	3.59	3.60	3.60	3.60	3.60	3.60	3.60	3.60	3.60
: Variation +50%	3.72	3.69	3.64	3.61	3.60	3.59	3.59	3.60	3.60	3.60	3.60	3.60	3.60	3.61	3.61	3.61
: Variation +25%	3.72	3.69	3.64	3.61	3.6	3.6	3.6	3.6	3.6	3.6	3.6	3.61	3.61	3.61	3.61	3.61
Attitude towards car commuting	**2002**	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**

: Variation +100%	4.36	4.35	4.33	4.32	4.32	4.32	4.32	4.32	4.33	4.33	4.33	4.33	4.33	4.34	4.34	4.34
: Variation +150%	4.45	4.44	4.42	4.41	4.41	4.41	4.41	4.41	4.41	4.42	4.42	4.42	4.42	4.43	4.43	4.43
: Variation +25%	4.14	4.11	4.06	4.04	4.03	4.03	4.04	4.04	4.04	4.05	4.05	4.05	4.05	4.06	4.06	4.06
: Variation +50%	4.27	4.26	4.24	4.23	4.23	4.23	4.23	4.23	4.24	4.24	4.24	4.24	4.24	4.25	4.25	4.25
: Variation +75%	4.32	4.30	4.28	4.28	4.27	4.28	4.28	4.28	4.28	4.28	4.28	4.29	4.29	4.29	4.29	4.29

Perception of how easy is reducing car commuting	**2002**	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**
: Variation +100%	4.47	4.46	4.44	4.43	4.43	4.43	4.43	4.43	4.44	4.44	4.44	4.44	4.44	4.45	4.45	4.45
: Variation +150%	4.33	4.30	4.25	4.23	4.22	4.22	4.23	4.23	4.23	4.24	4.24	4.24	4.24	4.25	4.25	4.25
: Variation +25%	4.63	4.62	4.60	4.59	4.59	4.59	4.59	4.59	4.60	4.60	4.60	4.60	4.60	4.60	4.61	4.61
: Variation +50%	4.58	4.56	4.54	4.54	4.54	4.54	4.54	4.54	4.54	4.54	4.55	4.55	4.55	4.55	4.55	4.56
: Variation +75%	4.52	4.51	4.49	4.49	4.48	4.48	4.49	4.49	4.49	4.49	4.49	4.49	4.50	4.50	4.50	4.50

Source: Own elaboration. The values in the table are the score obtained for the targeted variable “behavioural intention towards car commuting”. This variable is the main variable under study as it is the critical factor to answer the research questions of the project.