



## Analysis

## A transitions model for sustainable mobility

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## ABSTRACT

This paper reports on the development of a model for assessing transitions to sustainable mobility. The model uses the concepts of transition theory as a framework for assessing possible pathways by which a transition to a sustainable mobility society might happen. The modelling approach combines agent-based modelling techniques with a system dynamics structure. It is original in that there are two levels of agent. There are a small number of complex agents, which have an internal structure and are therefore subsystems within society, and a larger number of simple agents. Based on the UK data, the results show that Hydrogen Fuel Cell Vehicles (FCVs) come to dominate, but only in the very long run (after 2030), while biofuels and ICE (Internal Combustion Engine)-electric hybrids are the main alternatives to the regime in the next 10–30 years, because a) they are already developed and b) they fit better into current infrastructures. The model shows that technological transitions are most likely. Lifestyle change transitions require sustained pressure from the environment on society and behavioural change from consumers.

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## 1. Introduction

This paper reports on the development of a model for assessing transitions to sustainable mobility. The model uses the concepts of transition theory, (Geels, 2005; Rotmans, Kemp and van Asselt, 2001) as a framework for assessing possible pathways by which a transition to a sustainable mobility society might happen. In particular, the development of alternative social, behavioural and technological alternative niches to the current regime based on the motor car is modelled, so that the conditions for a successful transition can be identified. The modelling formed part of the EU MATISSE project and formed part of an Integrated Sustainability Assessment (ISA) exercise. The ISA process places emphasis on ‘scoping’ and ‘visioning’ through stakeholder interaction and therefore this modelling is intended to take account of both the expert opinions of specialists in the field of low-emission transport technologies and systems, as well as input from non-expert citizens on preferred technical and non-technical options for sustainable mobility.

From the perspective of sustainability, transport presents one of the major challenges. There is a considerable literature on transport

and sustainability (see Hensher and Button, 2003 for an extensive survey). Recent studies on the negative impacts of transport systems (e.g., Bickel and Friedrich, 2001; European Environment Agency, 2006; INFRAS, 2004) highlight problems for environment and health, including climate change, local air pollution, noise and accidents. Congestion and land use associated with transport infrastructure are also problems for most European countries, posing economic costs (INFRAS, 2004) and threatening biodiversity (European Commission, 2001b). Other environmental impacts associated with transport infrastructure include soil sealing and fragmentation of natural, semi-natural and agricultural areas (European Commission, 2001b). There are also several notable social problems associated with transport, such as reduced accessibility to basic services in some regions (e.g., SUMMA, 2005). Road transport is now one of the largest contributors to greenhouse gas emissions (GHGs) and transport is the sector with the highest growth rate of GHGs (see e.g. Hensher and Button, 2003; Köhler, 2006). However, transport is crucial for economic competitiveness as well as for commercial and cultural exchanges (European Commission, 2001a) and is therefore identified as playing a fundamental role in the EU Lisbon agenda for competitiveness, growth and employment. Furthermore, the car industry is the single largest manufacturing sector in the world (Nieuwenhuis, Vergragt and Wells, 2004; (Köhler et al., 2008a,b) and is one of the major generators of wealth and employment in the EU. The problem for society – and policy – is therefore how to retain the

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social and economic benefits associated with mobility while reducing the negative environmental, economic and social impacts from transport.

Policy solutions to tackle these persistent problems have focussed on improving technologies and (to some extent) encouraging modal shift, but these have done little to address the underlying growth in mobility demand. The benefit of technical measures to reduce vehicle emissions and noise has been outstripped by the increase in vehicle numbers, weight of vehicles (due to additional equipments), engine size, travel frequency and trip length (European Commission, 2001b). The rising demand for transport, particularly road transport, suggests a need for radical rather than incremental technological improvements as well as integrated approaches to reducing demand and encouraging modal shift. It has therefore been argued (e.g., Kemp and Rotmans, 2004; Nykvist and Whitmarsh, 2008) that radical systemic innovation – a ‘transition’ – in land-based transport is required in order to move away from the current regime and towards a more sustainable mobility system. Such a transition is likely to require both technological and institutional changes (e.g., electric and fuel cell vehicles, customised mobility, teleworking, zoning policies) (Elzen, 2005; Kemp and Rotmans, 2004). This modelling is intended to suggest how such a transition might happen and what conditions are necessary for such a transition to take place.

In the context of climate change analysis, the modelling literature has concentrated on processes of switching to new low-carbon technologies. There is a considerable recent literature on Hydrogen Fuel Cell Vehicles (FCVs) in transport. Dougherty et al. (2009) apply a full fuel cycle approach to quantify emissions and explore scenarios for the USA. They find that a transition to hydrogen can reduce greenhouse gas emissions, given zero-carbon energy supply, but that the transition will be slow, because of the very large and long term investments in ICE (Internal Combustion Engine) technology and infrastructure. Collantes (2006) uses a diffusion model, parameterised with data from a stakeholder survey. Given strong policy support, he finds that FCVs gain significant market share around 2040. Kim and Moon (2008) use an energy-economic model to explore scenarios of hydrogen adoption in Korea. Given high fossil fuel taxes and a high oil price, FCVs could have a 76% market share by 2044. Struben and Sterman (2008) develop a system dynamics model of technology diffusion with dynamic consumer preferences. They also find that policy support such as marketing programmes and subsidies must remain in place for a long time for FCVs to become self-sustaining. Mau et al. (2008) use an econometric analysis of consumer surveys of preferences in vehicles. A wide range of attributes as well as price determines choices, as well as the degree of diffusion, indicating a positive feedback effect. Using these results to parameterise an energy-economy model for Canada, they show that consumer preference dynamics are important in developing effective policies to support the uptake of clean vehicles. All of this work uses microeconomic approaches. Some recent work on transport and climate policy has combined macroeconomic modelling of economic processes with more detailed or bottom-up modelling of transport networks and technologies (e.g. Köhler et al., 2008a,b), but does not address issues of how institutional structures change. The modelling literatures do not address a fundamental question for sustainability and climate change policy: how do societies and institutional structures change and which social and institutional changes are necessary for a radical shift to sustainable transport systems? Transition theory has been developed specifically to address this question. There have been no previous modelling applications of transitions theory in transport, so this current work is a first step in social and policy analysis modelling in this field.

In Section 2, we briefly describe the theory and structure of the model and its application to the case of sustainable transport. Section 3 describes the application of this model structure, with the parameters and assumptions based on the UK data. Section 4 presents the results

for an initial analysis of the conditions under which a transition to a sustainable mobility system might occur. From these results, we are able in Section 5 to draw some conclusions on possible transition pathways and supporting policy.

## 2. Applying transition theory to sustainable transport

The analysis and model represents an innovative attempt to simulate transitions (i.e. radical, systemic change) within societal systems. The model is an implementation of a generic transition model structure described in Haxeltine et al. (2008). Bergman et al. (2008) provides a detailed description of the mechanisms in the model. The model structure is based on the ‘multi-level perspective’ developed by Kemp and Rip (1998), which encompasses three functional levels: ‘niche’, ‘regime’ and ‘landscape’ – with increasing structuration (Giddens, 1984) and coordination of activities, ranging from individual technologies and grassroots movements to larger-scale social structures and institutions.

Transition theory literature highlights the interdependency of institutions and infrastructures constituting societal systems and subsystems, which has created various types of lock-in that stifle innovation (Smith et al., 2005). These societal systems comprise interlocking economic, social, cultural, infrastructural and regulative subsystems, which are associated with a range of social groups. The stability and cohesion of societal systems are established and reinforced through cognitive, normative and regulative institutions (Geels, 2005). These institutions are represented by the concept of a *regime*. A regime can be understood as a particular set of practices, rules and shared assumptions, which dominate the system and its actors (Rotmans et al., 2001). Importantly, regimes typically focus on system optimisation rather than system innovation, because habits, existing competencies, past investment, regulation, prevailing norms, worldviews and so on act to lock in patterns of behaviour and result in path dependencies for technological and social development (Smith et al., 2005; Geels 2005).

Transitions require qualitative innovations, realised by a variety of participants, which change the structure of the system (Loorbach and Rotmans, 2006). Researchers have therefore highlighted *niches* – individual technologies and actors outside or peripheral to the regime – as the loci for radical innovation (Geels, 2005; Rotmans et al., 2001; Smith et al., 2005). The regime may be threatened from the niche level, or from changes at the broader *landscape* level of economic, ecological and cultural trends, or from internal misalignment amongst regime actors (Geels, 2005). Once a threat is recognised, regime actors will mobilise resources from within the regime, and in some cases from within niches, to respond to it (Geels and Schot, 2007; Smith et al., 2005). A transition occurs either when a regime is *transformed* or through *regime change*. In a *transformation* the regime responds to the systemic and landscape changes by changing some of its practices and rules, and possibly replacing some institutions and actors. On the other hand, when a regime is unable to weather the changes, it collapses or is overthrown, and is (eventually) replaced by a new regime better suited to the new conditions, constituting *regime change*.

### 2.1. Model description

The modelling approach combines agent-based modelling techniques with a system dynamics structure. It is original in that there are two types of agent. There are a small number of complex agents, which have an internal structure and are therefore subsystems within society, and a larger number of simple agents. The conceptual structure of the model is described in detail in Haxeltine et al. (2008) and Bergman et al. (2008) is a detailed description of the model.

The model uses the concept of practices as the metric through which agents position themselves in society and over which

behaviour is defined. Practices of both the complex and simple agents are each represented as point values along different axes, constituting a multi-dimensional *practice space*. Fig. 1 schematically shows a two-dimensional practices space, which might be e.g.  $P_x$  CO<sub>2</sub> emissions and  $P_y$  cost of transport. The complex agents (regime and niches) and the consumer agents are shown separately for clarity, but actually occupy positions along the same  $P_x$  and  $P_y$  practices axes. Consumer agents are points in the space, while in the figure the size of the regime and niche ovals is proportional to their relative support. In the model the consumer agents support the complex agent that is closest to them and therefore the positions of the regime and niches are based on clusters of support i.e. like-minded consumers. The positions of the consumer agents in the practices space change depending on landscape signals, so the regime and niches have to move, not only to grow but often just to maintain their support. Their movement strategies are explained below.

Practices are broadly defined and include for the example of transport technology production and consumption, transport service provision and use, and infrastructure provision and use. We have identified the smallest number of practices that can differentiate the various niches, empowered niches, and regime and which impact on the environmental, social and economic mobility criteria identified through stakeholder engagement work and literature reviews (see Section 3 below). The model is stochastic in that the simple agents are initially randomly assigned over the practice space, with an even distribution.

2.2. Implementing the multi-level perspective

The overall structure of the model is shown in Fig. 2. Unlike most agent-based models, the model has a hierarchical structure. The model includes the regime and niches as individual agents, with an extension of the concept of a niche to an *extended niche agent (ENA)*. There can be only one regime at any time, although the system might have periods in which there is no regime. There may be zero, one or a few ENAs and several niches at once. We define the type of the agent by its *strength* with thresholds separating them. The regime is by definition the strongest agent and dominates the system, while niches have much less strength. We also define ENAs – niches which have grown strong enough to pose a potential threat to the regime. An agent's strength determines its behaviour (strategy in practice space), its interactions with other agents, and (partly) its attractiveness to supporters. Complex agents have an internal structure, or *metabolism*, which determines their strength, although this is ultimately dependent on support from the consumer agents.

Each agent type (regime, niche, empowered niche agent) has a different behavioural algorithm for its movement in the practice space. The types we use are based on policy driven party dynamics of Laver (2005). The regime is an *aggregator*, adapting its practices to the centre of the consumer 'cloud' in the practice space, in an attempt to

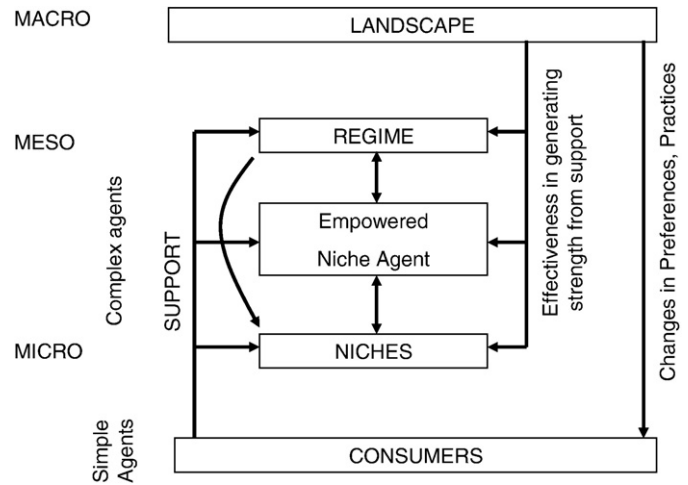


Fig. 2. Overall structure of the model.

maximise support. There is a restriction on the rate of change to reflect the tendency of the regime to display inertia. Laver has the aggregator attempting to aggregate *its own* supporters only. We add to this behaviour: when the regime's support falls below a threshold, it attempts to aggregate *all consumers* to increase its support. This attempts to capture the regime's tendency to be entrenched in its practices and to seek optimisation rather than innovation. ENAs are *predators*, moving their practices towards those of the largest agent, i.e., the regime, in an attempt to take support away from it. We depart from Laver in that in the absence of a regime, ENA behaviour switches to hunter behaviour as the niches. Finally, niches are *hunters*, continuing movement in the same direction as long as their strength increases, otherwise moving randomly in another direction. ENAs and niches are restricted to a certain range within the practices space. An example is that the FCV niche is restricted to low-carbon transport practices.

The regime and niche agents have an internal *metabolism*, including structure and practices. Structure is quantified by each agent having stocks of *physical capacity* and *institutional capacity*. The structure requires *resources*, which are obtained through the support of the simple agents or consumers. Resource generation depends on the agent's support and its production (physical) capacity, but can also be influenced by landscape signals and policy events. The agent's resource generation is a simple production function including output and price, assuming a constant ratio of price to cost. In this application, the support is implemented as the decisions of consumers to buy vehicles associated with the regime or a given niche, or to allocate their resources to alternative behavioural niches, such as a mixed-use urban structure niche with low demand for mechanised transport. The agent's institutional capacity also serves as its *strength*: its ability to

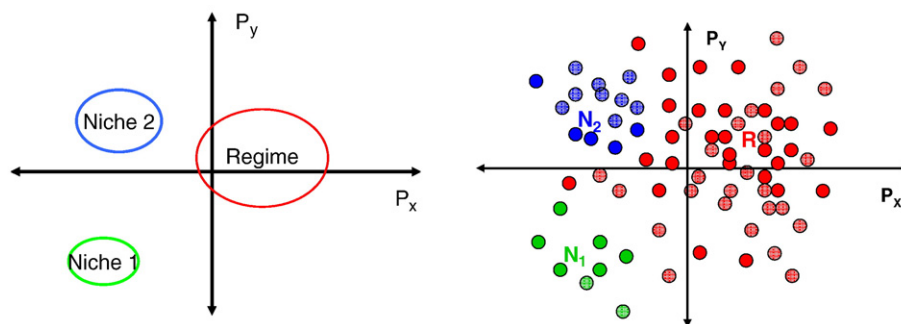


Fig. 1. Two illustrations of a two-dimensional practice space, with practice axes  $P_x$  and  $P_y$ . Left: Regime and niches, which can move in the space and interact with each other. Right: The consumer agents showing supporters scattered in the practice space, coloured by the agent they support, red = regime (R), green = niche 1 (N1), blue = niche 2 (N2). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

influence other agents, the landscape, and the simple agents or consumers.

The landscape, or macro-level, is an expression of slow changing world views and paradigms, macro-economy and material infrastructure, as well as the natural environment and demographics. The landscape is incorporated through two features of the model. A large number of simple agents (which can be thought of in this context as consumer agents) allocate support to the regime or a niche and hence determine the relative 'strength' of the regime and niches. Strength is an abstract concept that encompasses generation of resources and power through market, political and cultural processes. It provides a measure of the relative power and influence in society of the regime and niches. The decision of a simple agent is based on the regime's and niche's positions in practice space relative to the simple agent. This distance vector, for multiple practices, is used to calculate the attractiveness of the different niches and the regime using a formula similar to that of Schwoon (2006). The decision rule is then that the most attractive complex agent then receives the support of the consumer agent.

Secondly, landscape signals change supporters' preferences, causing them to move around the practice space. Each signal is a vector, i.e., it has a strength and a direction in the practice space, which determine its push on the supporters. This plays an important part in the dynamics of the model, as the changing locations of the supporters force the agents to adapt or lose support and power. This does not imply that the transitions are necessarily 'consumer led': the change in supporters' preferences is part of the system as a whole, changing an internalised part of the landscape. Another way in which landscape signals are used is to directly affect agents by changing resource gathering potential for a given set of practices, which can strengthen or weaken the agents, or weaken the attractiveness of a certain agent, e.g., the 'Green' movement reducing the attraction of ICE car-based urban transport.

### 2.3. Model dynamics

This hierarchical structure forms the basis of the model dynamics. The decision sequence of the model within a period is illustrated in Fig. 3.

The model runs as a dynamic simulation. The positions of regime and niche agents in practice space form the starting point in each time period. The position of simple agents in the practice space is then used to determine the level of support for the regime and niches. The regime and niches adapt their practices i.e. move in the practice space according to the support they have, their effectiveness given the

landscape signals and their 'culture' – implemented as a region in practice space to which they are restricted. Simple agents, which are initially randomly distributed across the practice space, also move in practice space according to the influence of landscape signals. This may change their allocation of support in future periods.

The regime and niche agents interact with each other and this plays an important role in model dynamics. The model explicitly includes these regime–niche interaction mechanisms:

- Adaptation is a change in practices, in order to improve fitness, i.e. to increase strength or support. Agents are constantly changing their position in the practice space (see agent movement above).
- Emergence of niches occurs in locations in the space where there are supporters, but no nearby agent.
- Absorption of a niche by the regime gives the regime new practices.
- Transformation is the change of an agent from one type to another. When gaining enough strength, a niche becomes an ENA, or an ENA becomes a (new) regime. When losing strength, a (deposed) regime transforms into an ENA, or an ENA becomes a niche. Transformation is possible in all runs, and is necessary for a regime change to take place.

### 2.4. Representing a transition

In the model implementation, we do not capture qualitative changes in structure, but define a transition as a significant shift in the system's dominant practices. There are two ways a transition can be represented in the model. The first is regime change, which occurs when an incumbent regime loses support and strength and an ENA with different practices takes its place, gaining strength to transform into the new regime. Unless the replacement is immediate, there will be a period of no regime in between. The second way a transition occurs in the model is through regime transformation, which occurs when the regime significantly changes its practices through adaptation and/or absorption of niches, moving to a significantly different location in the practice space.

## 3. Data and assumptions

The model framework described in Section 2 above has been applied to the analysis of personal (inland) transportation behaviour. This requires the regime and niches to be identified and suitable practice dimensions to be chosen. Then, data can be used to parameterise the model by initially locating the regime and niches in practice space for quantitative practices and positions in the qualitative practice dimensions can be determined as a consideration of the culture and behaviour of the agents. As is also typical in CGE models, the model was also calibrated such that the regime and niches matched the data in 2000. Since the model is a dynamic simulation model, this does not imply the assumption of equilibrium in the initial time period. Instead, the model was calibrated to provide plausible strengths of the regime and niches in 2010 as well as 2000. Finally, it is necessary to determine the landscape signals as exogenous inputs to the model. This was undertaken by writing a scenario storyline of a successful transition, which could then be interpreted in terms of parameterised landscape signals in the model.

### 3.1. Identifying the regime and niches

For surface transport, the dominant transportation technology is that of internal combustion engine powered car. This is widely recognised as forming the current socio-technological regime in transport (Köhler et al., 2008a). There is also an extensive literature on low-carbon technological and behavioural alternatives, surveyed in Hensher and Button (2003), while alternative social structures with

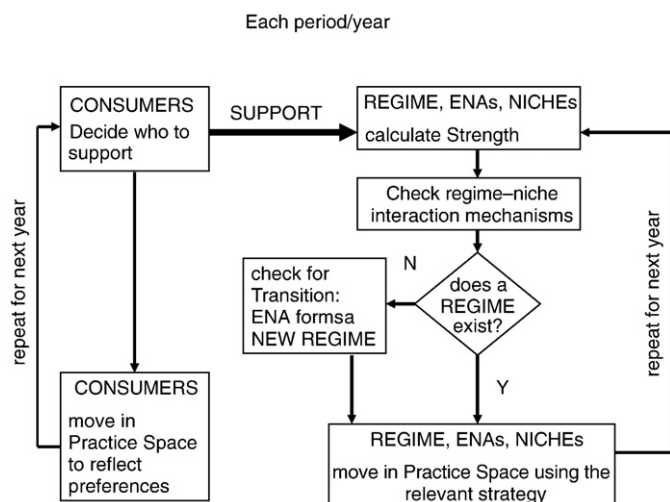


Fig. 3. Decision sequence of the model within a period.

regards to transport are discussed in Köhler (2006). These discussions allow a simple taxonomy of alternatives to the current regime:

1. Novel vehicle and fuel technologies, including biofuels, FCVs and ICE/electric hybrids;
2. A change in the use and ownership of vehicles towards increased car sharing and mode shift to more public transport use; and
3. Low mobility demand through changes to lifestyles such as homeworking/internet schools and shopping/entertainment through internet media (e.g., urban lifestyle with increased use of information and communication technologies [ICT]) and infrastructures (e.g., more mixed-zone developments enabling more extensive use of ‘slow modes’ – walking and cycling).

These three sets of alternatives lead to the following niche definitions. The car technology agents comprise the regime of Internal Combustion Engine (ICE) motor cars, and three niches: ICE/electric hybrid cars, biofuel cars and FCVs. Other niches following changes in ownership patterns are increased use of public transport and product to service shift (from car ownership to car sharing). Urban ICT – low transport demand can be identified as an adoption of slow modes (walking and cycling) and urban ICT for homeworking.

### 3.2. Practices

The practices were chosen to reflect a main criterion of sustainability (CO<sub>2</sub> emissions) and the main decision dimensions of passenger transport choice. The chosen practice dimensions are CO<sub>2</sub> emissions of vehicles (gCO<sub>2</sub>/km), cost of transport (€/year), ICT use, structure of the built environment (mixed use of zones affecting mobility decisions) and private and public demand split (measured in person km/year). Practices chosen are thus of two kinds: quantitative indicators, for which data is available and units are applicable (CO<sub>2</sub> emissions, cost, demand split); and qualitative indicators, for which we only give descriptive end points (ICT use, structure of the built environment).

### 3.3. Locating the regime, niches and consumers in the practice dimensions

Wherever possible, we have used real-world data to realistically identify the niches in the practice space. For the quantitative practice dimensions with units, data from early 2000 to 2003 is used (Nykqvist and Whitmarsh, 2008); for the qualitative indicators, estimates are made to distinguish their relative differences in their alignment with each practice. In particular, we have drawn on national (UK) data relating to transport indicators (e.g., demand, modal split; Department for Transport, 2005). Vehicle sales data and data on the development of alternative fuels were obtained from the European Automobile Manufacturers Association (2007) and national sources: the Vehicle Certification Agency (2006), and the ‘What you can do’ website (Whatyoucando, 2006). Complementary short personal communications with experts were conducted in a few cases to obtain data on aspects of niche development that are poorly documented in the literature or statistics. We use data on UK vehicles and attitudes, looking both at different car technology niches, as well as other modes of travel and options such as reduced mobility. Table 1 gives details of the initial values along the practice dimensions of the regime and niches and Table 2 details for the consumer agents.

Empirical evidence suggests slow growth in the UK of alternative fuels and propulsion technologies, although sales of low-emission conventional-fuel vehicles are increasing more rapidly. Development of the transport services niche area is somewhat ambiguous, with growth in the car service market and policies to support modal shift, but continued dominance of private car use. Finally, within the reduced mobility demand niche area, there are positive trends such as the growth of ICT for shopping and working, but little growth in the use of slow modes and continued urban sprawl. Further details can be found in Nykvist and Whitmarsh (2008). While all niches have lower CO<sub>2</sub>

**Table 1**  
The practices of the regime and the niches at time = 0, as specified by their coordinates in practice space (end points are 0 and 100).

	CO <sub>2</sub> gCO <sub>2</sub> /km	Cost €/year	Motorised private mobility pkm/year	ICT	Built environment	Motorised public mobility pkm/year
Regime (ICE petrol/diesel tech., high personal mobility and transport demand)	75 = 150 gCO <sub>2</sub> /km	67 = 4000€/year	47.5 = 9500 km/year (UK car use: 5900 m)	5 – reflecting percentages currently (in regime) using ICT in this way	10 = mainly single-use zones	4.75 = 950 pkm/year 10% of private motorised
Niche 1 (hybrid cars)	50 = 100 gCO <sub>2</sub> /km	87 = 4800€/year (= 120% of ICE)	47.5 = 9500 km/year (UK car use: 5900 m)	25 – reflecting “proximity to ICT wave” (high tech vehicle)	10 = mainly single-use zones	4.75 = 950 pkm/year 10% of private motorised
Niche 2 (biofuel cars)	37 = 75 gCO <sub>2</sub> /km (def as 50% of ICE)	73 = 4400€/year (= 110% of ICE)	47.5 = 9500 km/year (UK car use: 5900 m)	5 – reflecting percentages currently (in regime) using ICT in this way	10 = mainly single-use zones	4.75 = 950 pkm/year 10% of private motorised
Niche 3 (hydrogen/FCV cars)	7.5 = 15 gCO <sub>2</sub> /km (10% of ICE, if wind electrolysis)	100 = 6000€/year	32.5 = 6500 km/year (assume lower mobility due to tank constraints) (UK ~4000 m)	25 – reflecting “proximity to ICT wave” since high tech vehicle	10 = mainly single-use zones	12.2 = 2450 pkm/year (regime public of 950 + 3000/2 reduced private is replaced by 50% with public)
Niche 4 (public transport)	15 = 30 gCO <sub>2</sub> /km (20% of ICE)	20 = 1200€ (600€/year local transport + 600€/year long dist transport)	5 = 1000 pkm/year assumed low use of borrowed or hired car	5 – reflecting percentages currently (in regime) using ICT in this way	50 = support mixed zones to some extent	17.8 = 3540 km/year (typical commuting setting, with bus/light rail/metro 100 m = 1700, but accounting for other travel, × 2)
Niche 5 (slow modes)	0 = 0 gCO <sub>2</sub> /km (walking and cycling)	2 = 100€/year (cycle cost)	5 = 1000 pkm/year assumed low use of borrowed or hired car	50 By def (extensive use of ICT for shopping etc., but not forrunner of ICT)	100 = full supporter of mixed zones	10.6 = 2150 pkm/year (reduced private is 25% replaced with public)
Niche 6 (product to service shift: car share/hire)	62 = 125 gCO <sub>2</sub> (assuming cars hired slightly better than private ICE/benefit from sharing)	33 = 2000€/year (assume half cost of ICE since shared)	37.5 = 5700 pkm/year (38% of regime distance per year in UK)	25 By def (regime level use of ICT for shopping etc., and some replacement of car identity for urban ICT-lifestyle)	50 = support mixed transport as regime	14.2 = 2850 pkm/year (regime public of 950 + 3800/2 reduced private is replaced by 50% with public)
Niche 7 (urban ICT – low demand)	0 = (assume same as for slow modes)	17 = 1000€/year (high ICT costs)	5 = 1000 pkm/year (assume same as for slow modes)	100 By def	50 = support mixed zones, but still uses transport as regime	17.8 = 3540 km/year Same as public transport

**Table 2**

The initial ideal points and distribution (i.e., preferred, accepted or expected practices) of supporters by group.

	Mainstream car drivers	Green car drivers	Non-drivers
GHG emissions gCO <sub>2</sub> /km	75 high CO <sub>2</sub> emissions equal to that of REGIME value	37 Medium emission, equal to biofuels/HEV niche	15 Low emission, equal to public transport niche
Cost €/year	67 Medium cost equal to that of REGIME value	73 High cost, equal to biofuels/HEV niche	20 Low cost, equal to public transport niche
Personal mobility pkm/year	47.5 medium mobility equal to that of REGIME value	47.5 Medium mobility, equal to biofuels/HEV niche	5 Lower mobility, equal to public transport niche
ICT	5 Low ICT use equal to that of REGIME value	5 Low ICT use equal to that of REGIME value	5 Low ICT use, equal to public transport niche
Built environment	10 Equal to that of REGIME value	10 Equal to that of REGIME value	50 Medium support, equal to public transport niche
Motorised public mobility pkm/year	4.75 Equal to that of REGIME value	4.75 Equal to that of REGIME value	17.8 High public mobility, (only 50 because same end point as private)
Standard deviation within group	1.25 Diversity within group	0.75 Relatively homogenous group	1.0 Medium diversity

The bottom row is the standard deviation assumed within each group.

emission vehicles than the regime, FCVs have the lowest amongst alternative car technologies (this assumes hydrogen is produced from renewable energy). This puts FCVs close to the non-car niches along the CO<sub>2</sub> practice dimension. However, car-based agents have higher transport prices, with FCVs the most expensive. It is also worth noting that ICT starts by definition with very high IT use, while most agents have low use, and that slow modes strongly support mixed-use zones, with most agents tending towards single-use zones.

The built-in metabolism captures the gradual build-up of institutional and physical capacity to endogenously represent limits to changes in the practice space. Supporters start as 73% mainstream car drivers, who would prefer slightly lower CO<sub>2</sub> emissions than the regime offers, but are not willing to pay a higher price; 8% green drivers, who are willing to pay more for mobility, and want much lower CO<sub>2</sub> emissions; and 19% non-drivers, who rely on slow modes and public transport. The full list of consumer agents' practices at the start of a simulation is in Table 2. Each of the car niches was assigned an initial installed stock at setup, and each year one tenth of the cars are assumed to be replaced. In this first version of the model, we assume no growth in the overall car fleet. The cars scrapped each year are replaced in proportion to the proportion of current support to the regime and each niche.

The qualitative practices, are normalised on a scale of 1 to 100. For the ICT practice, this represents the proportion of activities that could involve the use of transport that are instead satisfied through ICT use (e.g. internet shopping, office work at home, etc.). For the built environment practice, the value represents the proportion of households living in mixed-zone developments (housing with factories/offices and community facilities) as opposed to single-use developments (typical suburbs or industrial zones).

### 3.4. Policies and landscape signals

Drawing on an extensive literature review and analysis of trends in European mobility (see Nykvist and Whitmarsh, 2008) and previous work to develop mobility transition scenarios (Kemp and Rotmans, 2004), we have developed an integrated technological and behavioural change narrative for a possible mobility transition 2000–2050 (see Table 3). This narrative is written as a historical account, as recommended by Elzen (2005). It was used to determine the characteristics of the landscape and hence the landscape signals (currently this narrative is an integrated European scenario, drawing in particular on UK data).

Five landscape and policy signals are used, in an attempt to capture major predicted changes and plausible relevant policies (as described in the narrative in Table 3): i) climate change influence on values strongly pushes supporters' preferences towards lower CO<sub>2</sub> emissions, and ii) acceptance of higher external cost, due to a rise in oil prices,

**Table 3**

Description of phases in a scenario of a successful transition to sustainable mobility.

#### 2000–10: Opening up of a regime under pressure

By 2000, government concerns about congestion, energy security, and climate change had led to a gradual shift away from the 'predict-and-provide' road building model of transport policy towards more demand management strategies. The private car remained dominant and the government tended to prioritise measures to tackle congestion (e.g., road pricing) rather than politically less popular measures to address rising demand, vehicle emissions, and social exclusion associated with road transport.

#### 2010–25: Take-off of public transport, ICT and alternative transport technologies

As congestion worsened and governments failed to reach their greenhouse gas emissions-reduction targets, demand management measures (congestion charging, parking restrictions and bus/cycle lanes) became more widespread. At the same time, growing hybrid and low-emission vehicle sales were stimulated further by supporting subsidies, rising fuel prices, and competition between car manufacturers. New vehicle technologies – such as biofuel, hydrogen fuel cell vehicles, battery electric and plug-in hybrids – were also introduced to the 'secondary niche' markets in this period: the additional functionality of mobile electric power meant that such vehicles enabled wealthy drivers, willing to pay a premium, to work or play in their cars, as well as travel. Economies of scale gradually made these alternative technologies cheaper and growing energy infrastructures meant they were more widely available. During this period, changes in social attitudes were more apparent. Greater value was attached to air quality, getting exercise, and social interaction compared to the right to personal, motorised mobility; cars were no longer seen as symbols of status or identity, but rather as functional mobility 'white goods' similar to refrigerators or cookers. Mixed-zone developments became more widespread, and so the distance between homes, workplaces, shops and leisure facilities decreased. More people walked and cycled to work as pavements were widened, cycle lanes extended, and shower facilities offered in many workplaces. Social interaction also increased as 'home zones', which restricted the amount and speed of traffic, were introduced in many towns.

#### 2025–40: Shared mobility, ICT and inter-modal transport challenge private car dominance

Experiments in park-and-ride and inter-modal transport hubs gave way in the 2020s to a widespread integrated urban transport system. Given the increased value attached to public and shared transport modes, Private Rapid Transport experiments (replacement of private vehicles by automated taxi systems) had limited success and consequently were not upscaled. By now, hydrogen and [or] electric infrastructures were widespread, and most former petrol pumps were now used to supply hydrogen or biofuels instead. However, biofuel markets were not expanding as rapidly as hydrogen and electric alternatives due to limited availability of European land for biofuel production. Increasing temperatures and weather extremes, associated with climate change, meant walking and cycling were not always viable. Emissions from transport had begun to fall, relative to 1990 levels, but the 60% cuts were still out of reach on current trends. Climate policies thus gave greater support for measures to reduce demand, including homeworking and mixed-use zoning.

#### 2040–50: Modal shift/ICT victory – demise of the private car

By the 2040s, fiscal incentives to promote uptake of alternative transport technologies were removed, as few ICE cars remained on the market. Forecasts indicated that by 2060 fossil fuels would be virtually abandoned, and this would symbolise the demise of the old regime. As climate change mitigation (and, to a lesser extent, sustainability) became routinely integrated into mainstream policy making, cities competed to be seen as most sustainable and improved their inter-modal transport systems.

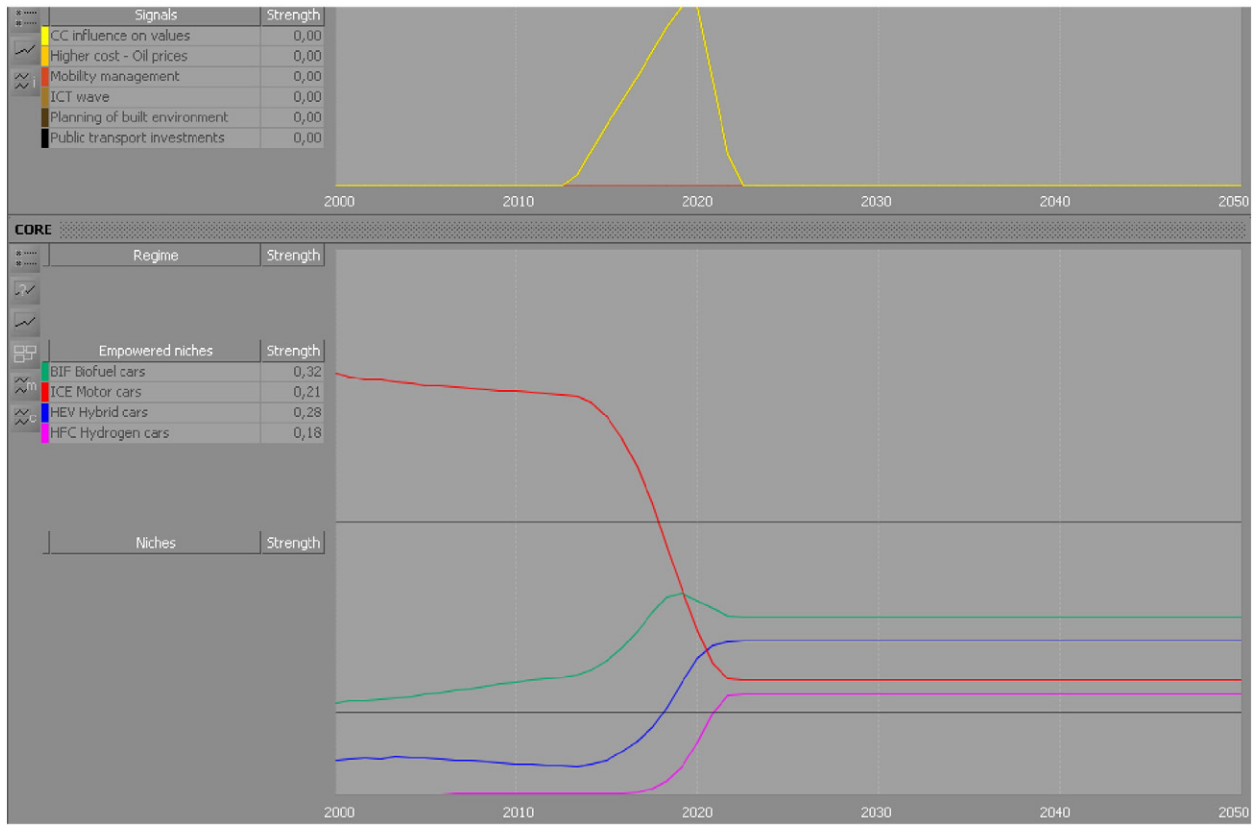


Fig. 4. Baseline case. Landscape signals and development of agent strengths.

increasing consumer's price practices, i.e. accepting a high price for the same quality of transport. Both are implemented as increasing step functions, appearing in the 2010s, and reaching maximum strength in 2022, as society reacts to particular events, such as storms, floods or droughts. An ICT wave (iii) starts in 2007 and increases linearly over time, increasing ICT use amongst supporters. The policies of (iv) public transport investments and (v) planning of built environment also act as weaker but steadily growing linear signals increasing public mobility and support for a planned urban environment with less transport requirement over time. These public policy measures are assumed to change gradually, because of the need to put into place large programs of expenditure and planning.

4. Results

Results are given for several runs, to demonstrate a transition and to explore the sensitivity of the results to the assumptions and landscape signals. Fig. 4 shows the landscape signals and the results for the relative strengths of the regime and niches for a baseline case with a signal of limited duration. From the transition narrative

detailed in Table 3, time paths of landscape signals were developed and are shown in Fig. 5. Fig. 6 then shows the results for the time paths of relative strengths of the regime and niches for this transition scenario. As well as the weak landscape signal baseline run, two control model experiments were run with the transition scenario landscape signals but without the regime and niche agents' internal metabolism (Fig. 7) and with the addition of learning curves for the costs of the car technologies (Fig. 8).

Each figure shows the results with repeated random initialisations of the positions of the simple agents in practice space. The boxes on the left of the figures define the colour codes for the different signals and also for the regime and niche relative strengths.

The baseline run shown in Fig. 4 shows that, while the regime is considerably weakened, a full transition does not occur. Here, where the landscape signal is only strong for a short period of time society worries about climate change, but then other concerns – possibly population growth, or economic depression etc. – become prevalent and climate change is forgotten again, the regime is weakened to the extent that it becomes one of the several empowered niches (ENAs), but in the time frame of the model no new regime emerges. This

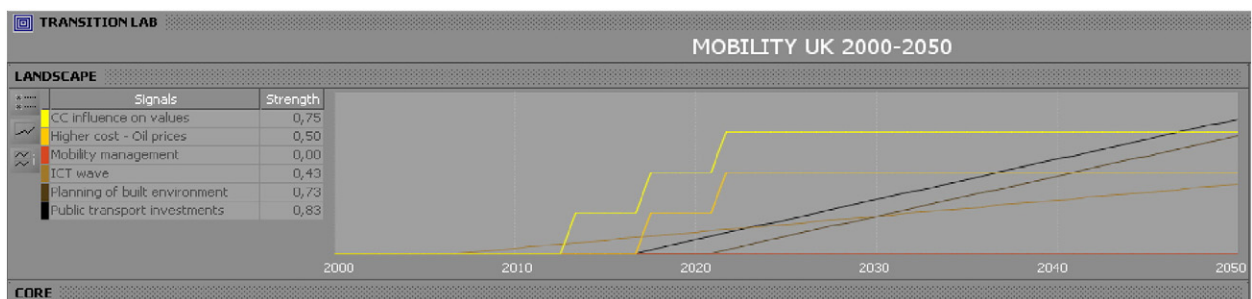


Fig. 5. Landscape signals for the transport model transition scenario.

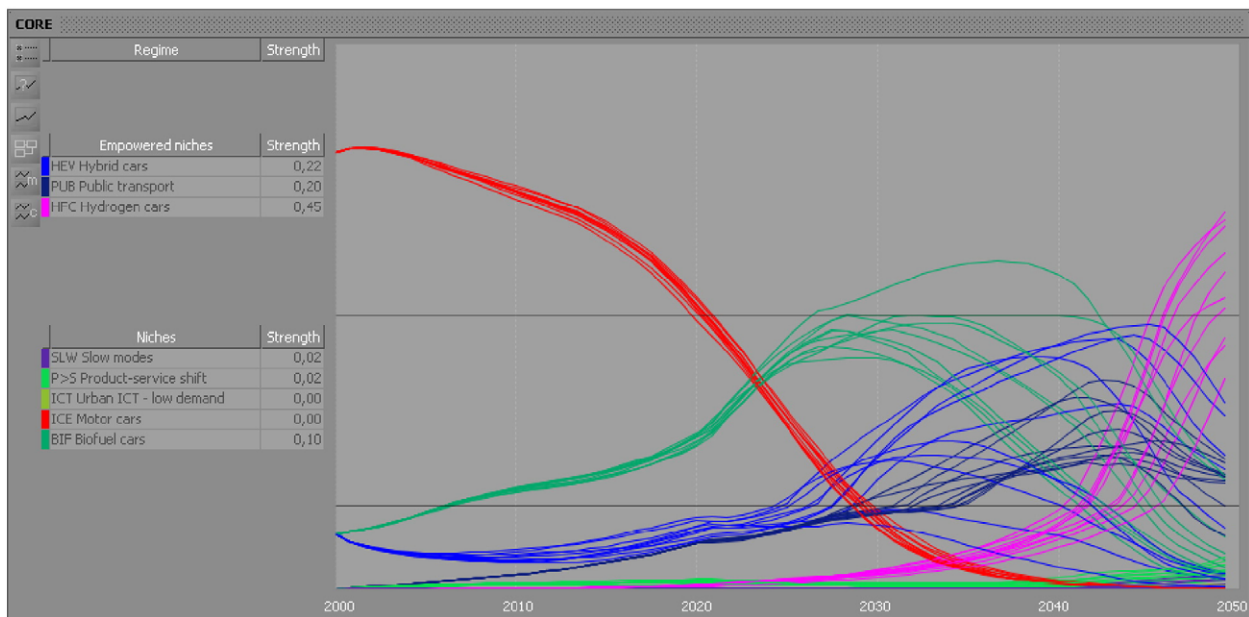


Fig. 6. Transition scenario run, demonstrating a transition to sustainable mobility.

demonstrates that the changes considered here will take a long time to diffuse throughout society and may not happen without continuing policy support. Policies or changes in behaviour that are not maintained over a considerable length of time will lead to some movement, but will not generate a lasting change in technology or institutions. Also, initial runs using explicit learning curves verify that the internal dynamics are indeed capable of representing restraint to growth.

The main result for a transition to a low-carbon transportation system is shown in Fig. 6. In terms of the interaction mechanisms described above, there is continuous adaptation and several instances of transformation. Since the initially defined regime and niches are distributed across most of the practice space, no new niches emerge. There are also no cases of absorption in this scenario. This demonstrates that the model, as calibrated to the transport system, is capable of

simulating a transition to a different regime in transportation, and in addition displays the complex time patterns of relative strength between regime and niches that are described in the transition literature, especially Geels (2005) and Geels and Schot (2007). Therefore, this prototype model has been successful in simulating regime–niche dynamics in the course of a transition. Also, the baseline run shown in Fig. 4 shows that this is not automatic, but critically dependent upon the 'landscape signals', as is argued in the transition literature.

The most important features of the model results are:

1. With and without the metabolism, FCVs come to dominate, but only in the very long run (after 2030). This is in accordance with the current literature on the adoption of hydrogen technologies as an engineering solution to greenhouse gas mitigation (e.g., European Commission, 2001a; Wehnert et al., 2004);

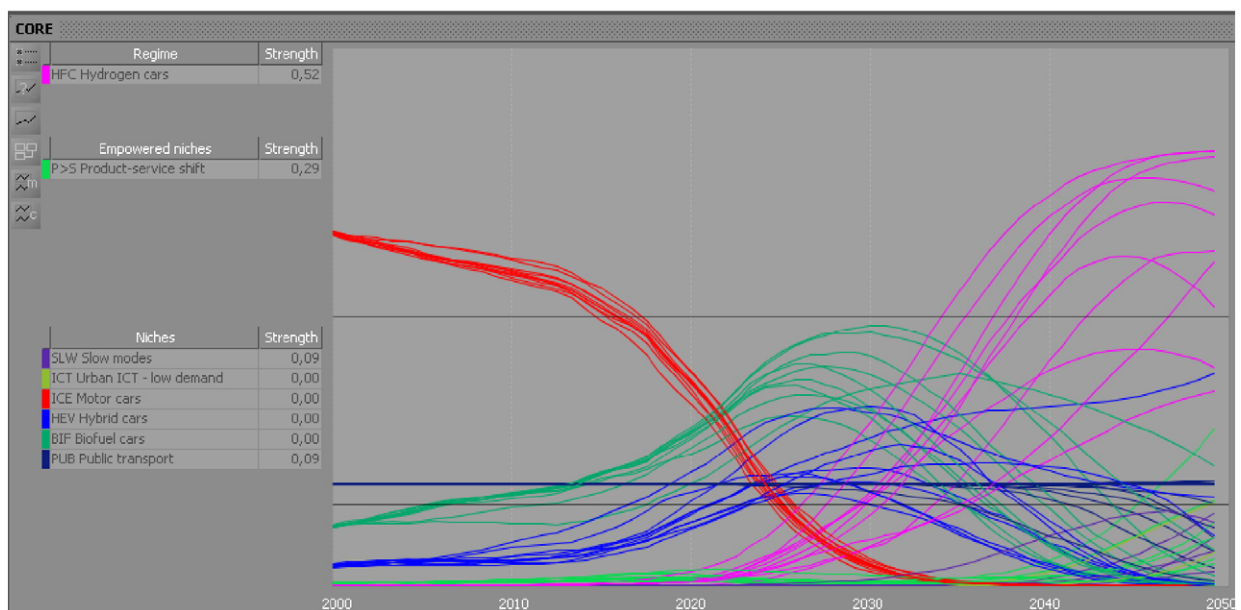


Fig. 7. Control runs without metabolism.

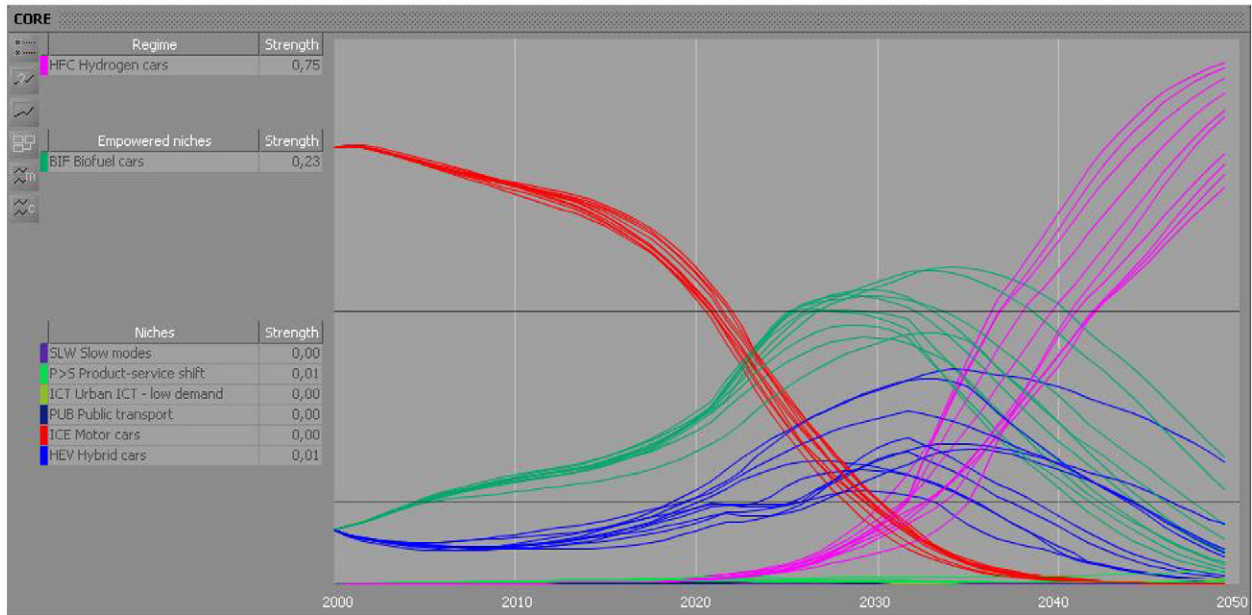


Fig. 8. Runs with learning curves.

- Biofuels and ICE-electric hybrids are the main alternatives to the regime in the next 10–30 years, because a) they are already developed and b) they fit better into current infrastructures and hence have lower costs initially;
- The niches with a more radical shift in lifestyles, product-service shift and even public transport do not have a significant share in any of the results. This suggests that such fundamental changes take a very long time, but also require other forms of support than are currently modelled. The model still represents mainly technology switching between different power systems for private cars. This is consistent with, and in part explained by, our stakeholder workshop and literature review findings: the stakeholders more closely aligned with the regime (automotive firms, energy companies, policy makers, mainstream public) are more in favour of technological change (and to some extent modal shift) than mobility management policies or radical lifestyle change. On the other hand, the more environmentally-conscious citizens we engaged with were strongly in favour of mobility management, as well as modal shift, but were less interested in technological change (Whitmarsh and Nykvist, 2008). These workshop findings afford us an insight into the difficulties of social change: the stakeholders associated with the regime are not interested in social change, emphasising instead technological change; since it is precisely those people who have the resources to bring about change, the direction of change is likely to be more technological than social. Viable social change occurs most easily when innovations are consistent with the interests of the dominant groups, and to some extent the existing infrastructures and systems. This is also evident from historical studies of transitions (e.g., Geels, 2005; Smith et al., 2005).

If all-electric vehicles were included, their improved environmental performance over hybrids, and equal or superior performance to FCVs (because they both rely on power generation and electric vehicles are more efficient well-to-wheel than FCVs) would suggest that electric vehicles would form the new regime and not FCVs. However there are battery problems, in that batteries still have a limited capacity for sizes practicable for personal vehicles (European Commission, 2001a; van den Hoed and Vergragt, 2004), so they would need a new infrastructure – trolley wires on long distance roads or

rapidly exchangeable batteries to produce a vehicle with endurance similar to FCVs or ICEs.

Comparing Figs. 6 and 7, the inclusion of the metabolism mechanism does not fundamentally change the structure of the results. However, it does considerably delay the take-off of the FCV niche. This is because both the biofuels and ICE-electric hybrid niches are more technically advanced in the period 2010–2020, when the landscape signals change consumers' behaviour. In this period, they present a better compromise between cost and environmental performance than FCVs, which are still expensive compared to these niches. It is only the continuing change in consumers' preferences that eventually enables the FCV niche to take over, because of its lower emissions than these two niches. Given the implementation of the metabolism, the biofuel and hybrid niches have time to build up institutional as well as physical capacity, which enables them to resist the growth of the FCV niche for a certain period of time, between 2030 and 2040. With increasing levels of support, public transport also grows in the long run, but is not able to dominate society's preference for private transport.

Fig. 8 shows the impact of including learning curves, decreasing costs of new technologies with increasing uptake. This shows how the learning curve provides an extra positive feedback mechanism, with the hydrogen technology being adopted more rapidly than in Fig. 6, once the technology takes off. However, although the general development of the car niches remains the same, inclusion of a specific learning curve does reduce the timing of the growth of FCV and the potential for non-car niches to develop.

These results demonstrate the innovative nature of this model. Although the underlying result of a slow transition to a very low-emission hydrogen technology is already well-known, this model brings several important new aspects to the analysis. Firstly, it is able to consider many different alternatives together. Therefore, it is able to reflect the complex interactions between the regime and the various niches, with different niche technologies having different possibilities at different points in time. This is a pointer for further work, both to establish connections between niches which might enable them to actually cluster together to form a new regime, and to assess the time path of emissions. This latter piece of information is critical in the climate policy debate, as it is this time path that will determine the long run climate response to anthropogenic greenhouse gas

emissions. Secondly, in contrast to existing transport and technology models, it includes a representation of important social structures involved in – and necessary for – sustainability transitions within transport systems.

## 5. Discussion and conclusions

This paper uses a novel simulation model, based on the transition framework, to consider the possibilities for a radical shift towards sustainable mobility. The model draws on extensive empirical and stakeholder work, which identified criteria for sustainability and looked at the structure of the current regime (individually controlled vehicles, powered by internal combustion engines i.e. motor cars) and possible niches that might provide the basis for a transition. This analysis has been used to develop a scenario storyline of a possible transition pathway and to identify key areas of innovation (niches) and activities (practices) to include in our mobility transition model. We used UK transport data to parameterise the model, which is an application to mobility systems of a generic transition model.

The results show that Hydrogen Fuel Cell Vehicles (FCVs) come to dominate, but only in the very long run (after 2030), while biofuels and ICE-electric hybrids are the main alternatives to the regime in the next 10–30 years, because a) they are already developed and b) they fit better into current infrastructures. The model shows that technological transitions are most likely. Lifestyle change transitions require sustained pressure from the environment on society and behavioural change from consumers.

We have identified three broad policy implications from this work. Firstly, a large-scale shift in the preferences – and therefore choices – of consumers and also strong and lasting policy action is a prerequisite for a transition to a sustainable mobility system. A corollary of this is that this shift must be maintained for a long time (20–30 years), or indeed permanently, for the radically different technologies to be able to develop to the point where they can out-compete the initially cheaper and preferred current and near-to-market technologies.

Secondly, what may seem to be the most successful alternative in the next 10 years may not be the best option in the long run. It is necessary to continue to support radical alternative technological niches, even while biofuels and hybrids begin to take off and challenge the ICE regime. Also, an implicit message from this analysis is that the links between different niches need to be considered. For example, FCVs use electric power trains, which are being developed for hybrids. This means that FCVs would be cheaper to adopt, once the infrastructure and technical demands of fuel cells have been successfully addressed. The overall policy message vis a vis technology is therefore that there is no one technological alternative to the ICE vehicle that is obviously superior to all others. We are still in a world where exploration of various alternatives is currently the best policy approach.

Thirdly, radical institutional and behavioural change will probably be harder to achieve than technological change. The challenge for policy makers is to inspire and connect to grassroots support for social change in order to effectively introduce potentially unpopular changes (e.g., fuel tax increases, parking restrictions); and to demonstrate the wider benefits of such changes (e.g., reduced air pollution, more reliable public transport) to garner this support. (Lessons from the London Congestion Charge show, though, that attitudes may change in favour of demand management policies after their successful introduction; [Downing and Ballantyne, 2007](#)).

There are some limitations of the current model analysis. Strengthening the signals for planning of built environment and for public transport investments might induce enough movement in consumers' preferences and choices to enable the more radical niches involving lifestyle change to take off. If all-electric vehicles were included, their superior environmental performance would suggest that electric

vehicles would form the new regime and not FCVs; but new infrastructure (e.g., trolley wires) or technological advances in battery performance would be needed to overcome current limitations in battery capacity. However, it would be possible to define all-electric cars as a niche that follows on from ICE-electric hybrids, thus avoiding the problem that a new niche would be extremely expensive. This would not be the case for all-electric vehicles themselves, as the R&D work on electric transmissions has already been undertaken for hybrids. This argument also applies to FCVs. The bigger issue, requiring more consideration, is that of infrastructures for delivering electricity or hydrogen. It can be speculated that, because the infrastructure for delivering electricity to moving vehicles is a mature technology (for trains and trolleybuses), it would be cheaper to introduce than a complete hydrogen delivery infrastructure. Exchangeable batteries and electricity sockets in car parks would also be relatively easy to introduce. The other area which requires more consideration is potential constraints on biofuels, which may be limited by land/food availability.

In this paper, we have demonstrated the innovative nature of the mobility transition model, in particular its capacity to consider many alternative innovations together, to reflect the complex interactions between regime and niches, and to represent social and institutional factors along with technologies in a simulation of radical socio-technical change. Further work should focus on establishing connections between niches and assessing the time path of emissions. This latter piece of information is critical in the climate policy debate, as it is this time path that will determine the long run climate response to anthropogenic greenhouse gas emissions.

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