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Climate change and the slow reorientation of the American car industry (1979–2012): An application and extension of the Dialectic Issue LifeCycle (DILC) model

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ABSTRACT

This paper uses the Dialectic Issue LifeCycle-model (DILC-model) to analyze the co-evolution of the climate change problem and strategic responses from the American car industry. The longitudinal and multi-dimensional analysis investigates the dynamics of the climate change problem in terms of socio-political mobilization by social movements, scientists, wider publics and policymakers. It also analyses how U.S. automakers responded to mounting pressures with socio-political, economic and innovation strategies oriented towards low-carbon propulsion technologies. We use a mixed methodology with a quantitative analysis of various time-series and an in-depth qualitative case study, which traces interactions between problem-related pressures and industry responses. We conclude that U.S. automakers are slowly reorienting towards low-carbon technologies, but due to weakening pressures have not yet fully committed to comprehensive development and marketing. The paper not only applies the DILC-model, but also proposes three elaborations: (a) the continued diversity of technical solutions, and 'ups and downs' in future expectations, creates uncertainty which delays strategic reorientation; (b) firms may develop radical innovations for political and social purposes in early phases of the model; (c) issue lifecycles are also shaped by external influences from other problems and contexts.

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1. Introduction

Climate change is one of the 'grand challenges' facing society, requiring low-carbon innovation in many sectors and industries. This paper is about low-carbon innovation and reorientation in the American car industry, which can be expected to be a difficult process for several reasons. First, climate change constitutes a major threat to the industry's core technology (internal combustion engines (ICE)) and vested interests linked to sunk investments in factories, skills and supply chains. So, to defend their interests and investments, firms are likely to be reluctant or hesitant to engage in low-carbon reorientation, and may actively resist (especially in early phases of the process).

Second, if automakers accept the need for low-carbon reorientation, they will have to invest in radical innovations, which in capital- and scale-intensive industries such as car manufacturing is very costly (not just because of R&D, but also because of factory

retooling, new production processes, establishment of supplier networks, etc.) and risky (there is no guarantee that technical reorientations succeed). These risks are compounded by the existence of *multiple* low-carbon innovations, which include: (a) advanced internal combustion engines (aICE), based on improved fuel-injection systems, turbo charging, advanced valve management, etc.; (b) bio-fuel and flex-fuels vehicles (FFV), which also build on existing technical competencies; (c) fuel cell vehicles (FCV); (d) battery-electric vehicles (BEV), which both would disrupt existing competencies, and (e) hybrid-electric vehicles (HEV) and plug-in hybrid vehicles (PHEV), which combine existing ICE-competencies and new battery and electronic competencies. The possibility of 'betting on the wrong horse' makes green reorientation a risky process with long-term strategic ramifications.

Third, because of the industry's reluctance and risk-aversion, green reorientation is likely to require increasing external selection pressures on automakers. Since avoiding climate change is a collective good problem and because low-carbon innovations offer worse price/performance characteristics (at least initially and under current frame-conditions), such selection pressures are unlikely to start in markets. Rather, pressures initially tend to come from social movements, public opinion and policymakers, and may later

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spill over to consumers. These pressures may go up, but can also go down, which creates additional uncertainty for automakers with regard to green reorientation (e.g. about future toughness of regulations or consumer willingness to pay for low-carbon innovations). Furthermore, automakers may actively try to influence socio-political pressures, which means that strategic considerations are not just techno-economic, but also socio-political. So, for several reasons, low-carbon reorientation in the car industry is likely to be a difficult and challenging process.

Against this background, the paper aims to describe and explain how American automakers have engaged with low-carbon reorientation since the emergence of the climate change problem, and how far they have progressed. To address these issues and guide the analysis, the paper uses the Dialectic Issue LifeCycle (DILC) model, which has been described in two previous papers (Penna and Geels, 2012; Geels and Penna, 2015) that analyzed the reorientation of American automakers in response to the problems of air pollution (1943–1985) and car accidents/safety (1900–1995), respectively. The DILC-model conceptualizes the co-evolution between the dynamics of a societal problem ('issue lifecycle'), in terms of social and political mobilization processes leading to pressures on an industry, and the dynamics of industry responses, including technical innovation and broader corporate strategies. The longitudinal interaction between a 'problem stream' and a 'solution stream' (Kingdon, 1984) is conceptualized as full of conflicts, tensions and struggles (hence the 'dialectic'-prefix) across socio-political, cultural and economic dimensions, unfolding through five phases (see Section 2).

The paper aims to make empirical and conceptual contributions. Empirically, the main contribution is to develop synthetic multi-dimensional account of low-carbon reorientation in the American car industry. The account is based on some original data-analysis of patents, newspapers and congressional records, but mainly aims to integrate many secondary sources (e.g. books, reports, academic articles). So, while acknowledging that a large literature already exists on various aspects of low-carbon cars (see also Section 3), we aim for a theory-guided integration. With the innovation studies community as our primary audience, we particularly aim to build on but go beyond the various studies in this community of low-carbon innovations, e.g. FCV (Bakker, 2010; Van den Hoed, 2005; Budde et al., 2012), HEV (Dijk and Yarime, 2010), BEV (Johnson, 1999; Dijk et al., 2013), and biofuels (Duffield et al., 2008). While these studies provide important insights about technical solutions, we suggest that a comprehensive analysis should also study interactions with the dynamics of societal problems related to mobilization, public attention and political will.¹ While these studies have analyzed innovation strategies such as R&D, patenting, and technology partnerships, a comprehensive analysis should also address political, socio-cultural ('framing'), and economic positioning strategies. And we suggest that a comprehensive analysis should go beyond single technology studies, and address the diversity of low-carbon innovations, because this creates additional problems for reorientation such as uncertainty about consumer preferences and therefore risks of 'betting on the wrong horse'. Our account thus builds on innovation studies' papers of low-carbon technologies, but also addresses other dimensions (mentioned in Section 3). We integrate the various studies using the DILC-model as a theoretical template, which enables a systematic and dynamic analysis of interactions between various selection pressures and industry responses.

¹ Some papers, especially those that investigate the dynamics of expectations (e.g. Bakker, 2010; Budde et al., 2012), do address some social and political dimensions, but this can be done more systematically.

With regard to the DILC-model, the paper aims to replicate the basic conceptual framework, broadening the model's empirical base with a new case study. The paper also aims to use three specificities of the case to make conceptual elaborations. First, while the technical solution was relatively clear in the two previous case studies (Penna and Geels, 2012; Geels and Penna, 2015), it is less clear in the climate change case what the 'best' solution is because of the diversity of low-carbon innovations. In fact, views about the 'best' solution have experienced ups-and-downs in successive hype-disappointment cycles (Geels, 2012), which enhance the strategic uncertainty firms face.² So, the paper aims to explore how the diversity of possible solutions conceptually affects the DILC-model. Second, the case will show various examples of firms developing new technologies for political and socio-cultural purposes. We will use these instances to problematize the distinction between 'symbolic' industry responses (political and framing strategies) and 'substantive' responses (technology development), which so far underlies the DILC-model. Third, the case will show that the climate change problem interacted with other problems such as air pollution, fuel efficiency, energy security, and the economic/financial crisis. This means that the study of issue lifecycles should not only look at internal problem dynamics (e.g. socio-political mobilization, agenda-setting, political struggles), but also acknowledge the importance of 'issue linkage', i.e. positive or negative linkages with other problems.

The paper is structured as follows. Section 2 describes the DILC-model and develops further ideas with regard to the three specificities. Section 3 discusses our quantitative-qualitative methodology. Section 4 presents the results of the quantitative analysis. Section 5 presents an in-depth longitudinal case study of climate change and the American car industry (1979–2012). Section 6 analyses the stage of the climate change issue lifecycle and the degree of low-carbon reorientation of American automakers, and discusses conceptual elaborations of the DILC-model. Section 7 provides concluding comments.

2. The Dialectic Issue LifeCycle (DILC) model

Penna and Geels (2012) developed the DILC-model by combining insights from issue lifecycle theory (to conceptualize the dynamics of social problems) and innovation studies (to conceptualize the dynamics of technical 'solutions'). They qualified the DILC-model as *dialectic* to highlight the struggles between the build-up of problem-related pressures and responses from incumbent industry actors. To conceptualize these interactions, the DILC-model uses the triple embeddedness framework (TEF) (Geels, 2014) as underlying model (Fig. 1). In the TEF, firms-in-industries face selection pressures from an economic environment (resource pressures from markets and suppliers) and a socio-political environment (legitimacy pressures from social movements, public discourse, policymakers). Firms-in-industries can respond to these pressures (as indicated with the bi-directional arrows in Fig. 1) through various strategies, e.g. innovation strategies and economic positioning strategies (supply chain management, operations management, marketing) towards the economic environment, and corporate political strategies (lobbying, financial contributions to political parties, constituency building, information strategies, etc.) and socio-cultural strategies (public relations, advertising) towards the socio-political environment.

The triple embeddedness framework (TEF) helps articulate the basic logic in the DILC-model: the lifecycle is conceptualized as unfolding through five phases, in which a societal problem

² We use the notion of hype-cycles, which was introduced by Gartner consultancy, in a descriptive rather than evaluative (derogatory) sense.

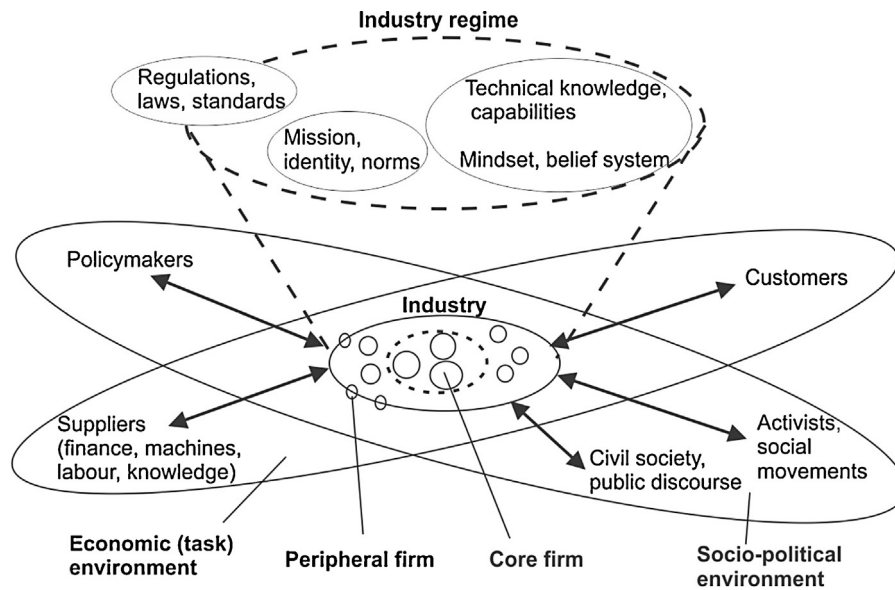


Fig. 1. Triple embeddedness framework of industries (Geels, 2014: 266).

subsequently affects *additional* selection pressures from various environments: (1) activists; (2) wider publics and public attention; (3) policymakers in policy sub-systems, who investigate the problem through hearings and inquiries and engages in debates about possible solutions; (4) politicians in macro-political arenas,³ who may introduce substantive legislation; (5) consumers and market demand. So, as an ideal-type, the DILC-model assumes that various selection pressures grow stronger over time and align with each other, which increasingly stimulate firms-in-industries to reorient. The other side of the DILC-model concerns industry responses to these increasing pressures, which tend to be defensive in the first three phases, when pressures mainly come from the industry's socio-political environment.

In the first three phases, incumbent firms are reluctant to make substantial change to address the problem, because they are 'locked in' to industry regimes (Fig. 1), which consist of four industry-specific institutions (Geels, 2014): (1) industry beliefs and mindsets; (2) identity and mission; (3) regulations and formal policies; (4) capabilities and technical knowledge. Firms are reluctant to change these core regime elements in the first three phases, and tend to fight and resist using socio-cultural and political strategies. In phase 1, they tend to downplay social problems. In phase 2, when they (are forced to) acknowledge the issue, a common tactic is the creation of 'closed industry fronts' (Geels and Penna, 2015), e.g. industry associations, which defend the industry as a whole (politically or through framing strategies). Firms may also use innovation strategies to defend the existing regime (developing incremental solutions). In phase 3, incumbent firms and industry associations will *publicly* defend the existing regime (using political and framing strategies to influence public opinion and the policy sub-system). *Privately*, however, they may begin to explore radical solutions in R&D laboratories to hedge against possible future policies or changes in the economic environment. These efforts may be spurred on by radical technology development activities from relative regime outsiders (e.g. foreign firms, suppliers, new

entrants), who see rising public concerns about the problem as an opportunity.

While the first three phases are mainly about socio-political mobilization and defence, the issue lifecycle gathers a new dynamic in phases 4 and 5, when the problem begins to affect the economic environment (Geels and Penna, 2015). In phase 4, escalating public attention propels the problem into the macro-political arena (True et al., 1999), where politicians may introduce radical legislations that substantially change the economic frame conditions (e.g. taxes, regulations, standards, subsidies, investments). Subsequent implementation of this new policy often leads to struggles between administrative agencies and the industry, which is likely to resist and fight back. In phase 5, the problem affects mass consumer preferences (because of changing views on appropriate behaviour or because of public policies), which creates market demand for radically new technologies.

Corporate attention to the problem intensifies in phases 4 and 5, as changing policies and consumer behaviour begin to affect the economic environment. While industry associations may still publicly resist policy implementation in phase 4, individual firms also begin to explore technical and market *opportunities*, which may lead to the crumbling of closed industry fronts (Geels and Penna, 2015). In phases 4 and 5, incumbent firms thus begin to reorient towards radical ('substantive') innovations, which is a costly and risky process that often proceeds gradually (March, 1991), from hedging and exploration (starting in phase 3) to strategic diversification (phase 4), which is accompanied by changes in some regime elements (technical capabilities and regulations), to full reorientation (phase 5), which is accompanied by more foundational changes in belief systems and mission. Reorientation may accelerate when first-mover advantages by leading firms results in 'jockeying for position' and an innovation race. Table 1 summarizes the main aspects of this co-evolution of problem-related pressures and industry responses in the DILC-model.

While the ideal-type representation in Table 1 assumes linear increases in various problem-related pressures, Geels and Penna (2015) elaborated the DILC-model by showing that pressures can also weaken, producing more complex patterns. (In the analysis of this paper (Section 6), we therefore follow Turnheim and Geels (2013) in developing a 'pressure table', which maps the temporal development of various pressures in the case study.) Geels and Penna (2015) also demonstrated the importance of emerging

³ The distinction between policy sub-systems and macro-political arenas comes from the punctuated equilibrium theory in political science (True et al., 1999). The former refers to less visible groups such as specialists in the bureaucracy, congressional subgroups, interest groups and stakeholders, whereas the latter refers to more visible actors in Parliament/Congress and the government.

Table 1
A Summary of the DILC-model dynamics.

Phases	Dynamics of societal 'problems' and associated 'pressures'		Dynamics of 'solutions' and strategies of incumbent industries	
	Socio-political pressures	Economic pressures	Socio-cultural, and political strategies	Technology and innovation strategies
1: Problem emergence, and industry neglect	The problem first emerges when activist groups articulate concerns. Uncertainty about causes and consequences gives rise to sense-making.	No specific pressure from task environment.	Incumbent firms do not recognize the problem, or downplay its importance.	No technology strategy is deployed in response to the issue.
2: Rising public concerns, and defensive industry responses	Activists create a social movement that pushes the issue onto public agendas. Increasing public worries create pressures on policymakers who express concerns and create committees (symbolic actions).	Relative regime outsiders (e.g. suppliers, foreign firms, new entrants) begin to develop technical solutions.	If further denial of the problem damages reputations, firms defend themselves by creating a closed industry front that contests claims from social movements and lobbies policymakers.	Firms may develop incremental technologies that stay within the bounds of the existing regime.
3: Political debates/controversies, and defensive hedging	Rising public attention pushes the problem onto policy sub-system agendas, leading to formal hearings and investigations.	Alternatives may find a foothold in small market niches linked to 'moral consumers'.	Industry actors argue that regulations are not necessary, because they will 'voluntarily' implement (incremental) solutions. They may also emphasize costs or technical complexity.	Incumbents <i>publicly</i> portray radical solutions as unfeasible. For defensive reasons, however, industry actors may hedge and privately explore radical solutions in laboratories.
4: Formation and implementation of substantive policy, and industry diversification	Escalating public concerns pushes the problem onto macro-political agendas where politicians may introduce radical legislation. This is followed by policy implementation by administrative agencies.	Regime outsiders lead developments targeted at the growing (but limited) 'moral consumer' market segment. However, concerns do not (yet) spill over to mainstream markets.	Firms and industry associations contest the formation and implementation of radical policies. First-mover firms may, however, argue for tougher regulations to raise costs for competitors.	Firms diversify and increase R&D investments in radical alternatives. Individual firms embrace the new technology more enthusiastically to 'jockey for position' in the expectation of growing markets. This could cause cracks in the closed industry front and lead to an 'innovation race'.
5: Spillovers to the task environment, and strategic reorientation	The problem may lead to new markets when public discourses lead to changes in mainstream consumer preferences or when regulators substantially change economic frame conditions (through taxes, incentives, legislation).		To take advantage of economic <i>opportunities</i> , incumbents reorient towards the new technology and markets. Addressing the problem also becomes part of the industry's core beliefs and mission, leading to further transformation of the industry regime.	

technical and economic *opportunities*, particularly (expectations of) substantial market demand, for industry reorientation in phases 4 and 5, besides socio-political pressures. So, small or stagnant green market demand is likely to hinder low-carbon industry reorientation.

This paper aims to make three further elaborations. First, the DILC-model implicitly assumes that there is *one* radical innovation to which incumbent firms reorient in the fourth and fifth phase. The case study is more complex, however, because *multiple* low-carbon cars co-exist simultaneously. Furthermore, views about the best low-carbon car have changed substantially in the last two decades (Geels, 2012). So, while Geels and Penna (2015) explored ups-and-downs in problem-related pressures, this paper also investigates the effects of ups-and-downs regarding various technical solutions. Because the multitude of technical solutions and their ups-and-downs creates additional uncertainty, it may be that hedging (in phase 3) lasts longer, delaying strategic diversification and full reorientation towards radical options (in phases 4 and 5).

Second, we aim to nuance the distinction between 'symbolic' and 'substantive' firm strategies, which the DILC-model borrowed from Mahon and Waddock (1992, p. 27), who defined these concepts as follows: "Symbolic action involves attempts to 'frame' an issue. (...) Substantive action, in contrast, involves definitive moves that attempt to actually change or deal with the existing situation in specific, identifiable ways. It often demands the expenditure of

resources (money, equipment, personnel, etc.) to minimally show progress in resolving the actual problem identified". The current DILC-model assumes that firms initially give more emphasis to symbolic actions (phases 1 and 2) and gradually shift towards more substantive action (particularly technological innovation) when problem-related pressures increase (phases 3–5). This paper aims to nuance this conceptualisation by recognizing that technological development can also be used for symbolic purposes (e.g. enhancing public reputations) and political purposes (e.g. showing that certain options are unfeasible or that regulations are not necessary) in early phases. "Carefully chosen displays of symbolism may circumvent the need for substantive change entirely. (...) Outputs [e.g. technologies], procedures, structures, and personnel can all signal that the organization labours on the side of the angels—even if these supposed indicators amount to little more than face work" (Suchman, 1995, p. 588). So, automakers may engage in radical innovation (e.g. low-carbon prototype cars) in early phases for symbolic and political reasons, e.g. signalling to external stakeholders that they are committed to solving environmental problems. This means that we may have to nuance the sequential view on technological reorientation in the current DILC-model (incremental innovation – hedging – diversification – full reorientation towards radical innovation).

Third, because of its lifecycle logic the DILC-model focuses mainly on the *internal* dynamics (struggles between actors concerned about a problem and industry actors) that drive the process

forward. The Triple Embeddedness Framework (Fig. 1) suggests, however, that the industry not only experiences pressures from the focal problem (in this case, climate change). Rather, industries typically experience multiple pressures in socio-political and economic environments, e.g. recessions leading to shrinking markets, rising oil prices that change market demand, other social or environmental problems (e.g. local air pollution, energy security concerns). So, a study of low-carbon reorientation should not only investigate the internal issue lifecycle dynamics, but also how other pressures in industry environments may influence these dynamics, positively or negatively. In other words, such a study must account for the possibility of interactions between multiple problem streams.

We will further explore these three issues empirically in the case study, and return to them in Section 6.

3. Methodology and data sources

The case study focuses on climate change and responses of the American car industry (1979–2012). We selected the car industry, because passenger cars are very high producers of carbon emissions worldwide (accounting to 12% of total US emissions in 2011⁴). We focused on the U.S. because it represents an extreme case: we expect struggle and contestation to be particularly present in America due to confrontational relations between industry and policy/society. Our focus on the U.S. has two principal limitations. Firstly, foreign-owned car companies also operate and produce in the American market. To address this limitation we include discussion of foreign carmaker strategies, which exert pressures on 'domestic' automakers.⁵ Secondly, American automakers operate in other parts of the world. We therefore also discuss some global developments (e.g. climate change policies in Europe and Japan) as pressures on the American car industry.

We apply a novel combined quantitative–qualitative methodology, initially adopted by Geels and Penna (2015). The novelty of this approach consists in using quantitative methods within an issue lifecycle framework (the DILC-model) to identify initial patterns of proxy variables through time. These initial findings are then further explored with an in-depth qualitative analysis to identify causal relationships and mechanisms. We also use the analysis of time-series to divide the whole period into shorter ones.⁶ The proxy variables are rough indicators and thus need to be used with some caution. For the quantitative analysis, we used the following proxies:

- For public attention we use the number of newspaper articles on climate change as proxy (Newig, 2004). We searched the Nexis database for newspaper articles (*New York Times*, *USA Today*, *Wall Street Journal*, and *Washington Post*) with the keywords "climate change", "global warming" or "greenhouse effect" (and derivatives) in their headlines.
- For policy-making activities (congressional attention) and policy-implementation activities (executive branch attention), we used climate-change related entries in the *Congressional Record* and the

Federal Register, respectively.⁷ We searched these publications in the *HeinOnline* database with the same keyword string as above.⁸

- We used article count in the *Automotive News* (American edition) as a proxy for how much attention American automakers dedicate to climate change (same search string as above). We also used this database to trace ups-and-downs in industry attention to different drivetrain technologies (FCV, BEV, HEV, aICE and biofuel/flex-fuel vehicles), searching for articles with keyword-strings related to each of them.⁹
- We use patents as a proxy for technical development by the auto industry. We searched the USPTO database for patents related to the different drivetrain technologies.¹⁰ Our search methodology follows Oltra et al. (2008) for the identification of 'eco-patents' on environmental technologies and 'green' products, which combines in the search string keywords and patent classes related to the focal-technology (see example in Table 2). This method allows for a reduction in 'noise' (i.e. exclusion of irrelevant patents, inclusion of relevant ones). We restricted our search to the three largest American car manufacturers (and their controlled subsidiaries¹¹): General Motors, Ford and Chrysler (the 'Big Three'). Duplicated patents were excluded.

The resulting set was ordered according to the patent's *priority date*, which is the date of the first filing of a similar claim in any patent office, in order to better reflect the timing of the invention. To address the lag between filing and issuing a patent (which leads to a decline in the number of patents in more recent years), we divided the number of patents of interest per year by the total number of patents per year by the selected carmakers to arrive at a percentage index.

We also plotted the market share (relative sales) of the different green technologies in the U.S. market (compiled from the *Electric Drive Transportation Association* (EDTA); the *U.S. Energy Information Agency*; and *Ward's Automotive*). A complication concerns figures for flex-fuel vehicles, which can be fuelled either with ethanol or gasoline or both, and thus may overestimate the share of 'alternative' fuel vehicles.

The quantitative analysis consists of two steps: (a) firstly, we performed a 'Quandt Likelihood Ratio' (QLR) test for unknown structural breaks (see Stock and Watson, 2011, pp. 600–603), in order to identify significant breaks in the time-series¹²; and (b) secondly, we triangulated these findings with a visual examination of the plotted time-series and our substantive knowledge of key events in the case study to establish sub-periods.

While this quantitative approach allows for the identification of general patterns and associations, it does not reveal causal relationships. To identify deeper causation, we also perform a longitudinal qualitative case study, which analyses interactions

⁴ See <http://www.epa.gov/otaq/climate/documents/420f13033a.pdf> [accessed 26.10.14].

⁵ While our focus is on the industry population and its environments, we also discuss firm-level dynamics. However, we do not account for *within-firm* struggles, which would add a fourth analytical level, being beyond the scope of this paper.

⁶ The combined quantitative–qualitative methodology is fully developed and elaborated in Penna (2014), who proposed the use of three quantitative approaches (namely, visual examination of time series representations of proxy indicators; meta correlation analysis; and statistical tests for unknown structural breaks) in combination with a narrative approach within an issue life-cycle framework.

⁷ The *Congressional Record* publishes transcripts of hearings, debates and speeches and bill proposals, indicating evolving attention to issues. The *Federal Register* publishes regulatory agency's notifications and rules and (presidential) executive orders, two key types of policy-implementation action at the U.S. Federal level.

⁸ Proxies for attention present certain limitations, such as not reflecting changes in the interpretation of the issue, size of articles, or intensity of congressional activity. We aim to further access the sensitivity and intensity of public and political attention to climate change in the in-depth qualitative case study.

⁹ Articles citing more than one technology were assigned to all cited technologies.

¹⁰ We used *AcclaimIP* patent search and analysis application: <https://www.acclaimip.com/> (last accessed on 12.04.13).

¹¹ Controlled subsidiaries were identified through the analysis of a selection of each company's financial reports (and filings to the U.S. Securities and Exchange Commission), combined with the knowledge of the authors about the automotive industry.

¹² Our tests included up to four lags (five restrictions), and were applied to the natural logarithm of the variables. All statistics' procedures were performed with Stata 12.

Table 2
Example of patent search string (HEV-related patents in the USPTO assigned to General Motors).

Technology	AcclaimIP search string	Keywords	Classes	Assignees
Hybrid-Electric Vehicles	<p>((PSCLS:180/65.21 OR PSCLS:903) OR (TTL:(("hybrid vehicle" OR "hybrid electric vehicle" OR "hybrid propulsion" OR "hybrid powertrain" OR "hybrid powerplant") NOT "fuel cell"))) OR (ABST:(("hybrid vehicle" OR "hybrid electric vehicle" OR "hybrid propulsion" OR "hybrid powertrain" OR "hybrid powerplant") NOT "fuel cell"))) OR (ACLM:(("hybrid vehicle" OR "hybrid electric vehicle" OR "hybrid propulsion" OR "hybrid powertrain" OR "hybrid powerplant") NOT "fuel cell"))) AND (AN:(("general motors" OR "Delphi Technologies" OR "delphi technology" OR "gm global" OR "gen motors" OR "delco electronics" OR "Saturn Corporation")</p> <p><i>Comment:</i> We searched for keywords in the patent's title (TTL), abstract (ABST) and claims (ACLM). The "AN" operator searches the patent assignee field for certain keywords. The operator "PSCLS" searches for patents with the defined <i>primary</i> patent class(es) and all subclasses under the specific parent class.</p>	<p>"hybrid vehicle", "hybrid electric vehicle", "hybrid propulsion", "hybrid powertrain", "hybrid powerplant"</p> <p><i>Comment:</i> We excluded patents citing "fuel cell". The assignee restriction increases confidence that the patents are related to car technologies.</p>	<p>180/65.21 (and subclasses), 903 (and subclasses)</p> <p><i>Comment:</i> The 65.21 subclass is for "hybrid vehicles" under the class 180 ("motor vehicles"). The class 903 is a specific class for HEV-related technologies.</p>	<p>"general motors", "delphi technologies", "delphi technology", "gm global", "gen motors", "delco electronics", "Saturn Corporation"</p> <p><i>Comment:</i> We included words related to General motors and its controlled subsidiaries that are known to file most of the OEM's patents.</p>

between problem-related pressures and industry responses. Primary sources for developments in civil society are articles from newspapers and magazines (*New York Times*, *Economist*). We also draw on governmental documents (CARB, EDTA/USDoE), industry journals (*Ward's*, *Automotive News*), and publications by automakers and their trade association. In addition, we build on secondary accounts of different aspects of climate change and the car industry: science, environmental movement and public opinion (Corfee-Morlot et al., 2007; Dunlap and colleagues); policy and legal developments (Duffield et al., 2008; Meltz, 2008); corporate cultural and political strategies (Doyle, 2000; Kolk and Levy, 2001; Luger, 2000); automakers' innovation strategies and technological developments (Abeles, 2004; Bakker and colleagues; Budde et al., 2012; Dijk et al., 2013; Johnson, 1999; Kemp, 2005; Lutsey, 2012; MacCormack, 2005; Mondt, 2000; Van den Hoed, 2005); broader industry contexts and financial dimensions (Ingrassia, 2010); environmental challenges facing the car industry (Sperling and Gordon, 2009). Drawing on various primary and secondary sources we aim to develop a comprehensive multi-dimensional analysis of the climate-change problem and car industry responses.

4. Quantitative results

Fig. 2 presents time-series representations of proxies for: (a) public attention to climate change; (b) congressional attention and executive attention; (c) attention by Automotive News; (d) aggregated Alternative Fuel Vehicle (AFV) patents by the Big Three. Fig. 3 presents time-series representations of proxies for: attention by Automotive News to electric-drive technologies, which comprises FCV, HEV, PHEV and BEV (Fig. 3a) and aICE technologies and biofuel/flex-fuel vehicles (Fig. 3b); Big Three patenting of specific technologies (electric-drive technologies in 3c and aICE and biofuel/flex-fuel vehicles in 3d). Fig. 4a shows the market share of alternative fuel vehicles and Fig. 4d shows the market share of Electric Drive Vehicles (EDV).

To determine periods and break points (already represented above with vertical dotted lines), we used the results of QLR-tests for structural breaks in selected time-series, presented in Table 3, which we have linked to certain key events: (a) the first break in public and congressional attention link with the 1988 Senate Hearings on global warming; (b) public attention, Congress and Automotive News have all breaks associated with Kyoto; (c)

all series have a break in the mid-2000s, when climate change became a highly salient issue; (d) patenting and sales time-series also have breaks associated with intra-industry events (e.g. GM's development of the EV *Impact* in early 1990s, the establishment of the battery development partnership USABC, Toyota's launching of the *Prius*, and the consolidation of the HEV market).

Based on this analysis and a visual examination of charts in Figs. 2(a–d), 3(a–d) and 4 (a and b) we distinguish five periods: 1979–1988 (when climate change had low salience); 1988–1997 (moderate public and political attention, and some patenting activity); 1997–2005 (gradual rise in public attention, political attention, and patenting); 2005–2009 (rapidly increasing public and political attention, accelerated patenting and HEV-sales); and 2009–2012 (declining public and political attention because of the financial crisis, oscillating HEV-sales, but increasing executive activity and patenting).

The charts in Fig. 3 show the occurrence of various technology hype-cycles. We distinguish five overlapping cycles: 1st BEV hype (1988–early-2000s); HEV hype (2001–2009); FCV hype (1995–2009); biofuel hype (2006–2009) and new BEV hype (2005 onwards). The ups-and-downs come out stronger in the Automotive News attention graphs (Fig. 3a and b) than in the patent graph (Fig. 3c and d). This suggests that technological development may continue after attention bubbles have burst. Throughout the whole period, there is steady rise in patenting of all alternative technologies (Fig. 2d), which indicates increasing development of low-carbon technologies, despite fluctuating industry attention to climate change (Fig. 2c). The qualitative case study will further analyze the drivers of various hype-cycles and their influences on the lifecycle process. Based on these quantitative results we advance four further observations.

- Industry attention and technology strategy towards flex-fuel vehicles and biofuels increased substantially by 2005 (Fig. 3b and d). Patenting activity, however, increased relatively less than industry attention, which suggests that biofuels and flex-fuels were incremental innovations (requiring some tinkering with ICE, but no substantial redesign that warranted patenting). The relatively low degree of biofuel patenting is even more striking if we consider the fact that biofuels/flex-fuels have reached some degree of market penetration (Fig. 4a).

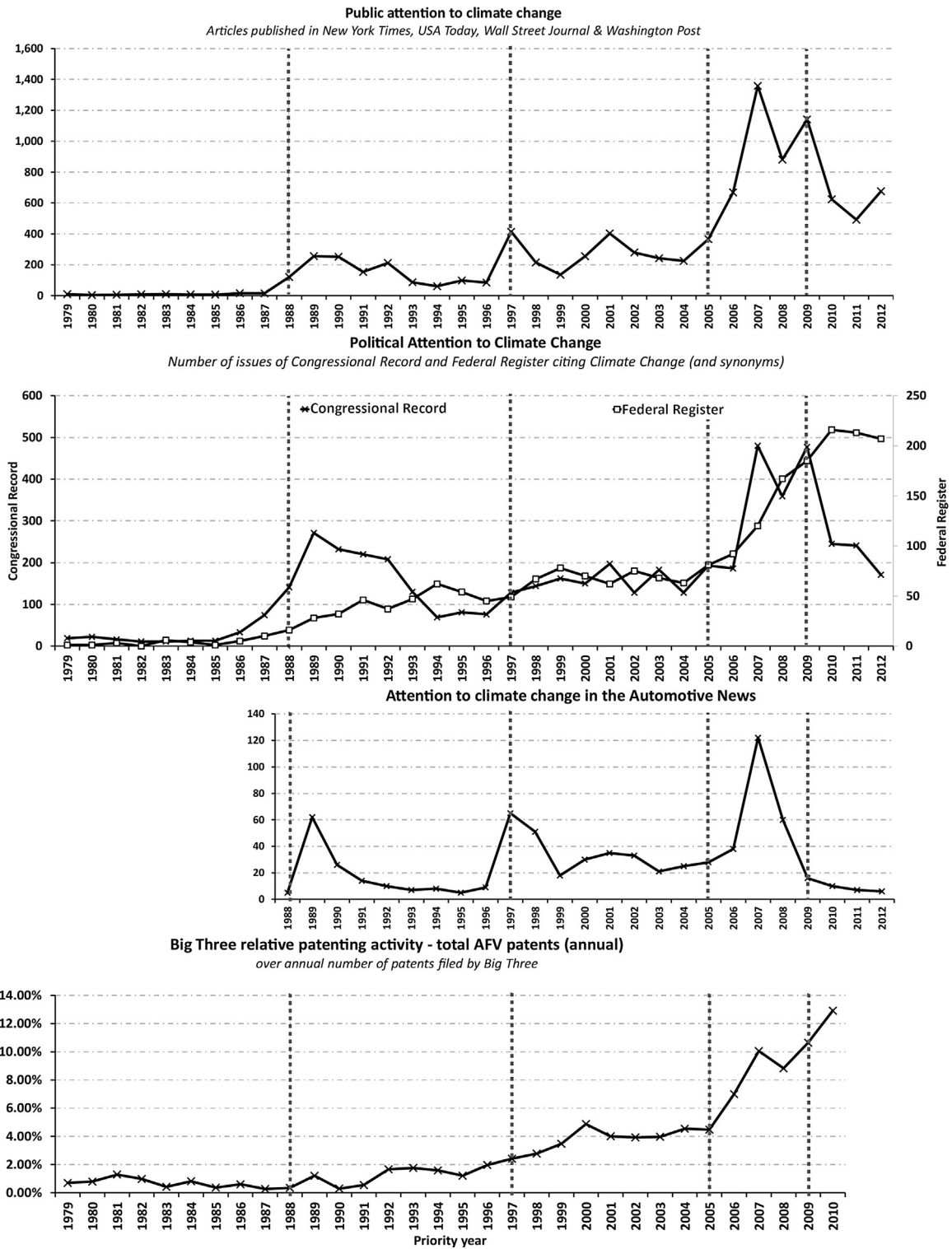


Fig. 2. (a–d, top-down) Visual representation of proxy variables defined in Section 3.

- Incremental improvements with aICE have been pursued throughout the entire period, but accelerated in the early 2005, indicating a ‘sailing ship’ effect, whereby threats from radical technologies stimulate old technology improvements.
- By 2010, there is substantial patenting activity for all technical options, which suggests that firms remain uncertain about which powertrain option will prevail, and therefore adopt a hedging strategy.
- Despite the attention and patenting in electric drive vehicles, Fig. 4a and b shows that actual market diffusion of alternative fuel vehicles is dominated by biofuel/flex-fuel vehicles (FFVs). In later periods, the share of EDVs grows, but still constitutes just a few percentage of the total market, creating uncertainties about mass diffusion of EDVs (the market share of EDVs remained stagnant at 3.52% in 2013 (EDTA, 2014)). This may make automakers reluctant to abandon ICE vehicles, as small

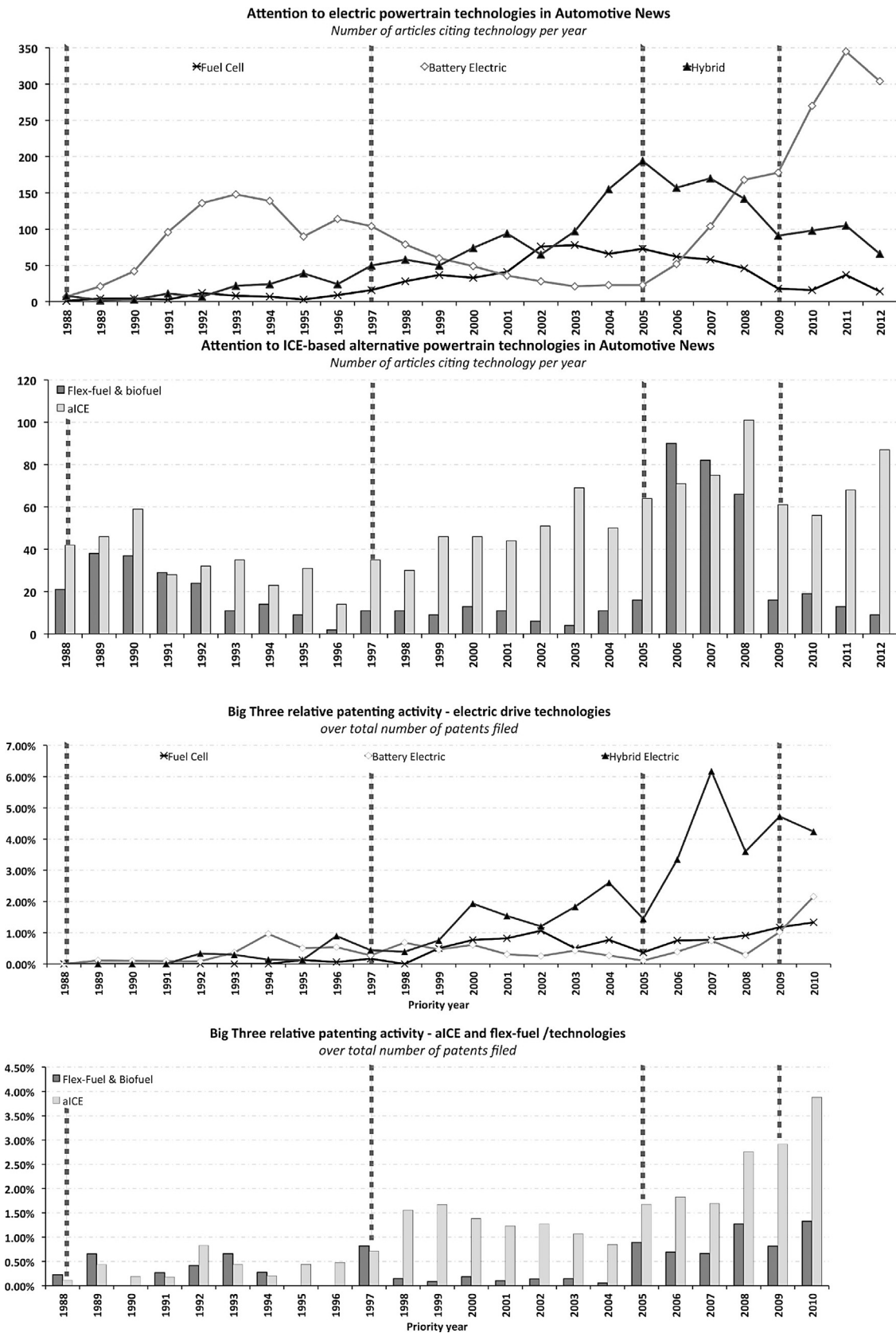


Fig. 3. (a–d, top-down) Visual representation of proxy variables defined in Section 3.

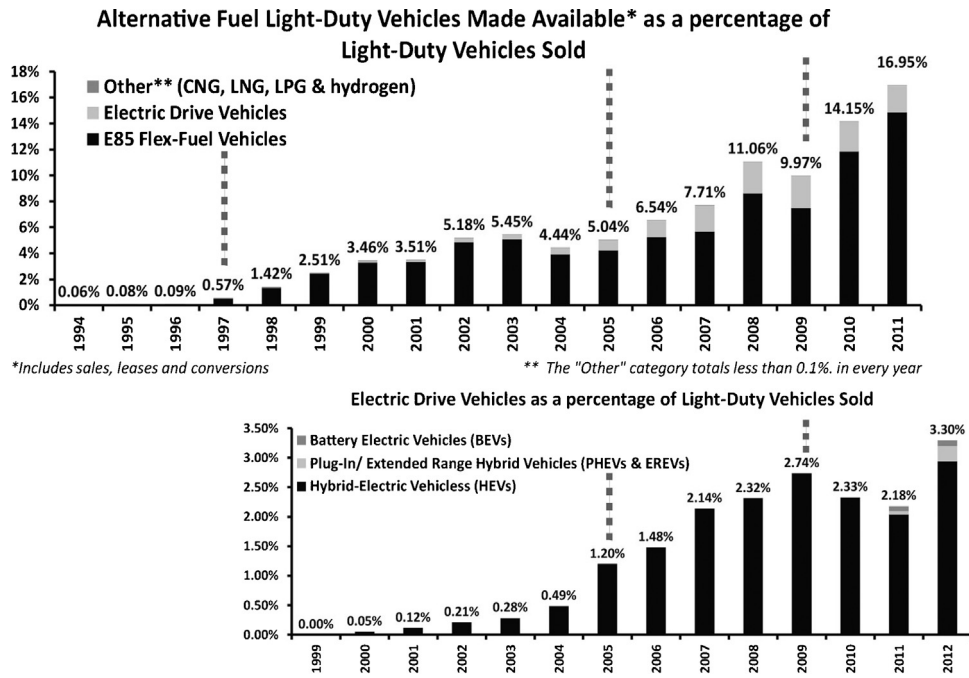


Fig. 4. (a and b, top-down) Market share of AFVs and EDVs, respectively.

EDV-sales do not (yet) offset the risks of strategic technological reorientation.

The next section will further analyze casual connections and dynamic relationships.

5. Qualitative case study of climate change and the U.S. car industry

We now turn to the qualitative analysis of the five periods: 1979–1988, 1988–1997, 1997–2005, 2005–2009, and 2009–2012. Using the DILC-model as an ideal-type, we describe for each period:

(1) problem-related pressures (from science, social movements, public opinion, policymakers); (2) response strategies from the car industry.

5.1. Problem emergence, sense-making and industry indifference (1979–1988)

5.1.1. Pressures around issue

5.1.1.1. Science, social movements, public attention. In the 1970s, climate change emerged as a permanent research topic at scientific meetings and conferences, where possible causes, effects and uncertainties were discussed (Corfee-Morlot et al., 2007). The environmental movement began calling for measures to tackle global

Table 3
Results of QLR tests for structural breaks and key episodes in the climate change issue lifecycle.

	Breaks	Key episodes
Public attention to climate change	1986–1988 [*] 1996 ⁺ 2005–2007 [*]	1988: New York Times announces “Global Warming has begun” 1997: Kyoto Protocol 2005: Hollywood’s <i>Day after tomorrow</i> 2007: Nobel Peace Prize to IPCC and Al Gore
Congressional attention to climate change	1984–1989 [*] 1992–1997 [*] 2006–2007 [*]	1988: Senate Hearings on Global Warming 1997: Debate on Kyoto Protocol 2005: Energy Security Act
Executive attention to climate change	2004–2007 [*]	2005: Second Bush (Jr.) administration 2007: Supreme Court’s decision on EPA responsibility to regulate GHG emissions from cars
Automotive News attention to climate change	1995–1998 [*] 2007 [*]	Before-1997: industry denies climate change After-1997: industry begins to acknowledge climate change 2007: Supreme Court’s decision (+ Nobel Prize to IPCC/Al Gore)
Big Three AFV patents	1986–1990 [*] 2005–2006 [*]	Late-1980s: GM develops EV model <i>Impact</i> Mid-2000s: multiple technology hype cycles, Big Three catching up with HEV technology
Electric Drive market share	2000 [*] 2003–2005 [*]	2000: Toyota starts selling Prius (HEV) in U.S. Mid-2000s: consolidation of HEV market niche
HEV market share	2000 [*] 2003–2007 [*]	2000: Toyota starts selling Prius (HEV) in U.S. Mid-2000s: consolidation of HEV market niche

^{*} Significant at 1% level.
⁺ Insignificant local peak of QLR statistic.

Table 4
CARB original sales requirements under the LEV/ZEV mandate (Kemp, 2005, p. 175).

Model year	Conventional vehicles	Transitional low emission vehicles (TLEV)	Low emission vehicles (LEV)	Ultra-low emission vehicles (ULEV)	Zero-emission vehicles (ZEV)
1994	90%	10%	–	–	–
1995	85%	15%	–	–	–
1996	80%	20%	–	–	–
1997	73%	–	25%	2%	–
1998–2000	48%	–	48%	2%	2%
2001–2002	–	–	90%	5%	5%
2003	–	–	75%	15%	10%

warming. Public attention remained low (Fig. 2a), because environmental news was dominated by other issues such as nuclear energy, acid rain and the ozone hole (Dunlap, 1992).

5.1.1.2. Policy-makers. American political activity was symbolic, leading to a few Senate hearings and research funding decisions (Rothenberg and Levy, 2012). Senator Al Gore and others wrote a public letter (1986) declaring to be ‘deeply disturbed’ about climate change and calling for policy action (Yergin, 2011).

While climate change received little attention, policymakers were very concerned about energy security because of the first (1973) and second (1979) oil crisis. In 1974, they had therefore enacted fuel economy regulations. The CAFE (Corporate Average Fuel Efficiency) standards started at 18 MPG for 1978 models and would increase to 27.5 MPG in 1985. Because American automakers were oriented towards gas-guzzling vehicles (and had just opened the new ‘light-truck’ segment), they found it hard to comply (Ingrassia, 2010), leading the NHTSA (National Highway and Traffic Safety Administration) to postpone the 27.5 MPG requirement to 1990. Although CAFE standards were originally created to address the energy security issue, by the mid-2000s environmentalists and policy-makers would call for their strengthening as a way to address CO₂ emissions.

5.1.2. Car industry issue responses

The car industry was unconcerned with climate change (Rothenberg and Levy, 2012). Automakers did engage with air pollution regulations by introducing the three-way catalytic converter innovation in 1983, but were generally not concerned about environmental issues (Penna and Geels, 2012). They were more interested in the opening up of the new market segment, starting with Chrysler’s *Minivan* (1983), and morphing into Sports Utility Vehicles (SUVs). This market segment, which commanded high profit-margins (Ingrassia, 2010), was purposively designated as ‘light-trucks’ (implying they were for commercial use), so that this category became subject to more lenient fuel economy standards (Luger, 2000).

5.2. Rising public concerns and the creation of a closed industry-front (1988–1997)

5.2.1. Pressures around issue

5.2.1.1. Science, social movements, public attention. Public attention increased in the late-1980s and early 1990s (Fig. 2a) because of hot summers (record-high temperatures, droughts), the 1988 Senate Hearing on global warming (see below), and framing struggles between scientists/environmentalists and climate-sceptics supported by industry (Doyle, 2000; Luger, 2000). The newly created (1988) *Intergovernmental Panel on Climate Change* (IPCC) also stimulated public attention with comprehensive assessment reports (in 1990 and 1996), which reviewed and integrated scientific findings (Corfee-Morlot et al., 2007).

5.2.1.2. Policy-makers. Political action occurred at multiple levels. The first IPCC report (1990) provided the basis for international negotiations, which resulted in the *United Nations Framework Convention on Climate Change* (UNFCCC) at the 1992 *Rio Earth Summit*. Although Rio-1992 established the goal of stabilizing greenhouse gas (GHG) concentrations, the Framework was a voluntary, non-binding agreement (Kolk and Levy, 2001). In 1995 (Berlin), signatory parties agreed that targets would be formulated for industrialized nations but not for developing countries. In 1996 (Geneva), parties accepted the findings from the second IPCC assessment report, and called for legally binding targets and timeframes (Corfee-Morlot et al., 2007).

At the U.S. Federal level, the 1988 Senate hearings marked the emergence of climate change as a political issue (in policy sub-systems and (briefly) at the macro-political level). The testimony of NASA climate scientist James Hansen was widely reported in the mass media, and politicians began jockeying for the fatherhood of a ‘global warming act’, proposing various bills that addressed global warming via fuel economy legislation or clean air policy (Doyle, 2000).¹³ These bills failed to pass because of strong corporate lobbying or threats that the President would use his veto (Luger, 2000). Instead of targets and regulations, Bush (senior) preferred a voluntary approach through public–private partnerships (PPPs) aimed at developing advanced technologies and promoting alternative fuels (mainly ethanol/methanol) (Duffield et al., 2008; Yergin, 2011). The newly elected (1993) president Clinton also preferred collaboration to legislation, and established the *Partnership for a New Generation of Vehicles*. In return for industry participation, he offered a moratorium on mandated fuel economy increases (Luger, 2000).

At the U.S. state level, California’s ‘Zero-Emission Vehicle’ (ZEV) mandate (1990) was a radical legislation that required the seven biggest automakers to sell a fleet mix that included different categories of vehicles according to increasingly stringent emission levels (Table 4) and setting a tough fine (\$5000) per non-compliant vehicle (Kemp, 2005). The mandate was initially formulated as a solution to local air pollution problems, but increasingly became part of California’s strategy to control GHG emissions (CARB, 2012). The ZEV-plan was in effect a sales mandate, because “battery-powered electric vehicles were the only zero emission automotive technology on the horizon” (Doyle, 2000, p. 274). By 1994, other states were considering to adopt the Californian ZEV mandate, which led the Big Three (GM, Ford, Chrysler) to start an intense lobbying campaign (Sperling and Gordon, 2009). The ZEV-regulation also established biannual reviews, which offered carmakers an opportunity to shape the policy process. While the original regulation survived the first two reviews, CARB (California Air Resources

¹³ Examples are the *Global Warming Prevention Act* (which included a fuel efficiency mandate of 45 MPG for cars and 35 MPG for trucks by 2004); the *National Energy Policy Act*; the *World Environment Act* (sponsored by Senator Al Gore); the *Global Environmental Protection Act* (calling for a 50% reduction in automotive carbon emissions, equivalent to a fuel economy standard of 55 MPG).

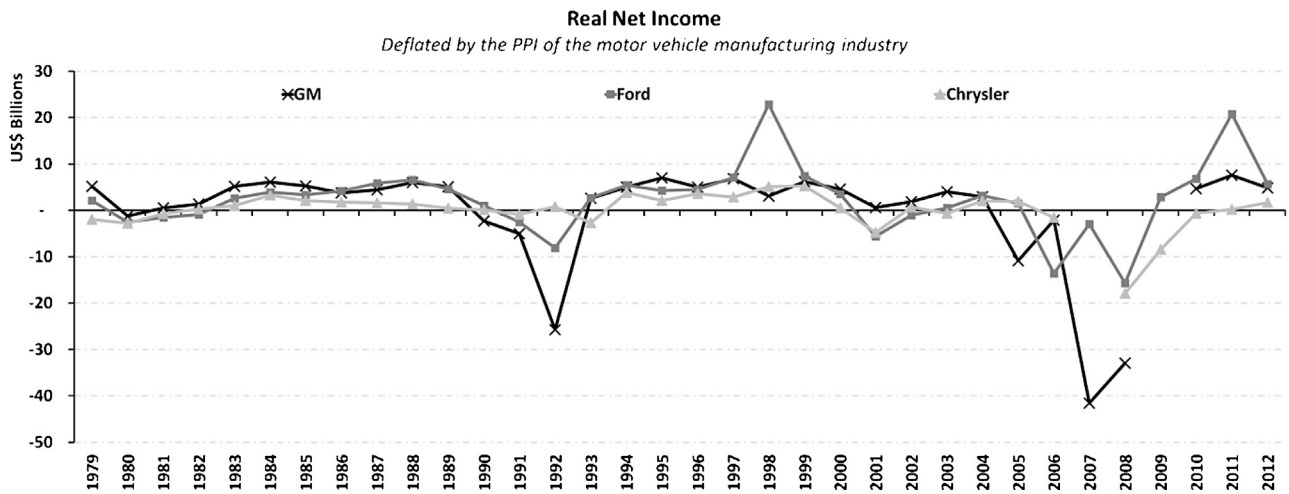


Fig. 5. Real net income (2012 dollars, deflated by the PPI) of the Big Three (Geels and Penna, 2015 and companies' financial statements) (from 1998–2006, Chrysler's figures correspond to the operating profit (loss) of the Chrysler Group of DaimlerChrysler).

Board) dropped the 1998–2002 requirements in 1996 under great pressure from automakers (Kemp, 2005).

5.2.2. Car industry issue responses

5.2.2.1. *Social-cultural strategies.* In 1989, the Big Three, the American Automobile Manufacturers Association (AAMA), and forty other American companies formed the *Global Climate Coalition* (GCC), which created a 'closed industry front' that attacked global warming science and accused the IPCC of downplaying uncertainties (Kolck and Levy, 2001). American automakers also set up civilian 'astroturf' organizations to create pressure on politicians. The *Coalition for Vehicle Choice* (CVC), for instance, initiated letter-writing campaigns to politicians and promoted the view that stricter CAFE standards would limit vehicle choice and 'outlaw' SUVs and pickups (Luger, 2000).

5.2.2.2. *Political strategies.* Automakers attacked the Californian ZEV mandate, with the AAMA officially establishing the strategic goal of "creating a climate in which the [California EV] mandate [...] can be repealed" (cited in Doyle, 2000, p. 294). For the ZEV-mandate's third review (1996) the Big Three aligned their positions, complaining about the state of battery development, low consumer demand, and lack of infrastructure (Johnson, 1999); "the automakers joined together to insure that none of them separately would go out ahead of the others – although GM clearly had the technological lead" (Doyle, 2000, p. 322). An independent 'Battery Technology Advisory Panel' also concluded that battery costs would represent a barrier to EV diffusion by 1998 (Kemp, 2005). In 1996, CARB decided to drop the 1998–2002 sales requirements.

American automakers also opposed Federal proposals to increase fuel economy standards. Financial contributions incentivized politicians to vote against legislation, resulting in "a strong correlation between the amount of money received from the auto industry and [Senators'] votes" on CAFE proposals (Luger, 2000, p. 168).

5.2.2.3. *Innovation strategies.* Environmental technology strategies of American automakers mostly focused on incremental innovations such as advanced-Internal Combustion Engine (aICE) technologies (Fig. 3d), which included improved fuel injection systems and lean-burn catalysts (Mondt, 2000). Another strategy to defend existing ICE technology was the development of ethanol-fuelled or flex-fuel vehicles (FFV), which were capable of running on methanol/ethanol or gasoline or a mixture of both (e.g. E85,

an 85% ethanol-gas mixture). Automakers also focused on FFVs because the 1988 *Alternative Motor Fuels Act* (AMFA) assigned CAFE credits to their production (Duffield et al., 2008). By 1997 almost 85,000 E85 Flex-Fuel Vehicles were sold, leased or converted (Fig. 3c).

Carmakers (except GM) gave relatively little innovative attention to alternative powertrain technologies (Van den Hoed, 2005). In the late 1980s, General Motors dedicated some resources to a radical innovation (BEV) for reputational reasons. The *Impact*-prototype was meant to demonstrate that GM was not a stale, boring company, but still mustered innovative capabilities (Johnson, 1999). But the *Impact* 'show-car' generated so much positive publicity at the Los Angeles Motor Show (1990) that GM announced it would market the car (Doyle, 2000). CARB interpreted this announcement as an indication that BEVs were sufficiently developed, and issued the ZEV mandate (Kemp, 2005). Subsequently, GM created a 400-person, \$300-million BEV programme (Doyle, 2000) to produce 25,000 vehicles per year by 2000 (Kemp, 2005).

To contain the possibility of an innovation race, the Big Three formed another closed industry-front (1991) so that all companies would move together technologically. The *U.S. Advanced Battery Consortium* (USABC) was a public-private partnership launched by President Bush (senior) and the Big Three. Although most of the funds came from the Department of Energy (DoE), the Big Three ran the programme and decided which battery developers and projects received grants (Doyle, 2000). The USABC fulfilled several roles for American automakers (Luger, 2000): (a) improving their public reputation; (b) controlling technical development; (c) managing technological expectations through the establishment of (unrealistic) mid-term goals (such as a minimum driving range of 150-miles); and (d) controlling the release of technical information to policymakers to prevent that standards would be ratcheted up. According to a former GM employee, "the automakers formed USABC to hinder rather than enhance product development by controlling research and development efforts" (cited in Doyle, 2000, p. 309).

In 1992, GM down-scaled its BEV project to a small \$32-million demonstration programme (Kemp, 2005). GM decided to lease its electric car for \$33,995, about half of real costs of \$78,000 (MacCormack, 2005). By 1996–1997, GM had leased about 760 units (MacCormack, 2005), which was far below initial expectations. Critics accused GM of deliberately under-promoting electric cars (Sperling and Gordon, 2009).

In 1993 American automakers also joined the *Partnership for a New Generation of Vehicles* (PNGV), another PPP to develop technological solutions to the issues of energy security and global warming. This \$300-million joint-venture with Federal research laboratories aimed at developing a ‘production prototype’ by 2003, capable of reaching fuel economy of 80 MPG, without sacrificing size, performance or safety (Doyle, 2000). PNGV served similar purposes as USBAC: directing technical developments, controlling technological expectations and playing on information asymmetries. In exchange for their participation the Big Three also secured a moratorium on Federal CAFE increases (Luger, 2000). The Big Three also used the PNGV to pre-empt regulatory action, claiming that self-regulation and PPPs were more effective than ‘command-and-control’ regulations. Although PNGV developed some new technologies (e.g. lightweight materials, lithium-ion battery cell, fuel-flexible processors for a fuel cell), the Big Three directed most research efforts towards incremental technologies for advanced diesel engines (e.g. lean-burn NO_x catalysts, diesel direct fuel injection systems) and (diesel) hybrid powertrains (Mondt, 2000).

5.2.2.4. Foreign automakers. In response to the ZEV mandate and PNGV, Toyota decided to develop a car with 100% fuel economy improvement, which in 1997 resulted in the Toyota *Prius* hybrid car. In 1997, Honda also demonstrated their *Insight* hybrid car (Doyle, 2000). HEVs were initially derided by American automakers, because twin-powertrains substantively increased costs. GM perceived HEVs as ‘interim’ technology, and decided instead to focus on fuel cells, which would “make hybrids obsolete” (MacCormack, 2005, p. 15). DaimlerBenz pioneered FCVs and unveiled a cumbersome prototype, the NECAR I [New Electric Car], in 1994. The smaller NECAR II (1996) triggered more enthusiasm (Budde et al., 2012) and put fuel cells on the map of zero-emission technologies.

5.2.2.5. Market positioning strategies. Climate change hardly affected American automakers’ market positioning strategies, which were firmly oriented towards selling profitable light-trucks. Car and truck sales fell in the early 1990s, because of the economic recession, causing major financial problems (Fig. 5). GM suffered major losses, because of additional expenditures for pension-fund commitments (Ingrassia, 2010). The financial situation improved after 1993, because of the booming light-truck market.

5.3. Political stalemate and defensive hedging (1997–2005)

5.3.1. Pressures around issue

5.3.1.1. Social movements, public attention. Public attention increased in 1997 (Fig. 2a) because of the U.N. meeting in Kyoto (Japan). Progressive businesses such as the *Pew Center on Global Climate Change* began to endorse the climate change issue (Rothenberg and Levy, 2012), advancing a ‘win–win’ discourse, which argued that proactive climate change strategies could benefit businesses. In 1999, environmentalists filed a petition to the EPA requesting it to undertake its ‘mandatory duty’ of regulating motor vehicle GHG emissions (Meltz, 2008).

5.3.1.2. Policy-makers. At the global level, the Kyoto Protocol (1997), in which many countries pledged to reduce GHG emissions by an average of 5% below 1990 levels by 2012, was a significant political step. Although the U.S. played a key role in the negotiations, Clinton/Gore never submitted the treaty for Senate ratification, because they anticipated rejection (Doyle, 2000). In Europe automakers signed a ‘voluntary’ agreement (in 1998) with the European Commission to reduce average new car emissions to 140 gCO₂ per kilometre (≈39 MPG) by 2008–2009.

In 2001, the newly elected President Bush (junior) rejected the Kyoto Protocol for being ‘unfair and ineffective’, creating regulatory

stalemate at the Federal level. Some U.S. congressmen proposed legislation to address GHG emissions. Senators McCain and Lieberman, for instance, proposed a cap-and-trade system in 2003, but the bill was never voted on. Other bills also faced strong opposition (Yergin, 2011). In 2003, EPA denied the petition filed by environmental groups, arguing that EPA did not have authority under the Clean Air Act to regulate GHGs (Meltz, 2008). The State of Massachusetts (with eleven other states, three cities, two U.S. territories, and several environmental NGOs) appealed, but this was rejected by an Appeals Court in 2005.

Although the government did not regulate, it stimulated technological development, particularly of fuel cells, with the 2003 *FreedomCAR and Fuel Partnership* and the 2004 *Hydrogen Fuel Initiative*, a \$1.2 billion research-funding project. These programmes, which were primarily motivated by energy security and only secondarily by climate change, tripled available funding and contributed to fuel-cell enthusiasm (Bakker et al., 2012).

Climate change policy also experienced difficulties in California. Because of limited market demand for low-emission vehicles, CARB’s fourth ZEV-mandate review (1998) gave automakers more flexibility, e.g. postponing some requirements, establishing a credit system (Kemp, 2005). In 2001, CARB recognized further barriers (cost, lead-time, technical challenges) and further amended the mandate, requiring only 2%-sales of ‘pure-ZEVs’ (BEVs and fuel cell vehicles) by 2003 (Kemp, 2005). It also accommodated latest technological developments, so that ‘Advanced Technology Partial Zero Emission Vehicles’ (e.g. HEVs) and ‘Partial Zero Emission Vehicles’ (e.g. natural gas and other aICE vehicles) could be used to meet the other 8% requirement. Automakers contested the amendment in court (see below), resulting in a court decision (2002) that prohibited CARB to enforce the programme. To overcome the political gridlock CARB’s 2003 amendments removed all references to fuel economy, delayed the ZEV requirements to 2005, and included a new compliance path to promote the diffusion of fuel cell vehicles: automakers would be exempted from the 2% pure-ZEV requirement if they increased sales of FCVs from 250 by 2008 to 50,000 by 2017.

Another development was that California adopted the *Pavley Act* in 2002, which instructed CARB to regulate GHG emissions from motor vehicles (Sperling and Gordon, 2009). In 2004 CARB issued new rules requiring 30% reductions in new car GHG emissions by 2016 (Lutsey, 2012).

5.3.2. Car industry issue responses

5.3.2.1. Socio-cultural strategies. American automakers initially endorsed the GCC approach of contesting climate science, influencing public opinion and lobbying Washington politicians (Doyle, 2000). But in the late-1990s, they changed their position because of several reasons: (a) fear that climate denial campaigns would damage their reputation in the context of increasing public concerns (Doyle, 2000); (b) foreign automakers benefitted from a ‘halo effect’ on their reputations for selling ‘greener’ cars (Abeles, 2004); and (c) American automakers faced credibility pressures from constructive business coalitions (*Pew Center*) and the ‘win–win’ business discourse. Ford abandoned the GCC in 1999, acknowledging climate change and calling upon the auto industry to show leadership. GM and Chrysler followed in 2000. This was a major change in position, weakening the industry’s closed industry front (Rothenberg and Levy, 2012).

5.3.2.2. Political strategies. Although American automakers acknowledged the climate change problem, they politically opposed Federal fuel economy standards. Also in California they testified against the ZEV mandate in CARB’s 2000 hearings, arguing that consumers were not willing to pay for BEVs (Sperling and Gordon, 2009). Automakers argued in favour of the ‘more promising’ fuel cell technologies, and cited their voluntary research

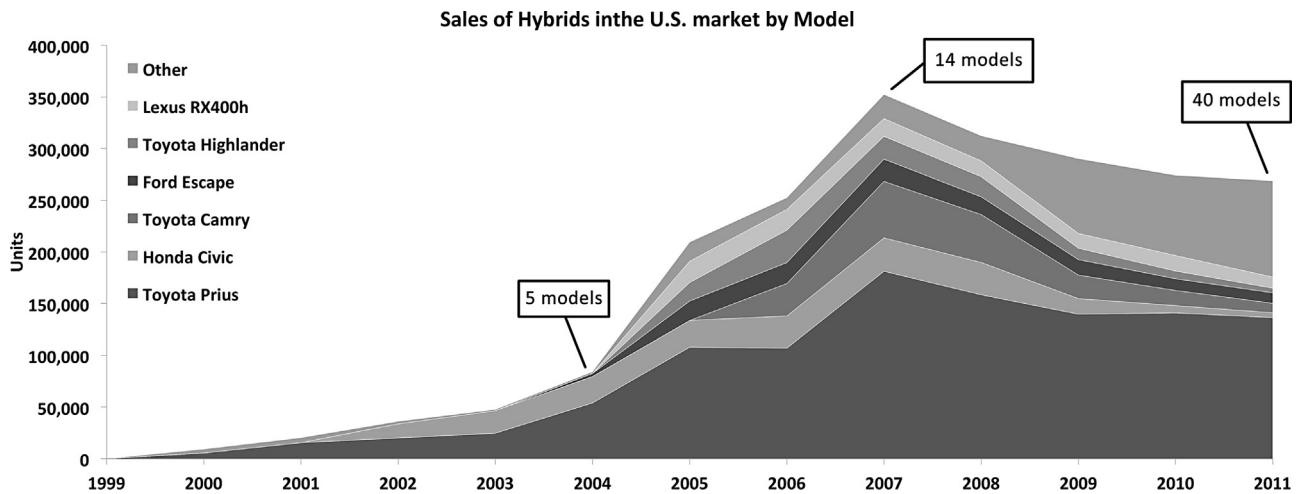


Fig. 6. Sales of HEVs in the U.S. market by model.

Source: Author's elaboration based on data from www.afdc.energy.gov/afdc/data/ (accessed 13.02.13).

initiatives to argue that regulation was not needed (Doyle, 2000). Although CARB relaxed ZEV requirements in 2001, the industry opposed any kind of ZEV mandate. GM therefore led a lawsuit against CARB, arguing that the ZEV-mandate was pre-empted by Federal CAFE standards (Meltz, 2008). The underlying motivation was that carmakers preferred to discuss climate change regulations at the Federal level, where they had a powerful lobbying force and support of many congressmen (Sperling and Gordon, 2009).

Automakers also opposed the Pavley Act (2002), suing the state of California by questioning (a) whether GHG was a pollutant under the CAA (which would allow California to set stricter emission standards); and (b) whether setting GHG emission standards was the same as setting CAFE standards (which was a Federal and not a state-level duty) (Meltz, 2008). The legal processes dragged on, gaining automakers several years of delay. Additionally, Detroit automakers secured 'political favours' from the Bush administration such as extended CAFE credits for vehicles that can burn E85, even if those vehicles never use anything but gasoline (Sperling and Gordon, 2009).

5.3.2.3. *Innovation strategies.* On technical dimensions, American automakers hedged. On the one hand, their main orientation remained the incremental improvement of ICEs and the marketing of flex-fuel vehicles. The combined share of aICE and FFV/biofuel patents in the Big Three annual portfolio trebled from 0.5% in 1996 to an average of 1.5% in 1997–2005 (Fig. 3d). On the other hand, they accelerated investments in alternative powertrain technologies, but without strong intention of mass-marketing (Doyle, 2000). Longer-term technology strategies shifted from battery-electric vehicles to fuel cell vehicles (Van den Hoed, 2005), causing a change in industry attention (Fig. 3a) and industry patenting (Fig. 3c). American carmakers also established the *California Fuel Cell Partnership* (1999), which was a cooperative joint-venture between CARB, incumbent automakers and oil companies (Sperling and Gordon, 2009). From 2000 to 2007, fuel cell enthusiasm resulted in increasing numbers of hydrogen/fuel cell prototypes and optimistic promises about technological developments and commercialization (Bakker and van Lente, 2009). But gradually these promises were projected further ('about 10–15 years') into the future, causing deflation of the hydrogen hype after 2006/7 (Bakker, 2010).

The PNGV made limited contributions to new technology development, with the industry's trade journal *Automotive News* recognizing that the Partnership produced 'few tangible results'

(Stoffer, 2002). Critics claimed that the benefits of PNGV were more political than technological.

5.3.2.4. *Foreign automakers.* PNGV had an unintended consequence, because foreign automakers perceived it as a serious technology development programme (Sperling and Gordon, 2009). In response, Toyota and Honda pushed the commercialization of HEVs, while Daimler-Benz (DaimlerChrysler from mid-1998) led fuel cell developments. The two-seater Honda *Insight* (introduced in the U.S. market in 1999) and the Toyota *Prius* (introduced in 2000) boosted the environmental and technological reputation of Japanese companies (Abeles, 2004). The *Prius*, in particular, became a personal statement of environmental consciousness (Abeles, 2004). Hybrid sales accelerated after 2004 and led to an innovation race in subsequent years, with the number of models for sale jumping from 5 in 2004 to 40 in 2011 (Fig. 6).

In this period, DaimlerChrysler became a leader in FCVs, fitting a fuel-cell system (costing \$35,000 apiece) on a 5-seat passenger car in 1999 (NECAR 4). This led its Chairman to declare that "the race to develop the fuel cell car is over [...] Now we begin the race to lower the cost to the level of today's internal combustion engine. We'll do it by 2004" (quoted in *The Economist*, 1999, p. 88). In 2000, DaimlerChrysler announced investments of \$1.4 billion to bring FCVs to market (Van den Hoed, 2005), with goals to sell 40,000 FCVs by 2004 and 100,000 by 2006 (Sperling and Gordon, 2009). These optimistic announcements triggered a 'fuel cell hype' and R&D race, with most car companies investing in FCV-research (Bakker, 2010) (see also Fig. 3a and b). FCVs seemed promising because of energy efficiency, quietness, quick refuelling, and zero emissions, without compromising on performance. But high relative costs and the lack of a hydrogen infrastructure formed problems for market uptake (Sperling and Gordon, 2009).

5.3.2.5. *Market positioning strategies.* The Big Three's positioning strategy continued to focus on flex-fuel vehicles, which helped them obtain CAFE credits. By 2005, flex-fuel vehicles (4.22%) made up the bulk of total AFV sales (5.04% of total U.S. light-duty sales) (Fig. 4a). In 2002, when it leased only 457 units of the second generation EV1, GM decided to discontinue production and lease contracts (Sperling and Gordon, 2009). This decision aligned with GM's political position (opposing ZEV mandate and climate change regulations) and shifting strategy towards fuel cells. The decision had negative reputational effects, because critics claimed that

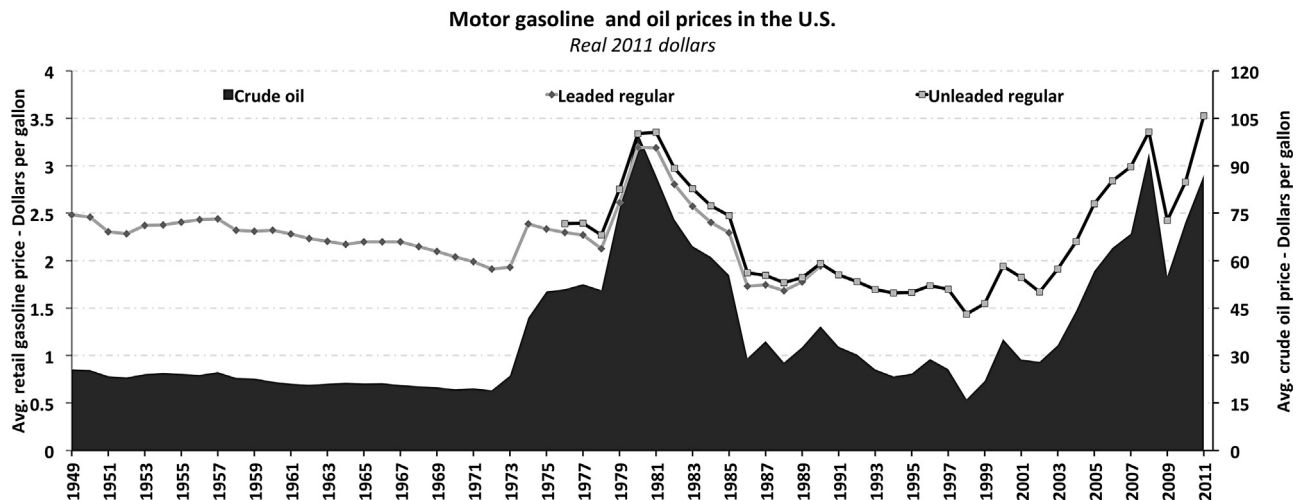


Fig. 7. Motor gasoline and oil prices in the U.S. in real 2011 dollars.

Based on data from the U.S. EIA (<http://www.eia.gov/petroleum/data.cfm#prices>, accessed 31.10.12).

it was a political move to obstruct the ZEV programme (e.g. the documentary *Who killed the electric car?*, launched in 2006 by a former EV1-leasee).

Overall market conditions for American automakers continued to decline. As foreign firms (especially Japanese automakers) gained market share, American automakers became increasingly reliant on the light-truck segment (Ingrassia, 2010). World-wide pressures accelerated consolidation in the global automotive industry, with Chrysler merging with Daimler (1998), Hyundai taking over Kia (1998); Renault and Nissan establishing the Renault-Nissan Alliance (1999); Ford acquiring Volvo (1999); GM acquiring Saab (2000).

5.4. Changing gear (2005–2009)

5.4.1. Pressures around issue

5.4.1.1. *Public attention.* Public attention greatly accelerated after 2005 reaching an unprecedented peak in 2007 (Fig. 2a), because of several catalytic events: (a) Hurricane Katrina (2005) became a powerful image of potential consequences of climate change; (b) Tony Blair declared climate change a top priority at the 2005 G8 meeting; (c) Al Gore's movie *An Inconvenient Truth* (2007) boosted climate change awareness; (d) the IPCC's *Fourth Assessment Report* (2007) reported a scientific consensus about an 'unequivocal warming trend'; (e) the IPCC and Al Gore were awarded the Nobel Peace Prize (2007). Increasing public attention created pressure on policymakers and industry.

5.4.1.2. *Policy-makers.* Oil prices, which had been rising steeply since 2003 (Fig. 7), caused concerns for the re-elected (2004) Bush administration, resulting in the 2005 *Energy Act* and the *Energy Independence and Security Act* (2007). These acts signalled a shift in policy-orientation, because they were the first comprehensive energy policies in more than a decade. They also contributed to unlocking the Federal regulatory stalemate. While these Acts were primarily motivated by oil prices and energy security concerns, they also stimulated low-carbon technologies in the transport domain. The 2005 *Energy Act* mandated a 100%-increase in the volume of ethanol mixed with gasoline between 2006–2012, and provided R&D subsidies for HEVs, FCV and advanced battery research. The 2007 Act mandated a further increase in biofuel production to 36 billion U.S. gallons by 2022 (Sperling and Gordon, 2009), making biofuels into a crucial national strategy and stimulating the diffusion of flex-fuel vehicles (Fig. 4a). The 2007 Act also raised CAFE

standards to 35 MPG by 2020, linking energy security and fuel efficiency to the climate change agenda.

In Europe, frustration with automakers, which were on track to miss the voluntary 1998 agreement, led policymakers (in 2007) to issue mandatory car-emission standards for 2015 (130 gCO₂/km or ≈42 MPG). Japan followed suit, setting its standard at 125 gCO₂/km (or ≈44 MPG) for 2015.

Also in 2007, a judicial decision about the 1999 petition broke the regulatory deadlock. In the case *Massachusetts v. EPA*, the Supreme Court ruled that (a) carbon dioxide and other GHGs are 'pollutants', and thus regulated under 1990 CAA; and (b) the CAA does not authorize EPA to make policy considerations (Meltz, 2008). This judicial order meant that existing fuel efficiency and environmental regulations could be extended to address climate change. It thus gave CARB the *right* to legislate GHG emissions in California. But CARB did not yet gain the *means* to implement the legislation, because automakers successfully lobbied the Administration not to grant California the necessary waiver (Sperling and Gordon, 2009). The argument was that the 2007 *Energy Act*, which tightened fuel economy standards, pre-empted the need for California to have its own GHG standards (Sperling and Gordon, 2009).

5.4.2. Car industry issue responses

5.4.2.1. *Socio-cultural strategies.* In response to escalating public concerns, automakers acknowledged climate change in their annual reports and signalled their engagement with sustainable mobility (Shinkle and Spencer, 2012). Marketing strategies also embraced sustainability messages (Abeles, 2004).

5.4.2.2. *Political strategies.* In 2007, GM, Ford and Chrysler joined the U.S. Climate Action Partnership (USCAP), which promoted market-based approaches (e.g. cap-and-trade legislation) rather than standards for GHG emissions (Yergin, 2011).

5.4.2.3. *Innovation strategies.* By 2006–2007 fuel cell enthusiasm began to diminish because of cost problems, technological barriers (e.g. hydrogen storage), and lack of hydrogen fuelling stations. The fuel cell hype was superseded by new expectations about HEVs, PHEVs, and BEVs (Fig. 3a and c). By 2005, sales of HEVs accelerated (Fig. 6), stimulating industry attention and patenting (Fig. 3a and c). Toyota's first-mover advantages triggered an innovation race (Fig. 6) with American automakers boosting their R&D and patenting activities (Fig. 3c and d), and introducing their own HEV-models. Ford produced its first full-hybrid (Escape) in 2004 (using licensed

technology from Toyota) and GM in 2007 (Sperling and Gordon, 2009).

5.4.2.4. *Foreign automakers and new entrants.* BEVs were revitalized by foreign automakers such as Renault-Nissan, which in 2002 announced a breakthrough in lithium-ion battery technology that would extend the driving range (Yergin, 2011). Renault-Nissan promised to market BEVs in 2010. A new automaker, Tesla Motors, further reinforced attention, due to its marketing of the *Tesla Roadster* (2006) in terms of style, verve, and performance, which gave BEVs a positive symbolic meaning (Yergin, 2011). The subsequent surge in interest in BEVs (Fig. 3a) spurred other automakers to reconsider the technology.

5.4.2.5. *Market positioning strategies.* Economic positioning of American automakers continued to focus on biofuels and flex-fuel vehicles, which sold in increasing numbers (Fig. 4a). The HEV market, which expanded rapidly after 2005, also attracted attention. Toyota's second-generation Prius, larger and more powerful but at similar price (\$20,000), led the way. By 2007, Prius was the 8th top selling car in the U.S (13 for all light-duty vehicles) (Sperling and Gordon, 2009). Other companies followed, leading to an innovation race and a rapid increase in the number of available models. Absolute HEV sales peaked in 2007 (Fig. 6), corresponding to about 2% of the U.S. light-duty vehicle market (Fig. 4b).

General market conditions worsened, as rising oil prices depressed sales of light-trucks. To continue to sell SUVs, American carmakers offered a range of 'marketing gimmicks', such as zero interest loans, rebates and free options. They also aimed to cover automotive losses with profits from financial divisions, which diversified into mortgages, including sub-prime (Ingrassia, 2010). Declining light-truck sales and 'legacy' costs (pensions, health care) caused major losses for American automakers, bottoming at net losses of \$40.5 billion for GM in 2007 (Fig. 5), when the subprime bubble burst. The outbreak of the 2008 financial crisis caused major financial troubles for the Big Three.

5.5. *The climate change issue at crossroads (2009–2012)*

5.5.1. *Pressures around issue*

5.5.1.1. *Public attention.* After 2007 public attention to climate change declined substantially (Fig. 2a), because concerns shifted to the financial/economic crisis. Additionally, conservative groups and think-tanks sponsored 'climate change deniers' who tried to reopen the scientific debate (McCright and Dunlap, 2010). These activities succeeded in creating more doubt in public opinions about climate change.

5.5.1.2. *Policy-makers.* International pressure also weakened, because climate negotiations in Copenhagen (2009) failed. In Durban (2011) countries agreed to delay talks about a successor treaty to Kyoto until 2015, which might come into force in 2020.

At the Federal level, however, the newly elected (2008) Obama administration strengthened regulatory pressures on automakers. The administration also bailed out Chrysler and GM (in 2009), which went bankrupt during the economic crisis. Using his strengthened negotiating position, Obama secured an agreement on CAFE and GHG emission standards between auto companies, government agencies (EPA and NHTSA), and California. Subsequently, executive branch activity increased sharply (Fig. 2b), with EPA and NHTSA accelerating the creation and implementation of mobile GHG-emission regulations and stricter CAFE-standards. The resulting 2009 *Light-Duty Vehicle Greenhouse Gas Emission Standards and Corporate Average Fuel Economy Standards Rule* (the 'LDV Rule') created GHG emission standards for light-duty vehicles starting in 2012, which increased 5% per year, until reaching 35.5 MPG

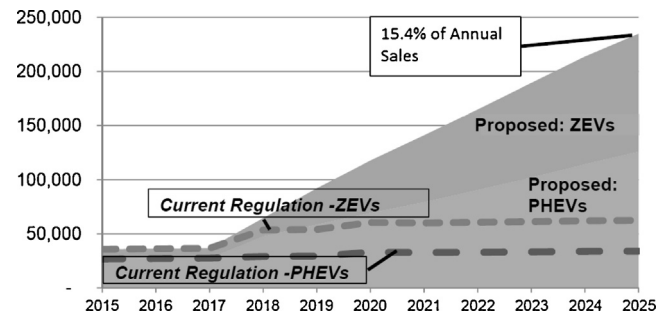


Fig. 8. Amendments to California's ZEV regulation
Source: CARB (2012, p. 3).

by 2016. The rules also allowed California to start implementing the Pavley Act in 2009. In 2011, the Federal government, California and automakers agreed on long-term GHG/CAFE standards (Lutsey, 2012), which would increase to 54.5 MPG by 2025. These GHG regulations remain weaker than those in Europe (and Japan), which is considering 95 gCO₂/km (≈60 MPG) for 2020.

Obama not only tightened regulations, but also supported green innovation. As part of the 'green stimulus' programme, he promoted a domestic battery industry, issuing \$5-billion in grants and loan guarantees to battery makers, entrepreneurs, major auto companies and equipment suppliers (Dijk et al., 2013). Obama also promised to bring one million PHEVs and BEVs to the road by 2015, signalling a shift in Federal technology priority from hydrogen/fuel cells to battery-electric vehicles (Bakker et al., 2012).

The stalemate for the California ZEV-regulations was unlocked by the 2007 Supreme Court decision and 2009 Obama deal with the automakers. CARB also modified the regulations to accommodate PHEVs: it created a new compliance path for 2012–2014, which allowed carmakers to sell less FCVs (ZEVs) and more PHEVs. But a 2012 amendment increased requirements for both ZEVs and PHEVs to 15.4% of annual sales in 2025 (CARB, 2012) (Fig. 8). Nine other U.S. states began procedures to also adopt a ZEV-mandate.

5.5.2. *Car industry issue responses*

5.5.2.1. *Socio-cultural strategies.* To increase the chances of Federal bailouts, American automakers tried to enhance their social and political legitimacy by subscribing to environmental and fuel economy expectations. GM's first Viability Plan (December 2008), for instance, claimed that: "General Motors well understands the challenges to energy security and the climate (...) and believes that (...) we must look to advanced vehicle technologies to reduce petroleum dependency and greenhouse gas emissions" (p. 4). With the surging interest in electric vehicles, automakers also showcased PHEV and BEV concept-cars such as the Chevy Volt. The first Viability Plan therefore included ambitious investment plans in green technologies (Table 5).

The Viability Plan was reviewed by the *Presidential Task Force on the Auto Industry* (ATF), which Obama created for fear of being accused of interfering with day-to-day management. The ATF rejected the focus on green cars, because of limited financial

Table 5
Investment plans in GM's first Viability Plan (2008).

Technology	Fuel economy improvement impact	2009–2012 investment
Hybrid (BAS+)	12–15%	\$467M
Strong hybrid (large vehicle)	30–35%	\$515M
Strong hybrid (small vehicle)	35–55%	\$315M
Extended range electric vehicle (e.g. Volt)	100–120%	\$758M

prospects (Rattner, 2010). GM's second Viability Plan (2009) therefore paid less attention to green innovation and did not include green resource allocations.

5.5.2.2. Political strategies. Because Detroit automakers needed Federal funds for survival, they became more cooperative towards environmental regulations and signed up to various CARB and CAFE agreements. But by 2012 they resumed defensive political strategies, arguing and lobbying against the ZEV-mandate. An industry petition to EPA against California's regulation argued that: "It is impossible to predict today whether infrastructural developments, oil prices, consumer confidence and other factors will converge such that automakers will be able to persuade buyers to [buy sufficient numbers of electric-drive cars]. Current data and trends suggest that it is highly unlikely that the industry will be able to meet that mandate" (cited by Nelson, 2013, online). Automakers also opposed the Californian ZEV-mandate in an attempt to discourage other states from adopting it.

5.5.2.3. New entrants. Most new automakers struggled in this period. Tesla Motors requested a \$350-million loan-guarantee in 2009 from the Department of Energy to develop a new model. After posting successive financial losses, Tesla announced its first-ever quarterly profits (and the only one to date) in early 2013, managing to repay its loan-guarantee earlier than expected. In the same year, it began sales of its Model-S, an award-winning battery-electric sedan that was cheaper than the high-performance Tesla Roadster. Fisker Automotive, which began selling a PHEV-model in 2011, went bankrupt two years later. BetterPlace, which pioneered a new business model based on leasing 'switchable batteries', also went bankrupt in 2013. BYD Auto (from China), which never delivered on its promise to sell an all-electric minivan model in the U.S. market, reported a 98% plunge in profits in 2012.

5.5.2.4. Innovation strategies. Before the crisis Ford and GM displayed BEV and PHEV-prototypes (Chevy Volt, Ford Airstream). GM even announced production plans for the Volt, signalling a shift in strategy from fuel cells to electric-drive vehicles. The financial crisis created delays, because the ATF was unenthusiastic about the Volt. But in 2010 the first Volt rolled off the factory production lines.

Following the (re)established Californian ZEV-regulations, automakers announced BEV commercialization plans to meet required sale-quotas. The *Green Car Reports* qualified many models (Chevrolet Spark EV, Ford Focus Electric, Honda Fit EV, Toyota RAV4 EV, and the Fiat 500e) as 'compliance cars', which are "not meant to lure in consumers, or sell in any kind of volume. They're only built to meet California regulations for zero-emission vehicles" (Voelcker, 2012, online). These models, which are conversions of existing gasoline vehicles rather than purposefully built BEVs, are sold below cost-price.

Despite the BEV-push, advanced-ICE (and flex-fuel) technologies remained automakers' preferred strategy to improve fuel efficiency, leading to accelerated deployment of aICE technologies such as variable valve timing, continuously variable transmission, gasoline direct injection, turbocharging, six-speed transmission, cylinder deactivation, and diesel engines (Lutsey, 2012).

5.5.2.5. Market positioning strategies. The \$3-billion 'Cash for Clunkers' scheme (2009), which offered consumers \$3500–4500 rebates, stimulated demand for HEVs and fuel efficient ICE-vehicles (Dijk et al., 2013). BEVs and PHEVs also entered the market, but sales remained low (Fig. 4b; Table 6), because of high prices.¹⁴

¹⁴ Even with favourable \$7500 Federal tax credits (and other state incentives), these models cost almost twice as much as similar ICE-models.

Table 6
Sales in the U.S. market of selected PHEV and BEV models.

	2010	2011	2012	2013	Total
Chevy Volt (PHEV)	326	7,671	23,461	23,094	54,552
Nissan Leaf (BEV)	19	9,674	9,819	22,610	42,122
Toyota Prius (PHEV)	–	–	12,750	12,088	26,838
Tesla Model S (BEV)	–	–	2,620	18,650	21,270

Source: Data from <http://hybridcar.com> and <http://green.autoblog.com/> (last accessed 23.03.14).

Because of the economic crisis, general market conditions worsened dramatically. Plummeting sales caused major financial problems for Chrysler and GM (Fig. 5). The government rescued both companies with a managed bankruptcy (2009) and substantial bailout (\$8 billion and \$30 billion loans to Chrysler and GM respectively), with Chrysler being later acquired by Fiat. All American automakers subsequently restructured (shutting down factories, reducing staff, disinvesting brands), cut costs and returned to profitability.

6. Analysis and discussion

6.1. Pattern-matching

The case study addressed one of the paper's goals, namely describing how American automakers engaged with the unfolding climate change problem. The case study showed, on the one hand, that the climate change problem had dynamics related to activities from various social groups (scientists, social movements, public attention, policymakers). On the other hand, it showed that industry responses and technical solutions had their own complex dynamics, which related not just to R&D investments, but also to broader beliefs, corporate and political strategies. To provide a further explanation, we perform a pattern-matching analysis (Yin, 1994; Geels and Penna, 2015), which compares core dynamics and mechanisms in the empirical periods with those predicted by the DILC-model for different conceptual phases.

The first period (1979–1988) matches well with DILC's phase 1: (a) scientists and environmentalists engaged in sense-making and draw attention to the problem; (b) firms remained unconcerned. A minor deviation from the conceptual phase 1 was that politicians engaged in early symbolic action (some Senate hearings and a letter by Al Gore and others).

The second period (1988–1997) displayed important dynamics of DILC's phase 2: (a) increasing public attention; (b) symbolic political action at the Federal level (publicized Senate hearings) and global level (UNFCCC, 1992), accompanied by the early build-up of a policy sub-system; (c) creation of a closed industry-front (GCC). But the period also had some deviations from the conceptual model: (1) at the state level, California's Zero Emissions Vehicle (ZEV) mandate formed a strong piece of regulation, which the model predicts in phase 4; (2) early engagement of macro-politicians (Presidents Bush Senior and Clinton), which the model posits to phase 4; and (3) an incumbent firm (GM) introduced a radical innovation (BEV), which the model predicts in phase 4. Nevertheless, we argue that this period is best characterized as phase 2, because of the following qualifications of the second and third deviation: the enactment of California's ZEV-mandate was motivated by local air pollution concerns; the macro-political Federal actions (mainly the USABC and PNGV partnerships) were not radical, but actually served to reinforce the closed industry front; GM promoted BEVs for reputational reasons, not in reaction to climate change concerns or regulation.

The third period (1997–2005) had a good match with phase 3 in the DILC-model, because: (a) public attention to climate change

further increased; (b) specialist expertise was elaborated in policy sub-systems (CARB, PNGV, USABC); (c) automakers acknowledged the problem, but opposed it politically causing controversy and deadlock; (d) limited macro-political pressure because Congress and the Bush-administration opposed regulation; and (e) automakers moved towards hedging strategies, maintaining their overall commitment to aICE and biofuels/FFV, but increasing R&D investments in more radical alternatives. The period also had a few deviations, because it included some elements from phase 4: (1) the political industry-front weakened as firms abandoned the GCC in the late 1990s; (2) foreign firms (Toyota, Daimler) aimed to secure first-mover advantages with radical innovations (HEV, FCV), which 'opened up' the industry front, and triggered innovation races.

The fourth period (2005–2009) had some elements from phase 4 in the DILC-model: (a) sharp increase in public attention; (b) engagement of macro-political actors (second Bush-administration, Supreme Court); (c) spillovers to the economic task environment through the emergence of markets for low-carbon technologies; (d) further opening up of the industry-front and innovation races in FCV, HEV and biofuels/FFV. Because many of these developments pointed in the 'right' direction, we qualified this period as 'changing gear'. But the period also had elements of phase 3, because some developments were not yet very strong: (1) regulatory pressure remained limited (because Federal policies were not radical); (2) market niches for electric drive vehicles remained small (2–3%); (3) continuing commitment of automakers to aICE and biofuels/FFV; (4) automakers did not fully commit to more radical alternatives for fear of making the wrong bet (which is reinforced by the experience of hype-cycles). This period is therefore best characterized as a 'phase 3½'.

The fifth period (2009–2012) is also ambiguous, because developments point in different directions. On the 'positive' side, this period has some elements of the conceptual phase 4: (a) climate change was addressed at the macro-political level (Obama administration); (b) administrative activity remained high (Fig. 2b); (c) the political position of U.S. automakers weakened (because of bankruptcy and bailout), which made them more receptive to social and political expectations about fuel efficiency and climate change; (d) automakers jockeyed for position with various low-carbon technologies, leading to high patenting activity across multiple categories (Fig. 3c and d). But the period also had 'negative' developments, which fit with phase 3: (1) decreasing public attention (Fig. 2a); (2) political attention to climate change decreased after 2009 (Fig. 2b); (3) new regulations are not radical and do not create a new market segment; (4) markets for HEV, BEV, PHEV remain small (2–3% of overall sales); (5) automakers remain committed to aICE and biofuels/FFV. Although car companies continue to invest in radical green options, they did not fully commit to any of them. This period is therefore also best characterized as a 'phase 3½' with conflicting developments.

This analysis suggests that most empirical periods had a relatively good match with a particular phase in the DILC-model. However, we should not expect a perfect match between the ideal-typical DILC-model and complex real-world cases. And, indeed, most periods were more complex in the sense that they contained characteristics from multiple phases. Nevertheless, we were able to give a main qualification of each period in terms of the DILC-model.

6.2. Assessing the degree of low-carbon reorientation

For the 33-year period, we identify an overall pattern, in which the climate change issue lifecycle followed the following phase-sequence: 1–2–3–3½–3½. This suggests that the issue lifecycle and industry reorientation got stuck between phases 3 and 4 in the last two periods (2005–2009, 2009–2012). One explanation, in terms of the DILC-model, is that problem-related pressures have not

sufficiently increased and aligned to stimulate automakers towards fuller reorientation. Most pressures were increasing in the first three periods, except for political pressures, which weakened both at the Federal and state levels. In the fourth period, pressures from social movements, scientists and wider publics increased strongly and there were some spillovers to market demand, also through the action of new entrants (e.g. Tesla). But the political pressure remained relatively weak, and was not strong enough to substantially affect mass markets (as the DILC-model would require for a shift towards phases 4 and 5). In the fifth period, political pressures grew somewhat stronger (although not 'technology-forcing'), but pressure from social movements, science and public attention weakened considerably because of the financial-economic crisis. Market pressures also stagnated, despite 'cash for clunkers' and other stimulus programmes. This analysis is summarized in Table 7. So, one part of the explanation of the lifecycle being 'stuck' is that the various pressures related to the climate change problem are not yet large enough, nor well-aligned,¹⁵ to stimulate full reorientation. The spillovers to the economic environment are still contained, as indicated by relatively small markets and not very tough policies, both of which are insufficient to motivate automakers to accelerate their strategies away from ICE technology.

The other part of the explanation relates to firm strategies and commitments to the industry regime. Although firms implemented some changes in elements of the industry regime, these changes are not yet very substantial or comprehensive. Firstly, automakers have developed some competencies in radically new technologies (fuel cells, electric drive). But they have not fully committed to them, giving instead more priority to the elaboration of existing competencies via advanced-ICE and biofuels/FFV. Secondly, industry beliefs have changed somewhat, with automakers no longer denying the climate change problem, and perceiving it as a relevant issue. But addressing climate change has not yet entered core mindsets or become part of the industry's identity and mission. Thirdly, industry-specific policies have been introduced, initially via technology-development programmes (USABC, PNGV, Hydrogen Fuel Initiative), and recently also via CAFE and fuel economy regulations. While these regulations create pressure on the industry, they are not radical policies and allow for compliance with aICE technologies.

This empirical assessment fits with the DILC-model, which suggests that substantial regime change does not happen until phase 4 or 5. In fact, the case shows much inertia related to: (a) the industry's economic orientation towards, and dependence on, large gas-guzzling cars; (b) the industry's belief that Americans prefer big cars; (c) policies (in period 2–4) with loopholes as a result of industry lobbying; (d) sunk investments in ICE technology, which American carmakers continue to defend with incremental innovation strategies (aICE, biofuels/FFV). The innovation races in FCV, HEV, and BEV have begun to undermine ICE dominance. But to avoid risks, manufacturers have so far aimed for "gradual, contained experimentation [of alternative vehicle technologies], as much as possible anchored within the status quo" (Wells and Nieuwenhuis, 2012, p. 1686). We therefore do not expect full industry reorientation towards radical green options in the next few years, because of high risks and costs, low market demand, and because of limited policy pressure. Instead, we expect automakers to continue to hedge and develop capabilities in multiple low-carbon technologies (see next section).¹⁶

¹⁵ Additionally, the climate change problem is currently not very strongly aligned to other problems (such as energy security or local air pollution). We thank one reviewer for emphasizing this point.

¹⁶ It is even possible that the climate change issue moves backwards to previous phases in the DILC-model, if pressures from policymakers, civil society and/or

Table 7
Summary assessment of the development of climate-change related pressures on the U.S. car industry.

	Activists, social movements, scientists	Civil society (public attention and concern)	Policymakers (Federal and California)	Market demand, consumers	Relative regime outsiders (suppliers, foreign firms, new entrants)
1979–1988	+/- (academic debates, but no pressure on car industry)	–	–	–	–
1988–1997	+ (issue rising on environmental agenda, new scientific evidence of climate change)	+ (rising public attention and concern)	Federal: + California: ++ (ZEV-mandate)	–	+/- (Daimler FCV)
1997–2005	++ (environmental groups petition EPA, mounting scientific evidence)	+ (stagnating public attention)	Federal: +/- (Bush rejects Kyoto) California: + (weakened ZEV, leading to stalemate)	+/- (small HEV sales/demand)	+ (Toyota and Honda's HEV)
2005–2009	+++ (environmental movements appeal against EPA rejection of petition; 2007 IPCC report + Nobel prize)	+++ (surge in attention, public sensitivity to climate change due to natural catastrophes)	Federal: + (increasing activity due to issue linkages between energy security and climate change) California: + (CARB new rights after 2007 Supreme Court decision)	+ (emerging HEV sales/demand)	+ (Toyota lead in HEV, Tesla and other new entrants)
2009–2012	+ ('climate gate' scandal; attempts from climate sceptics to undermine science base and create doubt; social movements focus on economic issues)	+ (declining public attention and sensitivity due to the economic crisis)	Federal: ++ (new regulation under Obama, but not very tough) California: ++ (Pavley Act and ZEV-mandate)	+ (stagnating HEV sales/demand and small BEV sales/demand (2013))	+ (Renault-Nissan push for BEVs, but weakening new entrant pressure)

Inexistent pressure = '-'; weak pressure = '+/-'; semi-strong pressure (growing or weakening depending on previous period) = '+'; strong pressure = '+++'; very strong pressure = '++++'.

6.3. Further explanation and conceptual elaborations

A further explanation for the lack of full low-carbon reorientation is the uncertainty associated with the diversity of technical solutions and the industry awareness of previous technology hype-cycles. These uncertainties are likely to delay full industry reorientation because automakers do not want to commit to the 'wrong' technology. This possibility is not yet accommodated in the DILC-model, which implicitly assumes that the technical solution becomes increasingly clear as the issue lifecycle progresses, so that, by phase 4, there is a single, clear-cut option towards which firms can reorient. Building on the complexity of our case, we therefore propose a conceptual elaboration, namely that the shift from phase 3 to phase 4 in the DILC-model requires the convergence of industry actors (and other stakeholders) towards a dominant solution.¹⁷ The absence of convergence in the case provides a further explanation of why the move towards phase 4 has not yet happened. A broader implication is that technical diversity, which innovation scholars often see as something positive, may have drawbacks in the sense of prolonging hedging (phase 3) and delaying diversification and reorientation (phases 4 and 5).¹⁸

markets weaken further. This analytical possibility (of moving backwards) was highlighted by Geels and Penna (2015) and empirically demonstrated with another case study. Alternatively, the climate change lifecycle could regain momentum in the coming years if it were to align with other problems (e.g. air pollution, energy security, rising oil prices). (We want to thank one reviewer for drawing our attention to the potential future importance of issue linkage).

¹⁷ The convergence of industry actors also actively contributes to making a solution dominant. But firms are not the only relevant actors in creating a dominant solution. Other actors (e.g. consumers, policymakers) also make contributions.

¹⁸ Industry actors and consultants (e.g. McKinsey) are increasingly talking about the possibility of sustained diversity in the future, including prolonged co-existence of multiple low-carbon technologies. This would raise the prospect of an alternative transition pathway, which would not proceed from one dominant technology to another (substitution pattern), but from one dominant technology to multiple co-existing technologies that are used in different market niches. While not excluding this possibility, our conceptual model would suggest that this is not a very likely

As a second elaboration we propose to nuance the sequential view of technological reorientation in the DILC-model (incremental innovation, hedging, diversification, full reorientation). Whereas the DILC-model assumes that incumbent firms do not engage in radical innovation until phase 3, the case study showed that automakers already developed and publicly displayed BEVs in the second period (followed by FCV, HEV, and PHEV in later periods). So, rather than a sequential process, radical and incremental innovation co-existed simultaneously in early periods. To explain this deviation, we problematize the distinction between symbolic and substantive action, particularly the idea that technology only represents substantive action in the economic task environment.¹⁹ So, the DILC-model should be elaborated to accommodate the possibility that incumbent firms can use radical innovation as part of political and socio-cultural strategies towards the institutional environment. The case study entailed several examples of this phenomenon:

pattern, as it will be very costly for car companies to maintain technical capabilities and production facilities at large scale for many different options (the co-existence of multiple infrastructures for gas, hydrogen and electric recharging would also be expensive). At a smaller scale, however, prolonged diversity of various technical options in small market niches (few per cent market share) would enable automakers to prolong the lifespan of their dominant technology (internal combustion engines) in mainstream markets. Sustained diversity of multiple low-carbon options in small market niches would, however, be detrimental with regard to addressing the climate change problem (since climate scientists indicate that global emissions should fall after 2020 in order to have a chance to reach the 2-degree target). (We want to thank one reviewer for asking us to elaborate our view on the diversity issue).

¹⁹ It is difficult to make ex-ante distinctions between symbolic and substantive actions, because of inevitable information asymmetries (thanks to one of the reviewers for drawing our attention to this point). The various examples of unfulfilled industry promises in our case study do, however, provide a lesson, suggesting that firm's statements about strategic commitment to green cars and related R&D programmes should be treated with caution by policymakers and not be regarded as evidence that no further policy action is needed.

- In 1990 GM showcased the *Impact* for reputational reasons (which had unintended consequences on CARB's perception of BEVs).
- The public private partnerships (USABC, PNGV), which officially aimed at developing new technologies, carried costs for the industry, but also offered political and reputational benefits: control of technology developments, control over information provision to policymakers, limiting internal competition, enhancing public reputation, signalling that self-regulation was better than formal regulation, signalling willingness to take substantive action, managing technical expectations.
- Toyota improved its green (and innovative) credentials with the Prius, creating an environmental 'halo effect'.
- The industry shaped social and political expectations by parading concept cars and prototypes and making promises about marketing plans. It has a track-record of missing these promises, and deferring new promises further into the future (often 5–10 years).

As a third elaboration, we propose that issue lifecycles are not only shaped by *internal* dynamics (struggles between problem-related pressures and industry responses), but also by other developments in the industry's economic and socio-political environments (which are thus *external* to the focal issue). This elaboration further helps explain some salient aspects of the case: (a) although the radical policy in the second period (the 1990 Californian ZEV-mandate) had important implications for the climate change issue, it was actually introduced in relation to the problem of local air pollution (this instance of 'issue linkage' helps explain some deviations from the DILC-model, which we noted above); (b) another instance of 'issue linkage' occurred in the 2005–2009 period when attention to energy issues, biofuels, fuel cells, and fuel efficiency increased not just because of climate change, but also because of concerns about rising oil prices and energy security; so, acceleration in this period partly happened because of coupling between various problems; (c) in last period, climate-change related pressures declined because of competition from financial-economic problems. Our case study therefore shows that internal problem-related dynamics and industry responses co-evolve with external developments, which a comprehensive analysis of corporate low-carbon strategies must take into account.

7. Concluding remarks

The paper has shown the usefulness of the DILC-model for comprehensive analyses of societal problems and industry reorientation. Our analysis of climate change, green cars and industry reorientation goes beyond many existing studies in the innovation studies field. Firstly, it looks not only at the 'solution stream' (technical innovations), but also at dynamics in the 'problem stream' (including multi-dimensional interactions with other problems). Secondly, it looks not only at innovation strategies, but also at political, socio-cultural and economic positioning strategies. Thirdly, it goes beyond *single* technology studies, looking at *multiple* low-carbon innovations. We suggest that this kind of comprehensive analysis can fruitfully be applied to other grand challenges (e.g. obesity, energy security, food safety) and other industries (agro-food, coal, oil, electricity, pharmaceuticals). We further suggest that the mixed methods approach in this paper is useful to link theory (the DILC-model) and empirical analysis. The quantitative structural-break analysis helps to systematically identify periods for the in-depth qualitative case study. Furthermore, the combination of various time-series is promising to analyze dynamics in both the 'problem stream' and the 'solution stream'. These methods could be further explored and elaborated in future research.

Although the DILC-model enables comprehensive analyses, we note as a qualifier that the paper concentrated on the climate change problem and focused primarily on technical solutions from automakers.²⁰ Broader transitions towards sustainable transport, which should address not just climate change, but also congestion, air pollution, noise and safety problems, are likely to require low-carbon propulsion technologies as well as wider system changes (Geels, 2012), including car sharing, intermodal transport, modal shift (more cycling and public transport), road pricing, and demand management. Understanding these wider system changes, which fall outside the scope of this paper, would probably involve less focus on the car industry, but still include other mechanisms from the DILC-model, e.g. socio-political mobilization, ups-and-downs in public attention, creation of political will, and emergence of markets. Such an analysis would also need to systematically account for alignments between *multiple* problems and how these could lead to a 'perfect storm' that can destabilize existing industries and systems (see Turnheim and Geels, 2013, for a historical example of this dynamic).

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²⁰ We want to thank one of the reviewers for this point.

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