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Managing the Diffusion of Low Emission Vehicles

Alexander van der Vooren and Floortje Alkemade

Abstract—There is significant uncertainty among technology providers, governments, and consumers about which technology will be the vehicle technology of the future. Governments try to stimulate the diffusion of low emission vehicles with diverse policy measures such as purchase price subsidies. However, the effect of such support measures on the speed and direction of technological change is unclear as different vehicle technologies might be preferred under different policy conditions. Decision makers, such as firm actors involved in green technology management, are thus strongly dependent on government policy when making strategic decisions. For these firm actors, determining their strategy regarding low emission vehicles is a complex task in a changing environment of coevolving consumer preferences, technology characteristics, and green technology policies. This paper presents an agent-based model of the competition between several emerging and market-ready low emission vehicle technologies and the dominant fossil-fuel-based internal combustion engine vehicles. The simulations illustrate the effects of different policy measures on technological change and their implications for the strategic actions of firm actors. More specifically, collaboration and standardization strategies can lead to synergies that contribute to technological change without risking early lock-in.

Index Terms—Agent-based simulation, consumer adoption, infrastructure development, sustainability, technological change.

I. INTRODUCTION

ENVIRONMENTAL and societal concerns have led to a search for more sustainable alternatives to the current fossil-fuel-based mobility system. Several technological options for low emission vehicles have emerged in recent years, among which are hydrogen, electric and hybrid cars, alongside cleaner, less polluting versions of the incumbent fossil-fuel-based technology [1]. These technological options differ with respect to their economic and environmental performance, their stage of development, and the extent to which they rely on the buildup of new infrastructure, but have in common that they compete to replace the current internal combustion engine as the dominant design for transport. Different types of actors attempt to influence these new technological trajectories: Government actors are involved as they seek to reach sustainability targets and because of the large investments and coordination problems that are associated with the buildup of new infrastructures; supply-side actors strategically compete and cooperate to stimulate the different technological options. For example, Budde et al. [2] found that Daimler followed a more cooperative strategy for the development of its hydrogen technology than for the development of its hybrid electric vehicles as the buildup of a hydrogen infrastructure requires the cooperation of a wider set of actors.

Firm actors involved in green technology management and investment have to determine their strategy in an environment of coevolving consumer preferences, technology characteristics, and green technology policies. This provides a complex task. Several authors have studied this complex setting, mostly focusing on either the supply-side (technology providers) or on how policy instruments affect the conditions for technological change ([3]–[6], etc.). In addition, several demand-side models [7]–[10] study the conditions under which a single new technology succeeds in replacing a dominant and locked-in technology. These models demonstrate that conditions in favor of technological change are:

1) consumer heterogeneity such as varying consumer preferences, different consumer groups, and experimental users;
2) early competitiveness of alternative technologies;
3) the valuation of technology characteristics of new technologies (preference changes);
4) backward compatibility of new technologies; and
5) local network externalities for the new technology.

These conditions enable the early adoption necessary for the diffusion of new technologies and can be influenced by supply-side and government actors to some extent.

Whereas theory thus emphasizes the role of consumers (adopters) in processes of technological change, many scenario studies and earlier models focus on the supply side, using highly stylized aggregated models of consumer behavior [11]–[14]. However, for firms that seek to bring new technologies to the market, it is pivotal to take into account consumer heterogeneity as this influences the particular market niches that are most attractive for the firm. In order to gain better insight into the strategic considerations involved in the transition to a more sustainable mobility system, it is therefore important to take both demand-side, supply-side and technological characteristics into account. The method of agent-based modeling [15]–[18] makes it possible to study such systems consisting of heterogeneous interacting agents, which are difficult to treat analytically.

This paper, therefore, analyzes the competition between several new and market-ready technologies and an incumbent technology in an agent-based simulation model. This model is applied in a simulation of currently available sustainable mobility technologies in order to study the influence of different demand-side (demand-pull) policy instruments on consumer adoption. This paper thereby focuses on the strategic implications for supply-side actors, as model results indicate that different policies require different strategic responses from suppliers.

The remainder of this paper is structured as follows. First, the theoretical framework is presented in Section II. Section III
then describes the agent-based model that simulates consumer adoption and the policy instruments that will be tested. Section IV analyzes and discusses the simulation results, and finally Section V concludes the paper.

II. THEORETICAL FRAMEWORK

Vehicles on fossil fuels are currently the dominant mobility technology; they are widely adopted, proven, relatively cheap, have sufficient supportive infrastructure, and benefit from different types of increasing returns [19]. A dominant technology is the one that wins marketplace allegiance, and the emergence of a dominant design is the result of the interplay between technical and market choices [20]. Often dominant technologies emerge out of the competition between a number of alternative technologies [21], [22]. For example, today’s dominant internal combustion engine vehicles (ICEVs) competed with electricity and steam-powered vehicles to succeed the old technology of horse carriages. The outcome of such a competition depends on the cumulation of small “historical” events and is therefore highly uncertain and unpredictable until a technology becomes dominant and gets locked-in [23].

The determinants for lock-in can be found in path-dependent processes [24] and increasing returns to adoption [25], [26] such as learning by using [27], scale economies, informational increasing returns, technological interconnectedness [28], and network externalities [29]. Because of these sources of increasing returns to adoption, the dominant technology continues to be chosen by both the demand- and supply-side actors and will improve further [23], thereby hindering the diffusion of alternative, possibly superior, technologies [30], [31].

As soon as society is locked-in into a dominant technology, technological substitution, which is the replacement of a dominant technology by a new technology, becomes difficult. A dominant technology establishes standards in terms of price and quality of the technological characteristics by which the new technology is evaluated, i.e., the dominant technology forms the selection environment for the new technology. This hinders substitution since new technologies at the time of emergence often show higher prices and poor performance in comparison to the incumbent technology [32]. When these new technologies depend on the availability of a physical infrastructure (that is incompatible with the existing infrastructure), overcoming lock-in is even more difficult. New technologies in the domain of energy and transport often require significant capital-intensive investments in infrastructure such as the construction of fuel stations or electricity grids [33], [34]. Due to these particular characteristics of technologies in the energy and transport sector and its public good nature, governments often intervene in technological substitution processes in this domain.

Although difficult to overcome, lock-in is nevertheless a temporary phenomenon from which escape is possible. Technology push, demand pull, or a combination of both mechanisms can give rise to new options or inventions that might replace existing technologies [35]. Demand-pull processes can either originate from consumers due to evolving preferences or dissatisfaction with the current (unsustainable) technological paradigm or from government stimulation (adapted regulation or available subsidies to develop alternative technological options). However, it is very difficult to determine ex ante which invention will lead to the replacement of the incumbent technology by a new technology [36].

Currently, several technological options exist that can (partially) substitute fossil-fuel-based mobility options [1]. This paper considers three types of low emission vehicles: plug-in hybrid electric vehicles (PHEVs); battery electric vehicles (BEVs); and hydrogen fuel cell vehicles (HFCVs). These technologies compete with each other and with the currently dominant fossil-fuel-based ICEVs. The degree of adaptation of a technology to its selection environment determines how successful a technology is in this competition [37]. A good fit between an option and the requirements of the environment, which could, for example, focus on sustainability, costs, or flexibility, makes a technological option promising. The selection environment comprises all factors that affect the competition process [38] such as institutions, spatial structure, and markets [39]. Favorable institutions such as rules, regulations, subsidies, social norms, agreements, and quality and safety norms can increase the probability of survival for an emerging technological system, i.e., for a specific low emission vehicle technology [40].

Given the inherent uncertainty of the innovation process, it is difficult to evaluate the different alternatives, complicating the decision about which and how many technological options to support. For vehicle technologies, support often takes the form of subsidies to install initial infrastructure or of purchase price subsidies decreasing the distance to market for the new technology.

Once technological alternatives to the dominant design become market ready (targeting either mass or niche markets), the market forms the main selection environment, where the price of the technology and the degree to which the technological characteristics of the new technology fit consumer preferences become the main selection criteria [41]. Adoption of a technology by consumers is the final stage of the substitution process as consumers eventually determine which technology is diffused through widespread adoption.

The selection environment is not static in this phase as consumer preferences evolve due to the availability of new technologies or due to exogenous forces that stress technological and service characteristics that differ from the characteristics of the current dominant design. Not only the new technological options benefit from this changing selection environment, the incumbent technology might also adapt to the changing environment (for a discussion of this so-called sailing ship effect, see [42] and [43]). For infrastructure-dependent technologies, the availability of infrastructure is an important determinant of user preferences [44], [45], which indicates that this problem of technological substitution is characterized by indirect network effects [29], [46], increasing the probability of lock-in. Establishing refueling standards for the new technologies is therefore a pivotal aspect of infrastructure development and the lack of standards might make it even more difficult to escape lock-in. When one of the alternative vehicle technologies succeeds in gaining a substantial market share or in replacing the dominant technology, the lock-in is overcome and the substitution process is complete.
A. Tradeoffs for Decision Makers

There is significant uncertainty among governments, technology providers, and consumers about which low emission vehicle technology will be dominant in the future. Governments try to stimulate the transition to sustainable mobility with diverse policy instruments such as subsidies for the purchase of cleaner vehicle technologies. Policy intervention can reduce uncertainty and resistance among consumers, which slow down the transition. However, the precise effect of such support instruments on the speed of the transition is unclear since different low emission vehicle technologies might be preferred under different policy conditions. Decision makers, such as firm actors involved in green technology management, are thus strongly dependent on government policy when making investment decisions. For these firm actors, determining their strategy in an environment of coevolving consumer preferences, technology characteristics, and green technology policies is a complex task involving several tradeoffs.

Different alternative low emission vehicle technologies such as the PHEV, the BEV, and the HFCV technology compete with the dominant ICEV technology to become the new dominant design in the future. Furthermore, these alternatives compete with each other for consumer adoption as well as for resources such as subsidies. Since it is difficult to escape lock-in, these technologies might benefit from collaboration. According to Van de Ven [47], stakeholders of competing alternative sustainable technologies must “run in packs” cooperating with each other as they seldom have the resources, power, and legitimacy to go it alone. Standardization is one of the most important cooperative strategies in the mobility sector as it creates network externalities and might lower the costs of escaping lock-in. For example, the standardization of charging infrastructures for electric vehicles could attract early adopters and create economies of scale. Conformation to standards can thus be beneficial for technological change, but for each individual firm it is most beneficial if its own technology becomes the standard, which often leads to the so-called standard wars that cause delay in adoption and uncertainty among all actors involved.

Running in packs can also increase the success of lobbying for generic support policies. Generic support policies such as a carbon tax stimulate the adoption of more sustainable alternatives. Such generic policies avoid picking winners and the risk of early lock-in. In addition to joint lobbying for generic support, firms can also lobby for technology-specific support. Specific-support policies such as the construction of infrastructure and purchase price subsidies for one of the vehicle technologies can assist early adopters in overcoming barriers and can create a competitive advantage for that technology. According to Azar and Sandén [48], such specific-support policies are needed for the mobility system in order to reduce uncertainty for private investors and to bridge the gap between invention and large-scale diffusion.

Moreover, specific support can accelerate the transition toward a more sustainable society when the supported technology is a so-called “stepping stone” toward other preferred technologies. A stepping-stone vehicle technology is the one that is more sustainable than the currently dominant technology but that is not considered as a desirable end state [49] for sustainable mobility. Therefore, investing in a stepping-stone technology creates the risk of undesired lock-in into this technology. For example, hybrid vehicles and vehicles running on natural or biogas were seen by the Dutch Transition Platform as a stepping stone toward a hydrogen-based mobility system. More recently, hybridization is seen as a stepping-stone technology toward all-electric vehicles [49]. A common infrastructure, standardization, and other factors such as coevolving consumer preferences can create synergies of which several technological options can benefit; this has strategic implications for decision makers concerning the question whether to support competing technologies that can function as a stepping-stone technology.

Another strategic concern for decision makers is the timing of investments and other activities such as lobbying. Firm actors are competing to be the first with a market-ready technology. First-mover advantages arise when the new technology determines industry standards, raises expectations, and generates funds [50], [51]. As discussed previously, another important source of first-mover advantages arises from the increasing returns to adoption that characterize infrastructure-dependent technologies.

Summarizing, the tradeoffs for managers relate to the extent to which infrastructure is shared, the presence of a stepping-stone technology, the presence of competing technologies, and the timing of possible strategic actions. Furthermore, these strategic considerations also depend on the presence of generic or specific policy measures for technology support. The model presented in the next section provides insights in these tradeoffs for different policy environments.

III. Model

This section describes a model of the competition for consumer adoption between different alternative vehicle technologies and the incumbent locked-in vehicle technology. Each vehicle technology is characterized by different characteristics that describe its performance, a different price, and a different level of infrastructure availability. Consumers repeatedly make adoption decisions based on infrastructure availability and on the degree to which an affordable technology fits their preferences. Fig. 1 gives an overview of the different model components (vehicle technologies, infrastructures, and consumers) and their interactions. Each model component can be influenced by policy instruments, thereby eventually affecting the adoption decisions of consumers. In the following, a more detailed description of the model components and their interactions is given.

A. Vehicle Technologies

In the model, a vehicle technology $i$ is described by its performance on a set of service characteristics $X_i \in [0,1]$, as by Lancaster [41] and Savioitt [37], and by its price $P$. Examples of service characteristics $x_i \in X$ of a vehicle technology are its driving range, acceleration, and emissions. Not all characteristics are considered equally important and changes in the
characteristics that are valued by consumers, i.e., changes in the selection environment, are an important driver of technological change [35].

The current dominant design shows high performance on the characteristics that are currently considered important by consumers as it has coevolved with and is adapted to its selection environment. When the selection environment changes (due to, for example, technology-push or demand-pull factors), consumers may take into account a different set of technological characteristics when making their adoption decision. New technological options may perform better on these newly evaluated service characteristics than the incumbent technology, leading to an increase in consumer adoption of the new technologies. This is not necessarily the case, however, as incremental innovation may also improve incumbent performance in the new direction. This model of coevolving preferences and technologies is described the following.

The different vehicle technologies studied in the model (ICEV, PHEV, BEV, and HFCV) can each be described by four service characteristics. At the time of market introduction, the initial performance of the technologies on these characteristics differs. The four characteristics are: 1) functionality, including the driving range and refueling time of the vehicle performance; 2) performance, including acceleration and top speed of the vehicle; 3) fuel consumption; and 4) emissions. Functionality and performance are characteristics that are traditionally focused upon by both consumers and producers; these characteristics are labeled as traditional characteristics T1 and T2. Fuel consumption and carbon emissions, labeled as sustainability characteristics S1 and S2, describe the environmental performance of the vehicles and have become increasingly important over the last decades.

ICEVs show high performance on the traditional characteristics that consumers perceive as important such as range and top speed and also on the price of the vehicle [52], but relatively poor performance on characteristics such as fuel consumption and local emissions. BEVs do perform well on fuel consumption and emissions, but not so well on the traditional characteristics. The model starts from the assumption that the emergence of new technological options such as BEVs expands the set of service characteristics that consumers consider in their adoption decision. On average, emerging low emission vehicle technologies are assumed to outperform the incumbent technology on these newly considered sustainability characteristics but not on the traditional characteristics at the time of market entry.

Besides performance on service characteristics, vehicle purchase price also influences consumer decisions. The price of the alternative low emission vehicle technologies is assumed to be higher than the current purchase price of the ICEV technology whereby hydrogen vehicles (HFCV) have the highest purchase price. Table I illustrates the initial performance and price of the different vehicle technologies considered in the paper [1].

The initial performance level on each of the characteristics was thereby chosen so as to reflect the current relative performance levels of the different technological options. The vehicle technologies are presented in rank order of its initial performance on the sustainability characteristics: initially ICEV is considered as the least and BEV as the most sustainable technology.

B. Infrastructures

Vehicle technologies depend on the availability of a specific refueling (or recharging) infrastructure and consumers consider the availability of this infrastructure in their adoption decision. There exist interdependencies between the infrastructures of different vehicle technologies. For example, the PHEV technology is compatible with both the fossil-fuel-based infrastructure and the energy infrastructure (electricity grid), as illustrated in Fig. 2. ICEVs depend on the availability of fossil-fuel-based infrastructure only. HFCVs are compatible with hydrogen infrastructure only. PHEV technology thus benefits from improved availability of both fossil-fuel-based and electric infrastructure. The infrastructure availability $A_{i(t)}$ for a specific vehicle technology $i$ at time $t$ is given by the following equation:

$$A_{i(t)} = \sum_{g=1}^{G} A_{g(t)} \kappa_{i-g}$$

where $A_{g(t)}$ is the availability of infrastructure $g$ at time $t$, $G$ is the number of different infrastructures, and $\kappa_{i-g}$ is the compatibility factor of technology $i$ with infrastructure $g$. For example, when the PHEV technology depends 25% on the fossil fuel infrastructure ($\kappa_{PHEV, fossil fuel} = 0.25$), 75% on the electric infrastructure ($\kappa_{PHEV, electric} = 0.75$), and 0% on the hydrogen infrastructure ($\kappa_{PHEV, hydrogen} = 0$), and the current availability of these three infrastructures is 1 (fossil fuel based), 0.3 (electric), and 0.45 (hydrogen), respectively, the infrastructure available for the PHEV technology is $A_{PHEV(t)} = 1 \times 0.25 + 0.3 \times 0.75 + 0.4 \times 0 = 0.475$. The development of an infrastructure $g$ over time is further explained below in Section III-A.

C. Consumers

The consumers in the model are seeking to buy a vehicle and will adopt a vehicle technology when there is a vehicle on the market that meets all their requirements. Consumers are myopic as they do not take into account the positive and negative consequences of their behavior, but base their decisions solely on

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1The different performance levels are implemented as follows: very poor (0.1); below average (0.2); average (0.3); above average (0.4); excellent (0.5). The initial price is either low (0.2), high (0.4), or very high (0.45).
The consumer are drawn from a normal distribution with a mean equal to this reference point. Preferences for the performance characteristics of that technology is calculated. Preferences for the performance on each characteristic function as thresholds. In case vehicle technologies meet or exceed the preferences $\Phi$ of a consumer on all characteristics $x$, the utility a consumer derives from adopting that technology is equal to 1 [upper part of (2)]. When technology performance does not meet consumer preferences on one or all characteristics, consumer utility is a function of the distance between preferences and actual technology performance. In this case, the consumer gains the highest utility from the technology that is closest to its preferences [lower part of (2)].

$$U_i = \begin{cases} 1, & \text{if } x \geq \varphi_x \forall x \in X_i, \varphi_x \in \Phi \\ 1 - \frac{\sum_{x \in X_i} (x - \varphi_x)^2}{\varphi_x^2} & \text{else} \end{cases} \quad (2)$$

6) Select and adopt technology: Finally, the consumer weighs the utility and price of the technologies taken into consideration. When multiple options are considered, the consumer adopts the technology with the highest utility/price ratio: $U_i / P^i$, where $\beta$ determines the importance of price in the adoption decision of the consumer. The adoption decision of a consumer thus consists of both hard (rules 1, 3, and 4) and soft constraints (rules 2, 5, and 6).
D. Policy Measures

Different policy instruments can affect the decision-making process of consumers by influencing consumer preferences or technology prices (see also Fig. 1). These instruments can be generic, aimed at all vehicle technologies, or technology specific. Whether generic or specific, policy instruments vary in timing and duration. Duration in the model is either temporary (10 time steps) or permanent (entire model run). Most policy measures are temporary although some countries have implemented long-term energy and climate policies; in this paper, policies that lead to the construction of new infrastructure are also considered permanent as the decay of infrastructure is generally slow [53].

1) Generic Instruments: A carbon tax on the vehicle purchase price makes vehicle technologies with a low performance on the emissions characteristic (S2) more expensive. This tax is permanent from the time of implementation onwards ($t = 0$, $t = 25$, $t = 50$, or $t = 75$) and is calculated by a linear function for vehicle technologies that perform below excellent (0.5) on the emissions characteristic (S2) at time $t$: $\text{Tax}_{x_i}(t) = 0.05 - 0.125 \cdot (S2_{x_i}(t) - 0.1)$. Hence, the carbon tax is highest when the technology performs very poor (0.1) on the emissions characteristic and declines linearly to zero for technologies that perform excellent (0.5) on this characteristic. Initially, all vehicle technologies, except for the BEV technology, are taxed (see Table I).

2) Specific Instruments: Technology-specific support starts at the time of emergence of a specific vehicle technology. The model considers two forms of technology-specific support: 1) the construction of additional initial infrastructure $\text{Infra}$, which is a permanent measure; and 2) a temporary technology-specific subsidy $\text{Sub}$ on the purchase price.

E. Model Dynamics

The interactions of the different model components determine the dynamics of the model. Technology service characteristics, consumer preferences, technology prices, and infrastructure availability change over time. In Fig. 3, the interactions between the main components are labeled. These interactions will be explained in the following. The model starts from a situation of lock-in into the ICEV technology, the incumbent technology. “Lock-in” is defined as the situation, where the incumbent technology is adopted by 90% of consumers and where the availability of the technology-specific infrastructure is (close to) 100%. The BEV and PHEV technologies arrive in the market at time step zero of the simulation. At that moment, 90% of the consumers drive the ICEV technology. When new vehicle technologies emerge, it is assumed that some initial infrastructure will be available to attract the first users. The HFCV technology arrives somewhat later in the market at time step 5, as this vehicle technology is currently not yet market ready. The different vehicle technologies evolve over time starting at time step zero.

1) Technology Dynamics: Radical innovation occurs when low emission vehicle technologies such as PBEV or HFCV enter the market. After market introduction, technologies continue to evolve due to incremental innovation and learning effects. Technological progress (arrow $A$ in Fig. 3) in a specific vehicle technology improves the competitive position of that vehicle technology and results in an increase in the number of adopters when the direction of change aligns with consumer preferences (arrow $B$). A technology improves when its performance on the different technological characteristics improves. As the outcomes of R&D are highly uncertain, technological progress due to incremental innovation is modeled as a stochastic process, as in [54] and [55]. Each time step of the model [56], [57] innovation can only occur in one characteristic of a vehicle technology, representing a focus of the firm’s innovation efforts. Furthermore, innovation is path dependent [24]; once a firm has built up substantial technological capabilities in engine efficiency, additional R&D efforts in this area are more likely to lead to successful innovation than R&D efforts in areas where the firm has no capabilities. Performance increases are thus more likely if previous incremental innovation has focused on this characteristic.

The probability that characteristic $x \in X_i$ of technology $i$ is selected for innovation is equal to the cumulative number of innovations in characteristic $x$ of technology $i$ divided by the cumulative number of innovations in all characteristics of vehicle technology $i$ ($\text{Cum}_{x_i} / \text{Cum}_i$). The state of a characteristic after incremental innovation is given by (3), where $\gamma$ is the incremental innovation rate. The effects of incremental innovation are large at first, but the effects of subsequent incremental innovations in a characteristic diminish over time

$$x_{i(t+1)} = x_{i(t)}^\gamma.$$  

Besides these changes in quality, the prices of vehicle technologies also change over time. Arrow $C_1$ in Fig. 3 represents the effects of a price decrease on consumer adoption, which are twofold: First, a price decrease makes the technology affordable to a larger group of consumers, which might result in an increase in adoption. Second, a price decrease increases the utility/price ratio of that technology which might also lead to an increase in adoption. The price of a technology decreases over time due to scale economies and learning by doing. An increase in the diffusion of a vehicle technology causes a decline in a vehicle’s

![Fig. 3. Dynamics of a demand-side model of consumer adoption: (a) technological progress; (b) technological performance, (c1) price, and (d1) infrastructure availability determine the competitive position of vehicle technologies and therefore the number of adopters. (c2) Adoption affects price represented by a standard learning curve. (d2) Adoption attracts investments in infrastructure.](image-url)
purchase price [58], [59] (arrow $C_2$). This relationship between price and the number of adopters is given by a standard learning curve [60], [61]:

$$P_i(t) = P_i(0) \left(\frac{c_i(0)}{c_i(t)}\right)^\alpha$$  \hspace{1cm} (4)

where $P_i(t)$ is the price of technology $i$ at time $t$, $P_i(0)$ the initial price of the technology (see Table I), $c_i(0)$ the initial number of consumers, $c_i(t)$ the cumulative number of consumers of a technology, and $\alpha$ the learning ability of a technology.

2) Infrastructure Dynamics: Infrastructure codevelops with the size of the adopter group, representing indirect network externalities. On the one hand, an increase in infrastructure availability can enlarge the group of potential adopters because more consumers will take the vehicle technology into consideration (arrow $D_1$). On the other hand, an increase in the number of adopters of a vehicle technology leads to a higher availability of the infrastructure(s) for that vehicle technology because this attracts investors (arrow $D_2$) [53]. Infrastructure availability $A_g$ is described by the following:

$$A_g(t) = \max \left( A_g(t-1), A_g(0) + \sum_{i=1}^{I} S_i(t) \kappa_{i-g} \right)$$  \hspace{1cm} (5)

where $A_g(0)$ is the infrastructure availability at the time of emergence and $S_i(t)$ is the market share of a vehicle technology, which is equal to the number of consumers that possess technology $i$ at time $t$ divided by the total number of consumers $N$. The constant $\kappa_{i-g}$ is the compatibility factor of infrastructure $g$ with technology $i$. Therefore, the adoption of different vehicle technologies might contribute to the development of a particular infrastructure $g$.

3) Consumer Dynamics: In the model, a consumer’s individual preferences change over time following the maximum observed performance on a characteristic, as described in Section III-C, whereas budget constraints and infrastructure requirements are fixed. An individual’s preferences for the performance of a vehicle technology on the service characteristics are endogenously related to the development of these characteristics, which reflects the idea that both technology-push and demand-pull mechanisms are important in innovation processes [35]. Hence, an incremental innovation in a certain characteristic not only directly improves the competitive position of that technology (arrow $B$) in Fig. 3, but also causes a shift in consumer preferences.

IV. SIMULATION RESULTS AND DISCUSSION

This section describes the effects of different policy measures on the outcomes of the process of technological change. In the model described previously, substitution occurs when the market share of the ICEV technology drops below the market share of one of the emerging low emission vehicle technologies. However, substitution is neither a sufficient nor a necessary condition for a sustainability transition to occur. For example, it could be the case that the newly emerged technology has a lower performance regarding sustainability compared to the incumbent technology. Additionally, it is possible that no substitution occurs and the incumbent remains dominant while becoming more sustainable. A sustainability transition can thus be realized in different ways [62] and it is critical to not only take into consideration whether technological substitution takes place, but to consider the evolution of the service characteristics of the vehicle technologies as well, when studying the effects of different policy measures.

Each policy measure is simulated for 20 runs. For each simulation run, it is determined: 1) whether technological substitution occurred; and 2) whether a transition toward more sustainable vehicle technologies took place. For each run, the average performance on the different service characteristics is recorded (weighted over the market share of the adopted technologies). A simulation run is labeled as a transition when the average performance of one or both of the sustainability-related characteristics, fuel consumption (S1) and emissions (S2), has substantially improved relative to the other characteristics. Fig. 4 illustrates the possible combinations of the occurrence of substitution and transition. The two graphs in one cell of the matrix belong to the same simulation run. The top graph in each cell shows the market share of the different vehicle technologies over time, and the bottom graph shows the average performance on each of the service characteristics over time.

Since the market share of the ICEV technology is almost 100% at time step zero, average performance at that time is determined by the initial performance of the ICEV technology, which scores excellent at the two traditional performance characteristics, T1 and T2, but less on the sustainability-related characteristics S2 (very poor) and S1 (below average) (see Table I). Although all four possible combinations of the occurrence of transition and substitution were observed in the simulation runs, the transition, no substitution case (top right of the matrix in Fig. 4), occurred most frequently over all simulation runs presented in this paper (in 91 out of 220 runs), while the case no transition, substitution (left bottom of the matrix in Fig. 4), had the lowest occurrence (in 2 out of 220 runs). The transition, substitution case, occurred in 64 out of 220 runs, and the no transition, no substitution case, occurred in 63 out of 220 runs.

As a benchmark, Fig. 5 shows the model outcomes for the case without policy support in two different scenarios. The left side of Fig. 5 corresponds to a situation in which the environmental concerns of consumers are low and the sustainability-related vehicle characteristics have only a small influence on the direct utility of consumers. Fig. 5 illustrates that in this case the incumbent ICEV technology hardly looses any market share (averages over 20 simulation runs). In this benchmark case, no technological substitution took place and the ICEV technology remained the dominant design, although in 50% of the model runs, a transition to sustainability occurred, which was caused by the stochastic nature of technological change in the model, as shown by the histogram. The right side of Fig. 5 illustrates a scenario, where the sustainability-related and the traditional performance characteristics contribute equally to consumer utility (the default model setting). In this scenario, 6 out of 20 runs

2 More specifically, the model outcome is considered as a transition when the average performance on one or both sustainability characteristics substantially improves and is at least average (0.3) for emissions and above average (0.4) for fuel consumption.
Fig. 4. Substitution–transition matrix: single runs representing the different combinations of the occurrence of transition and substitution. The cells in the left (right) column represent runs in which (no) substitution occurs. The cells at the top (bottom) row represent simulation runs in which (no) transition is observed. The two graphs in each cell belong to the same simulation run. The bottom graph in each cell shows the average performance on a specific characteristic over all adopted vehicles, which determines whether or not a transition occurred. The top graph in each cell presents the market share of the different technologies, which determines whether or not substitution occurred.

Fig. 5. Market share of the different vehicle technologies, averaged over 20 runs for two scenarios: No policy support: low environmental concerns (left) and moderate environmental concerns (right). The histograms show how often a vehicle technology was dominant after 100 time steps and the associated number of sustainability transitions (gray).
showed substitution and in 13 out of 20 runs a transition occurred. The PHEV technology is most prominent as alternative for the ICEV technology, followed by the BEV technology, and the HFCV technology hardly gained any market share. The figure illustrates that the effects of consumer selection pressure are substantial in the model.

**Carbon tax:** Fig. 6 shows the effects of the introduction of a carbon tax at different times ($t = 0, 25, 50,$ or $75$). In comparison with the benchmark, the carbon tax leads to increased market share for the low emission vehicle technologies, and a higher number of transitions and substitutions. The individual plots in Fig. 6 illustrate the importance of the timing of the tax. First, the market share of the low emission vehicles increases with a later introduction of the tax up until $t = 50$ but then decrease again for $t = 75$. In this latter case, the positive effects of the tax are not realized within the 100 step time frame of the simulations. When the tax is introduced early, at $t = 0$ and $t = 25$, PHEV realizes the highest market share of the low emission vehicle technologies as in the benchmark scenario. Although PHEV is not the most sustainable technology, it outperforms the other low emission vehicle technologies on the traditional characteristics. When the tax is introduced later at $t = 50$, the BEV technology overtakes the PHEV technology in terms of average market share. Initially, the BEV technology performs excellent on the sustainability characteristics but performs relative weak on the traditional characteristics. At $t = 50$, the BEV technology had the time to develop solutions for these bottlenecks, which creates a window of opportunity for successful diffusion at the moment of tax introduction. Also, in terms of the number of runs that a technology becomes the dominant design within 100 time steps, the BEV technology benefits most for a tax introduction at $t = 50$. Overall, PHEV technology benefits only slightly from the tax introduction compared to the benchmark scenario. The HFCV technology does not benefit from a carbon tax.

Second, the observed number of transitions and substitutions is compared to the benchmark scenario. The number of transitions increases compared to the benchmark scenario in Fig. 5 and is around 16 (out of 20 runs) for each time of introduction. Thus, the carbon tax provides incentives for a transition toward sustainability. However, according to the observed number of substitutions, the carbon tax does not provide a selection pressure sufficient to support fast technological change as for a tax introduction at $t = 0$ and $t = 25$ half of the transitions are realized by increased sustainability of the incumbent technology. Only for a tax introduction at $t = 50$, most transitions are associated with substitutions by low emission vehicles.

**Technology-specific support:** In the model, technology-specific support consists of infrastructure investments and a temporary purchase price subsidy at the time of market
introduction. Fig. 7 presents the results when specific support is given to the BEV technology (left), the PHEV technology (center), and the HFCV technology (right). Both the support for the BEV technology and the support for the PHEV technology lead to competitive advantages for the BEV technology due to the dependence on a common infrastructure. Note that the average market share of the BEV technology is highest when the PHEV technology receives specific support. Specific support for the HFCV technology, which has a larger distance to market, leads to lower overall sustainability results. Both the number of substitutions (3 out of 20 runs) and transitions (11 out of 20 runs) are significantly lower in case of specific support for the HFCV technology than in case of specific support for the PHEV (14 transitions and eight substitutions) or the BEV technology (17 transitions and eight substitutions).

The model outcomes illustrate that the PHEV technology can serve as a stepping-stone technology for the BEV technology. Supporting or investing in the PHEV technology may thus also be an effective strategy for those that seek large-scale deployment of the BEV technology. In the model presented here, there is no risk of becoming locked-in into the PHEV technology due to the compatibility between infrastructures. Cooperation between suppliers and the standardization of the required infrastructure for PHEV and BEV technologies may thus lead to synergies of which mainly the BEV technology benefits.

The importance of infrastructure compatibility and standardization is further illustrated in a rerun of the model with technology-specific support but without infrastructure-related compatibility between PHEV and BEV. In this experiment, both technologies solely depend on their own technology-specific electric infrastructure such that the adoption of either PHEV or BEV has no positive feedbacks on the other technology. Fig. 8 presents the outcomes of these simulation runs for BEV (left) and for PHEV (right). The figure illustrates that the dependence on a common infrastructure is crucial for this stepping-stone effect to occur since the BEV technology gains hardly any
market share when supported. In the Dutch energy and mobility transition, management framework the BEV technology was proposed as a stepping-stone technology toward a sustainable mobility system based/dominated by HFCVs [49]. As the BEV and HFCV technology do not have a shared infrastructure, this transition pathway is not supported by the model outcomes.

V. CONCLUSION AND MANAGEMENT IMPLICATIONS

The simulation of coevolving consumer preferences, low emission vehicle technology characteristics, and environmental policies enable us to derive strategic implications for firm actors involved in green technology management. The simulations suggest three important implications for strategy.

First, the results illustrate that the impact of consumer selection pressure on the future success of different low emission vehicle technologies can be substantial. In the model, consumer adoption decisions codetermine the direction of technological change. Combined with the presence of increasing returns to adoption, the model illustrates that it is not necessarily the most sustainable technology that becomes dominant. This is in line with earlier results by Arthur [19], [23] and Zeppini and van den Bergh [63] for technologies that do not depend on a specific physical infrastructure. Current scenario studies on future sustainable mobility systems mostly focus on supply-side developments related to technology improvement and cost reductions. This model illustrates the need for both firm actors and policymakers to include heterogeneous and evolving demand in their forecasts.

Second, the results illustrate the effects of the timing of policy measures in relation to the stage of development of the technology. Early introduction of a carbon tax favors technologies that are relatively similar to the incumbent technology over more sustainable alternatives. Technologies thus benefit most from the introduction of a carbon tax when their characteristics are well aligned with consumer preferences. This is in line with findings by Geels and Schot [62] and Alkemade and Suurs [51] who state that the timing of pressure on the regime, which creates windows of opportunity for technological change, is particularly important. Strategic implication of these timing effects include the need to take into account the stage of development of a new technology when considering investments, or lobbying for market support measures such as a carbon tax as it is not necessarily the most sustainable alternative that benefits most in terms of market share.

Third, the results illustrate how common infrastructures can facilitate stepping-stone effects. Collaboration and standardization strategies can lead to synergies that contribute to technological change without risking the early lock-in into one of the supported alternatives. This implies that “running in packs” and making a technology compatible to other new or old technologies creates opportunities for technological change. Such standardization efforts are important both from the perspective of technology managers and policy makers as standardization allows the coexistence of different low emission vehicle technologies and decreases the risk of technological lock-in. It is thereby important to focus standardization efforts not only on a single technology group such as PHEV, but extend the effort to include possible future technology generations such as BEV.

Overall, the results illustrate the value of using a bottom-up simulation approach for evaluating different policy measures. Agent-based simulation models can help firm actors to adapt their strategy in response to such policies.

APPENDIX

TABLE II

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Interpretation</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Consumers</td>
<td>Number of consumers</td>
<td>1,000</td>
</tr>
<tr>
<td>$a$</td>
<td>Set of consumer preferences</td>
<td>c [0, 1]</td>
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<tr>
<td>$b_{v}$</td>
<td>Consumer preferences for characteristic $v$</td>
<td>$N(0.5, 0.1)$</td>
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<tr>
<td>$\beta_{v}$</td>
<td>Budget constraint</td>
<td>$N(0.4, 0.1)$</td>
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<td>$\eta$</td>
<td>Infrastructure availability requirement</td>
<td>$N(0.6, 0.1)$</td>
</tr>
<tr>
<td>$\xi$</td>
<td>Importance of price</td>
<td>$N(0.6, 0.1)$</td>
</tr>
<tr>
<td>$\nu$</td>
<td>Replacement rate</td>
<td>1/3</td>
</tr>
<tr>
<td>$\psi$</td>
<td>Utility of consuming the set of service characteristics of technology $i$</td>
<td>$c [0, 1]$</td>
</tr>
<tr>
<td>Vehicle technologies</td>
<td>Set of service characteristics $y_{i}$ of technology $i$</td>
<td>$c [0, 1]$</td>
</tr>
<tr>
<td>$\pi$</td>
<td>Performance of service characteristics</td>
<td>$c [0, 1]$</td>
</tr>
<tr>
<td>$x_{max}$</td>
<td>Maximum observed performance on a characteristic $z$</td>
<td>$c [0, 1]$</td>
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<tr>
<td>$i_{s}$</td>
<td>Index for technologies</td>
<td>$c [0, 1]$</td>
</tr>
<tr>
<td>$t_{h}$</td>
<td>Number of different technologies</td>
<td>$c [0, 1]$</td>
</tr>
<tr>
<td>$t_{l}$</td>
<td>Infrastructure availability for technology $i$</td>
<td>$c [0, 1]$</td>
</tr>
<tr>
<td>$T_{i}$</td>
<td>Infrastructure availability of infrastructure $y$</td>
<td>$c [0, 1]$</td>
</tr>
<tr>
<td>$G$</td>
<td>Index for infrastructures</td>
<td>$c [0, 1]$</td>
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<tr>
<td>$N_{i}$</td>
<td>Number of different infrastructures</td>
<td>$c [0, 1]$</td>
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<tr>
<td>$\alpha$</td>
<td>Incremental innovation rate</td>
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<td>$\eta_{l}$</td>
<td>Learning ability</td>
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<tr>
<td>$\eta_{p}$</td>
<td>Price of technology $i$</td>
<td>$c [0, 1]$</td>
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<td>$\phi_{(r)}$</td>
<td>Cumulative number of adopters at time step $r$</td>
<td>$c [0, 1]$</td>
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<tr>
<td>$\phi_{(r)}$</td>
<td>Market share of technology $i$ at time $t$</td>
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<tr>
<td>$\phi_{(r)}$</td>
<td>Traditional characteristic $l$ (Functionality) &amp; 2 (Performance)</td>
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<tr>
<td>$\gamma_{(r)}$</td>
<td>Cumulative number of innovations in characteristic $y$ of technology $i$</td>
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<td>Cumulative number of innovations in all characteristics of technology $i$</td>
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<td>$\gamma_{(r)}$</td>
<td>Initial number of cumulative adopters</td>
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<td>$\gamma_{(r)}$</td>
<td>Initial number of cumulative adopters</td>
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REFERENCES


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