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When do incumbents adopt radical net-zero technologies? Analysing differences in strategy trajectories of European truck manufacturers towards alternative vehicle technologies

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ABSTRACT

Net-zero vehicle technologies are essential to curb CO_2 emissions from heavy-duty road transport. This study investigates the innovation strategies of European truck manufacturers following the EU's decision to limit CO_2 emissions of heavy-duty vehicles in 2019. Our analysis is based on interviews with managers from all European truck manufacturers and publicly available documents covering the period from 2018 to 2021. We find four different types of strategy trajectories: *proactive diversifier, focused leapfrogger, initial incrementalist*, and *diverse follower*; these range from manufacturers with proactive strategies towards all alternative technologies to those favouring more incremental technologies and displaying laggard-like behaviour towards more radical technologies. Our analysis reveals that these types show a close match to key markets, resources and competencies, research investments, knowledge acquisitions, and expectations towards low-carbon technologies and infrastructures. Additionally, we uncover interdependencies with other segments and markets, the growing political weight of the vehicle industry through infrastructure provision, and the consolidating market impact resulting from necessary collaborations to achieve ambitious (political) decarbonisation targets with increasingly stringent policies. We conclude that both technology-neutral and technology-specific policies can restrict the adoption of potentially more efficient net-zero technologies and recommend leveraging firm-level determinants for more effective net-zero policy mixes.

1. Introduction

Replacing diesel trucks by more sustainable alternatives is key to curbing the growing greenhouse gas (GHG) emissions from road freight. However, alternative fuel vehicles (AFVs) only accounted for 3.4 % of newly registered trucks in the EU in 2022, with 0.6 % being electrically chargeable and 2.8 % running on alternative fuels like natural gas or biofuels (ACEA, 2023). To address the issue of low registrations, EU policymakers introduced CO_2 emission standards for heavy-duty vehicles (HDVs) in 2019. The standards require a 15 % emissions reduction from 2025 and a 30 % reduction from 2030 (Regulation, 2019/1242).[1] Since then, all European truck manufacturers have announced or added AFVs to their portfolios, showcasing that the net-zero transition has entered the take-off phase (Rotmans et al., 2001). Nevertheless, uncertainties prevail around the future of the sector and multiple alternatives have been discussed as replacements for diesel-powered trucks including bio- or synthetic fuels, hydrogen and electricity.

With limited resources and under the time pressure of urgent transitions to sustainability, firms need to make decisions for or against technological innovations with varying degrees of disrupting the previously diesel-based heavy-duty road transport system. These choices can lead to lock-ins and more or less efficient system outcomes, ultimately influencing the overall speed of transitions. In the truck transport sector in Europe, the firms making these selection decisions are predominantly system incumbents, i.e. original equipment manufacturers (OEMs) like Volvo Trucks, Daimler Truck or IVECO. This contrasts with the earlier transition in the energy sector, where a higher number of diverse new market entrants played a significantly larger role alongside

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[1] The European Commission has since released a proposal to strengthen the standards further (European Commission, 2023), which we address in the discussion section.

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established utilities in the shift from fossil fuel-based energy production to renewable alternatives (Stenzel and Frenzel, 2008).

Unlike in the transitions in the energy sector, where new market entrants became active alongside established utilities in switching from fossil fuel-based energy production to renewable alternatives (Stenzel and Frenzel, 2008). International newcomers in the sector, such as Tesla or Nikola Motor have announced and are implementing plans for alternative fuel trucks, respectively, but have not sold vehicles at scale yet.

Yet, such dominance in an industry does not necessarily signify overall resistance to net-zero transitions; instead, incumbents can play a potentially crucial role in positively contributing to and shaping sustainable system change (Berggren et al., 2015; van Mossel et al., 2018). More specifically, studies on the private passenger vehicle sector have shown that car manufacturers are not a homogeneous group but follow different strategies towards alternative vehicle technologies even under the same policies (Mazur et al., 2015). In this paper, we ask whether this is also the case for the AFV innovation strategies of European truck manufacturers in their transition away from fossil fuels, with a particular focus on the role of policy change. We compare their strategies before and after the introduction of the CO_2 emissions standard for heavy-duty vehicles (HDVs) (Regulation, 2019/1242) – a policy aimed at harnessing the power of creative disruption as driver for innovation and at contributing to technology phase-out (Kivimaa and Kern, 2016).

Capturing patterns in incumbents' innovation strategies over time can provide insights into how and why manufacturers select specific technology alternatives over others at certain points in the transition and under the corresponding policy mixes with their core instruments. If the overall societal and policy goal is to achieve a system-optimal move away from diesel as a GHG emitting technology, such insights could be useful for future policy changes aimed at enabling a successful and resource-efficient transition as well as a climate-neutral transformation of key industry players, thereby ensuring their survival on future markets. In addition, investigating the strategy development in the net-zero transition of the heavy-duty vehicle sector also provides important insights for designing decarbonisation policy mixes for similar sectors that still need to accelerate their net-zero transition.

The emerging research on incumbent vehicle manufacturers in net-zero transitions has so far focused on detailed case studies of a selection of manufacturers rather than patterns across industry (Berggren et al., 2015; Mazur et al., 2015). The focus of this early research has been on strategic patterns, analysing aggregated firm innovation strategies according to proactiveness across all technologies at one point in time. Thereby, this research has aimed to identify a continuous and stable innovation type for each firm, e.g. always being proactive towards new technologies or always being a laggard, irrespective on the point in time or technology in question (Wesseling et al., 2015a). Therefore, it provides limited insights into dynamic developments. As a consequence, we do not know whether manufacturers follow different strategies over time, differing in the radicality of the technologies they focus on at a given point in time, and how proactively they engage in their development and manufacturing. This research gap leads us to ask:

> How and why do the trajectories of manufacturers' technology innovation strategies for AFV differ during the policy-induced take-off phase of the net-zero transition in the heavy-duty trucking sector?

For this analysis, we build on an industry-wide set of interview and publication data. In contrast to the well-covered modelling approaches on the diffusion of AFVs (see for example Brito et al., 2019 or Gnann et al., 2015), we focus on the understudied supply side of the innovation system. Rather than aggregating the ongoing processes under technology market shares, this approach allows a closer look at the reasons for different firms‘ strategic technology decisions and consequential developments towards their market introduction and diffusion, thereby providing valuable evidence for transformative policy-making. To characterize firms' technology innovation strategies towards AFVs in relation to the same policy environment and explain their trajectory changes throughout the ongoing transition, we draw on previous studies from sustainability transitions and innovation management to offer two advancements. First, we develop and apply a novel typology for technological innovation strategies in times of sustainability transitions which (i) captures the degree of disruption that the AFV innovations present to the previous paradigm of diesel combustion in the truck sector and (ii) assesses the proactiveness of manufacturers towards each technological innovation in their strategy. Second, to explain the resulting strategy trajectory types, we inductively code our data alongside five factors. These factors for explaining firm-level strategy differences are deductively derived from economics, strategic management, and sociology literatures and include market demand, firm competencies, dynamic capabilities, and expectations. For further insights into the varying strategy trajectories, we also analyse the firms' corporate political activities. In addition to categorizing our data alongside these five factors we inductively add sub-categories emerging from our rich empirical material. This combination of a pre-structured deductive but supplementary inductive approach enables us to strike a balance between breadth and depth in unpacking the net-zero technology innovation strategy trajectories of all manufacturers of heavy-duty vehicles in Europe.

In the following Section 2, we present the theoretical background for incumbent reactions to changing policy environments and differentiating technology innovation strategies, culminating in our typology to capture strategy developments in net-zero transitions. Section 3 introduces our qualitative multi-method research design, which draws on an extensive set of documents, as well as interviews with all key truck manufacturers on the European market. Section 4 introduces the research case of heavy-duty road transport with its particularities and recent developments. Our results are presented in Section 5: in Section 5.1 we first describe the OEMs' strategy changes over time by applying our proposed technology innovation typology; in Section 5.2 we then compare and explain the identified trajectory types using the aforementioned five factors. Finally, in Section 6 we discuss our findings and derive policy implications. Section 7 concludes by outlining potential avenues for further research.

2. Theory-based development of typology and explanatory factors

In this section we develop our typology for differentiating the technology innovation strategies of incumbent firms in policy-driven net-zero transitions. We also derive five factors to corroborate and explain different types of strategy trajectories, drawing on key determinants of firm differences from economics, strategic management, and sociology.

2.1. Towards a typology for capturing technology innovation strategies in policy-induced net-zero transitions

Since incumbents display both system-retaining as well as system-challenging behaviour (van Mossel et al., 2018), their strategies can be expected to include technologies with different degrees of challenging the established system and to show different levels of proactiveness in developing and bringing such alternative technologies to market. Additionally, in-depth case studies of manufacturers reacting to more stringent policies in the passenger vehicle sector suggest that their proactiveness towards different technological innovations at different points in time can vary (Mazur et al., 2015). Based on existing classifications of technology innovations strategies, we consequently develop a technology- and time-specific typology to capture the firms' technology innovation strategies in transitions.

2.1.1. Classifying technology innovation in policy-driven net-zero transitions

Among the abundant classifications of *innovation* available to innovation researchers (Garcia and Calantone, 2002), the literature on technological innovation in sustainability transitions of the transport sector has so far largely focused on the dichotomy between incrementalism and radicality of innovations (Hekkert et al., 2005; Wesseling et al., 2015a). Correspondingly, the innovation strategies of firms could either be incremental, supporting technologies that only differ slightly from the status quo, or radical, supporting technologies that differ drastically from the established ones. For example, Hekkert et al. (2005) focus on 'fuel chains' to assess the radicality of vehicle innovations and move from internal combustion engines powered by compressed or liquid natural gas (CNG/LNG-ICEV) as the least radical towards hydrogen fuel cell vehicles (FCEV) as the most radical, while battery-electric vehicles (BEVs) are not yet included in their study. We argue that including BEVs would necessitate a conceptual adaptation of their work because BEVs not only require changes in the 'fuel chain' but a complete switch from a fuel-based carrier logic to an electricity-based system logic with, among other aspects, different components, infrastructure, and use patterns. We therefore suggest to classify AFV technology innovations as either *reinforcing the dominant fuel-based sector logic or challenging it*, going beyond the consideration of production processes that are included in 'fuel chains' to also include actor links, market structure, and behavioural change. We use the terms *incremental* and *radical* as shorthand to refer to the extremes of this scale describing the necessary changes in the underlying mental model or paradigm associated with these technologies, represented by the fuel-based and electricity-based system logics at each end (Tidd and Bessant, 2014). Hydrogen-based vehicle innovations occupy a place in the middle of this scale, with hydrogen combustion at the lower end and FCEVs at the higher end as an intermediate between a fuel-based and electricity-based system.

2.1.2. Classifying strategies for technology innovation in policy-driven net-zero transitions

After categorizing the technology innovations themselves, the *strategies* of incumbent firms towards these technologies can be classified. In strategic management, an innovation strategy is described as "a framework to guide the process of change [determining] what we'll spend our scarce resources on and why" (Tidd and Bessant, 2014, pp.21–22). Developing such a strategy entails analysing the strategic options, selecting which to pursue, and plans for implementation. Wesseling et al. (2015b) synthesize previous literature and specify this process for technologies by considering "innovation strategy as a timed sequence of internally consistent resource allocations to the development and commercialization of technologies that are new to the firm itself and/or its markets, to achieve long-term profitability" (pp.89–90). In addition to prioritizing specific new technologies, innovation strategies are therefore also characterized by the timing of activities. We account for this strategic timing in terms of a firm's proactiveness towards a specific innovation in relation to other firms. The resulting classification ranges from 'first movers', who are early to innovate and enter a market, through to 'laggards', who exploit the status quo, are less prone to innovate and enter markets later (Wesseling et al., 2015a). Although Wesseling et al. (2015a) refer to the technology-specificity of innovation strategies pointed out by Teece et al. (1997), ultimately they analyse an aggregated innovation strategy for all technologies at the firm level, similar to previous studies. Our approach, in contrast, takes up the call by Oliver and Holzinger (2008) to study the potential simultaneous usage of multiple strategies for different technologies; what we refer to as a technology mix in the firm's overall innovation strategy. Following their suggestion for political strategies, we expect that firms might be following different strategies, i.e. different *levels of proactiveness*, towards different technologies at the same point in time. To gather novel insights into these technology mixes in innovation strategies and their trajectories, we retain the differentiation between technologies in our assessment and differentiate between proactive and laggard behaviour towards each technology.

2.1.3. The time dimension: phases of net-zero transitions

We situate our analysis in the take-off phase of the net-zero transition of heavy-duty transport, following the early conceptualization by Rotmans et al. (2001), who distinguished four phases of sustainability transitions - predevelopment, take-off, breakthrough (or acceleration), and stabilization - in contrast to the simplified three-phase model (Kanger and Schot, 2016; Kivimaa et al., 2019; Trencher et al., 2021). We prefer the four-phase model as we consider the take-off phase, in which 'the process of change gets under way because the state of the system begins to shift' (Rotmans et al., 2001, p. 17), to be a particularly relevant time for the strategic selection processes of incumbents since it determines which pre-developed technology alternatives will continue into the acceleration phase. Both the take-off and the acceleration phase can be shaped by policy mixes (Kanger et al., 2020), and while certain policies can lead to initial opposition of industry, those with transformative and technology-specific signalling can "trigger an earlier technology breakthrough" (Bhardwaj et al., 2020, p.321; Fox et al., 2017).

While authors of related studies draw parallels to the 'era of ferment' (Berggren et al., 2015; Magnusson and Berggren, 2011), in which different designs of the same technology exist in parallel and eventually culminate in a single dominant design (Anderson and Tushman, 1990), we consciously follow a transitions logic. That is, we consider the selection between different AFV technologies to be more far-reaching than simply choosing different designs of the same technology. We also consider the possibility that technologies may continue to exist alongside each other rather than the emergence of only one dominant technology (Sandén and Hillman, 2011). As firm strategies and resulting system changes go beyond individual product developments, we argue that simply copying previously used terms could be misleading. We will therefore refer to the take-off phase rather than the 'era of ferment' to capture the time during which multiple alternative technologies are strategically considered.

Our focus on the take-off phase of net-zero transitions and the wider selection processes between different AFV technologies in firm strategies also distinguishes our work from studies on innovation diffusion. These

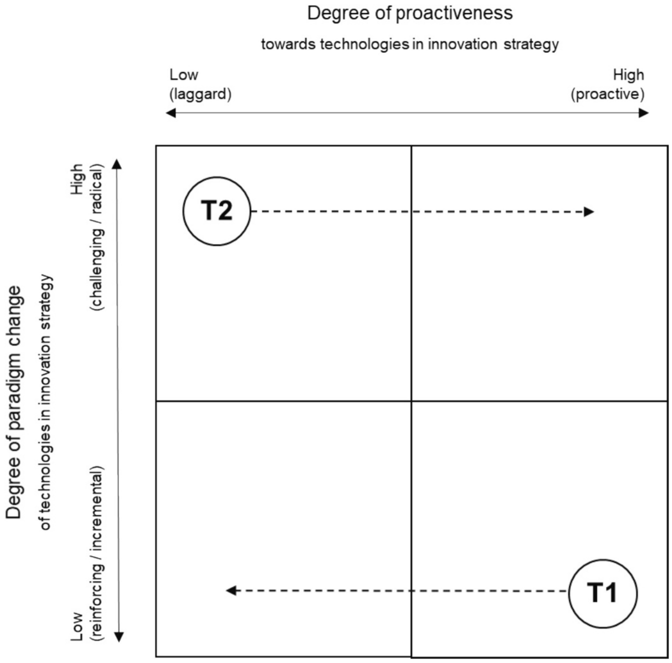

Fig. 1. Typology of technology innovation strategies. *Note:* A stylised example with two technologies (T1, T2) at opposite ends of challenging the existing paradigm (shown for one point in time). Dashed arrows indicate the theoretical potential for different degrees of proactiveness.

studies put an emphasis on individual adoption decisions towards single AFV technologies in the market (Rogers, 1983). The diffusion process of an innovation is split into five sequential phases with distinct adopter groups (in terms of their type and numbers). In contrast, our focus on transition phases on the one hand allows for the simultaneousness of multiple and interacting technology diffusion processes happening in parallel, and on the other hand foregrounds the interplay of technology phase-in and phase-out processes characterizing net-zero transitions.

2.1.4. Resulting typology for technology innovation strategies in net-zero transitions

These theory-based decisions towards capturing types of innovations (*paradigm-challenging* vs *paradigm-reinforcing*) and types of innovation strategies towards individual technologies (*proactive* vs *laggard*) result in the following typology of technology innovation strategies applied in this transition analysis and depicted in Fig. 1.

To address the time dimension in our analysis, positions in the quadrant will be determined for each firm and each technology included in their strategy mix, first for the pre-development phase and then again for the take-off phase of the transition. In our case study, this relates to the individual AFV technology strategies towards long-haul trucks before 2019 and after 2019. The emerging innovation strategy trajectories will then be compared between firms.

2.2. Towards explanatory factors for technology innovation strategy trajectories

Once the types of strategy trajectories of manufacturers in net-zero transitions are identified, we want to understand them better. For this, we draw on five concepts that have been widely used in the literature on strategies and firm differences to explain changing firm strategies in ongoing net-zero transitions. To the best of our knowledge, no single analytical framework exists on the firm-level determinants of technology innovation strategies, mirroring the same gap for innovation strategies in general (Karlsson and Tavassoli, 2016). We have therefore brought together explanatory factors from different but related theories in economics, strategic management, and sociology for our exploration of the changes and differences in firms' net-zero strategy trajectories. From economics, we include the *demand conditions* under which a firm operates, including its market shares and diversity (Karlsson and Tavassoli, 2016). Depending on these conditions different innovation strategies are expected, which we assume for technology innovation strategies as well.[2]

From strategic management and the resource-based view (RBV) in particular, we include two further factors. The *resources and competencies* that a firm has previously developed can influence its innovation choices. While these resources and competencies do not have to be product-specific, high-technology competencies directly related to current innovations can be considered a competitive advantage and are therefore relevant for devising an innovation strategy (Pierce et al., 2008). In addition, in times of industrial change, the way existing competencies are used, innovatively combined and renewed has been shown to be key, with "the speed and degree" (Teece, 2010, p. 692) to which firms can do this determined by their *dynamic capabilities* (Ambrosini and Bowman, 2009; Barreto, 2010; Werner et al., 2022). A firm's dynamic capabilities therefore influence the radicality of its possible innovation strategies (Stalmokaitė and Hassler, 2020). Dynamic capabilities are commonly captured through the processes of sensing, seizing, and reconfiguring (Teece, 2007), but their definition and operationalization are still widely discussed (Ambrosini and Bowman, 2009; Darmani et al., 2017). In our analysis, we consider five proxy activities (Ambrosini and Bowman, 2009; Cao, 2011; Eisenhardt and Martin, 2000; Madsen, 2010): (1) investments in R&D and (2) the evaluation of competitors to approximate *sensing* processes; (3) recruitment of new personnel and (4) alliances or collaborations as *seizing* processes; and (5) re-organization of structures and routines as *reconfiguration* processes.

From the sociology of organizations we include *expectations* as another factor, which has been found to be an important influence on strategies and activities in situations with high uncertainties and specifically during sustainability transitions (Bakker, 2014; Budde et al., 2012; Budde and Konrad, 2019; Konrad et al., 2012). This fourth factor responds to calls for acknowledging that a firm's environment influences what managers consider strategically possible and sensible, i.e.: "how a strategist or a top-management team represents a given competitive setting, affects what strategic position is ultimately pursued" (Gavetti et al., 2012, pp. 9–10). We focus our attention specifically on technology expectations, because expectations concerning competitors and future

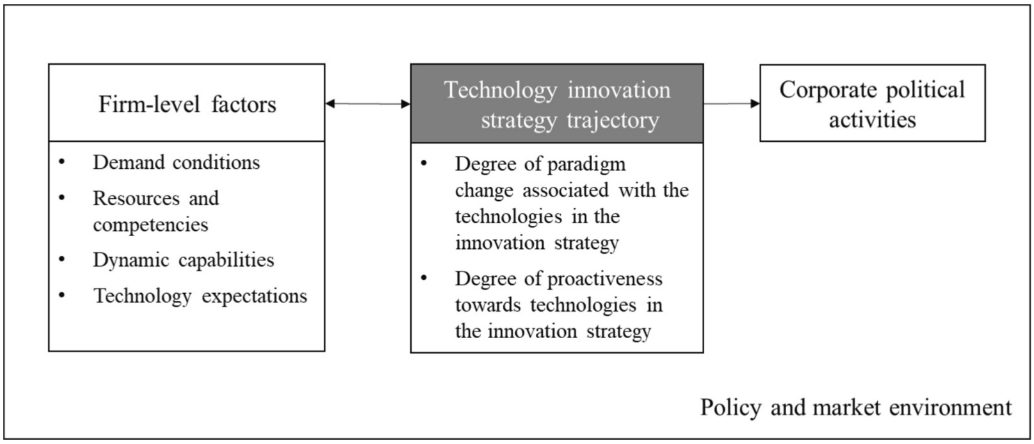

Fig. 2. Summary of firm-level factors to characterize and explain incumbents' technology innovation strategy trajectories.

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[2] Other determinants discussed in the economics literature such as established routines stem from the so-called behavioural theory of the firm (Cyert and March, 1963; Gavetti et al., 2012) and can be traced forward to the (dynamic) capabilities approach in strategic management and sociological approaches around expectations (Gavetti et al., 2012), which we address below.

Table 1
Number of documents and interviews per manufacturer.

	No. of analysed documents					No. of analysed transcripts
Manufacturer[1]	Annual reports	Press releases	Tweets	Newspaper articles*	LinkedIn posts	Interviews
DAF	4	14	54	1	1	1
Daimler Truck	4	39	152	91	17	2
IVECO	4	24	3	26	4	1
MAN Truck & Bus	3**	10	31	11	17	1
Scania	4	9	104	7	19	1
Traton Group	3***	12	52	22	–	1
Renault Trucks	4	11	72	2	2	1
Volvo Trucks	4	23	167	10	3	2
Sum (total n)	30	142	635	170	63	10

Note: *Only counted towards manufacturer if a direct quote is included. **Not available for 2021 at time of publication. ***Not available for 2018.

[1] For connections between brands and parent companies see Section 4 and Fig. 5.

policies are covered by our assessment of a firm's dynamic capabilities and, as introduced below, its corporate political activities. Matching previous findings, we nevertheless expect the technology expectations of each firm to not only be informed by their own competencies and interests but also by perceived collective expectations of the industry and public towards AFV technologies (Bakker, 2014).

Finally, firms react to their market and policy environment in distinct ways through so-called corporate political activities (CPAs) (Hillman et al., 2004). CPAs include a range of proactive and reactive activities with which firms aim to influence policy. Proactive CPAs include, for example, lobbying for favourable regulations through industry associations or providing information to policymakers about the potential effects of a regulation on the firm. In contrast, examples for reactive CPAs include firms trying to anticipate and prepare for policy changes (Hillman et al., 2004). For the energy transition, it has been shown that the choice of the type of CPA and the degree to which a firm adapts its resource base define the proactive or reactive nature of the firm's policy management strategies (Lux et al., 2011; Stenzel and Frenzel, 2008). We hence consider CPAs, particularly those that can be observed from the outside, an important reflection of the underlying strategic goals of individual firms - not to explain but to corroborate our findings on their strategy trajectories.

We summarize these five factors utilized for unpacking net-zero technology innovation strategies and their trajectories in Fig. 2.

3. Research design and methods

Our study follows a qualitative approach and draws upon multiple data sources, including both documents and expert interviews, which are integrated through a type-building qualitative text analysis (Kuckartz, 2013, 2018). A qualitative approach was chosen since no unified theory exists for explaining differences in innovation strategies between firms and because we aim to characterize and explain differences over time and a qualitative approach enables such a tracing process seeking types and causal explanations (Eisenhardt, 1989; Yin, 2009). Moreover, statistical approaches for comparing firms would be of limited value given the small sample size of key truck manufacturers in Europe ($n = 7$).

3.1. Case selection

We investigate the case of the net-zero technology transition in the heavy-duty vehicle sector in Europe between 2018 and 2021 by applying our typology. To study incumbent strategies, all seven leading truck manufacturers in the European market were included in the analysis (see Table 1 and Section 4). The focus on Europe and European manufacturers was chosen because R&D spending on the automotive sector in the EU is the highest in the world, despite this market constituting only 16.4 % of global commercial vehicles sales (ACEA, 2022b). Additionally, all globally operating leading manufacturers sell a substantial share of their vehicles in the EU and decarbonization policies there were consequently expected to have a key impact on their strategies (see online supplementary material). Our data collection was focused predominantly on manufacturer statements in Germany, as this represents a dominant market in the EU in which all studied manufacturers were active and where most already partook in R&D project consortia on alternative fuel truck technologies (Fraunhofer ISI, 2021; HoLa, 2022; Ministry of Transport Baden-Württemberg, 2021). However, as most truck manufacturers operate globally, the innovation strategies we identify also reflect the incumbents' considerations beyond Germany and Europe (see online supplementary material).

We chose the time frame 2018–2021, because it captures the transition from the predevelopment phase to the take-off phase in the European heavy-duty vehicle sector. Prior to 2019, multiple alternatives to the diesel engine had already been developed to market readiness, and the EU regulation on CO_2 emission standards for heavy-duty vehicles increased the pressure to roll out these technologies, marking the start of the take-off phase. Such policy interventions have already been studied as triggers of more ambitious innovation strategies of incumbents in the car sector (Bohnsack et al., 2015; Mazur et al., 2015; Wesseling et al., 2015a) and we expect similar developments for truck manufacturers.

3.2. Data collection

The analysis builds on an extensive, novel dataset incorporating both firm-specific documents for each of the seven truck manufacturers, such as annual reports or press releases, and also direct CEO and manager statements, compiled from articles and original interviews – a rich database we created in an iterative between-methods triangulation (Flick, 2008; see Table 1).

For our document analysis, which served as the starting point for our analysis, we collected annual reports, press releases, and official firm Tweets[4] from 2018 to 2021. Annual reports and press releases on alternative fuel trucks were collected from official firm websites. Additionally, all OEM Twitter[3] accounts (see Appendix A) were scraped with a modified Python script based on Beck (2021) and the resulting tweets were reduced to those including at least one alternative fuel truck technology. The goal was to extract information about innovation strategies from annual reports and press releases and gather further information on the prototypes and launches of new technologies from press releases and tweets. The gathered initial data served well in this respect, particularly for the first part of our research question. However, the collected documents were primarily focused on outcomes and only partly and briefly contained explanations for the chosen technologies and strategies.

Direct insights of OEM managers were therefore gathered to

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[3] We refer to the social media platform Twitter, which was renamed "X" after the data collection was completed.

Table 2
Overview of expert interviews.

Manufacturer/Brand	No.	Interviewee position	Date
DAF	1	Manager AFVs	October 2022
Daimler Truck	1	Manager CO_2 strategy	July 2021
	2	Manager electric mobility	January 2022
IVECO	1	Manager AFVs	April 2022
MAN Truck & Bus	1	Engineer electric mobility	January 2022
Renault Trucks	1	Manager electric mobility	January 2022
Scania	1	Manager AFVs	July 2021
Traton* Group	1	Manager electric mobility strategy	July 2021
Volvo Trucks	1	Manager AFVs	July 2021
	2	Manager electric mobility	January 2022

complement our document-based data. For collecting these CEO and manager statements, we used primary and secondary data: Regarding the former, we conducted qualitative interviews with the managers responsible for strategy making and the implementation of alternative fuel vehicles (see Table 2), whereas for the latter we collected direct quotes of managers and CEOs from newspaper articles and personal LinkedIn posts.

The collection of primary data comprised ten semi-structured expert interviews with key managers and were carried out by the first author between July 2021 and March 2022, and in October 2022 (see Table 2). Questions covered the professional background of the interviewees, their evaluation of the different AFV technologies available at the time, the respective advantages and disadvantages, their perceptions of other actors' evaluations of these technologies, and of the interactions between these technologies. Questions were also asked about strategic changes towards AFVs over time at the respective firm and about managers' expectations of future developments.[4] All the interviews were conducted as online video interviews using Microsoft Teams and were recorded and transcribed. The interviews lasted between 30 and 60 min, with an average of 42 min.

The collection of secondary data as source of CEO and manager statements consisted of newspaper articles of leading nation-wide publications in Germany, excluding tabloids, which were collected from the database LexisNexis with a search string for alternative fuel trucks based on a previous quantitative study (anonymised peer-reviewed reference). To identify only articles with relevant direct quotes, the search string was supplemented with manager and CEO names (see Appendix A). LinkedIn posts on alternative truck technologies were collected from the CEO profiles and managers concerned with alternative truck technologies of all observed truck manufacturers from 2018 to 2021 (see Appendix A).

3.3. Data analysis

Our data analysis focused on strategies and related justifications or motivations. To assess whether manufacturers fall into succinct types, we subjected the data to a thematic qualitative text analysis and a supplemental type-building text analysis according to Kuckartz (2013) (see Fig. 3 and online supplementary material).

We followed a mixed deductive and inductive approach and coded according to the principle of subsumption. All documents and transcripts were integrated and analysed in a joint MaxQDA project. As Fig. 3 shows, the first and second part of the research question were each answered with a distinct data analysis approach but building on the same document base.

4. Status and current developments in the decarbonization of heavy-duty long-haul road transport in the European Union

With around 6 million vehicles in use in 2020 (ACEA, 2022c), heavy-duty trucks make up the smallest share (around 16 %) of the total fleet of approximately 36 million commercial vehicles in the EU (ACEA, 2022a, 2023), but are responsible for more than two thirds of GHG emissions from commercial road transport (ACEA, 2020). Multiple alternatives have been developed to address the growing CO_2 emissions from trucks (see Table 3 for an overview).

The development and market introduction of these technologies started in the small- and medium-duty truck segment [5] but has now also moved to heavy-duty trucks, which are more difficult to decarbonize. In this study, we focus on this most challenging segment: trucks that are heavier than 18 tons and have a range of >200 km, i.e. a vehicle segment beyond 'urban' applications (TNO, 2022) which can cover the reference annual mileage of a heavy-duty vehicle in the existing CO_2 regulations (ICCT, 2021). The technology transition in the truck segment has only

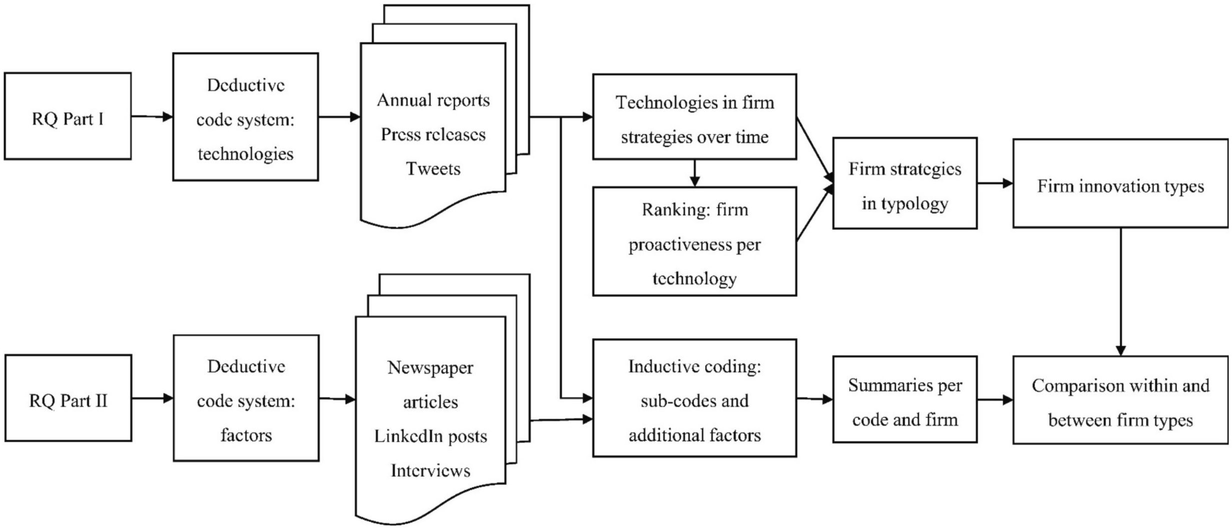

Fig. 3. Steps of the data analysis. Note: RQ Part I refers to the "how" and RQ Part II refers to the "why" of the research question.

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[4] The interviews conducted in 2021 additionally contained questions on electricity-based renewable methane; the interviews conducted in 2022 on ERS.

[5] The small- and medium-duty truck segment includes vehicles up to 8 or 18 tons respectively, which are primarily used in short-distance applications such as urban deliveries.

Table 3
Alternative truck technologies and their relationship to the dominant sector paradigm.

Alternative truck technology	Abbreviation	Dominant paradigm	Degree of paradigm change from diesel
Battery-electric vehicle	BEV	Electricity-based	High
Electric road systems[1]	ERS	Electricity-based	High
Fuel cell electric vehicle	FCEV	Hybrid (fuel- and electricity-based)	Medium to high
Plug-in hybrid electric vehicle	PHEV	Hybrid (fuel- and electricity-based)	Medium
Hydrogen combustion engine vehicle	H_2-ICE	Fuel-based	Low to medium
Gas combustion engine (biofuels or Power-to-Gas)	G-ICE (bio-/PtG)	Fuel-based	Low
Diesel combustion engine (biofuels or Power-to-Liquid)	D-ICE (bio-/PtL)	Fuel-based	Low

[1] Classification for combination with BEV vehicles (classification would be lower for first generation test vehicles with diesel hybrid configuration).

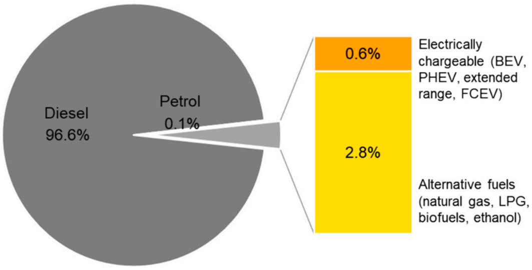

Fig. 4. EU truck registrations 2022 by fuel type based on ACEA (2023). Note: Includes medium- and heavy-duty trucks. Total registrations (100 %) in 2022 were 283,833 units (ACEA, 2023).

started recently: even when including all truck segments, the majority of new trucks sold are still powered by diesel (see Fig. 4), with almost no registered sales in the heavy-duty segment, and, so far, there is no clear solution for how to replace fossil fuels in this sector.

The truck sector in Europe is predominantly shaped by five companies with a total of seven brands: Daimler Truck, Volvo Group (Volvo Trucks, Renault Trucks), Traton Group (Scania, MAN Truck & Bus), CNH Industrial (IVECO[6]), and Paccar (DAF) that together made up 95 % and 97 % of the medium- and heavy-duty truck market in Europe in 2016 and 2021, respectively (EEA, 2018; Luman and Soroka, 2022). The truck market exhibits special characteristics that are important to keep in mind when transferring our results to a different case. First, the market is characterized by only a few manufacturers, and this limited competition has led to challenges concerning cartel law in the past (European Commission, 2016). Second, the market offers small margins and low scalability due to a higher diversity in vehicle types and lower sales volumes than in the passenger sector (Berggren et al., 2015). These two characteristics mean the commercial vehicle market poses high entry barriers. In recent years, new manufacturers such as Tesla or Nikola Motor have aimed to disrupt the market, but have not yet sold vehicles at scale. Outside of Europe and North America, for example in China, manufacturers such as Dongfeng or FAW have greatly increased their sales over the last ten years, including zero-emission heavy-duty vehicles (Fang et al., 2023; Shen and Mao, 2023). With the growing importance of their home markets, these manufacturers will play a key role in the decarbonisation of heavy-duty road transport. Nevertheless, the number of internationally operating truck manufacturers has remained small, with European manufacturers exerting the broadest influence through their globally distributed sales and total revenues (Statista, 2022).

To meet global CO_2 reduction targets, the EU has set CO_2 emission standards for heavy-duty vehicles newly registered in the EU (Regulation, 2019/1242). These take 2019 as a baseline and increase from a mandatory CO_2 emission reduction of 15 % across all vehicles sold after 2025 to a reduction of 30 % after 2030 (Regulation, 2019/1242). In 2024, the stringency of the targets was increased to a reduction of 45 % by 2030, 65 % by 2035, and 90 % by 2040 (Regulation, 2024/1610). Additionally, targets for individual manufacturers registering these vehicles will be set from 2025 onwards, with only up to 5 % of transfers possible between manufacturers (Regulation, 2024/1610). Efficiency measures and other incremental adjustments will not be sufficient to meet the 2030 target, so compliance with this policy has increased the pressure on manufacturers to widely introduce alternative fuel heavy-duty vehicles to the market from 2019 onwards (European Commission, 2023; Nationale Plattform Zukunft der Mobilität, 2020).[7] On the infrastructure side, the technology-neutral Alternative Fuel Infrastructure Directive (AFID, Directive, 2014/94) of the EU required all member states to adopt a national policy framework for the deployment of infrastructure for alternative fuels, ranging from gas to charging infrastructure. While this policy mentioned heavy-duty vehicles predominantly in connection with LNG, it has now been revised into a Regulation (Regulation (EU) 2023/1804) with distinct, technology-specific requirements for heavy-duty vehicle infrastructure, focused on electric charging and hydrogen refuelling and with a less specific side reference to adequate LNG infrastructure.

5. Results

In Section 5.1, we apply our typology to describe the technology innovation strategy trajectories of truck manufacturers, for which we derive their strategy types for two time periods (before the policy change in 2019 and after) based on assessing their degree of paradigm-change and proactiveness. This is followed by Section 5.2, where we report our findings concerning strategy determinants and compare these within and between strategy trajectories.

5.1. *Firms' technology innovation strategy trajectories in the take-off phase of the transition*

We find that between 2018 and 2021, all truck manufacturers modified their technology innovation strategies towards heavy-duty AFVs for Europe, aligning them with the tightened net-zero policy.

5.1.1. *Identifying firms' technology innovation strategies over time (2018–2021)*

In a first step, we compiled an overview of each manufacturer's technology innovation strategy, taking stock of which AFV technologies they announced to be working on or were already offering on the market for each of the four consecutive years 2018–2021 (see Fig. 5). To contextualize these strategies in the transition, the overview also includes the key EU regulations outlined in Section 4.

The overview presented in Fig. 5 shows four main developments. First, there is a visible increase in the number of pursued alternative technology options since 2019 – coinciding with the year the EU's CO_2 emission standards for heavy-duty vehicles entered into force. Second, Scania, Volvo, and Daimler have advanced from strategic announcements towards serial production of heavy-duty long-haul BEVs in the observed time frame, and since 2021 all OEMs have included BEVs for this segment in their technology innovation strategies. This recent

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[6] IVECO has since separated from CNH Industrial (January 2022).

[7] According to our conceptualization, this marks the end of the pre-development and start of the take-off phase of the transition.

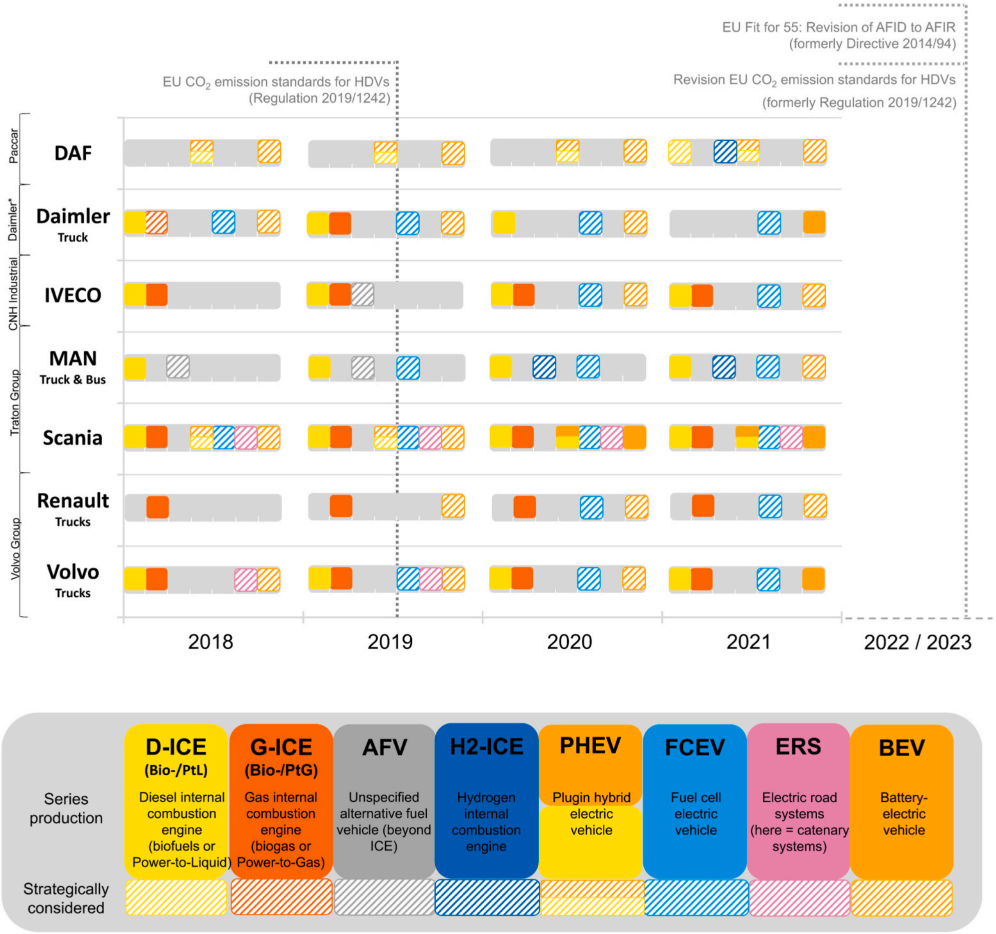

Fig. 5. Truck manufacturers' technology innovation strategies towards AFV between 2018 and 2021. *Note:* All entries refer to heavy-duty AFV technologies for the segment >18 t and range >200 km. Innovation activities related to diesel, e.g. to meet Euro VI standards, are not included. Brand affiliations with larger firms are indicated vertically on the left. Key EU policy changes after 2021 are indicated with dotted lines on top of the figure. *Daimler Truck AG has been independent from Daimler AG since December 2021.

consolidation was described by one of the interviewees: "*Worldwide, there has been a technology commitment to battery-electric drives in transportation. No world conference was necessary for that, but it is as if such a conference had happened. And this development cannot be stopped and should not be stopped.*"[8] *(Daimler Truck, interview, 2021)*. Third, despite this recent agreement about the general importance of BEV, the figure also illustrates that no two technology innovation strategies are exactly the same and that both the focus and the number of pursued technologies differs between firms. As the same interviewee explains: "*[...] nobody has enough petty cash to do everything and that is why one has to focus a little bit on particular things and this is how differences between strategies come about.*" *(Daimler Truck, interview, 2021)*. While Scania, for example, openly pursued six different AFV technologies to decarbonize heavy trucks in 2021, Daimler chose a more consolidated innovation strategy based on the two technologies BEV and FCEV. In addition, all but one manufacturer were considering FCEV in 2021, but none had it ready for serial production and only one manufacturer was still considering ERS after two had still been open to the technology in 2018. Finally, only one manufacturer (Daimler Truck) had, as of 2021, dropped their low- (but not net-zero) carbon technologies from their portfolio.

5.1.2. *Classifying strategies according to our typology into trajectories (before and after 2019)*

In a second step we classify the identified technology innovation strategies of individual manufacturers based on our typology (see Fig. 6).[9] We introduce shading to differentiate between three degrees of paradigm changes in the technologies according to Table 3 from low (represented by diesel and gas ICEs used with bio- or PtX fuels) through medium (represented by H2 ICEs, PHEVs and FCEVs) to high (represented by ERS and BEVs).

The figure shows clear differences between manufacturers' technology innovation strategies. Based on our typology, proactiveness towards AFV technologies with a high degree of challenging the paradigm is located in the top right corner of each chart ('paradigm-challenging first mover'), while lagging behind others and betting on incremental technology changes is located in the bottom left corner ('paradigm-reinforcing laggard'). However, none of the firms can be placed in only one quadrant. Instead, all manufacturers have focused on technologies at different levels of disruption and/or varied their degrees of proactiveness. Based on this categorization and changes over time, we therefore identified four types of what we call trajectories of technology innovation strategies in the net-zero transition (see Table 4).

Based on the dynamic pattern of their AFV innovation strategies, Scania and Volvo are characterized as *proactive diversifiers* (referred to

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[8] Translation of quotes cited in this manuscript from German to English by study authors.

[9] For the remainder of the paper, shortened brand names will be used.

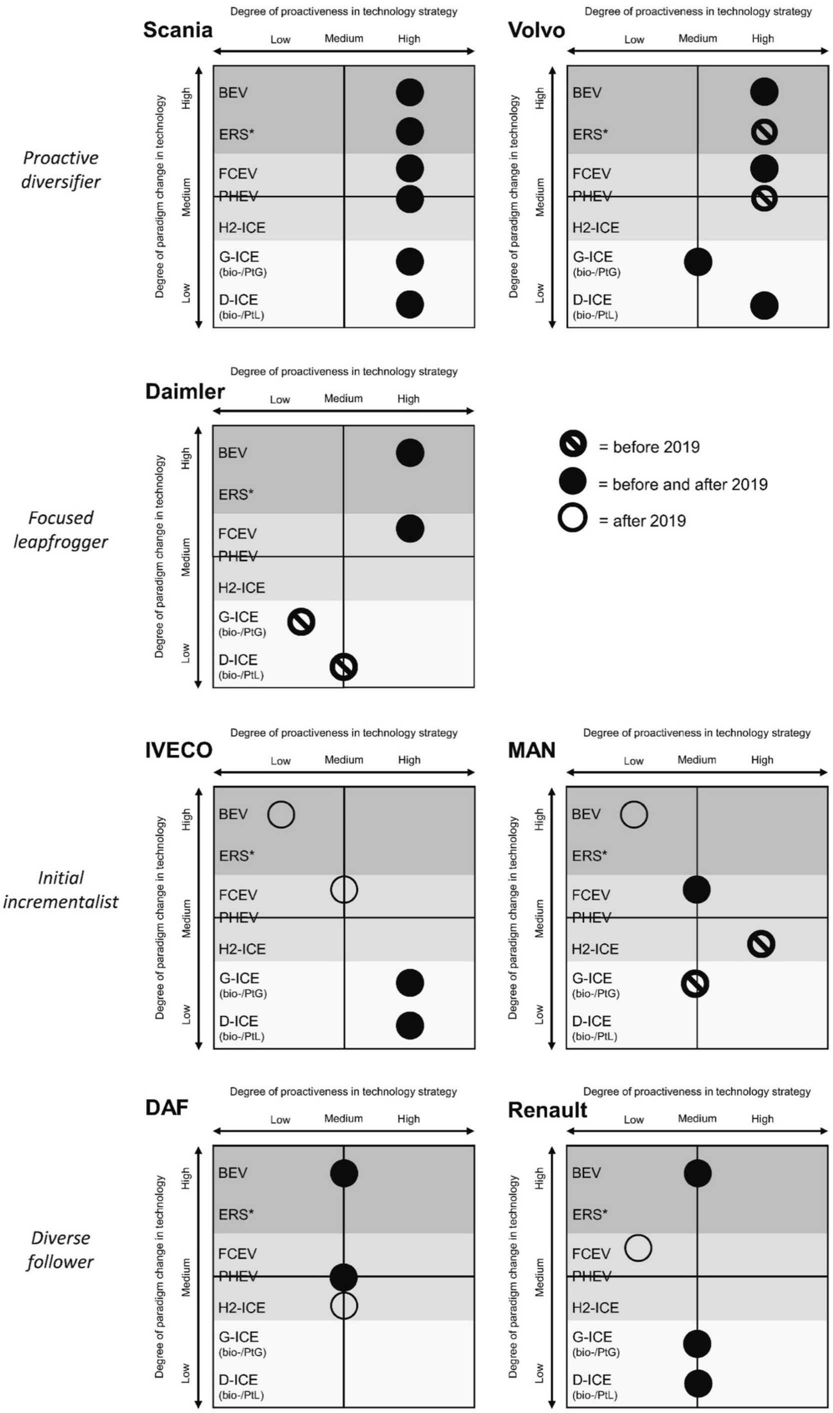

Fig. 6. Trajectories of technology innovation strategies for heavy-duty AFVs (alternative fuel vehicles) according to degree of paradigm change and degree of proactiveness. Note: x-axes display technology proactiveness relative to other manufacturers' plans and activities; activities trump announcements of plans (see Appendix B for a full overview); y-axes display the degree to which the technologies challenge the existing diesel fuel-based paradigm; circle designs indicate whether technologies were part of the technology mix in the strategy before and/or after the 2019 EU CO2 emission standards for heavy-duty vehicles. *combination with BEV vehicles.

Table 4
Identified trajectory types of technology innovation strategies and matching firms.

Proactive diversifier	Focused leapfrogger	Initial incrementalist	Diverse follower
Scania Volvo	Daimler	MAN IVECO	DAF Renault

here as *"diversifiers"* for short), the first innovators in vehicle technologies at every level of difference from the current technology paradigm around diesel trucks. In other words, these firms were both first movers in introducing alternative fuels for diesel engines and offering gas engine vehicles as well as moving towards more radical technologies like plug-in hybrid trucks, fuel cell electric trucks, electric road systems, and battery-electric trucks. In addition, these two *diversifiers* retain technologies at every level of disruption in their strategy until 2021 (the last

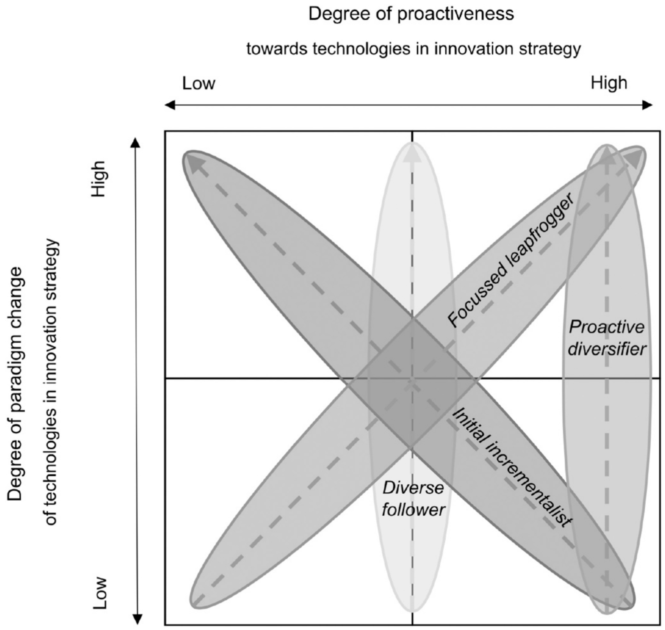

Fig. 7. Observed trajectory types for technology innovation strategies in the transition to net-zero trucking. The figure shows the types we identified for our case, but it can be easily seen that some possible additional types could potentially be found for other cases (e.g. low degree of proactiveness and pursuing all levels of technologies over time).

year of the analysis).

The innovation strategy trajectory displayed by the manufacturer Daimler Truck makes the firm a *focused leapfrogger* (*"leapfrogger"* for short) in our typology. *Leapfroggers* are characterized by initially slow progress towards types of AFV innovation that represent low challenges to the dominant paradigm, such as alternative fuels for diesel engines and gas vehicles, followed by a later omission of these technologies from their portfolio in favour of proactive progress towards the more radical technologies of fuel cell vehicles and battery-electric vehicles.

According to our typology, IVECO and MAN can be characterized as *initial incrementalists* which later become more radical and diverse (referred to in short as *"incrementalist"*). This type is characterized by initially proactive progress towards low-challenging alternatives, such as alternative fuels for diesel engines and gas vehicles, followed by comparatively late movement towards highly paradigm challenging technologies like fuel cell electric vehicles and battery-electric vehicles. Additionally, the communicated strategy contains technologies that challenge the paradigm at both low and high levels even after the adjustment.

DAF and Renault are examples of the final trajectory type of an AFV innovation strategy, *diverse followers* (*"followers"* for short). These manufacturers have developed a diverse and consistent approach to decarbonizing trucks that challenge the currently dominant paradigm at different levels. They have not been the most proactive among the manufacturers for any of the technologies, but display a low to medium level of proactiveness.

Fig. 7 provides an overview of the identified trajectory types for the case of AFV technology innovation strategies.

By assuming a dynamic perspective and thus looking at the trajectories of firms' technology innovation strategies it becomes clear that each strategy spans multiple technologies, at multiple points in time and typically different levels of proactiveness. For these four identified innovation strategy trajectory types, we now turn to explaining them through the lens of firm-level determinants.

Table 5
Global vehicle sales.

Type	Brand	Vehicles sold in 2021	Net income in 2021
Proactive diversifier	Scania	85,930 (heavy trucks)	14.2 billion €
	Volvo	119,544 (heavy-duty >16 tons)	20.2 billion €
Focused leapfrogger	Daimler	417,095 (medium and heavy-duty)*	39.8 billion €
Initial incrementalist	IVECO	46,949 (medium and heavy-duty)	12.6 billion €
	MAN	66,837 (trucks only)	10.9 billion €
Diverse follower	DAF	49,000 (heavy and medium duty)	5.7 billion €
	Renault	27,475 (heavy-duty)	5.1 billion €

Note: *Estimation based on other manufacturers' vehicle sales and EU market shares; based on available Daimler statistics, total vehicles sold minus buses = 436,000.

5.2. *Explaining similarities and differences within and between types of technology innovation strategy trajectories*

In this section, we apply our literature-based set of explanatory factors to assess whether they can explain differences between firms belonging to the same or different trajectory types.[10]

5.2.1. *Demand conditions*

The first factor are demand conditions in the market environment, captured by (1) global vehicle sales in terms of revenue and delivered vehicles, (2) market shares, and (3) key markets of the manufacturers.

Regarding the first aspect, we find that global vehicle sales of each manufacturer are largely consistent with the identified types. Globally, Daimler Truck - as the only *focused leapfrogger* - stands out with the highest revenue of almost 40 billion euros in 2021 and >400,000 delivered vehicles (see Table 5). Volvo Trucks and Scania - both *proactive diversifiers*- are next in the ranking, followed by the *initial incrementalists* IVECO and MAN and finally, with some distance, the *diverse followers* DAF Trucks and Renault Trucks. Sales figures are largely consistent with and thus help explain the trajectory types, although differences between Scania and the *incrementalists* are small, blurring their distinction. The same is true for vehicle sales where numbers are largely consistent with types but the *follower* DAF Trucks sold a slightly higher number of heavy- and medium-duty vehicles than IVECO, an *incrementalist.*

Market shares in Europe, as the second aspect, were nearly equally distributed between the manufacturers in 2021, with only the *follower* Renault Trucks and the *incrementalist* IVECO below or around 10 %. Daimler as the only *leapfrogger* led with 19 % and all the others held a market share of around 15 %. This small differentiation in market powers is therefore not expected to fundamentally help in explaining the different strategy trajectories.

For the final aspect of demand conditions, our analysis reveals differences in the key markets of each manufacturer, thereby providing some explanations for the chosen strategy trajectories. The share of the European market in the firms' total sales differed clearly between types: *leapfrogger* Daimler made the smallest share of their sales in Europe (16 %), followed by the *diversifiers* Volvo and Scania (43 % and 50 %), the *incrementalists* MAN and IVECO (67 % and 54 %), and finally the *followers* DAF and Renault Trucks, conducting most of their sales in Europe (86 % and 89 %). Daimler Truck, as a *leapfrogger*, additionally stood out from the other types with the most globally diverse reach and a large share of its truck sales in the NAFTA region (35.5 %) and Asia (24.5 %). A similar importance of the North American market for vehicle sales could only be observed for the *diversifier* Volvo (20 %). *Diversifiers* Volvo

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[10] A detailed overview of our results, including relevant evidence and original quotes, can be found in the online supplementary material.

and Scania shared a key focus on Latin America (23 % and 25 %) with the *incrementalists* MAN and IVECO (30 % and 34 %), differing from the *leapfrogger* Daimler and the *followers* that sold a smaller share of their vehicles in this market (11.5 % and <5 %).

5.2.2. Resources and competencies

Resources and competencies as our second firm-level factor were assessed for all AFV innovation activities in a firm mentioned from 2018 onwards. Our analysis shows similarities within the identified types and differences between the types, with only a few exceptions.

The *proactive diversifiers* Scania and Volvo pointed to established competencies matching the diverse set of technologies in their strategies from 2018 on. They could draw on competencies developed from producing electric buses, with eight to ten (Scania) and more than ten (Volvo) years of experience, but also referenced established competencies around the more incremental technology of (bio-)gas engines. Volvo additionally mentioned previous R&D around hydrogen and fuel cells.

Focused leapfrogger Daimler predominantly communicated competencies connected to more than two decades of experience with fuel cells developed in the car segment and through small and temporary R&D efforts on fuel cell buses. Analysed firm statements also mentioned their general involvement in electrification research and past R&D on electric drives for buses. The *leapfrogger's* competencies were not only communicated later than the *diversifiers'*, with one statement in 2019 and all others from 2020 onwards, but consequently also more focused.

Both *initial incrementalists* mentioned competencies in a limited way. MAN briefly referred to an early electric bus prototype from the 1970s on Twitter and, even less directly, to well-established combustion engine technologies as a good basis for introducing hydrogen combustion for trucks. IVECO mentioned experiences and resulting competencies more extensively, but exclusively for gas vehicles. Overall, the demonstrated competencies show less breadth than those of the *diversifiers* and are less paradigm challenging than those communicated by the *leapfrogger*.

The *diverse followers'* statements on previous competencies also focused on low- to medium radical technologies like the *incrementalists'* but were less frequent and concise and referred most to general competencies of the industry. DAF referred to the general competencies of all truck manufacturers in constructing combustion engines and considered hydrogen combustion a sensible extension of this previous approach. Renault did not refer to its own competencies, but rather to those of its parent company, the Volvo Group, for developing hybrid and electric buses.

5.2.3. Dynamic capabilities

The third firm-level factor relates to dynamic capabilities for which we consider four different activities. Our findings on all activities matched the identified types, particularly providing explanations for the differences between *diversifiers* and *leapfroggers* on the one hand and *incrementalists* and *followers* on the other, except for the evaluation of competitors, which all types reported to a similar extent.

5.2.3.1. Industry collaboration. For the first capability-related activity, AFV industry collaborations, we find evidence that overall, the collaborations matched the AFV technologies in the firms' strategies, but also indicated new areas of development (and areas in which their in-house and previous competencies needed supplementing). While the collaborations of *diversifiers* and the *leapfrogger* focused predominantly on AFV components and infrastructure, *incrementalists* and *followers* additionally collaborated on alternative fuel vehicle technologies directly. The *diversifiers* started their collaborations early, with Scania's collaborations ranging from battery development (2018) to biogas production (2019) and Volvo collaborating on charging infrastructure (2018), fuel cells (2020), and batteries (2021) As the exception to the component and infrastructure focus of the *diversifiers,* Volvo also pursued a hydrogen truck collaboration with Daimler Truck, IVECO, and oil companies OMV and Shell. *Leapfrogger* Daimler focused its collaborations on the value chain of FCEV but also on the component of battery cells. Both *incrementalists* focused on hydrogen collaborations but collaborated on battery-electric AFVs as well - MAN on the latter through their parent company Traton, and IVECO as a core part of its strategy on both BEV and FCEV with US manufacturer Nikola. Key collaborations of the *followers* took place through the firms' parent companies: Renault used synergies from collaborations of Volvo Trucks for BEV and FCEV, and DAF developed their own battery-electric trucks through joint ventures but was also connected to the FCEV collaborations of its parent company Paccar with Toyota and Shell.

5.2.3.2. Research investments. The analysis of firms' communicated R&D investments on AFVs, as the second capability-related activity, revealed a match with the strategy trajectory types according to their timing and quality. *Diversifiers* and the *leapfrogger* were early to make R&D investments in the electrification of trucks (2018) and *diversifier* Scania was also early to communicate a corresponding reduction in their development budget for conventional drives. In contrast, the *leapfrogger* Daimler communicated that R&D investments *"were made primarily in new technologies (emission-free vehicles) and the further development of existing products [, including] optimizing fuel efficiency and powertrains."* (Daimler, annual report, 2021). Investment statements on AFVs by *incrementalists* were only found from 2019 onwards, with MAN specifically referencing the stricter emissions standards in multiple jurisdictions as a motivation. Most mentions of R&D investments on AFVs by *incrementalists* MAN and IVECO referred to collaborations and their parent companies, Traton and CNH Industrial. IVECO also specifically addressed their smaller development budget in comparison to its competitors stating: *"we cannot overtake the others in terms of R&D spending but we can be smarter with faster work on pragmatic and innovative solutions"* (IVECO, newspaper article, 2022). Apart from some individual statements about early investments in electrification at Renault Trucks (2018), *followers* communicated R&D investments in battery-electric trucks (DAF & Renault) and fuel cells (DAF) through their parent companies Paccar and Volvo Group.

5.2.3.3. Ability to re-organize. As a third activity indicating dynamic capabilities, we assessed the firms' ability to re-organize and form new units or departments on AFV technologies. Overall, a greater number and earlier re-organization activities suggest that *proactive diversifiers* and the *focused leapfrogger* had internal capabilities to adjust to new policy and market demands whereas *initial incrementalists* and *diverse followers* rather profited from dynamic capabilities of their parent companies. The majority of re-organizations focused on BEV as the most paradigm-challenging technology. The earliest internal re-organizations around electric mobility were announced in 2018 by *diversifier* Volvo and *leapfrogger* Daimler. While no direct announcement for Scania could be found, a job advert from 2018 indicated the recent establishment of an 'e-mobility solutions' department, too. Additionally, both *diversifiers* announced their own battery assembly plants in 2021, and *leapfrogger* Daimler a pilot for battery production in 2020. *Leapfrogger* Daimler also announced their own fuel cell production together with *diversifier* Volvo under the new company Cellcentric in 2020. *Re*-organizations at the remaining companies were not entirely consistent with trajectory types. The *incrementalist* MAN announced a new internal e-mobility division in

2021, also benefiting from synergies with Traton's overarching e-mobility team, which was established in 2019. *Incrementalist* IVECO, on the other hand, did not communicate internal re-organizations around AFVs, but focused on its collaboration with Nikola. *Follower* Renault behaved similarly to *incrementalist* MAN by announcing a new R&D plant including electrification in 2021 and benefitting from the synergies with Volvo. The *follower* DAF, however, did not communicate any re-organization around AFVs despite their early introduction of smaller range battery-electric trucks in 2018.

5.2.3.4. Knowledge acquisition. To assess the fourth activity, knowledge acquisition through personnel change, we focus on top management and find that all seven manufacturers have had CEO changes since 2018 except the *follower* Renault Trucks. Firms predominantly appointed CEOs who had a long history with the respective firm, except for the *incrementalists*. Here, the CEO of MAN, appointed in 2020, had previously worked at car manufacturers related to the brand (Volkswagen and Seat) and the subsequent CEO switched positions from Scania, a manufacturer under the same group (Traton), in 2021. At IVECO, another *incrementalist*, the CEO newly appointed in 2019 had previously worked for the competitor Daimler Truck. All types therefore have changed the knowledge base of their leadership by changing personnel, with the largest changes made by *initial incrementalists* who acquired external knowledge in this position, matching their trajectory from incremental towards more radical solutions.

5.2.3.5. Evaluation of competitors. The fifth activity we consider to capture firms' dynamic capabilities refers to their evaluations of competitors' AFV strategies. Such evaluations were rarely mentioned in documents and mainly voiced in the interviews. This can be attributed to the fact that truck manufacturers are subject to strict cartel laws and are cautious about communicating their knowledge of competitors' strategies and activities. Some interviewees also made a point of only knowing about other firms' strategies because these were communicated publicly: *"[…] I know of course that Mercedes had test vehicles that I also saw on the street; that they worked on LNG vehicles. But why they finally changed their opinion, I mean for that I can only refer to the publications of Mercedes."* (anonymized manufacturer interview, 2021[11]*)*. While the gathered data show that all firms evaluated their competitors' activities on specific AFV technologies to some extent, and thus have a good overview of the market, the lack of clear differences means that this activity cannot contribute to explaining the observed trajectory types.

5.2.4. Expectations towards AFV technologies

The fourth firm-level factor captures technology expectations, for which we differentiated between expectations about vehicle technologies, components, and infrastructure technologies. Expectations were closely tied to individual technologies in the firms' strategies but only partly helped to explain the types. We found more pronounced and positive expectations towards electrification of *diversifiers* and the *leapfrogger* versus *incrementalists* and *followers* and most diverse and focused expectations of the former two but also inconsistencies between *diversifiers* and *incrementalists* towards hydrogen and gas fuels and technologies.

5.2.4.1. Vehicle technologies. The breadth of expectations towards vehicle technologies varied between types. *Proactive diversifiers* Scania and Volvo expected multiple AFV technologies at different levels of challenging the current paradigm to remain important in the future: *"There won't be one technology that will 'rule everything'. There will instead be parallel technologies over time and we will also need the combustion engine for many many years to come […] powered by renewable biofuels."* (Henrik Henriksson, Scania, LinkedIn, 2021). Similarly, *initial incrementalists* expected combustion engines to remain a key technology for trucks in the future, but were later voicing expectations for electric trucks and hydrogen (2020). In contrast to this breadth, *focused leapfrogger* Daimler communicated the expectation that only BEV and FCEV would play a major role in truck decarbonization. *Diverse followers* voiced the least but also focused positive expectations about FCEV (Renault) and (hydrogen) combustion (DAF) for long-haul transport.

Expectations towards specific technologies also largely matched the types. *Diversifiers* had early, positive expectations towards the electrification of long-haul trucks (Scania in 2018, Volvo in 2020) as did the *focused leapfrogger* Daimler (2018). *Initial incrementalists* voiced such expectations later: MAN specifically adjusted their communications from expecting that electrification would only become key for trucks with a range up to 200 km (2018), to expecting potential future ranges of 700–1000 km (2021), and IVECO communicated expectations about BEVs later and considered them a stepping stone towards FCEV (2020). *Followers*' few electrification expectations focused mostly on low ranges, with the interviewed Renault representative specifying that they would only expect electric long-haul electric transport under conditions such as *"batteries with a new type of cell chemistry [beyond silicium or solid state] that would lead to substantially higher energy densities and lower weight."* (Renault, interview, 2022). As the only type, *diversifiers* also expected electric road systems (ERS) to play a role in truck transportation in the future, but Volvo stepped back from this expectation in 2021.

Expectations towards hydrogen were less consistent with types. Among the *diversifiers*, Volvo communicated positive expectations about FCEV, which Scania did not expect to play a significant role in the future. *Incrementalists* were similarly divided with IVECO expecting a potential future marked domination of FCEV and MAN only expecting FCEV as one alternative but a larger role for electrification. *Leapfrogger* Daimler expected that FCEV would become mainstream and competitive in the 2020s. Similarly, both *followers* expected a role for FCEV, especially in long-haul applications. *Incrementalist* MAN and *follower* DAF also voiced positive expectations around H_2-ICE.

Expectations towards gas vehicles were consistent with types except for *incrementalist* IVECO that portrayed positive expectations towards gas vehicles like the *diversifiers* and unlike the other *incrementalist* MAN. Both the *leapfrogger* and the *followers* showed no expectations about gas trucks or biofuels.

5.2.4.2. Component technologies and fuels. We differentiate between expectations towards batteries, hydrogen, bio- and e-fuels, and find that the magnitude of expectations towards battery cells clearly stand out. For the development of battery technologies, *diversifiers* and the *leapfrogger* voiced consistently positive expectations about, communicating for example that *"battery cells will become cheaper and have a longer life span."* (Scania, press release, 2019), and that *"range is expected get better in the near future through improvements in [existing] batteries [and] high hopes for solid-state batteries which could increase the range up to 1600 km on a single charge."* (Volvo, press release, 2020). *Incrementalists* were inconsistent, with MAN more positive than IVECO, and *followers* had the least pronounced positive expectations about battery development.

Expectations about hydrogen were voiced by all firms but only partially consistent across types. The *leapfrogger* Daimler and the *incrementalist* IVECO had the most positive communications about future (green) hydrogen availability, while the *diversifier* Scania and the *incrementalist* MAN had the least positive ones. The second *diversifier* Volvo as well as the *follower* Renault communicated more neutral expectations, outlining the related expected challenges.

For biofuel availability, *diversifier* Volvo expected "*Europe-wide the greatest potential in terms of production volumes*" (Volvo, newspaper article, 2020) and *incrementalist* IVECO that they "*will easily suffice […] to cover the existing stock of trucks multiple times*" (IVECO, newspaper

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[11] Quotes of this subsection are anonymized because it addresses the most sensitive information that manufacturers provided.

article, 2020). Other OEMs did not voice expectations towards biofuels. Expectations towards e-fuels were consistent with trajectory types. *Diversifiers* Volvo and Scania's parent company Traton (also speaking for *incrementalist* MAN) had neutral to positive expectations towards electricity-based methane in the future and expected such e-fuels as a niche but not "*a mainstream solution*" in the future since "*it does not work overnight to establish the infrastructure for the production [...] and the costs are high [so] we expect, that it will come too late to be an interim solution and is too expensive for a long-term solution.*" (Traton, interview, 2021). *Leapfrogger* Daimler more drastically assessed e-fuels as unrealistic to reach 2030 targets because "*[optimistically], the first large commercial plants could maybe start operation around the year 2030.*" (Daimler, interview, 2021). *Followers* did not address e-fuels in their expectations.

5.2.4.3. Complementary technologies. Expectations towards complementary technologies revolved around electric charging infrastructure and hydrogen infrastructure. The *diversifiers* Scania and Volvo did not voice clear expectations about future developments of charging infrastructure. *Leapfrogger* Daimler's communicated expectations changed over time. In 2019, Daimler considered that "*charging infrastructure was lagging behind*" (Daimler, newspaper article, 2019), not expecting improvements until 2022. In 2020, the *leapfrogger's* expectations towards charging infrastructure became more positive but the *focused leapfrogger* still expected that the construction of fast chargers would be a "*tremendous challenge*" (Volker Hasenberg, Daimler, LinkedIn, 2022).

For hydrogen infrastructure, *diversifier* Scania expected that "*the building of an initial infrastructure for green hydrogen will probably take until the end of the 20s*" (Traton, newspaper article, 2021). In 2019, *leapfrogger* Daimler still voiced "*doubt that a hydrogen fuel station will be in operation until [2030].*" (Daimler, newspaper article, 2019) but later (2021) matched the *diversifiers*, expecting hydrogen infrastructure to achieve sufficient coverage until the end of the 2020s. Similarly, in 2021, *initial incrementalist* IVECO expected infrastructure for producing and using hydrogen within the 2020s based on their engagement in networks like H2Accelerate. The firm also still expected a growing LNG infrastructure network in 2020. Overall, however, *incrementalists* and *followers* were less concerned with infrastructure provision and *followers* did not communicate any specific expectations.

5.2.5. Corporate political activities

Finally, we find that corporate political activities largely reflect and match technology innovation strategy trajectory types. Overall, *diversifiers*, the *leapfrogger*, and to some extent also *incrementalists* were most active in lobbying for policy changes and specific policy designs, while *followers* mainly reacted to policies in their CPAs and focused on highlighting their compliance with legislation (see Table 6).

In the following, we focus on the lobbying activities around the 2019 Regulation on CO_2 emission standards for heavy-duty vehicles as the key EU policy milestones under discussion in the observed time frame. Scania called the 2019 fleet emission targets "*ambitious*" (Scania, newspaper article, 2019) but focused on how to fulfil them once they were in place. Similarly, Volvo stressed that they considered the demanded emissions reductions important and not surprising, and said that they were ready for the challenge (Volvo, newspaper article, 2019). In contrast, before the adoption of the policy, Daimler openly criticized the targets as too strict and stated that a reduction of fleet emissions by a third until 2030 was "*technically and economically not feasible*" (Daimler, newspaper article, 2019). Similarly, *incrementalist* MAN was "*astonished at what happened there - to put it cautiously.*" (MAN, newspaper article, 2019) and considered the targets "*highly ambitious*" (MAN, newspaper article, 2019). Despite their general agreement on its target strengths, Volvo engaged in lobbying on the details of this policy and urged the EU to include biofuels in fleet emission standards as a non-polluting option following a well-to-wheel in contrast to a tank-to-wheel perspective. *Incrementalist* IVECO lobbied for this inclusion of biofuels as well, following successful previous efforts for the inclusion of LNG trucks in purchase incentives and continued toll exemptions in Germany. *Follower* Renault stressed their general agreement with emission restriction regulations, but also the limitations of a tank-to-wheel approach while incrementalist MAN and follower DAF did not appear to lobby the CO_2 emission standards specifically.

A match between CPAs and trajectory types was especially visible for the general strategy difference between *proactive diversifier* Volvo and *focused leapfrogger* Daimler. While Volvo, in one of the interviews, stated that "*[...] politics should also rather stay technology-neutral in their government aids. Because only through saying 'we develop in multiple directions' you will at some point achieve technological breakthroughs [...]. I don't think that it will be as clear as with the diesel. For that, we have too many options still.*" (Volvo, interview, 2022), Daimler criticized technology neutrality and stated that: "*this technology neutrality kills us. As a society, [...] both on the cost side as well as regarding timing, we can just not afford to build up parallel infrastructures for multiple systems. Technology neutrality is correct in a beginning phase, as long as I cannot judge in which direction it is going. But at some point, [policymakers] need to make a decision [...] to provide planning certainty.*" (Daimler, interview, 2021). Daimler was also the only manufacturer that openly took a stance against certain AFV technologies, namely gas and catenary trucks (one type of ERS), and demanded that these should no longer be supported by policies.[12]

5.2.6. Synthesis

In the second part of our analysis, we used five factors to explain the different AFV strategy trajectories of truck manufacturers in Europe between 2018 and 2021. This analysis revealed that a large number of firm-level determinants differed between firms in consonance with the identified trajectory types; however, we also found some inconsistencies where factors were found to be similar for manufacturers across types. Table 7 summarizes our results.

Based on these results, we answer our research question in the following way. First, incumbent manufacturers' strategies differ in both timing and radicality of their chosen technologies with respect to (their departure from) the established sector paradigm. In a first static assessment, the overview shows differences at each point in time and across firms. Here, our technology-differentiated typology reveals differences in proactivity and radicalness – with clear changes over time as well. Taking into account this dynamic aspect, we find four types of strategy trajectories of firms for the take-off phase of the net-zero transition in heavy-duty trucking: (1) *proactive diversifier*, (2) *focused leapfrogger*, (3) *initial incrementalist*, and (4) *diverse follower*. Second, these trajectory types show matches with selected firm characteristics, in particular their key markets, resources and competencies, research investments, knowledge acquisitions, and expectations towards AFV technologies and infrastructures. As Table 7 shows, we only find very limited inconsistencies in these matchings, which can, for example, be explained by the weight placed on the same technologies in two firms' strategies or by firm connections through parent companies or collaborations.[13]

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[12] This also showed in 2021, when the focus of *leapfrogger* Daimler was on communicating clear demands for charging and especially hydrogen infrastructure in the AFIR at EU level, illustrated by the following tweet: "*We welcome newly named rapporteur @IsmailErtug for #AFIR! Our Mercedes-Benz GenH2 Truck is paving the way for sustainable transport, now the EU needs to step up their ambition for EU-wide #hydrogen infrastructure.*" (Daimler, Tweet, 2021).

[13] These connections or collaborations, for example, align competencies and expectations between firms in different types such as *diversifier* Volvo and *leapfrogger* Daimler on hydrogen or *diversifier* Scania and *incrementalist* MAN on electrification.

Table 6
Corporate political activities per type.

Type	Firm	Focus	CO_2 emission standards HDVs (EU 2019/1242)	AFIR	CO_2 price (for transport)	Tax breaks for alternative fuels	AFV purchase incentives	CO_2-based tolls/AFV toll exemption	Emission trading system for transport	Removal of fossil-fuel subsidies	Night/ Sunday delivery permits	City access restrictions	Toll exemption
Proactive diversifier	Scania	Main focus: charging infrastructure for BEV (incl. Call for fast charging infrastructure since 2020) Additionally: - (Bio-)gas vehicles and infrastructure - Electricity grid enforcements - Early CPAs: driving permits for AFVs on Sundays and at night	x		x	x	x	x	x	x	x	(x)	
	Volvo Trucks	Main focus: charging infrastructure for BEV Additionally: -(Bio-)gas vehicles and infrastructure - H_2 infrastructure for FCEV	x		x	x	x					(x)	(x)
Focused leapfrogger	Daimler Truck	Main focus: H_2 infrastructure for FCEV and charging infrastructure for BEV (fast charging not central part of CPAs, mentioned once) Additionally: - Green energy and green hydrogen - Against political support for gas vehicles and ERS	x	x	x	x	x*	x			x		
Initial incrementalist	IVECO	- Main focus until 2019: gas vehicles and infrastructure - Main focus communicated since 2021: H_2 (and small extent for BEV)					x**						x**
	MAN	Main focus communicated since 2021: charging infrastructure for BEV (large share on fast charging infrastructure) Additionally: - H_2 and gas infrastructure (mentioned once each)	x		x			x					
Diverse follower	DAF Trucks	- Electricity grid enforcements - Early focus: AFV developments communicated as reacting to access restrictions in cities										(x)	
	Renault Trucks	Main focus: meeting fleet emission reduction targets Previous focus: AFV developments communicated as reacting to access restrictions in cities	(x)				(x)					(x)	

Note: *For BEV and FCEV. **For gas vehicles. x = lobbying for policy introduction or specific design; (x) = reaction to policy after introduction.

Table 7
Synopsis of findings on firm-level determinants and match with types.

Determinant		Main findings	
		Supporting evidence for differences among types	Conflicting evidence not explaining type
Demand conditions	Vehicle sales global (revenue/net income and vehicle deliveries)	- Large differences in revenue and vehicle deliveries between the types. - *Leapfrogger* standing out with largest revenue.	- Inconsistency between diversifiers: sales of one manufacturer closer to incrementalists. - Inconsistency between followers: delivered vehicles of one manufacturer closer to *incrementalists*.
	Market share heavy trucks Europe	- *Leapfrogger* with slightly larger market share than other types (biggest difference to one *incrementalist* and one *follower*).	- No substantial differences in market shares in Europe between types.
	Key markets	- Share of manufacturers' sales in Europe as key difference between types, from almost entire sales (*followers*) to around a sixth (*leapfrogger*). - Diverse and strong presence on multiple markets as key difference between *leapfrogger* and other types. - Substantial share of manufacturers' sales in the South American market as a difference between *diversifiers* and *incrementalists* from other types.	- Inconsistency between *incrementalists:* one manufacturer closer to *diversifiers* for share of sales in Europe. - Inconsistency between *diversifiers*: strong presence in North American market of one manufacturer as commonality with *leapfrogger*.
Resources and competencies		- *Diversifiers* and *leapfrogger* with more communication of competencies than *incrementalists* and *followers.* - *Incrementalists'* and *followers'* competencies focus on less paradigm-challenging technologies than *diversifiers'* and *leapfrogger's*. - *Leapfrogger* with more focused competencies (focus FCEV, also BEV) than *diversifiers* (focus BEV, also FCEV and gas).	- Inconsistency between *diversifiers*: communicated fuel cell competencies of one manufacturer as commonality with *leapfrogger*. - Inconsistency between *incrementalists*: communication of (bio) gas competencies of one manufacturer like *diversifiers*.
	Industry collaboration	- Collaboration focus of *diversifiers* and *leapfrogger* on components and infrastructure; collaboration focus of *incrementalists* and *followers* on vehicle technologies. - *Diversifiers* and *leapfroggers* with more direct collaborations; *incrementalists* and *followers* with more collaborations through their parent companies.	- Inconsistency between *diversifiers* and focus irregularity of *leapfrogger*: one manufacturer with a collaboration on vehicle technologies with *leapfrogger* and with one *incrementalist.* - Inconsistency between *incrementalists*: one manufacturer with more collaboration through parent organization like *followers*.
Dynamic capabilities	Research investments	- Earlier R&D investments on truck electrification by *diversifiers* and *leapfrogger* than by *incrementalists* and *followers.* - Clearer statements of reducing investments in combustion vehicles from *diversifiers* compared to other types. - *Incrementalists* with later statements about investments in AFVs than all other types and focus of investments of *incrementalists* and *followers* through parent companies.	- Communicated R&D investments of all types since 2019 predominantly on most paradigm-challenging technologies FCEV and BEV.
	Ability to re-organize	- *Diversifiers* and *leapfrogger* with earlier and more re-organizations around paradigm-challenging technologies than *incrementalists* and *followers.*	- Inconsistencies between *incrementalists* and between *followers*: synergies with parent companies' re-organization of one manufacturer similar to one *follower*; one manufacturer each not communicating re-organizations.
	Knowledge acquisition through personnel change	- *Initial incrementalists* with external CEO changes in contrast to all other types.	- Inconsistency between *followers*: one manufacturer with no CEO changes since 2013.
	Evaluation of competitors		- Evaluations of competitors at all firms; no clear differences between types.
Expectations	Expectations towards AFV technologies	- *Diversifiers* with most breadth in technology expectations in comparison to all other types. - Early expectations about electrification of long-haul in *diversifiers* and *leapfrogger* in contrast to later or hesitant expectations for this technology and segment in *incrementalists* and *followers*. - Continued expectations for combustion engines (with alternative fuels) communicated by *diversifiers*, *incrementalists*, and *followers* in contrast to *leapfrogger*. - *Leapfroggers* and *followers* with no expectations about gas trucks and biofuels. - *Followers* with positive expectations about hydrogen combustion.	- Inconsistencies between *diversifiers* and between *incrementalists*: greater focus on FCEV of one manufacturer each, similar to *leapfrogger* and *followers*. - Inconsistencies between *incrementalists*: one manufacturer with positive expectations towards (bio)gas trucks like *diversifiers*.
	Expectations towards component technologies	- *Diversifiers* and *leapfroggers* with more positive expectations towards batteries than *incrementalists* and *followers*. - *Leapfrogger* with more positive expectations towards hydrogen than other types. - Expectations towards e-fuels negative by *leapfrogger,* as a niche solution by *diversifiers* and *incrementalists,* and not addressed by *followers*.	- Inconsistencies between *incrementalists*: one manufacturer with more positive expectations towards batteries like *diversifiers* and *leapfroggers*; one manufacturer with more positive expectations of hydrogen availability like *leapfrogger*; only one manufacturer with (positive) expectations towards biofuel availability. - Inconsistencies between *diversifiers*: one manufacturer with negative expectations about hydrogen availability like one *incrementalist.*
	Expectations towards complementary technologies	- Expectations about charging infrastructure only voiced by *leapfrogger;* increasingly positive but expected challenges for fast charging. - Positive expectations towards hydrogen infrastructure by *diversifiers* and *leapfrogger*. - Positive expectations towards LNG network by *incrementalist* and no other types. - No infrastructure expectations by *followers*.	- Inconsistencies between *incrementalists*: positive expectations towards hydrogen network by only one manufacturer like *diversifiers* and *leapfrogger*; positive expectations by only one manufacturer towards LNG network.

Note: We exclude CPA here as these hold a separate spot in the analysis to corroborate the identified strategy trajectories (see Section 5.2.5). * Few publicly available statements.

6. Discussion

We discuss our findings along three key themes for which we also derive policy implications: segment and market interdependence, infrastructure provision, and technology neutrality.

6.1. *Interdependence with policy-driven technology transitions in other segments and markets*

Our analysis shows that the net-zero transition of heavy-duty vehicles is inextricably connected with developments in related market segments and global markets.

Regarding related market segments, we find that firms active in multiple segments can benefit from cross-system learning. For example, truck manufacturers that also offer passenger cars and/or buses already early on had to react to emission-related policies in these segments, and could later transfer their new competencies around alternative low- and zero-carbon technologies to heavy-duty vehicles. Key policy examples are strict urban emission regulations and public procurement programs, which supported the development of AFV city buses (Bergek and Berggren, 2014; Berggren et al., 2015), and car emissions regulations, which supported the development of alternative technologies, such as FCEV at Daimler in the 1990s and 2000s (Bohnsack et al., 2015; Mazur et al., 2015). Stricter emission-related policies in adjacent sectors can also result in advantages of one alternative technology's value chain over others. For example, developments in battery technology, a key component for battery-electric trucks, were intensified by the electrification of cars. For the net-zero transition of heavy-duty vehicles this means that diversified firms active in multiple segments may have an initial advantage over others regarding alternative technologies.

Regarding global markets, our findings show that globally operating manufacturers optimize their AFV innovation strategy and technology portfolio for their 'core markets' and therefore have an incentive to lobby for European support for those AFV technologies they can also sell in other markets. This shows, for example, in the importance placed on fuel cell electric trucks: European manufacturers most proactive towards this technology, i.e. *diversifier* Volvo and *leapfrogger* Daimler, also have the largest presence of all European manufacturers in the NAFTA region. In this region, policies for reducing heavy-duty vehicle emissions include targets of similar ambition as in the EU, especially in the pioneering market of California (California Air Resources Board, 2020), yet the likelihood of long-haul transport being electrified is lower, among other factors due to less densely populated areas and less developed power grids in comparison to Europe (Mauler et al., 2022; Neuhausen et al., 2022). This also shows in the focus on FCEV for applications beyond short-haul of new US-American truck manufacturer Nikola, a potential competitor now collaborating with *initial incrementalist* IVECO on the development of BEV and FCEV. Recent US policy developments at the national level, including national emission reduction targets for heavy-duty vehicles (US EPA, 2023) and the Inflation Reduction Act (IRA, 2022 (IRA), Pub. L. No. 117–169, 136 Stat. 1818, 2022), could both further increase the innovation pressures in this market and incentivize hydrogen production and usage by promising lower prices (Lux et al., 2021; The White House, 2023). Overall, this highlights the importance of international dynamics already in the take-off phase of net-zero transitions (Rogge and Goedeking, 2024).

For policymakers, this implies that they are well advised to acknowledge the different starting points and global perspective of manufacturers, which requires governments to have (or develop) capacities for evaluating the impact of policies in related market segments and global markets for their domestic target industry. First, such capacities allow policymakers to consciously decide whether or not to level the playing field between those firms with previously developed competencies for AFV technologies and those without. Second, they also enable policymakers to decide whether supporting industry access to key components or fuels developed in other sectors would be a good course of action, for example by attracting the relevant component industry, or whether to offer support for developing alternatives that are less dependent on these components or fuels, e.g. through publicly funded R&D programmes. Third, up to date knowledge about global industry activities allows policymakers to critically examine manufacturer's lobbying claims and consolidate them with government interests when devising increasingly technology-specific policies such as the AFIR and deciding whether and why to support the costly build-up of a dual infrastructure.[14] Not accounting for such interdependencies and relying exclusively on technology-neutral policies can indirectly favour technologies diffusing from related segments and markets. While such synergies can accelerate a transition and as such can be desirable, if not intended, they can also lock-in a development that benefits certain firms and industries more than others, thereby influencing power relations in industry and between countries.

6.2. *Re-negotiation of industry and government roles around complementary technologies: from vehicles to infrastructure*

The increasing involvement of manufacturers in infrastructure provision raises questions about power relations between government and industry in the transition. Our results on collaborations, expectations, and corporate political activities show that infrastructure as a complementary technology, which previously did not form a core product of manufacturers, has gained importance in their strategic behaviour during the take-off phase. This is particularly relevant for those firms that occupied a proactive role at some point in time. While governments have the historical experience for commissioning and/or building large-scale infrastructures, in the net-zero transition, they are facing uncertainties about which alternative infrastructures should be built. For this, governments have to largely rely on technological knowledge of industry, who were, however, pursuing and thus lobbying for multiple alternatives. Until recently, the quest for technology neutrality has resulted in EU policymakers asking member states to set goals for building infrastructure for any of the available alternative fuel technologies for heavy-duty vehicles (AFID, Directive, 2014/94 before its update into the AFIR, Regulation (EU) 2023/1804). As our results show, the lack in focused government infrastructure initiatives resulting from such technology-neutral policies combined with the parallel establishment of strict fleet emission reduction targets shifted the burden of quickly establishing infrastructure to manufacturers as they needed to fulfil fleet targets by selling more AFVs to their customers which required ensuring they could charge or refuel them.

This extension of manufacturers' core business necessitated collaborations – even for high-income and globally diverse firms like the *diversifiers* and *leapfrogger*, which had previously not pursued such collaboration for developing new vehicle technologies. Yet, building up the associated infrastructure requires large-scale investments and bears the risk of large stranded investments if not widely used, and thus forming coalitions for infrastructure development improved investment security. These infrastructure collaborations extend previous joint lobbying efforts, e.g. through ACEA, as they encompass joint assets and as such provide 'infrastructural power'. For example, the coalitions on megawatt charging initiated by *diversifiers* and *leapfrogger* signify large power structures that now go beyond lobbying because they have large infrastructure investments behind them. At first sight this might seem

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[14] Hydrogen infrastructure could, for example, be included in addition to battery-electric charging as a requirement for Europe because individual manufacturers convincingly show that electrification is not sufficient. If policymakers, however, know about manufacturers' global interests in selling FCEV elsewhere, they can either decide to re-evaluate this assessment or to consciously support the inclusion of FCEV in European policies as a matter of industrial policy to support a key European industry even though battery-electric trucks might dominate in Europe in the future.

like the virtue of governments' pursuing technology neutrality, as they did not have to select an AFV technology before more is known about the potential of each technology. Yet, having that decision instead being taken by some firms to strategically invest into the infrastructure for the technologies in their portfolio does not automatically avoid potentially detrimental lock-ins due to premature technology selection.

Rather, following a technology neutral policy approach has narrowed choices for policymakers to the options pursued by the more proactive and typically large manufacturers as later deviations would otherwise disadvantage these manufacturers by effectively declaring some of their previous large-scale infrastructure investments futile. Under technological uncertainty this is an understandable course of action for governments but may disadvantage or even exclude potentially beneficial infrastructure options, such as electric road systems, on which none of the large vehicle manufacturers' coalitions has a focus (see Fig. 5 and Plötz et al., 2024). From a perspective of limiting system and thus transition costs this could lead to a less efficient use of resources. Also, there is a risk for increased power concentration in a small number of firms if vehicle manufacturers also cover infrastructure provision for trucks rather than independent infrastructure developers and in turn a greater dependence of the government on only a few firms for the success of the net-zero transition of the sector.

This implies that governments should actively pursue a wider view on the advantages and disadvantages of certain infrastructure options, thereby going beyond the perspective of manufacturers and their interests in each of these options. This is especially the case if alternative infrastructures have very different characteristics and input requirements, like regular and fast charging infrastructure with large energy requirements at point sources, versus electric road systems with more distributed energy requirements, versus hydrogen infrastructure with its larger energy demands necessitating renewables inside the country as well as imports. Moving venues from vehicles to infrastructure gives a larger role to industry, and policymakers should carefully evaluate where societal interests overlap with industry interests - and where they do not - to ensure the most beneficial future system configuration according to a balanced set of assessment criteria for the net-zero transition.

6.3. *Implications of technology neutrality for competitive market structure*

While technology neutrality of policies can be beneficial for supporting the development of multiple alternatives in early phases of net-zero transitions, we find that in the take-off phase it has a number of detrimental effects, including for safeguarding a competitive market structure in already fairly consolidated sectors.

Our analysis shows that firms making early and high investments in incremental, paradigm sustaining technology alternatives establish competencies that they may not be able to harness later on for more radical, paradigm challenging alternative technologies required for reaching net-zero targets. This means that path dependencies do not only exist between established and alternative technologies, but can also quickly develop for alternative technologies. For firms with high income and high R&D budgets, this can result in them 'cutting their losses' once net-zero policy ambitions become credible, e.g. through implementing stricter standards (Rogge and Dütschke, 2018). For example, the *leapfrogger* Daimler abandoned gas trucks altogether when the 2019 EU CO_2 emission standards for heavy-duty vehicles were adopted. However, manufacturers may also retain these incremental technologies not suitable for reaching net-zero targets if sales in other markets with high demand for this technology form a large part of their turnover, and additionally develop more paradigm-challenging technologies, as the *diversifiers* Scania and Volvo show. Yet, for firms with more restricted R&D budgets, proactive investments in more incremental technologies that turn out to be insufficient for reaching net-zero targets can create more serious path dependencies. To adapt to the changing political landscape with increasing climate mitigation ambitions they have to collaborate on their core product to stay competitive, such as the *initial incrementalist* IVECO.

This implies that the introduction of unexpectedly stringent targets, such as those in the 2019 EU CO_2 emission standards, after an initial lack of credibility of ambitious climate targets and previous support for all infrastructure options will impact companies differently even if formulated in a technology-neutral way. Such improved consistency and thus credibility of policy mixes benefits early movers betting on strict climate policy and thus investing in radical net-zero technologies, while it disadvantages companies that have betted on incremental low-carbon solutions only. Such companies initially attempting climate policy compliance with paradigm sustaining innovation strategies are now faced with an increasing need for collaboration. Given that the European truck market was already heavily consolidated in 1998 (Kelp, 2000) and is now even more so, the few remaining firms have nearly equal shares in the European truck market. Further consolidation can exacerbate the cartel law issues of recent years resulting from price agreements between manufacturers due to a lack of competition.

Therefore, our research case suggests that policymakers should strive to reduce policy uncertainty and improve the credibility of their climate policy ambitions in order to avoid market consolidation. One way to achieve this is to introduce ambitious and credible targets from the very beginning, which implies backing them up by strict standards early on. This way, valuable R&D investments would not be captured by incremental technologies but instead be targeted right away into net-zero ones. In our case, where policy makers' quest for technology neutrality had a detrimental impact on the competitive market structure, this could be alleviated, for example, by providing R&D subsidies for smaller firms now that policy stringency has been increased, making radical technology changes necessary to achieve net-zero ambitions. If such complementary policies are not considered in the policy mix, technology neutrality may eventually result in larger tasks for cartel law later on in the net-zero transition of the already fairly consolidated heavy-duty vehicle sector.

7. Conclusions

In this paper, we analysed how incumbents' technology innovation strategies towards alternative fuel vehicle options have differed during the policy-induced take-off phase of the net-zero transition in the heavy-duty truck sector and how the observed patterns can be explained. We found four different types of strategy trajectories for truck manufacturers associated with the 2019 policy change: *proactive diversifier, focused leapfrogger, initial incrementalist,* and *diverse follower*. The deliberate disaggregation of innovation strategy over time and for different disruption levels of technologies reveals that the level of proactiveness towards technologies is not uniform for all incumbents throughout a transition. Firm-level determinants can explain some of these differences and indicate aspects that can be strengthened by policies directed at firms, such as competencies towards more radical technologies. Further research could take a closer look at the connections between these firm-level determinants and strategic differences and test them with quantitative statistical approaches. A triangulation with quantitative text analysis methods or modelling approaches could furthermore shed light on the connection between the identified types, market expectations, and the diffusion of technological innovation in the sector. Additionally, applying the strategy trajectory typology to other industries could show whether the trajectory types found here match firms' strategies in other sectors undergoing a net-zero transition as well.

We conclude that knowledge about the firm-level determinants of more or less radical technology strategy trajectories can promote the understanding needed to facilitate effective policy mixes for the take-off phase of a net-zero transition. Just as technology neutrality can inadvertently support net-zero technologies that some firms have developed in adjacent sectors or for other global markets, moving too late towards more technology-specific policies can disadvantage firms that made investments into incremental technologies as a result of regulatory uncertainty about future stringency of decarbonisation policies. With more granular knowledge about strategy trajectories, policymakers can more consciously approach such potential interactions and differentiated effects to encourage acceleration and avoid potentially inefficient lock-ins or sunk costs when designing credible net-zero policy mixes harnessing the power of creative destruction.

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CRediT authorship contribution statement

Aline Scherrer: Writing – original draft, Visualization, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Karoline S. Rogge:** Writing – review & editing, Visualization, Supervision, Funding acquisition, Conceptualization.

Declaration of competing interest

None.

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Appendix A. Data collection details

List A1: Publications for the LexisNexis search.

Daily and weekly newspapers

- Süddeutsche Zeitung (incl. Regional issues)
- Frankfurter Allgemeine Zeitung
- Handelsblatt
- Die Welt
- Die Welt am Sonntag
- Die ZEIT (incl, ZEIT Magazin)
- taz, die tageszeitung
- Stuttgarter Zeitung
- Stuttgarter Nachrichten
- Nürnberger Zeitung
- Nürnberger Nachrichten
- Börsen-Zeitung
- Wirtschaftswoche online

Sector publications

- Transport - Die Zeitung für den Güterverkehr (Magazine for heavy-duty transport)
- Energie & Management
- AUTOHAUS Online
- Deutsche Verkehrszeitung DVZ - Deutsche Logistik Zeitung (German transport/logistics magazine)
- manager magazin
- Automotive World
- VDE publications (German Association for Electrical, Electronic & Information Technologies)

List A2: CEOs and managers for the newspaper article and LinkedIn search

- Harry Wolters (DAF Trucks, President)
- Heino Schroeder (DAF Trucks Germany, CEO)
- Ron Borsboom (DAF Trucks, Executive Board Member)
- Willem van Sambeek (DAF Trucks Germany, CEO)
- Martin Daum (Daimler Truck, CEO)
- Karin Radström (Daimler Truck, Executive Board Member)
- Stefan Buchner (Daimler Truck, Member of the Board of Management)
- Andreas Gorbach (Daimler Truck, Member of the Board of Management; Head of Truck Technology)

- Volker Hasenberg (Daimler Truck, Manager for CO_2 strategy)
- Giondomenico Fioretti (IVECO, Alternative Propulsion Business Development Director)
- Thomas Hilse (IVECO, Brand President)
- Pierre Lahutte (IVECO, Brand President)
- Marco Liccardo (IVECO, Vice President Medium & Heavy Trucks Global Product Line)
- Gerrit Marx (IVECO, CEO)
- Luca Sra (IVECO, President Truck Business Unit)
- Christian Sulser (IVECO, Operative lead Germany and Switzerland)
- Joachim Drees (MAN Truck & Bus SE, CEO)
- Alexander Vlaskamp (MAN Truck & Bus SE, CEO)
- Andreas Tostmann (MAN Truck & Bus SE, CEO)
- Frederik Zohm (MAN Truck & Bus SE, Executive Board Member)
- Frederic Ruesche (Renault Trucks, Managing Director Germany)
- Bruno Blin (Renault Trucks, President; Volvo Group, Executive Vice President)
- Christian Levin (Scania, CEO; Traton, CEO)
- Henrik Henriksson (Scania)
- Matthias Gründler (Traton, CEO)
- Roger Alm (Volvo Trucks, President; Volvo Group, Executive Vice President)
- Lars Martensson (Volvo Trucks, Environment and Innovation Director)
- Helene Mellquist (Volvo Trucks Europe, President)
- Claes Nilsson (Volvo Trucks, President)
- Peter Prijak (Volvo Trucks, Sales Director Germany)
- Peter Ström (Volvo Trucks, Managing Director Germany)

Table A1
Overview of data sources.

(1) Document data	(2) OEM manager insights
Annual reports ($n = 30$)	Interviews (managers) ($n = 10$)
Press releases ($n = 142$)	Newspaper articles with direct quotes (managers and CEOs) ($n = 170$)
Tweets ($n = 2318$, coded $n = 635$)	LinkedIn posts (managers and CEOs) (n = 63)

Table A2
Coded tweets per manufacturer.

Manufacturer	Twitter handle	Coded	Replies to users
DAF	@DAFTrucksNV	54	0
Daimler Truck	@DaimlerTruck	65	13
Daimler Truck & Bus*	@DaimlerTruckBus*	87	7
IVECO	@IVECO	3	0
MAN Truck & Bus	@MAN_Group	31	4
Renault Trucks	@RenaultTrucksCo	72	1
Scania	@ScaniaGroup	104	0
Traton** Group	@TRATON_GROUP	52	3
Volvo Trucks	@VolvoTrucks	167	12
Total		635	40

Notes. *Until 2021. **Only tweets coded with statements specific to MAN or Scania.

Appendix B. Strategy assessments

Table B1
Proactiveness assessment per manufacturer and ZEV technology.

Manufacturer	D-ICE (bio/PtL)	G-ICE (bio/PtG)	H_2-ICE	PHEV	FCEV	ERS	BEV
DAF	–	–	2	2	–	–	2
Daimler Truck	2	3	–	–	1	–	1
IVECO	1	1	–	–	2	–	3
MAN Truck & Bus	1	2	1	–	2	–	3
Renault Trucks	2	2	–	–	3	–	2
Scania	1	1	–	1	1	1	1
Volvo Trucks	1	2	–	–	1	1	1

Note: Focus on vehicles >18 t and with a range >200 km. Mixed measure of announcements, development activities and actual sales start (sales start trumps announcements). Additional document research for D-ICE and G-ICE before 2018 to determine proactiveness. Scores range from most proactive (1) to least proactive (3); no communicated activities or announcements are indicated by ‘–‘. Multiple combinations of measures can lead to firms occupying the same proactiveness level (e.g. a score of ‘1’ for both the firm with the earliest announcements and a firm with comparatively late announcements if the sales start for this technology of the latter happened before the sales start of the former).

Data availability

Data has been partly anonymised and is included in the supplementary material. The publicly available data that was analysed can be shared upon request.

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