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Low Carbon Transitions Pathways in Mobility: applying the MLP in a combined case study and simulation bridging analysis of passenger transport in the Netherlands

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Abstract

The analysis addresses two critical gaps in the literature on low-carbon mobility transitions: 1) scenarios of low-carbon mobility concentrate on technological substitution and have only a limited representation of niche-regime interactions and behavioural change, and 2) detailed qualitative analysis of socio-technical transitions dynamics have limited utility in developing future projections. It applies the Multi-Level Perspective on transitions, combining case studies of mobility niches in the Netherlands with simulations of transitions pathways using the MATISSE model, by applying the bridging approach proposed by Turnheim et al. (2015). The iterative, combined qualitative case study and quantitative simulation approach develops transition pathways including both behavioural and technological change.

The results show that both technological substitution to low carbon cars or a reconfiguration pathway away from car ownership to mobility lifestyles based on new public transport or cycling and walking for local trips are possible. However, while there is empirical evidence for the initial stage of a technological substitution to battery electric vehicles, transitions away from car ownership as the dominant mobility lifestyle have to overcome an established regime and will require major changes in culture and behaviour as well as support for new priorities in the institutions of transport planning.

Keywords: bridging; sustainable mobility; Multi-Level Perspective; agent based model; behavioral change.

1. Introduction

This paper explores the challenges and opportunities of bringing about low-carbon mobility futures. Adopting a socio-technical framing, it explores the complex interactions between emergent niches and established regimes in transitions pathways towards sustainable personal mobility. It combines qualitative case study and quantitative simulation approaches to address two critical gaps in the literature on low-carbon mobility transitions: 1) scenarios of low-carbon mobility such as Clarke et al. (2014) concentrate on technological substitution and have only a limited representation of niche-regime interactions and behavioural change and 2) detailed qualitative analysis of socio-technical transitions dynamics “have a limited ability to formulate stylised future projections” (Turnheim et al. 2015p. 242).

The transition pathways include both techno-economic processes and socio-technical niche-regime dynamics. This required that we undertook an iterative, structured, but selective process based on the bridging approach proposed by Turnheim et al. (2015). This proposes that an iterative dialogue around shared concepts and representations can be an effective way in which to combine different analytical tools for sustainability pathways, including socio-technical transitions studies and modelling. A bridging analysis is necessary because behavioural change in transitions to sustainable mobility is a qualitative phenomenon that is part of a co-evolutionary process in the socio-technical system of mobility – aspects that modelling strategies currently do not adequately represent. Equally, socio-technical studies of transitions can benefit from adopting a more prospective orientation to inform governance challenges.

We apply this new analytical approach to the Multi-Level Perspective on transitions (MLP), (Geels 2005; Grin et al., 2010), combining case studies of mobility niches in the Netherlands with simulations of transitions pathways using the MATISSE model (Köhler et al., 2009). We present an application to the Netherlands, because the Netherlands has an extensive and stable structure of bicycle and public transport use in addition to the automobility regime, and hence presents extensive opportunities for learning about prospective paths. The use of the MATISSE model has a major advantage for such an approach in that it is built around the niche-regime structure of the MLP and is therefore largely aligned with the transitions case study design – building on a certain degree of pre-existing methodological bridging.

Sims et al. (2014) identifies mobility as a sector where large-scale changes are required for transport to become sustainable. Scenarios that achieve an EU 80% greenhouse gas (GHG) emission reduction target relative to 1990 by 2050 require 60% reduction efforts in transport CO₂ emissions (Hof et al. 2016, European Commission 2011). In order to achieve such large-scale reductions, a combination of changes is necessary, not just a switch to low carbon fuels.

This understanding has not yet initiated a transition in mobility. Passenger transport is dominated by the automobility system. Geels et al. (2012) suggest that a transition away from automobility is a particularly difficult challenge for achieving sustainability and Banister (2008) shows that current practices of transport planning cannot alone deliver sustainable mobility. Personal mobility choices are dependent not only on the mobility systems available, but also on the structure of the built environment, lifestyles and on culture (Köhler, 2006).

Assessments of transitions in mobility (Geels et al, 2012) show that the dynamics of a transition to sustainability is an issue of a complex (socio-technical) system in the sense of complexity science (Andersson, Törnberg & Törnberg, 2014). As argued by Rotmans and Loorbach (2010), in contrast to the limited set of scenarios generated for future socio-technology pathways such as Clarke et al. (2014), there is no one identifiable path for a given set of initial conditions. Instead, scenarios of transition pathways into the future need to represent the interactions between the niches, regime and landscape in a way that reflects the

co-evolutionary dynamics, applying greater open-endedness to the exploration of possible futures.

Köhler et al. (2009) used the MLP to develop the MATISSE agent-based model (ABM) of transitions in mobility. They show that the interactions between households' mobility choices and the niches or the regime are critical in determining adoption patterns of different mobility lifestyles and technologies. Current mobility systems may be experiencing early signs of an emerging transition pattern, but there is still considerable uncertainty in terms of the possible trajectories. The results indicate that a transition to sustainable mobility is dependent on continued policy support for low carbon technologies. Banister, Crist & Perkins (2015) make a similar argument about the benefits of continuity in low-carbon mobility funding, suggesting that they contribute to long-term benefits by enhancing productivity growth, strengthening skills and employment prospects. This is similar to the argument of Foxon et al. (2013), who suggest that prospective low-carbon transitions pathways are determined by underlying societal and political choices about the desired shape of systems. This leads them to focus on critical branching points along transitions paths where future development options are opened up or closed down. Such branching points are a particular feature of the MATISSE¹ results, which are not part of most modelling scenarios (Köhler et al, 2009).

These recent studies of transitions, both case studies and modelling, still place much higher weight on technological change compared to changes in culture and lifestyles. As with the studies reviewed in Sims et al (2014), behavioural changes and alternative lifestyles are not major influencing factors in the scenario studies, except as consumer responses to price changes which does not consider the lock-in effects of the automobility lifestyle and transport planning regime (e.g. van Sluisveld et al., 2015 address behavioural change using the IMAGE large scale integrated assessment model through applying preference changes to relative prices in the utility function). Therefore, as emphasised by Sims et al (2014), behaviour change and lifestyle choices need to become more central aspects of the exploration of mobility futures (including enabling and hindering effects).

The quantitative scenarios developed with the MATISSE model provide a consistent basis from which socio-technical analysis can venture into the future (socio-technical scenarios) to explore expected hurdles and branching points (identified from MATISSE scenarios). Quantitative scenarios are, though, inadequate for understanding the endogenous dynamics of transitions. They tell us little about the negotiations and struggles between social interests shaping transitions. They also do not articulate the significant mechanisms that are mobilised in shaping transitions in particular ways. Socio-technical scenarios, as we use them here, are storylines that allow us to think in a structured, but broader way about possible future transition pathways (Elzen et al, 2004; Hofman and Elzen, 2010). We present storylines written in the past tense to develop a 'history of the future'. This allows an understanding of how the mobilisation of critical events and mechanisms (e.g. 'branching points', 'sailing ship effects', 'missing the wave') shapes how the scenarios unfold over time. In this way, storylines are guided by the logic of the MLP and socio-technical understanding, but are flexible enough to accommodate the endogenous logic of transition pathways. This

¹ The MATISSE model is described in Annex A, with detailed descriptions in Bergman et al. (2008) and Köhler et al. (2009). Holtz et al. (2015) and Köhler et al., 2018 discuss the advantages of simulation modelling for this kind of future-oriented transitions analysis. Simulation models are able to assess the dynamics that arise from multiple interacting (non-linear) processes, such as the co-evolutionary process of niche and regime interaction.

recognises that transition pathways can be shaped in a variety of ways depending on the mechanisms mobilised by interests at various points in time.

2. Methodological considerations

In this section, we describe the methodological frame mobilised to combine modelling and socio-technical transitions analysis in a joint evaluation of prospective transitions pathways. This can be seen as an application of the methodological principles set out by Turnheim et al. (2015), who suggest structuring joint analysis around a process of alignment and bridging, understood as:

“[identifying] the joint elements around which an integrated ‘meta-perspective’ on sustainability transitions pathways can be articulated in terms of applied concepts, problem-frames and empirical domains [...] Once such common understanding and coherence about the overall phenomenon has been established, there is then a need for a two-way interaction to occur, in the context of a specific problem- solving process.”
(Turnheim et al., 2015, p.246)

We apply these general principles to the combination of two analytical perspectives (agent-based transitions modelling and socio-technical transitions analysis), and propose how this can be operationalised around a number of practical steps.

While the MATISSE model captures a wider range of actor, behavioural dynamics, niche-regime interactions and user preferences than conventional modelling tools, it requires inputs in terms of the changes in consumer preferences and landscape factors. These include the possible governance interventions and actor strategies. Combining the consistent dynamics of the model with more appreciative qualitative analysis hence appears promising. This is further shown by the socio-technical scenarios produced (section 4.2) and the governance implications (section 5.2), which could not be inferred by mobilising MATISSE alone.

Figure 1 provides an overview of this methodological design. We elaborate on both perspectives in section 2.1 with the alignment and bridging steps in section 2.2. We also return to these methodological considerations in section 5.

Figure 1: Operationalisation of ‘alignment and bridging’ process between socio-technical analysis and quantitative systems modelling

2.1 *Analytical perspectives mobilised*

2.1.1 Socio-technical transitions analysis using the MLP

For the analysis of existing and emerging socio-technical dynamics in land-based mobility, we mobilised the Multi-Level Perspective on Transitions (MLP) (Grin et al., 2010) as a methodological framework. The MLP distinguished between three levels of structuration for innovative activities: niches, regimes, and landscapes. The interaction of dynamics across these levels produce different kinds of socio-technical pathways (Geels and Schot 2007).

Existing regimes are inherently stable configurations of technical components, material infrastructures and institutions that have developed over long periods of time. Such co-evolutionary developments tend to generate strong dependencies between various elements in socio-technical configurations, which can be seen as different sources of lock-in (Geels, 2005). Lock-in is further reinforced by the actions and strategies of powerful actors who have a vested interest in maintaining the status quo. Analysing the various sources of lock-in the strategies of established actors, and their responsiveness to emerging challenges allows us to develop notional evaluations of the (in-)stability of established regimes (see ‘regime analysis’ in Figure 1).

Radical innovation tends to emerge in niches, which are protective spaces relatively shielded from dominant selection pressures (Smith and Raven, 2012) wherein innovative solutions can be nurtured (through e.g. R&D, pilots, field trials, gradual exposure to markets). Such innovation is often developed by new entrants, which can be seen as challenging or distinguishing themselves from existing regimes. Analysing a number of emerging niche-innovations along different dimensions (e.g. techno-economic, socio-cultural, political-institutional) allows us to develop notional evaluations of niche momentum i.e. its speed of growth and the strength of the factors supporting that growth (see ‘niche analysis in Figure 1).

Niche-regime interactions take place in the context of socio-technical landscapes, which are broader contexts affecting the direction of socio-technical change, as well as opportunity structures. Relevant landscape dynamics include long-term trends (e.g. urbanisation patterns, environmental awareness) and more acute shocks (e.g. wars, oil price hikes, nuclear accidents) that can significantly contribute to creating pressure for change.

Combining niche and regime analyses enables us to develop notional evaluation of the potential for niches to break through and replace or change the regime.

2.1.2 Agent-based modelling of the MLP using MATISSE

The model chosen for the scenario development was the MATISSE model. This implements the niche, regime and landscape structure of the MLP, enabling the alignment between the two analytical perspectives: socio-technical analysis and the quantitative simulation modelling. In order to address the need to undertake analysis in detail of the changes in values that cause behavioural change in a transitions framework, the MATISSE model uses an agent-based modelling (ABM) approach (Köhler et al., 2018). This approach explicitly models the actors involved. Both the niches and regime are mobility providers and there are also consumer agents who choose to travel using a niche or regime transport systems. The niches and regime are not just a single technology but also represent mobility lifestyles, which can be dominated by one technology (motor cars for the regime) but do assume that consumers use more than one technology - even motor car drivers may use other modes sometimes. Hence each niche and the regime represents a travel pattern that is a distribution over car technologies, public transport and cycling/walking. The niches and regime also include the factors of built environment and ICT use to influence transport demand. Furthermore, in contrast to the large scale climate policy models, a large number of

the consumer agents are explicitly represented. This enables a range of behaviours to be modelled, permitting an exploration of the range of behaviours that could develop from the range of behaviours enacted at present. The model simulates the dynamics of the choices of consumers for how they travel - associating themselves to either a niche or the regime, generating time paths of the consumer shares of niches and the regime.

The model is calibrated to reflect the position of the niches and regime in 2015 in the Netherlands (using the number of trips and not passenger km).

A major challenge of agent-based modelling is to calibrate the behavioural parameters in a plausible way. Since the decisions involved are complex, it is not possible to represent the details of the psychological processes of the agents. However, it is possible to represent a range of behaviours that are calibrated to the range of behaviours shown in the statistics of travel mode choices, based on the main influences identified in the transport behaviour literature. Köhler (2006) and Geels et al. (2012) argue that culture and the built environment influence mobility decisions as well as the technological and economic characteristics of the transport modes. Bergman et al. (2008) describe for the MATISSE model the details of the consumers' decision-making process that incorporates these factors.

A consumer's decision about whether to adopt a niche travel behaviour or the regime is a function of different variables: environmental emissions, cost, the desire for private motorised mobility, the use of public transport, the desire to live in a compact or suburbanised local environment, the use of ICT to replace travel and the perceived convenience of travel using a given niche or the regime from door-to-door. These variables represent the application of the idea of 'practice dimensions' as described in the Annexe to mobility. The niches and regime are positioned along scales of these decision variables or practices. The strength or importance of niches and the regime is dependent on the share of consumers that choose the regime or a particular niche. A proportion of consumers are able to choose to change their niche or regime in each year, and the speed of growth or decline of the niches and regime are determined by these choices. Changing the dynamics of consumers' behaviour in the model, together with changes in the landscape assumptions for policies, oil prices etc. that influence the prices of technologies, generate the alternative pathways of transition.

2.2 Joint evaluation of prospective transitions

2.2.1 Alignment

In practice, the alignment process requires the adoption of a common problem-frame and applied concepts through which to analyse transitions and associated challenges. For this purpose, we mobilised the MLP and a simplified typology of transitions pathways as elements of an 'alignment infrastructure'.

The MLP provides as general heuristic through which to understand transitions processes, i.e. as produced by patterns of interactions between socio-technical niches, regimes, and landscapes, and so structures analytical processes in both research streams mobilised. The socio-technical analysis identified relevant niches and regime (i.e. the MLP was mobilised as analytical protocol), which were also used as the elements of the simulation model (i.e. the model structure is built on MLP principles). The MATISSE model has an additional level, the household consumers who provide the basis of support for the niches and regime. This model structure is summarised in the annexe and is described in detail in Bergman et al. (2008) and Köhler et al. (2009). The landscape level of the MLP was conceptualised as general changes in the factors influencing the choices of the consumer households, such as the importance attached to climate change in mobility choices. The other aspect of alignment was to come to

a joint understanding of the choices and practices of niches, the regime and also consumer households as represented in the model. This alignment process was used to develop an analytical protocol for the socio-technical analysis.

The research process was further structured by our reliance on a typology of transitions pathways, which we derived from various proposals elaborated by Smith et al. (2005), Geels and Schot (2007). Transitions pathways have become increasingly recognised as a concept that can support reflections on transitions governance whilst drawing on a variety of perspectives (Rosenbloom, 2017). Two sets of scenarios were developed, one representing a technological substitution pathway for power trains in vehicles to low carbon drives, the other representing a reconfiguration pathway in which changes in mobility lifestyles away from mobility based on personal ownership of a car. This enables the difference between a technology substitution scenario, as used in the current literature, to be contrasted to a scenario involving widespread behavioural change. Furthermore, socio-technical analysis of transitions dynamics actively sought to make sense of past, current and emerging developments in terms of their ‘fit’ to underlying pathway, referring to the above typology.

The scenario projections were then developed by using the MATISSE model to investigate how consumer values (or preferences) combined with changes in the relative prices to consumers of the regime and the niches (also allowing for cost reductions through adoption and learning) would have to change to generate a transition to a different regime

2.2.2 Bridging

The quantitative modelling and socio-technical analysis were parallel work streams with relative methodological autonomy. The process is illustrated in figure 1. In between these streams, a ‘bridging space’ provides a methodological buffer where research interaction can occur: iterations of learning, interpretation and negotiation. This space is structured by the adoption of common concepts and problem-frames (e.g. MLP as heuristic, ideal-typical pathways), but also necessities such as data requirements and the inputs/outputs of research procedures that need translation (and agreement as to how this should be done). The difficult, intensive and time-consuming nature of such interactions is not to be underestimated. The interdependencies generated between research streams also require attention to issues of timing and sequencing of activities.

The socio-technical analysis generated qualitative assessments of a) the current momentum of niches and b) the degree of regime inertia (resulting from a combination of landscape pressures and observed regime strategies). Dimensions considered included technical, economic, socio-cultural and policy developments. These results clarified the niches to be considered and their potential, landscape pressures and regime inertia/stability.

A series of expert workshops were held to discuss the details of the model structure and variables, such that the niches in the model could be defined and parameter values for the niches and regime agreed between the case study team and the modelling team. Thus the structure and the parameterization of the model used for simulation were defined using the results of the detailed case study analysis, involving modelling and social science expertise. Empirical data for the Netherlands were taken from CBS (2015).

The next set of interactions through the bridging space sought to establish a small set of ideal pathways to be used as a structure for a scenario analysis. These were developed based on existing typologies (Geels and Schot, 2007; Geels et al, 2012), and qualitative-quantitative assessments of potential for the niches to gain significance. In the case of sustainable mobility, there is a clear trend of technical substitution as alternative fuels and drive trains for cars – often seen as less risky and challenging from a market and policy perspective than switching to different transport modes. We however also observe a range of behaviours that differ from owning and driving a car, which imply the possibility of a reconfiguration

pathway. These pathways were then used to determine the possible changes in behaviour that should be simulated, through the changes in the choices of households and the consequent developments of practices (see the annexe for an explanation of practices) in the niches and regime. The model was then run to generate exploratory scenarios of the substitution and reconfiguration pathways. The initial results were checked against the assessments of the status of the niches and regime, as assessed by the socio-technical analysis.

The next iteration involved rerunning the model such that the model runs and output were consistent with the assessments of breakthrough potentials. This delivered a final set of model runs and outputs for the transition pathways. These show the growth and decline of not just the initial regime, but in some cases intermediate niches that grow to form a large share of households' mobility lifestyles when the initial regime has declined, but then are actually overtaken by a further niche. Therefore, there is often more than one branching point where the current state can move towards more than one niche, dependent on the actual behavioural choices of households at the relevant point in time.

In parallel, we also developed socio-technical scenarios for the substitution and reconfiguration pathways, based on the assessment of the niches and their momentum and the regime and sub-regimes and the destabilising factors that were identified in the case studies. These 'socio-technical scenarios' (Hofman and Elzen, 2010; Nykvist and Whitmarsh, 2008), presented in section 0, were conceived of as a speculative qualitative exercise in producing "histories from the future", based on the identification of critical prospective branching points suggested by modelling outputs and narrative exploration of possible events (in terms of niche, regime and landscape developments) that could plausibly lead to required changes. Storylines focussed specifically on interactions and struggles between actors (the endogenous logic) in re-orienting transition pathways. Rather than exogenous shocks, the focus was on developing storylines that incorporated branching points and core generative mechanisms at different points in time. Hofman and Elzen (2010) show that since this method is based on the MLP, it enables an explanation of linkages and developments. It focusses on paths with a variety of linking options and co-evolutionary patterns. Examples of core generative mechanisms derived from the literature include stepping stones, cumulative and recombinant paths (Safarzyńska et al., 2012), scaling up mechanisms, hybridisation (Raven, 2007), innovation cascades, sailing ship effects (Geels, 2002), technological hypes and dead ends (Bakker et al, 2014). In doing this, the approach taken was that the scenarios were written in the past tense, as a 'history of the future' that were organised in two time periods (2015-2035 and 2035-2050). Inevitably, developing the scenarios involved some guided speculation as to how events may unfold (see section 0). Concerning landscape changes, in all pathways we assumed an increasing importance of environmental and climate awareness, leading to stricter policies and normalisation of low-carbon imperatives. In the reconfiguration pathways, we assumed that politics and notably issues around distributional justice and the democratisation of low-carbon initiatives became more salient, as well as novel cultural interpretations of work and leisure time. The modelling results were used as an additional source of guidance, providing simulations into the future of pathways consistent with the breakthrough analysis from the socio-technical analysis.

This step concentrated attention on the sets of detailed conditions and possible generative mechanisms that could underpin the ambitious transitions suggested by the different pathways focussing primarily on the identification of branching points from modelling runs. Rather than to be taken at face value, this step should be seen as part of a process in which scenarios are used as 'learning machines' (Berkhout et al., 2002) informing us on detailed governance considerations and choices ahead. These socio-technical scenarios, because inherently interlinked with model runs, also provided the basis for the storylines for the final joint scenarios.

This approach has several important implications for the scenario results. The quantitative scenarios developed with the MATISSE model provide a solid basis from which socio-technical analysis can venture into the future (socio-technical scenarios) to explore expected hurdles and branching points (identified from MATISSE simulations) and offer qualitative analysis of resulting societal and governance choices ahead. The simulation results provide explicit information on possible dynamics of the niche-regime interactions. This is an example of the benefits identified in Holtz et al. (2015). This is a major methodological advance, achieved through applying the concept of alignment and bridging to deliver a co-construction of a sustainability transitions analysis into the future.

The bridging methodology also strengthens the simulation analysis. Although the MATISSE model is a highly simplified model of transitions, the model has been calibrated using new empirical data for the niches and regimes for specific empirical cases, using the available statistical data for the shares of the different mobility behaviours and their practice characteristics. Secondly, the MATISSE model is a simulation system with a large number of individual agents and a system structure that is designed to enable transitions – changes in the niche-regime system configuration – to emerge. Through the alignment between the niche momentum and regime analyses and the model structure, the detailed knowledge generated about actor motivations and challenges can be applied to the behavioural specification of the actors in the model. This implies a highly flexible system, with a very large range of possible outcomes, even though the initial state is calibrated to historical data. The socio-technical analysis performed an MLP analysis, which provided detailed knowledge of actor motivations and attitudes that could be used to constrain the agents' behaviours in the model. As with other forward-looking models, a scenario structure is necessary to constrain the possible set of outcomes. The implementation of the scenario structure of the pathways ensures that the exploratory scenarios are consistent with the results of the case study analysis.

3. Socio-technical analysis

The socio-technical analysis assessed niche momentum (section 3.1), regime stability and opportunities (section 3.2), and identified potential emerging pathways (section 3.3) for the Netherlands. Further details are in Turnheim et al. (2015b).

3.1 *Niche momentum analysis*

Niches of alternative mobility lifestyles and technologies that were active in the Netherlands (year of analysis was 2015) were identified (Turnheim et al., 2014). An extensive list of niche innovations with a potential to contribute to a prospective transition of mobility within the coming decades in the land-based personal mobility domain was compiled. Policy documents and existing literature on emerging (sustainable) transport technology and mobility transitions research (Geels 2012, Nykvist and Whitmarsh 2008, Skinner et al 2004, Farla et al 2011) were reviewed. The recent development trajectories of these niches (2000-2015) were analysed along three dimensions: techno-economic (innovation and markets), socio-cultural (actors, networks, framings) and governance and policy. These factors were assessed to give a qualitative assessment of the 'momentum' of a niche i. e. its speed of growth and the strength of the factors supporting that growth (see

Table 1).

Table 1: Socio-technical analysis: niche momentum in the Netherlands (Turnheim et al., 2014)

Niche	Momentum	Main drivers of momentum
Battery electric vehicles (BEVs)	++ Moderate	<ul style="list-style-type: none"> - Multiple hype/disappointment cycles - Currently renewed momentum with indications that a significant threshold has been passed - Market deployment of commercially viable vehicles - Progress towards charging infrastructure rollout and national deployment targets - Enthusiastic involvement of fleet operators - Successful deployment of hybrids vehicles as a 'stepping stone' - Increasing public exposure. <p>BUT achieving high density and interoperability of charging opportunities crucial for the stabilisation of development trajectory</p>
Internal combustion engine /electric hybrid vehicles (HEVs)	+++ High Beyond niche	<ul style="list-style-type: none"> - high momentum: mass commercialisation, important market share, stable design features. No longer a niche? - Stepping stone within a broader vision of 'electric mobility' - Gradual introduction of electric features within conventional cars paving the way for electric vehicles - Rapid shift towards plug-in hybrids <p>BUT unlikely that it will survive a mobility transition in the long-run because of limited environmental benefits and technical compromise involved</p>
Hydrogen fuel cell vehicles	0 low	<ul style="list-style-type: none"> - Technologically at an experimentation (demonstration) stage - Precursor market experiments just emerging - High costs - considered as option for the medium and long term (2030 and beyond) <p>BUT doubts because of repeated hype cycles to date</p>
Biofuels	++ Moderate	<p>Path creation initiated in the 1990s with hype/disappointments</p> <ul style="list-style-type: none"> - Driven by EU policy since the early 2000s: market creation for biofuels <i>blending</i> - Flexifuel niche is small and stagnant (in Europe) - Technological diversity: 1G and 2G biofuels, in reaction to low carbon controversy <ul style="list-style-type: none"> • Progress on 1G commercialisation • Remaining doubts about commercial viability of 2G - Recent deployment of pilot & commercial plants indicates stabilisation <p>BUT concerns about traceability & scope for sustainably scaling up</p>
New forms of 'on demand' car use; Car sharing	+++ High	<ul style="list-style-type: none"> - Positive signs of increasing momentum in recent years - Urban markets developing fast. New services, new locations, etc. - Increasingly embeddedness in existing automobility networks (e.g. manufacturers, car hire services, municipalities) - Positive cultural and symbolic meanings (e.g. environmental, congestion) - Linked to high innovation rate (e.g. ICT, electric vehicles, insurance, business model) - May be envisioned as integral part of future mobility systems with a different role to play in a variety of pathways - Source of continuity with the past and a bridge to the future.

This analysis of niches indicates that several vehicle technologies are making progress, although they still represent a small level of activity compared to the established mobility lifestyles. Hybrid internal combustion engine (ICE) -electric vehicles are the most developed technology niche, while car sharing schemes are also increasingly popular. Biofuels have a lower momentum, while Hydrogen has not developed into a niche with a market.

3.2 Regime (in)stability and landscape pressures

The regime(s) of personal mobility in the Netherlands were analysed (Turnheim et al., 2015b), with particular emphasis on exposure to landscape pressures, internal stability/inertia (e.g. actors strategies, supporting institutions) and resulting tensions. This supported an assessment of regime stability and potential 'cracks' that may generate opportunities for the breakthrough of niches (see Table 2). The Netherlands was found to have a dominant and highly stable automobility regime, but complemented by a rail public transport and cycling

systems that are extensive (in terms of the share of trips) and stable enough to be regarded as ‘subsidiary regimes’. The degree of lock-in and path dependency of these regimes, the possible cracks and tensions that arise within them were assessed. The automobility regime faces several tensions, but these are not yet strong enough to destabilise the regime. The Netherlands presents a particularly interesting case of a multiple regime structure, in which the cycling and public transport alternatives have grown and stabilised to the extent that they display the stability and inertia characteristics of a regime (e.g. in extensive and slow changing infrastructure, systems, actors, and rule sets), as opposed to the rapid but uncertain growth of a niche.

Table 2: Socio-technical analysis: regime stability in the Netherlands (Turnheim et al., 2015b)

Regime	Lock-in, stabilising forces	Tensions, problems
Automobility	Strong <ul style="list-style-type: none"> - Culture of the age (individualism, private ownership, etc.) - Precedence of economic rationale - Infrastructure: Sunk costs; planning patterns that favour commuting - Ageing society (more older citizens with reduced autonomous mobility capacity) - Globally automobility growth 	<ul style="list-style-type: none"> - Environmental awareness (especially, pressures to reduce GHG emissions) - Revitalisation of sustainable alternatives - Rising fuel prices; debates on Peak oil; - Congestion, leading to inconvenience and air pollution - Information society - New forms of mobility services as growing alternative to conventional car ownership - Ageing society (new, specialised demand pockets) - Young people are showing moves away from automobility, supporting in particular cycling
Public transport	Strong <ul style="list-style-type: none"> - Thoroughly developed and under public control - Rail is the main public transportation means for long-range mobility (its network covers most of the national territory and all major cities) - Buses share infrastructure elements with cars, which strengthens their existence and gives them flexibility in planning and operation (as opposed to rail) - As the bus system depends on the same infrastructure as cars, it is relevant for niche experiments with e.g. alternative engines and fuels (potential incremental ‘green’ changes) - There have been important efforts to integrate public transport (e.g. making connections between rail and buses easier) and support multimodality (e.g. park and ride; cycle sheds at train stations) - Ticketing simplification and reliable travel information 	<ul style="list-style-type: none"> - Urban cores have become strongly connected through railways and highways, which partly led to longer travel distances but also reinforced car usage - Buses suffer from a somewhat negative cultural representation, i.e. ‘people transport’, slow, infrequent, etc.
Cycling	Strong <ul style="list-style-type: none"> - High-density territorial organisation and dedicated infrastructure (comprehensive network of bicycle paths) - Integrated traffic planning - Cycling generates a major commercial market 	<ul style="list-style-type: none"> - E-cycling has contributed to overall increased cycling rates in recent years but, in part, been replacing conventional bicycle journeys (rather than car journeys)

3.3 Potential transitions pathways

In terms of transition pathways, a technological substitution pathway could develop through several alternative power train systems, of which the hybrid internal combustion engine–electric has the strongest momentum. This period of growth in hybrid vehicles can act as a ‘stepping stone’ for battery electric vehicles (BEVs), which use a similar technology, but have the potential for greater emissions reductions than hybrids. The further development of BEVs would require the range anxiety problem to be solved through infrastructure and institutional developments (e.g. charging networks, regulatory and financial incentives) and

some behavioural change (e.g. adaptation of travel patterns such as charging at home and at work for daily trips and having longer rests on long trips).

In terms of a wider reconfiguration to lower car use by means of fundamental behavioural change as well as technological innovation, two possibilities can be identified. Because public transport and cycling already have considerable stability and institutional support in the Netherlands, they could relatively easily expand if pressure on the internal combustion engine automobility regime increase and the regime weakens. One possibility is the development of a new public transport regime, with the level of service enhanced by internet communications to deliver on-demand public transport with personalised facilities on board. A mobility lifestyle combining cycling and walking in compact urban structures with reliable integrated public transport links for longer trips is also a possibility, because these modes together can technically meet the mobility needs met by ownership of a car (although requiring significant changes in mobility behaviours and supporting infrastructure). These possibilities should be seen as illustrative extreme cases, because car sharing, cycling and public transport could all be used by one consumer household to meet the different components of mobility needs.

4. Joint scenarios and storylines

4.1 Generating the scenarios and storylines

The outputs of the bridging analysis applying the Geels and Schot (2007) typology were therefore two sets of scenarios of transitions pathways: technological substitution to BEVs and reconfiguration to public transport or local mobility through cycling and walking. Table 3 summarises the scenarios. These scenarios consist of a qualitative storyline with an illustrative model run to make the example clearer. In section 2, we report modelling scenario outcomes and describe their general features. The generation of the scenarios in the MATISSE model is summarised; assumptions and input parameters that generate the different scenarios are compared. In section 3, we identify the main branching points for each scenario, and briefly present socio-technical scenario storylines, as well as governance implications.

It is important to emphasise the illustrative nature of these scenarios. The MLP describes socio-technical transitions as resulting from complex processual interactions (Rotmans and Loorbach, 2010), between niche and regime dynamics. Since niches and regimes each consist of complex socio-technical subsystems, it is not possible to predict the dynamics of development. However, the bridging approach does enable an assessment of the niches and regimes to be combined with numerical simulation to provide a set of scenarios of pathways with consistent qualitative and quantitative information, resulting in plausible transitions pathways.

The illustrative simulation results show the progress of different niches and the regime for the different scenarios of transition pathways. The graphs show the proportions of consumers choosing each niche or the regime in the scenario. For the car-based regime and niches: ICE, hybrid, biofuels hydrogen and BEV, mobility is still centred on ownership of a private vehicle. Both public transport and cycling may include the use of cars, mainly through car sharing. It should also be noted that the simulation results show a complex and therefore uncertain pattern of changes, which do not necessarily end in a stable state by the end of the assessment period 2050 and may involve a number of intermediary options that emerge but then recede (something that most modelling approaches do not consider).

The different scenarios are generated through different changes over time of the decision parameters in the consumer choice functions - the practices in the annexe. At the beginning of the simulations, most consumers want individual, mechanised mobility at current (2015)

price levels and are satisfied with current emissions. Many households prefer to live in individual houses, rather than high density apartment blocks. In the Netherlands, a significant proportion of consumers (around 40% of trips in 2015)use cycling as an important day-to-day transport mode, often combined with public transport.

Table 3 Summary of transition pathway scenarios

	Transition to BEVs	A New Public Transport Regime	Dominance of local mobility
Pathway Type (Geels & Schot 2007)	Technological substitution	Reconfiguration	Reconfiguration
Dominant technology	- BEV cars and light EVs	- Public transport with internet-based real time booking, on demand transport, personalised user space on board - Car sharing	- Cycling and walking - Use of ICT to reduce travel demand - Towns with mixed districts and small distances in contrast to urban sprawl
Values and norms in mobility	- High importance of the environment - Households still want to own their car	- High importance of the environment - Reduced importance of car ownership	- High importance of the environment - Reduced importance of car ownership - Private mobility still desired - A desire to live in compact, mixed urban areas
Policy	- EV infrastructure developed - Phase-out of ICE cars	- Intelligent public transport networks and ICT infrastructure developed - Phase-out of ICE cars	- Extension of cycling and walking infrastructure and conversion of roads to cycle ways - Change urban planning to develop compact, mixed use districts with roads and parking for mass cycling without cars - Phase-out of ICE cars - Restrictions on car use in towns
Landscape developments	- Increasing impacts of climate change raise perceived important of climate change mitigation - Increasing fossil fuel prices - Near zero carbon / renewable energy available for (public and private) transport		

In the technological substitution pathway to BEVs, the choice functions of the consumers are changed in the model, such that consumers demand continuous improvements in environmental performance. At the same time, the costs of ICE vehicles increases. However, the value of individual, mechanised mobility remains the same. These changes in the model parameters generate models results where low carbon cars replace ICE cars. BEVs come to dominate, under the assumption that they use zero carbon electricity and therefore have better environmental performance than ICE-electric hybrid cars.

For the reconfiguration pathway, two contrasting possibilities emerged from the modelling analysis. One is a transition to a public transport regime. Here, the choice functions were changed such that consumers demand improved environmental performance. In addition, the parameters were changed to reduce the demand for individual private mobility. The

convenience parameter of public transport changes such that it is almost the same as privately owned vehicles (justified as new internet based on demand, seamless transport services with very low waiting times). The other possibility is a growth of the cycling niche to a locally based lifestyle based on settlements of small distances, where most local trips are undertaken by cycling or walking. This scenario was generated by changing the consumers' choice parameters to require very low emissions, as in the other scenarios. The choice parameters were also changed to require a continuously increasing use of ICT to reduce travel demand and a continuous change away from a low density, suburban built environment to high density settlements where housing, local amenities and services together with places of work are close together.

4.1.1 Comparison of model scenarios

The different scenarios are generated by alternative changes in consumers' choice functions across the practice dimensions. These changes in weighting can be interpreted as the results of policies and other interventions, or the reaction of consumers to external events in the Landscape. The technological substitution pathway to BEVs comes through a high rate of change in consumers' requirements for reduced emissions. The narrative in section 4.3.1 illustrates this by government policy to support BEVs and hybrids. This is reinforced by a shift in the Landscape to place a higher weighting on environmental performance, in response to an increasing awareness of climate change impacts. At the same time, there is a government policy to discourage ICE cars. The difference in the 'user convenience' practice parameter models the difference in range between ICE cars and BEVs is reduced through government policy.

Compared to the technological substitution scenario, the reconfiguration scenarios involve alternative changes in practices. The increase in the importance of lower emissions performance is not so rapid and there is no wide ranging support from government policy for charging infrastructure to improve the convenience of BEVs. Instead, in the transition to a public transport regime, there is a fundamental change in government policy and consumer attitudes towards mobility. Government policy to phase out ICE cars is complemented by government policy to improve public transport. The shift in consumers' practices away from ICE car ownership is combined with a shift in practices towards living in compact cities instead of private car-based suburbs and a strong change towards modern forms of non-private transport. This includes car sharing and internet-based public transport. The new public transport systems are more attractive by the introduction of on-demand public transport systems that reduce weighting time and provide door-to-door services. The initial surge in car-sharing reflects these trends. The new public transport systems take some time to introduce, because they require new infrastructures and control systems, whereas car-sharing does not require extensive infrastructure investment. As the new public transport systems become available, they combine with changes in the landscape exogenously input into the model as changes in the practice variable 'built environment' (see Annexe for an explanation): the shift towards living in compact cities, supported by planning for new urban structure to move away from a road - based structure towards the new public transport systems which require less space and enable more green areas and pedestrian precincts.

The transition to a dominant cycling and walking regime is generated by combining the changes towards a compact urban form and increased use of public transport with a cultural shift towards using ICT to reduce travel demand. The move away from ICE cars, supported by government policy and an increasing weight on emissions reduction is the same as in the public transport reconfiguration. The overall pattern of change is similar to the public transport reconfiguration for a period of up to 20 years, but eventually the cultural shift towards less travel demand means that the use of cycling and walking increases.

In summary, the three transitions pathways involve different government interventions as well as differing changes in culture (i.e. in the landscape which influences consumers' desires and hence decisions). The initial decline in ICE use is steepest in the public transport reconfiguration because the assumed practice changes in the use of public transport and also the desire to live in a more compact urban environment are assumed to be very strong and there is a readily available alternative - car-sharing - which partly satisfies these needs and can be rapidly expanded with current vehicles and roads.

4.2 Scenario outcomes

Figure 2 Technological substitution to BEVs in the Netherlands

In the technological substitution pathway to BEVs, increasing importance is placed on the environment, but car-based mobility prevails. The accompanying simulation results are shown in figure 2. The result of imposing changes in consumers' priorities towards better environmental performance is that the ICE regime loses support, because it fails to improve the technology fast enough. BEVs initially compete with hybrids as they initially form similar combinations of improved environmental performance and cost, but (assuming low carbon electrical energy) win out in the long run as BEVs' range problems are solved by more infrastructure and user familiarity leading to higher perceived convenience. Initial high costs of BEVs through batteries are a concern, but battery costs come down with learning effects as adoption increases. In order to achieve a transition to low-carbon mobility by 2050, a rapid move away from ICEs is necessary.

Figure 3 Reconfiguration pathway to a new public transport regime in the Netherlands

The reconfiguration transition pathway shown in figure 3 is an illustration of moving away from the car to public transport. The ICE regime comes under pressure through the increased importance placed on environmental performance, accompanied by a change away from the culture of individual car ownership. The transition has two phases. There is a growth in car sharing followed by a take-off in public transport use. Public transport then grows rapidly. This is a result of the development and introduction of on-demand real time public transport with minimal waiting times and also a higher quality of on-board service, with high capacity internet and virtual reality systems for office work or ICT based leisure activities. These make public transport much more convenient. While the majority of consumers in 2015 are assumed in the model to perceive owning a car as the most convenient form of mobility, the new public transport systems become to be perceived as just as convenient. The high level of cycle use is stable, which means that the new car sharing trips and public transport trips directly substitute for private cars. Car sharing remains as an alternative for cross-country trips to small population density destinations or other circumstances where demand is limited.

Figure 4 Dominance of local mobility: an alternative reconfiguration pathway.

In the transition pathway to local mobility, there are two phases of change in the reconfiguration process. The initial change in consumers' priorities to better environmental performance encourages the growth of hybrid cars and then car sharing from around 2020. Then, as in the transition pathway to public transport, new public transport systems generate a rapid growth in the choice for public transport. The difference here is that, in the longer run after 2030, a further change in consumers' choices occurs so that cycling and walking is used for most local trips while some people keep hybrid cars or use car sharing for longer distance and use ICT for more remote communication. To a limited extent, public transport and car sharing is used for longer distances.

4.3 Branching point analysis storylines, and governance implications

4.3.1 Technological substitution to BEVs

This scenario postulates that a critical branching point is reached around the present time (2017-2018). BEVs take off and come to dominate hybrid electric cars as the replacement for ICE cars (which rapidly decline in importance). The range anxiety problem is solved by a combination of a rapid charging infrastructure for long distance trips and widespread availability in homes and offices. Hence, a technological substitution happens.

Socio-technical Scenario Storyline

2015-2025: Developing a fascination for electric mobility

During this period, BEVs experienced a significant upward swing, characterised by massive sales increases (up to 25% of households or 2 million BEVs by 2025), the rollout of charging infrastructure, increasing variety of BEV models, and declining costs of production. This was strongly supported by the Dutch government strategy, based on MIE (2014), which saw electrification of road transport as a major contributor to climate mitigation in the Netherlands, with the objective of large-scale introduction of BEVs and fuel cell vehicles by 2050. Hybrid

electric vehicles (HEVs) also continued their market penetration. This initial ‘success story’ significantly raised the status and desirability of e-mobility, hand-in-hand with deliberate strategies to destabilise the ICE, in particular a deliberate petrol phase-out policy. The Dutch government plan to move towards having only carbon free cars for sale by 2035 (Dutch Energy Agenda, 2016, p.73) was implemented. A phase-out of petrol cars was announced, with corresponding measures to dramatically step up the roll out of BEVs (with a little help from HEVs). etc.), predictable mobility patterns (public transport), high ‘user willingness’ and lower cost barrier (high-performance ground-breaking vehicles, Government procurement, etc.). The range anxiety myth associated with electric mobility was tackled through 1) the widespread rollout of conventional charging in residential, business, and public e-parking areas, 2) early investments in fast chargers and their public demonstrations in dedicated ‘e-mobility corridors’, 3) improvements in battery performance to enable extended range or reduced charging times, and 4) the simplicity of these services greatly enhanced by tracking and geo-location apps. This improved the perceived convenience of BEVs and enabled them to out-compete hybrids. A comprehensive portfolio of innovation and deployment support enabled a rapid scaling-up of electric mobility. The main market focus was set where the existing barriers to development were smallest or most easily overcome, such as high-intensity of localised short trips (via taxis, deliveries, urban car sharing).

2025-2035: Can electric mobility be truly democratic?

The period up until 2035 was characterised by a decade of truly impressive industry build-up with diffusion amongst an increasing number of households, supported by an initially costly charging infrastructure, dimensioned to allow for rapid growth. The main challenge and question for the coming period was whether electric mobility would stand the trial of mass democratisation and deployment in the lesser affluent and environmentally committed sections of society. A number of other tensions emerged, in particular related to an increasing pressure on the ‘special status’ that electric mobility had enjoyed in these early years. Lightweight electric vehicles (LWEVs), which had enjoyed impressive market penetration since 2010, had expanded beyond early niches. Two major innovations supported the mass deployment of LWEVs to make up for unaffordable larger BEVs (by 2025, the price of BEVs was almost on a par with conventional ICE equivalent vehicles): dedicated lanes and modular design.

From a cultural-cognitive perspective, BEVs fully installed themselves as the mainstream high-end driving experience. A national electric mobility innovation culture had been installed, along with the commitment to the democratisation of BEVs, and the increasingly uncontested defiance of everything petrol. This generally positive climate made things much easier. Perhaps the most challenging policy project was the development of LWEV-lanes throughout the country.

2035-2050: Looking back: What a journey!

By 2035, it was clear that the present was electric. By 2050, electric mobility had produced something barely recognisable from the conventional cars of 2015. New design features had generated completely new kinds of artefacts centred on high-performance BEVs and modular LWEVs with all sorts of add-ons (sidecars, miniature trailers, etc.). BEVs had become the standard vehicle for long journeys, but LWEVs were preferred for shorter journeys involving urban centres. Though BEVs had become affordable, they were still much more expensive than LWEVs, less practical as a daily option. The use of cars by non-drivers was facilitated with tremendous improvements in self-driving technology, which enabled the unmanned delivery of BEVs (and LWEVs) at point of use, when needed. The electrification of the car had been pioneered by a number of Dutch, Norwegian and North American companies, who were now benefitting from expanding markets globally. LWEVs, a Dutch invention, were proving extremely successful in all sorts of applications worldwide, opening up a massive market for exports. User acceptance was no longer an issue. Electric mobility was firmly established as the new societal norm, showing no more demographic disparities between, for instance, urban and

rural users or different age groups. ICEs were regarded as anachronistic. Policy measures that were hitherto regarded as ‘radical’ became accepted across the political spectrum and soon went unquestioned.

4.3.2 Reconfiguration Pathway to a new public transport regime in the Netherlands

In this pathway, an initial branching point is a move away from individualised mobility, due to increased environmental awareness. Netherlands

The second branching point in this scenario is the peaking of the car sharing lifestyle, possibly due to the continuing improvement in the public transport lifestyle and the increasing support of public transport through the institutionalisation of planning and infrastructure measures replacing car provision by increased public transport provision.

Socio-technical Scenario storyline

2015-2030: Who needs to own a car?

This period saw a rapid reduction in privately owned petrol cars, which were replaced by car sharing and public transport. Whilst the development of car sharing was largely due to the emergence of market opportunities and new models of consumption, the decline of the ICE and the further rise of public transport use were the outcome of deliberate planning at both national and local levels of Government. The development of the Netherlands government ITS plan for intelligent transport infrastructures (MIE, 2012) was extended to new intermodal systems. The National Traffic and Transport Plan (SER, 2001) was updated to emphasise the need for transport to contribute to achieving the goals of the Paris Agreement on Climate change. Increasing awareness of climatic problems and air pollution fuelled a democratic movement to step up efforts to dramatically reduce emissions from transport. A 15-year phase-out of petrol cars (by 2035) was announced and corresponding measures taken to roll out public transport from 2020.

Conventional ICE cars were experiencing increasing pressure, in large part due to their poor environmental performance, and deliberate petrol phase-out policy. Rising emissions standards for new cars, tough anti-congestion zoning, and prohibitive petrol taxes meant that new ICE vehicles became increasingly costly and there were now clear signals that they would start to become unaffordable in the foreseeable future.

Consumers' desire for improved environmental performance was compounded by a loss of interest in the car culture of car ownership as representing freedom and control.

From a user perspective, following an emerging trend, the younger generation with less disposable income as well as urban professionals with shifting priorities quite naturally did not engage with private car ownership, and welcomed the rapid development of alternatives. By 2025, the number of cars in circulation had shrunk by more than a third of its 2015 levels, and so had the average usage rate. Strategies were devised to further raise the profile and use of public transport. Given the existence of an extensive train network for medium and long distances and of metros, trams and buses for shorter and more local trips, the main challenges to grow markets consisted in encouraging customers, extending coverage, and maximising the use of existing infrastructure. The major successes in reducing car use in the Netherlands were due to an early move towards radical new forms of mobility, involving a shift away from private ownership (supported by the emergence of car sharing) and the development of a robust, efficient and far-reaching public transport system with numerous options for multi-modality.

2030-2050: Winning over the last car drivers

After a dramatic decline of private car ownership, supported by increasingly convenient and far-reaching multi-modality, and aggressively dissuasive policies, the number of motorists stabilised at ca. 3 million. Despite the continued implementation of phase-out strategies, it proved very difficult to cut back automobility any further. HEVs and Fuel Cell vehicles using climate-neutral power generation now provided an alternative for the last standing private motorists. In exchange for the maintaining of special permits, motorists were incentivised to convert from

petrol to HEVs and Fuel Cell vehicles. By 2045, only 100,000 petrol cars remained in the country – largely collectible models displayed on rare occasions.

The convenience and reliability of public transportation was improved along a number of priority objectives following from the previous period: infrastructure investment, a society-wide agenda promoting flexible and local lifestyles, and further multi-modal and modular integration. Plans for new infrastructure investments increased the number of railway tracks and capacity in high-intensity corridors linking major cities, but also in and around regional commuter towns, where population movements had concentrated. The new lines greatly relieved the railways and absorbed most of the traffic. By 2035, a national strategy for a ‘freetime society’ had taken shape, setting out a legal framework institutionalising shorter working hours and greater flexibility in the personal management of these reduced working hours. This provided greater clarity for public transport planning, and enabled effectively more malleable and diversified commuting patterns.

The continued rise of public transportation went hand in hand with a data- and ICT-driven process of logistical optimisation. The continued collecting of massive volumes of passenger information enabled the provision of adaptive services in real-time, the dimensioning of infrastructure investments in the longer run, the coupling of multiple modes of transportation, and the planning of housing developments.

4.3.3 Dominance of local mobility: an alternative reconfiguration pathway

The first branching point is an initial increase in the adoption of electric hybrids and some car sharing due to environmental concerns. Then the next branching point is that mobility lifestyles in the Netherlands begin to change so that non-car based modes prevail. As in the reconfiguration pathway to public transport, improved public transport through ICT systems reducing waiting time and the declining interest in a car-based lifestyle result in increased public transport use. The final branching point is the start of a longer-run transition to cycling and walking in conjunction with extensive changes in urban form, which eventually substitutes a locally based mobility lifestyle for a car-based lifestyle. This might be enabled by extensive infrastructure changes and town planning, such that cycling and walking become more convenient.

Socio-technical Scenario storyline

2015-2035: The rapid substitution of the petrol car

This period was characterised by strong environmental pressure paving the way for a very rapid decline of petrol cars, largely replaced by hybrid cars, followed by an expansion of public transport. Increasing awareness of climate and air pollution problems, exacerbated by severe floods that further exposed the vulnerability of large parts of the Netherlands, fuelled a democratic movement to dramatically reduce emissions from transport.

Building on recent success with BEVs and HEVs in car share fleets and private cars, the Government decided to initiate a nation-wide substitution policy. By 2025, few petrol-only cars were registered in the Netherlands, by 2030, 85% of the remaining car stock had been replaced or fitted with add-on batteries, and by 2035 virtually all but a handful of collectible cars (ca. 100,000) were effectively Plug-In Hybrids. At the same time, local strategies to reduce the need for travel were initiated in cities, reinvigorating and extending the geographical scope of the movement to free up urban cores that had led to car-free centres. Government decided to support some experimental actions for ‘super-local mobility’ in specific areas, by granting further devolution of powers to local Government in experimental locations, investing in the conversion of roads for innovative cycling infrastructure, and strengthening connection with public transport infrastructure.

All municipalities over 100,000 inhabitants (but also smaller towns) were implementing zero emission zones, freeing up the streets in a shift toward ‘reclaiming the city’. Following a strategy that had proved successful in nature conservation projects, reclaiming efforts focussed on

reconnecting areas by designing cycling and walking mobility corridors and revitalising them by encouraging the development of local and sustainable activities. This experiment had an influence on large mobility infrastructure. By 2025, the declining number of motorists freed up space on highways. The Ministry of Infrastructure and the Environment approved a proposal for the partial re-appropriation of roads for ‘cycling superhighways’ in order to stimulate high-speed cycling and e-cycling. In parallel, national strategies were devised to further raise the profile and use of public transport, mainly as a preparatory step to enable further decarbonisation of mobility in the future. Thanks to successful marketing and pricing strategies, particularly oriented at converting motorists, train users grew rapidly. Public transportation had increased substantially by 2030. A critical aspect concerned integration with cycling and other lightweight vehicles, particularly in denser areas.

2035-2050: We can get by locally

After the successful implementation, uptake, and diffusion of policy measures in the previous periods, mobility to 2050 was shaped, most notably, by developments within the spatial planning domain as well as by ideological changes and new value systems within society. These focused especially on a strong revaluation of ‘the local’ and coincided with a downright boom of health awareness. By 2035, petrol cars had virtually been eradicated. Automobility had receded from all cities and towns over 100,000 inhabitants, due to the implementation of the zero emission zones. Plug-In Hybrids were still numerous and commonplace, but restricted to inter-city travel on increasingly fewer lanes on highways, and to local transport in more remote areas. The reclaiming of streets and roads, starting from urban areas, sprawled in a gradual but steady pattern, first to corridors extending and linking urban areas together, then to fringe areas. In mobility terms, cycling and walking were predominant – and indeed the congestion of cycling lanes and their punctual overflow was at time overwhelming. Telecommunications and the relaxing of physical presence requirements at work was crucial for this shift towards a more decentralised society to happen.

This spatial development oriented towards localism was in stark contrast with what happened beyond those village- and city-regions. Significant improvements in public transport, particularly rail transport over long distances serviced the bulk of personal mobility needs for journeys beyond 20kms. Large city-regions had developed large networks of tramlines. As the trend towards sustainable localism installed itself even further as dominant social and economic principle, the need to travel long distances diminished. Cycling and walking became the main means of mobility, as the population lived, worked, and played at a very local level, or – where necessary – through remote practices enabled by telecommunications. The transition to slow modes had been supported by a deep cultural shift towards sustainable localism, which had fundamentally altered urbanisation patterns, and the way the Dutch population lived. The government had been highly instrumental in supporting this shift by investing in large infrastructure experiments, which were so successful that they became the dominant model for organising space, community and living patterns.

5. Discussion

5.1 Reflections on the bridging process

This analysis has operationalised a new method for the analysis of potential transitions to sustainability. The application of the bridging process proposed by Turnheim et al. (2015) involved placing a new emphasis on the methodology of interaction between two approaches: transition case studies to develop sociotechnical scenarios and simulation modelling. The methodology developed involved processes of learning, of data and category interpretation and also of negotiation between the transitions case analysis and the simulation modelling.

Learning

Several features of learning can be identified. There was learning in terms of alignment: coming to a common understanding of the features of the socio-technical systems to be analysed. This involved agreeing a common set of research questions and objectives. Emphasising behaviour change in mobility transitions was an important objective. The bridging process was enabled through an agreement to structure the transitions futures around the concept of transitions pathways.

To implement the bridging process, it was necessary to come to a detailed agreed understanding of the simulation model and its parameterisation. This involved learning about the structure of the simulation model and how the model implements regimes and niches, their growth processes and interactions and dependency on the choices of household consumer agents. This enabled the development of the MATISSE model, agreeing the niches and regimes to be considered and the parameterisation of their determining features – their practices.

The bridging process itself generated learning about the potential ranges of co-evolutionary pathways. The assessments of niche momentum and regime stability combined with the model experiments to constrain the range of transitions pathways. In particular, the socio-technical scenario analysis defined the potential directions of the technological substitution and the reconfiguration pathways. Since this method was developed specifically for sustainability transitions analysis, it generates information in terms of transition pathways with feedbacks and qualitative change (Hofman and Elzen, 2010). This also contributed to the bridging process.

The application of the bridging strategy showed that alignment of theory and categories is critical for addressing the limitations of ‘conventional’ modelling, but also for making scenarios of transition pathways concrete and hence easier to understand. The fundamental system changes in the socio-technical system of mobility in the Netherlands require changes in the culture of mobility. The interpretation of changes in attitudes and behaviour were associated with changes in the strength of the niches and regimes. This enabled transition pathways to be developed which embody the current assessment of mobility regimes and niches and are consistent with empirical evidence about mobility behaviour.

Interpretation of data and categories

The bridging process involved interpretation and alignment of the structural features of the MLP: niches, regimes, landscape. This was necessary for an assessment of how the different niches and regimes/sub-regimes might be combined in transitions pathways, to provide a structure for the simulation modelling. A new approach to transitions case studies was the assessment of niche momentum, regime tensions, and breakthrough opportunities with potential branching points as indicators of the potential future transitions dynamics.

The alignment of categories was necessary for the interpretation of case study data to agree the parameterisation of variables in the model that determines the agents’ choices and actions in the model setting.

Negotiation: imposing constraints on possible futures by identifying generative mechanisms that can be used to select scenarios

The attempt to develop scenarios of wider system reconfiguration in mobility with a methodology that is consistent and informative is particularly difficult in an analysis using the MLP. This is because the MLP assumes co-evolutionary processes between niches and regimes and their socio-technical subsystems and also because a transition is understood as a non-linear process. These structural features mean that there is a very wide range of possible futures. In order to achieve new insights into these futures, it is necessary to limit the

possibility space through a qualitative assessment, involving negotiation between the disciplines in the bridging process. Key negotiation interfaces included:

- the interpretation of the cases to select *a sub-set of possible niches for detailed analysis* and *agree a structure for the transition pathways in terms of niches and regimes*;
- the application of the qualitative understanding from the transition cases was mobilised to identify an initial state for the forward-looking analysis, including the current dynamics of niche and regime that limit the range of feasible futures. This was a crucial additional constraint on possibilities for the breakthrough of mobility niches or the growth of subsidiary regimes;
- the understanding of the socio-technical system developed through the qualitative transition analysis was then used to develop transitions pathways storylines, based on the simulation results together with the qualitative insights of the transitions analysis. For this step, the quantitative development trajectories proposed by the modelling exercise (Figure 2, Figure 3, Figure 4) had to be broken down to identify branching points, and then supported by the joint crafting of plausible storylines mixing qualitative explanatory techniques along techno-economic, policy, and socio-cognitive dimensions. The storylines therefore incorporate the choice of niches that might develop into new regimes and understanding of generative mechanisms for possible transitions pathways, as developed in the transitions case studies. The simulation runs were constrained to reproduce the qualitative features of the storylines. In the technology substitution pathway, these were the active discouragement of ICE cars and policy support to overcome range anxiety with respect to BEVs. In the reconfiguration pathway, the generative mechanisms were, in addition to increasing environmental awareness of consumers, the change in local urban planning and transport planning to empower a cultural shift towards 'living locally'.

The advantage of this process of negotiation is that the pathways of change are illustrated by socio-technical scenario storylines and simulation results that have been made consistent with each other in an iterative analysis process. This involves a much more complicated (and iterative) analytical procedure than the use of models to develop scenarios of transitions to a low carbon society prevalent in the literature, even when, as in the case of the IPCC Assessments, storylines accompany the simulation results (IPCC, 2000).

The three scenarios generated by this process illustrate three very different transition pathways. The results show that technological substitution is possible, given the supporting infrastructure (for BEVs in our example). In the MATISSE model, this is required in order to change the behaviour in the model - the removal of range anxiety for BEVs, represented as an improvement in perceived convenience. The other two scenarios are very different and show the possibilities of more structural behavioural change. The current regime is dependent on the car culture of owning and driving one's own vehicle and if this is weakened, other mobility lifestyles based on collective transport or mobility with a much reduced use of cars become possible.

The MATISSE simulation is a different approach to assessing long term developments compared to climate mitigation simulations such as Clarke et al. (2014). The development of intermediary states in the MATISSE model is determined by the assumptions in changes in consumer attitudes and policy interventions. In both the public transport and local mobility reconfiguration pathways, car sharing has a phase of acceleration, which therefore could also form a new mobility regime. In the case of the transition to public transport, if there is limited public policy support for the next generation of internet based intermodal public transport

systems with the supporting 'smart' infrastructure, the improved convenience of public transport might be limited and car sharing could take off and form a new regime.

Filling in the knowledge gap on lifestyle/behavioural change

The use of an agent-based modelling (ABM) modelling approach has enabled the analysis to show how scenarios not usually considered by simulations of low carbon mobility can develop. This can happen because an ABM model can directly represent the fundamental insight of the MLP framework - that radical change often happens first in a small niche.

This is an important message for policy planning in general. If it is accepted that large scale changes are needed, especially in the area of climate change, where mitigation action has to come through policy action (Köhler, 2012), this change will probably have to start at a small scale and be developed in niches. The MLP provides a theoretical framework for this and simulations then have to allow for a distribution of consumer and other actors' behaviours. ABM is an effective method for including a range of different behaviours in the simulation which is not available in most simulation models, especially at the highly aggregated level necessary for global climate change mitigation policy analysis.

5.2 Reflections on bridging outcomes (governance)

Our scenarios, because they are constrained by the sustainability policy objectives of the Netherlands, demand transition pathways – in particular, a destabilisation of ICE in all three pathways with varying speeds and intensities. We see that with strong commitment and supportive strategies and investment, as well as with necessary behaviour changes and societal trends, these pathways are possible. The local mobility pathway presents challenges not so much in terms of the speed of change, but the scope and depth of change for a society to become almost entirely reliant on cycling and walking (and hence much shorter distances travelled) for virtually all personal mobility requirements.

The emergence of alternatives is perhaps less challenging in the Dutch context, as there is already a relatively favourable policy environment for low-carbon mobility transitions at present. Nonetheless, the breakthrough of specific alternatives, while currently 'possible', requires significant changes in society and policy to be realised. Policymakers, in particular, play an important role in recognising and accelerating the momentum of relevant niche innovations and to overcome lock-ins – in particular ICE. Simultaneously, however, policymakers are reliant also on other actor groups and civil society for the legitimisation of action or the break-up of specific resistances. Strict policies can only be introduced successfully with the right backing and actor coalitions in place.

We wish to make a number of additional observations:

1. **Forcing through socio-political dimensions.** Our storylines – for all pathways – rely on a fair amount of public pressure for environmental issues (conveyed by social movements) and consistent and deliberate policymaking strategies to support path-breaking innovation and reduce commitment to established regimes. The value of this is to highlight the role of governance in bringing about and making sense of change (as opposed to purely techno-economic rationales).
2. **The role of deliberate strategies.** The storylines further highlight the importance of decision-making at different levels and by different factions of society (government, industry, users, etc.), most effectively in alliances. In all pathways, specific measures are set out to deliberately destabilise the conventional car industry and users, whilst more positive measures are intended to support specific alternative mobility modes. In both the public transport and local mobility pathways, experimentation – often at local level – plays an important role, where local

coalitions of activists and policymakers become aligned to jointly deliver on community and policy goals, and eventually address the environmental challenges linked to mobility.

3. **Stepping-stones, transitional innovation and re-combinations.** The role of intermediate or transitional innovations has been particularly important in these scenarios. The development of drive train and battery technologies for hybrids is equally relevant for BEVs, such that an initial acceleration of the uptake of hybrids can also enable the growth of BEVs. In the public transport pathway, car sharing could be the first step away from the desire to own one's own car, opening up the possibility for other forms of public transport. The wide acceptance of car sharing and public transport could enable the longer term changes in urban planning and consumers' desires for urban environments with less emphasis on roads for cars and more emphasis on smaller scale infrastructures for cycling and walking. Sometimes, they may be seen as stepping-stones as in the case of hybrids that allow further electrification of mobility but in a more gradual, tempered way. In other instances, they may be seen as buffers, as was partly the case for car sharing that allowed a more gradual phase out of the automobile.

5.3 Insights for low carbon mobility in the Netherlands

The pathway of technological substitution to BEVs is supported by current Netherlands transport policy, but even given the current acceleration of EVs, the provision of a charging structure may be necessary to complement an increasing awareness of climate change. Consumers may then be willing to switch from ICE cars. This switch can be accelerated by a phase out policy, as illustrated in this scenario.

Transition pathways away from cars are dependent on other aspects of transport and urban planning. These types of transitions would require a shift in mobility and planning policy in the Netherlands. The Netherlands has exceptionally well developed public transport and cycling networks. This provides the possibility to develop these networks and move to alternative mobility regimes. Policy for new ICT based transport services and 'smart' transport infrastructure for e.g. on-demand public transport systems can improve the convenience of public transport and personalised ICT services on board can respond to the expectations of current users. A transition to cycling and walking based mobility can be supported by a combination of policies. A programme to support the use of ICT through home working and high quality internet based live stream communications would need to be combined with planning that promotes mixed use town developments where home, work, and shopping and leisure activities are mostly within easy reach for pedestrians and cyclists. This includes the restriction on space and roads for cars, which even in the Netherlands is still limited.

The three scenarios should be regarded as notional ideal cases, to illustrate the range of possibilities for low carbon mobility. All the scenarios have a mixture of electricity based transport technologies. The public transport and local mobility pathways both involve a change in consumers' attitudes to car ownership and driving. It is possible that changes in institutions and the legal framework to allow autonomous vehicles will contribute to such changes, even if the changes are made for cars produced for individual owner-drivers. Support for BEVs could combine with driver assistance systems and autopilots to take mobility towards the reconfiguration pathways.

It can be argued that the technological substitution is easiest to support, because it involves a strengthening of the direction of current policies - to eliminate the sale of ICE cars and to support the uptake of electrically powered vehicles, which are still individually owned and use the current road infrastructure. The reconfiguration transitions pathways require a change

in direction of mobility policy. In the case of a transition to public transport, this requires the active development of new public internet infrastructures and a change in town planning to urban forms that are designed to prioritise public transport links and intermodal access. For a transition to a cycling and walking regime, this involves a further change to make urban forms prioritise cycling and walking as the main form of urban mobility, including the geographical redistribution of housing, workplaces and services.

6. Conclusions

This paper addresses a fundamental difficulty in the assessment of low carbon mobility futures. The insight of transitions analysis is that fundamental system change processes will be necessary to achieve a low carbon mobility society. A transition to low carbon mobility involves technological and social or behavioural change. Although mobility futures are usually developed using simulation models, these models do not reflect the understanding of transitions as co-evolutionary processes between niches and regimes. Behavioural change is also limited in most studies (Sims et al., 2014).

Turnheim et al. (2015) propose a methodological framework for combining qualitative and quantitative analysis of sustainability transitions pathways. They call this a bridging process involving alignment and bridging between qualitative and quantitative categories and results. This paper has applied this bridging framework to the case of low carbon mobility transitions. The MATISSE agent based model was structured and parameterised using the results of a transition analysis to identify niches and regimes for incorporation in the model. The simulation results were part of an iterative negotiation process of development of qualitative storylines, consistent with the simulations. The research process delivered a methodological co-construction of qualitative transitions analysis and simulation model development.

The bridging process enabled the analysis to address behavioural change as an integral feature and a necessary condition for sustainability transitions in a way that is not possible with current large scale techno-economic models of climate mitigation policy. The simulation model using an ABM approach enabled the analysis to allow for different behaviours and changes over time of behaviours in the population of consumers. However, this also raises further difficulties. As figure 1 shows, a complex research process is required that requires extra time and resources for development of the iterative alignment and bridging process.

The results show that a technological substitution to low carbon cars (BEVs in this example) would require not only a strengthening of current policies to move away from ICE vehicles and support the development of mobility using electric vehicles, but also a change in attitudes to place a higher priority on reducing the environmental impact of personal mobility. Reconfiguration pathways away from car ownership to mobility lifestyles based on new public transport or cycling and walking for local trips require transitions away from car ownership as the dominant mobility lifestyle. These have to overcome a well-established auto-mobility regime and will require major changes in culture and therefore behaviour as well as support for new priorities in the institutions of transport planning and urban development.

These findings are for the case of the Netherlands, a society that is exceptionally supportive of cycling and public transport. However, the ICE car does constitute the regime, even here, which suggests that similar processes may be possible in other societies. Further work could apply this example of a bridging approach to other countries, to examine the conditions under which such transitions away from mobility based on the ICE car are possible in the longer run.

The methodology developed here can be extended through the involvement of stakeholders in the bridging and alignment process. The socio-technical analysis could be extended through transition experiments to generate data from stakeholders' experiences of the alternatives².

The analysis has developed a new method for the study of sustainability transitions pathways, a first example of bridging between socio-technical analysis and quantitative simulation. This has enabled the development of a combined analysis, which explicitly considers niche-regime dynamics and a detailed simulation of behavioural change as a driver of these dynamics.

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Annexe A Brief description of the MATISSE Model

The model used is a development of the model described in Köhler et al. (2009). 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 MATISSE model implements the Multi-Level Perspective on transitions using an Agent-Based Modelling (ABM) approach (Köhler et al., 2018), as illustrated in figure 5. 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 sub-systems within society, and a larger number of simple agents. The complex agents represent the regime and niches, while the simple agents represent households or consumers. The macro-level Landscape represents changes in society generally, which may exert pressure on the regime and/or support the development of niches.

There can be only one regime at any time, although the system might have periods in which there is no regime. There may be one or 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. An agent's strength determines its behaviour (strategy in practices space as described below), its interactions with other agents, and (partly) its attractiveness to supporters. Niche and regime agents have an internal structure, or *metabolism*, which determines their strength, although this is ultimately dependent on support from the consumer agents.

Figure 5: Structure of the MATISSE 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 are each represented as values along axes, constituting a multi-dimensional *practices space*. Agents are differentiated by their positions in the multi-dimensional practices space. Figure 6 schematically shows a two-dimensional practices space, which might be e.g. Px CO₂ emissions and Py 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 Px and Py 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. The model is stochastic in that the simple agents are initially randomly assigned over the practice space, with distributions of car

drivers and a smaller set of 'green mobility' consumers. In the model the consumer agents choose to adopt the practices (transport characteristics in the current example) of 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. The movement strategies i.e. the development strategies of the regime and niches are explained below.

Figure 6: Two illustrations of a two-dimensional practices space

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 practices space, coloured by the agent they support, red = regime (R), green = niche 1 (N1), blue = niche 2 (N2).

Practices are broadly defined and include for the current example of mobility:

CO2 emissions
cost
use of mechanised individual transport (mostly cars)
use of ICT to reduce travel demand
use of public mechanised transport (train, bus, taxi)
urban structure (extensive with suburbs, compact with high rise buildings and public transport)

User convenience (is the main transport mode immediately available and long as well as short distance, or is there a waiting time and/or restrictions on range without changing modes)

The model is stochastic in that the simple agents are initially assigned in groups (car drivers, green car drivers, public transport users and cyclists& pedestrians) over the practice space, with a stochastic distribution of the supporters in a group around a central value for the group.

Each agent type (regime, niche) 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 maximise support. There is a restriction on the rate of change to reflect the tendency of the regime to display inertia. We add to Laver in that 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. Niches are *hunters*, continuing movement in the same direction as long as their strength increases, otherwise moving randomly in another direction. Niches are restricted to a certain range within the practices space. An example is that the BEV niche is restricted to low carbon transport practices.

The validation of the behavioural parameters in an ABM presents a challenge because of the very large number of behavioural parameters in such models. Each agent is individually parameterised (in the MATISSE model over 1000 consumer agents) as well as the niches and regime. While the empirical validation of individual behavioural parameters for such a large number of individual agents was not feasible, the socio-technical case study analysis did enable empirical evidence on the development of the niches to be collected and used to calibrate the distribution of behavioural parameters over the individual consumer agents in the MATISSE model.