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Influence of Regulation on Research and Technology Maturation: A Bibliometric Investigation of Research in Aftertreatment Technology

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Abstract

Environmental risk has emerged as a primary concern globally, with air pollution being the most significant contributor to this risk. The United Nations Framework Convention on Climate Change (UNFCCC), the Paris Agreement, Net Zero emission targets, and growing concern about climate change and air pollution are pushing for rigorous emission norms. Vehicular emission has been identified as a major contributor to air pollution. Health alarms and increasing public concern have led to the development of stringent regulations for abating vehicular emissions. Efficiency in controlling vehicular emissions (Aftertreatment Systems) has emerged as one of the critical factors for the competitiveness of automobile companies. Aftertreatment systems are complex systems with various components that must be integrated to develop an effective mechanism for vehicular emission control. Scientific leads provide the key inputs for the technology development of aftertreatment systems. The influence of regulation on scientific research in an area provides a novel understanding of a demand-pull model of research, increasing regulation creating demand driven research. This aspect has not been researched to that extent and more so applying the bibliometrics approach. The present paper is centred in this direction. It examines the key regulations implemented over different periods for controlling vehicular emissions and their influence on aftertreatment research. A sophisticated bibliometric science mapping approach is applied to capture the temporal and longitudinal evolution of research in aftertreatment, covering the period from 1991 to 2023. The paper provides interesting insights into research shaped by regulations and concludes by drawing policy implications.

Introduction

Environmental risk has emerged as a primary concern globally, with air pollution being the most significant contributor to this risk. WHO has prescribed guidelines for air quality standards that provide countries with a clean air benchmark for avoiding health risks due to poor air quality. Clean air has a significant positive impact on Sustainable Development Goals; attaining clean air has emerged as one of the key targets set by different countries for attaining SDG goals. The air quality standards of countries have been set at different levels, and OECD countries have set high standards. Research over the years identified the major pollutants and their effect on health. Vehicular emission was identified as one of the major contributors to air pollution; progressively, many pollutants emitted from tailpipes were found to have severe adverse impacts on the air. This raised health alarms and increasing public concern led to stringent regulations for abating vehicular emissions. The major effect on global automobile market was visible with the need to bring effective interventions for abating vehicular emissions. The case of Volkswagon highlights how contentious and severe implications can happen due to violation of emission standards. Volkswagon was caught by the U.S. Environmental Protection Agency (EPA) in installing a ‘defeat device’, a software in diesel cars and SUVs that helps circumvent EPA emissions standards for certain air pollutants. It was designed to detect when the vehicle is undergoing emissions testing and turns full emissions controls on only during the test. These vehicles were found to emit up to nine times more pollution than emissions standards allow. This also created a huge reputation damage on Volkswagon globally and also it had to pay a $2.8 billion to settle the penalty imposed. It is estimated as early as 2014 that over 70 percent of light vehicles sold worldwide are subjected to vehicle emissions standards (IIS 2014). Huge capital is being devoted by major automobile companies for developing effective post-treatments (aftertreatment technologies). Research provides the leads for technology pathways for developing exhaust-abating products. R&D efforts in the development of sophisticated aftertreatment systems is driven in response to the increasing regulation. In other words, the strict emission standards are leading to the demand for development of sophisticated aftertreatment systems; a ‘demand-pull’ driven by market needs of creating aftertreatment systems that complies with emission regulations (Frenkel et al., 2014).

Emission standards have become the legal requirements governing air pollutants released into the atmosphere. Emission standards set quantitative limits on the permissible amount of air pollutants released from specific sources over specific timeframes. They are generally designed to achieve air quality standards and to protect human life. Vehicular emission standards have evolved and become more stringent over the years limiting the amount of pollutants that vehicles and engines can emit. The mechanism of fuel combustion and exhaust emissions largely relies on fuel and engine design properties. Many approaches are used to reduce engine exhaust emissions into the atmosphere. An integrated approach of considering both ‘internal factors’ that result in better engine combustion and ‘aftertreatment’ technologies that can reduce already borne pollutants in the exhaust stream is needed for emission reduction from engines. The internal factors influence the combustion chamber and fuel delivery systems. An aftertreatment system is a method or device for reducing harmful exhaust emissions from internal combustion engines. In other words, it is a device that cleans exhaust gases to ensure that the engines meet emission regulations. The aftertreatment systems are used to reduce NOx, CO, PM, and BC emissions and are continually evolving to control tailpipe emission pollutants that are identified as causing environmental risks and health hazards. Balancing the factors is highly challenging as some conditions favour the reduction of these emissions, while some situations lead to an increase in the emissions (Gajbhiye et al., 2022). An amalgamation of internal factors and aftertreatment technologies in engines is a big challenge in modern engine technology.

Reducing the pollutants deriving from engines represents an interesting scientific and technological challenge. It has high commercial value as upstream research is a crucial driver of invention and innovation. As regulation standards are getting more stringent globally and public concerns are increasing, the need for more sophisticated aftertreatment systems is increasing. In particular, one of the critical factors for the competitiveness of automobile companies is their efficiency in controlling emissions. Research is happening intensively to develop advanced filters for creating more efficient aftertreatment systems. Vehicular tailpipe emissions significantly threaten human and environmental health (WHO, 2019). Incomplete combustion in the engine is one of the significant reasons for combustion pollutants, with hydrocarbons (HC), carbon monoxide (CO), and nitrogen oxide (NO_x) being the significant pollutants realized during this process. HC is responsible for soot formation and Particulate matter ($PM_{2.5}$), which negatively affect human health. CO reduces the flow of oxygen in the bloodstream and is particularly dangerous to a person with heart disease. CO_2 does not directly impact human health, but it is a ‘greenhouse gas’ that traps the earth's heat and contributes to the potential for global warming (Jalali et al., 2022). NO_x is the major pollutant that acts as a precursor for tropospheric ozone (O_3) formation, resulting in several allergenic diseases. The vehicular emissions thus has severe implications for adverse impact on clean air. Clean air is now closely monitored through various instruments in different countries. Clean Air Act in the USA has set national ambient air quality standards (NAAQS) primarily focussing on six major air pollutants: particulate matter (PM10 and PM2.5), ground-level ozone (O3), Nitrogen dioxide (NO20, Sulfur dioxide (SO2), Carbon monoxide (CO), Lead (Pb). Environmental Protection Agency (EPA) is the regulatory authority in the USA that monitors environmental pollution, within its ambit is seeing that automobiles manufactured domestically and imported do not violate vehicular emission. European Clean air policy calls for member states to adopt measures that as a minimum level aligns with WHO air quality standards. Other countries are also adopting stringent guidelines for Clean Air. Emission reduction measures are at the centre stage of the policy programmes in EU. Horizon Europe and Cohesion fund to support clean air initiatives by at the local, regional, and national levels.

Increasing evidence of vehicular emissions being one of the key factor of air pollution is leading to framing more stringent emission norms. Research is also highlighting newer pollutants from vehicular tail pipes that need to be controlled and limiting particle size ranges with varied dimensions from 10-300 nanometers (nm). The US standards are designed in terms of Tiers with the current being Tier 4, Europe has Euro standards with current being EURO 6/VI regulations, China has stage 6 emission standards. Standards in different countries have been primarily framed from Euro and US standards. India for example has BS standards primarily framed from Euro standards. Euro 7 exhaust emission is introducing stricter regulations for various pollutants and regulations on contaminants that have not been regulated until now, such as nitrous oxide (N_2O). The US is implementing new rules limiting fine particulate pollutants to 9 ug/m3 (micrograms per cubic meter of air). Meeting the stringent limits requires a catalytic system with great complexity, size of units, and number of units, as well as increased fuel consumption. Overall, the common theme among these regulations is the focus on reducing emissions of harmful pollutants from vehicles to improve air quality and human health. However, there are differences in the specific pollutants targeted and the standards set. US EPA ensures stricter compliance for domestic and important automobiles with the regulation for vehicular emission control. Similar measures are visible for EU member countries. Other countries are also adopting measures in similar directions.

Objective and Research Questions

Regulation standards for vehicular emissions are becoming more stringent, expanding the scope of pollutants and particle size range with varied dimensions from 10-300 nanometers (nm) that need to be controlled. This creates concerns for automobile manufacturers as they have to demonstrate to the regulatory authorities that their vehicle meets the vehicular emission standards of that country. Automobile firms compete to establish efficient aftertreatment systems, pushing much attention to research and development. Countries compete in manufacturing and export, with the automobile sector as one of the key areas that bring economic growth, jobs and a long-term competitive edge. It directly and indirectly contributes to many related industries. The countries, particularly those having strong automobile sectors, are also devoting substantial funding to automobile research and technology development. With emission control becoming a key area, funding for developing different components for efficient aftertreatment systems has become an active area of research.

Research papers can provide a good indication of what types of research are happening in cutting-edge areas that contribute to developing technological capacity. Research papers are also published in cutting-edge areas to defend against competitor firms and prevent them from patenting. The key argument the study makes is that stringent regulations is pushing research in this area towards the development of sophisticated aftertreatment systems. We posit that aftertreatment research is shaped by regulations over different periods. The study will provide an idea of how, in a demand-driven area which is highly science-intensive, regulation motivates research.

The following research questions are posed to address the study's objectives, i.e., the influence of vehicular emission regulations on research in aftertreatment technologies.

- What pollutants are regulated in different periods, and how does it map with research activity?
- How central and developed are those research themes in different periods?
- Which are the most important topics in terms of research productivity and impact?
- What is the overall landscape of research in this area, and what it indicates?

Literature Review

Knowledge embodied in publications are important explicit outputs of R&D. Publication analysis using tools and techniques of bibliometric offers the advantage of enabling an objective, quantitative analysis of prominent, explicit outputs of R&D. Bibliometric has been applied extensively to understand the structure and dynamics of a research field, its intellectual structure, trends and evolution (Leung, Sun and, Bai, 2017). The relationship between disciplines, fields, documents, or authors can be spatially represented through bibliometric mapping (also called science mapping) (Small, 1999). New sophisticated tools and techniques of bibliometrics are helping in diving deep to understand the evolution of a research field, the emerging key areas, and other essential insights (Cartes-Velásquez and Manterola-Delgado, 2014).

A few bibliometric studies have been undertaken in vehicular emissions and subdomains of aftertreatment systems. Egan, Mohammadpour, and Salehi (2023) present a bibliometric analysis of research from ship emissions. The temporal evolution of the field was undertaken based on keywords. The two topics, 'energy efficiency' and 'emission reduction', were found to be prominently dominating from 2014 to 2020. Additionally, the increase in the term 'climate change' occurs in the same period as terms such as 'LNG' and 'emission control', showing the increasing trend towards sustainable maritime transport. This is seen again between 2021 and 2022 in terms of 'green shipping' and 'fuel sulfur content', as well as 'energy efficiency' remaining a frequently occurring term. This provides a good indication of the topics where research is taking place. Tian et al. (2018) identified trends and characteristics of carbon emissions research in the transportation sector from 1997–2016. Bibliometric analysis was based on keywords assigned to publications to identify critical topics in this field. Ruegg and Thomas (2011) examined the extent to which US Department of Energy-supported combustion engine research and how it was linked to downstream advances in vehicle engines and innovation in other industries. Huang et al. (2017) attempted to uncover the frontier research areas in selective catalytic reduction Technology (SCR). Ai et al. (2023) analysed the global research landscape and hotspots in SCR. Their study identified five major SCR research areas: catalyst, reductant, deactivation, mechanism, zeolite. Zeolite was found to be the most widely studied SCR catalyst.

Analysis of research evolution in aftertreatment systems covering combustion engines and Selective Catalytic reduction technology has been undertaken so far. There is, however, no study that has captured the overall research landscape of the aftertreatment system and the different components within it. No study in this area has examined the regulations and its implications for aftertreatment research. The present paper is motivated by this as it attempts to see how emission regulations shape aftertreatment research.

Methodology and Data Collection

Emission control regulation for vehicular emission was examined from key influential sources primarily from European and US regulations. The evolution of regulations in these two countries has influenced regulations in other countries. It thus provides a good measure to capture the pollutants identified and specific attributes for control over different periods. The study uses a highly sophisticated science mapping tool, SciMAT, to capture the themes or topics in specific delineated periods (temporal analysis) and track the evolution of research fields through consecutive periods (longitudinal study). This software applies the bibliometric technique of co-word analysis, helps to construct a co-word network through co-word analysis and applies a clustering algorithm to identify the research themes (Coulters, Monarch & Konda, 1998). Two dimensions, namely 'centrality' and 'density' characterise each topic (Callon, Courtial, and Laville, 1991). Centrality measures the external interaction among each network and can be understood as the relevance value of the topic. The internal cohesion of the network is measured by density; it can be interpreted as a measure of the theme's development. Based on centrality and density, SciMAT allows a research field to be represented through a Strategic diagram and thematic network. A strategic diagram is a temporal analysis of one selected period. A four-dimension quadrant can represent the critical characterization, see Figure 1.

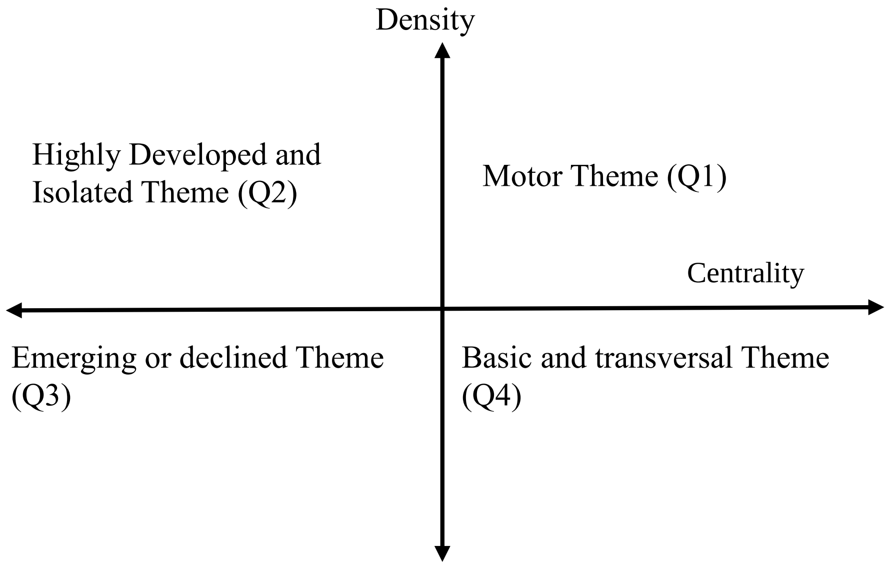

Figure 1. A Stylised Representation of Strategic diagram.

These quadrants are defined as follows (Cobo et al., 2012): The upper-right quadrant (Q1) is identified as "Motor themes", characterised by internal solid ties among the sub-topics (high density) and also connecting activity with other themes (high degree of centrality). The upper-left quadrant (Q2) hosts topics with strong internal ties but weak external links. They stand as specialized themes on the area's periphery. The lower-left quadrant (Q3) includes themes in which sub-topics are not connecting to each other (low density), and also, they are not connecting to different themes (low centrality). They can be emerging or declining themes. The lower-right quadrant (Q4) has themes in which sub-topics are loosely connected (low density) but are well connected to different themes (high centrality). A longitudinal analysis leads to a thematic area, a set of themes that have evolved across different sub-periods. The other themes are nodes in a network. Themes are connected to a network through edges. This helps to create a thematic area based on longitudinal analysis. Various indexes can be applied to normalize the data and provide weightage. A theme could belong to a different thematic area or not come from any. The coherence and diversity that lead to the formation of an area can be discerned through this analysis. It is more valuable if quantity and quality performance indicators are applied to understand the theme development and evolution. Quantity measured through publication count is a proxy for research intensity, and quality is measured through citations and citation-based indicators that act as a proxy for research influence and impact. The present paper used this comprehensive approach: a strategic diagram and thematic network constructed based on publication count, total citations, and h-index (Hirsch, 2005) to capture the impact of themes and thematic areas.

Data set

The metadata for the study was based on papers downloaded from the Web of Science (WoS). Core components of aftertreatment technology on which all the technologies have been primarily based were identified based on a literature review of aftertreatment technology and consultation with subject experts. This helped to develop the search string to extract records for the study. Selective Catalytic Reduction (SCR) and the lean NOx trap (LNT) are the representative technologies devoted to reducing NOx under lean-burn operation conditions. At the same time, soot removal is mainly performed by Diesel Particulate Filters (DPF). Various new combined technologies have been introduced for NO_x removal (i.e., LNT–SCR) and the simultaneous removal of NO_x and soot, like SCR-on-filter (SCRoF), in series LNT/DPF and SCR/DPF and LNT/DPF and SCR/DPF hybrid systems (Marinovic et al., 2022). Diesel Oxidation Catalysts (DOC) are comprehensively preferred emission control systems for heavy-duty and light-duty vehicles in many countries such as Europe, the USA, and Japan. Gasoline particulate filters (GPFs) are emerging as helpful after-treatment filters for meeting the limits of ultrafine particles in gasoline/petrol vehicles. Highly efficient exhaust filters capture most of the vehicle's particulate emissions, including excellent particles, preventing them from leaving the exhaust pipe or possibly entering the atmosphere. These terms were introduced to capture the records for the study. The final search string that had the slightest noise and provided the most relevant records was (("SCR", or "selective catalytic reduction" or "DPF" or "Diesel Particulate Filter" or "EGC" or "Exhaust Gas Circulation", or "DOC", or "Diesel Oxidation Catalyst" or "LNT" or "Lean NOx trap" or "GPF" or "Gasoline particulate Filters") and ("aftertreatment*")). This search string was applied to the Topic Search, which includes the topic, abstract, authors' keywords, and keyword plus (indexed words assigned to papers by WoS). The study covered the period from 1991, when the first publication on this topic appeared in this database, till 2023. Keywords were the most critical analytical unit for the study as they are seen as a signal to the fundamental concepts/topics of the research paper (Bhattacharya and Basu, 1998). The author, journal, and keywords given by the WoS database were taken for each document to have a more exhaustive corpus.

The extracted data was pre-processed using SciMAT to remove duplicate and misspelt terms. Corresponding full names replaced abbreviations with a mapping table, e.g., SCR by Selective Catalysts Reduction and Particulate Matter by PM. This helped create a consolidated group of keywords representing the same theme. The research activity in this field has been prominently visible since 1995. Hence, the period taken was from 1995-2023 for in-depth analysis. This period was delineated into six phases: 1995- 2007, 2008-2011, 2012–2015, 2016-2019, 2020–2023, to capture the diachronic changes of the field's evolution more effectively. Also during the identified periods, regulations were introduced that had major impact on vehicular emissions.

For each phase, themes were created through a strategic diagram, and a performance table was extracted. The co-occurrence keyword was normalised using the Salton index before undertaking the co-word analysis to create a thematic network. Salton's cosine formula for normalisation was taken as it is more effective in capturing links between high and low-cited papers (Hamers et al., 1989). Area detection was done based on a thematic analysis of each period. The Inclusion Index detected the conceptual nodes (nexus) between research themes of different periods. The inclusion index is the overlap measure (e.g., Jones and Furnas, 1987; Rorvig, 1999; Salton and McGill, 1983). The inclusion index has been chosen because the weight of the thematic nexus is a good measure of the overlapping between themes. Based on the identified search string, highly cited papers were also identified for each period. This helped to provide further insights into the science maps.

Results

The study identified 802 publications in aftertreatment research indexed in WoS till 2023, with the first publication appearing in 1991. This includes 614 Articles (76% approx.), 212 proceeding papers (26% approx.), and 33 (4% approx.) review articles. Conferences in a technology-driven field bring in diverse stakeholders from academia, industry and government and primarily draw attention to how the field is

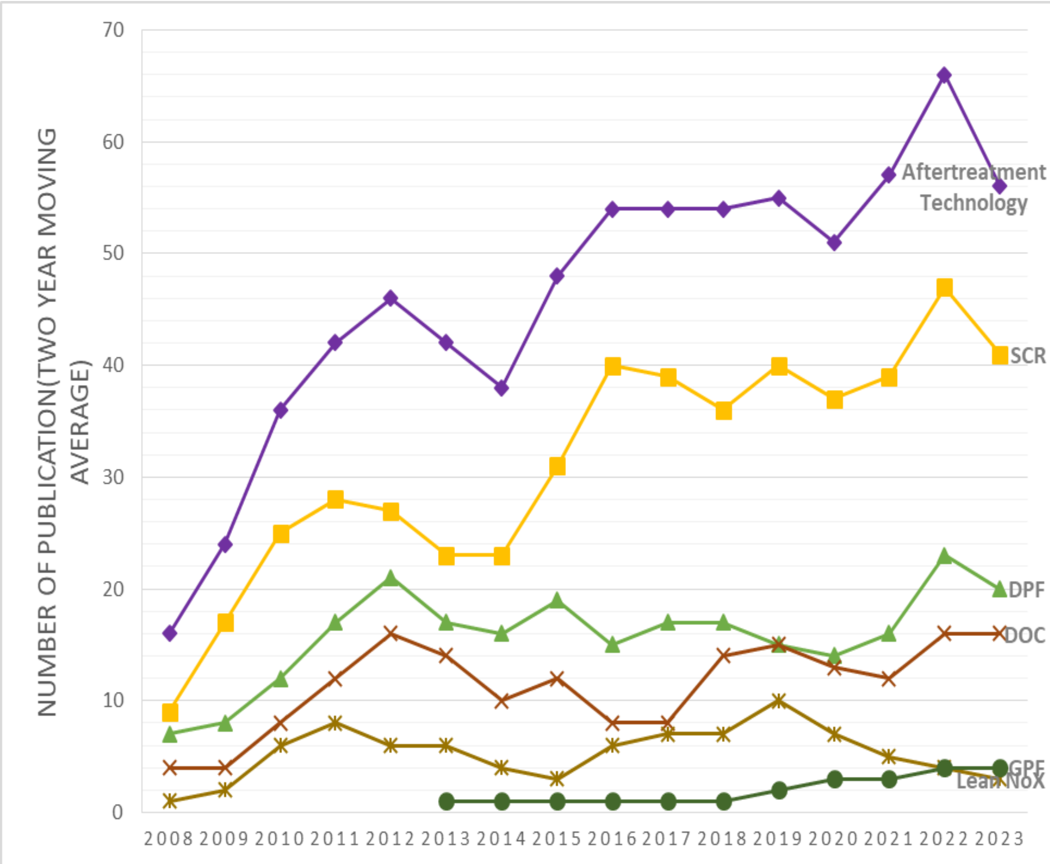

Figure 2. Research Publications in Aftertreatment and its Key Subcomponents from 2007-2023 based on two-year Moving Average.

evolving and future possibilities, among others. The conference papers indexed by WoS are also an indication of recognition of the intellectual contribution of the conference. Four key conferences, namely ASME (The American Society of Mechanical Engineers), the Internal Combustion Engine Division Fall Technical Conference, the American Control Conference, and the International Congress on Catalysis and Automotive Pollution Control, stand out as a dominant influence. All these conferences are held in the US, showing that it is the key location point for meeting varied stakeholders such as researchers, industry, and policymakers to address the current challenges in the field.

Figure 2 highlights the publication trend overall and in key sub-domains from 2007 onwards based on a two-year moving average. The earlier period is not represented as there were, on average, three publications per year from 1991, totalling 74 publications till 2006. The overall publication trend shows increasing intensity in some key research areas/topics in the aftertreatment system. Countries have largely patterned their emission policies on European regulations making it the most widely followed emission regulation globally (ICCT_Euro 6-VI-briefing-Jun2016). The research trends thus unsurprisingly closely match with the strict regulations being introduced in different phases over the years in European Union i.e. Euro standards. The influence of US Regulations, i.e. Tier regulations, also has a strong influence as the adoption of emission standards for the road transport sector in the two leading global markets (Europe and North America) has led to the global proliferation of emission-regulated vehicles through exports (Crippa, M. et al. 2016). Development and deployment of more advanced systems and components are needed to meet the emission norms. High research activity is visible in SCR (Selective Catalytic Reduction), which is unsurprising as it is a critical component of an aftertreatment system in diesel engines. It is primarily used in reducing tailpipe emissions of nitrogen oxides (NOx) and involves several components packaged together with other parts of the emissions control system. DPF (Diesel Particulate Filter) helps collect and oxidize carbon to remove particulate matter (PM). There is a continuous demand to develop high-end DPF filters. Diesel Oxidation Catalyst (DOC) aids in this process with continuous demand to create advanced catalysts, making this an active area of research. Research activity in the Gasoline Particulate Filter (GPF) is from 2014. Strict particulate matter (PM) emission limits for gasoline engines, including particle number (PN) limits, became regulated from Euro 6 introduced in 2014. The GPF function for gasoline engines is similar to what DPF does for diesel engines. The research trends are seen in Lean NOX Traps (LNTs) from 2013. LNTs technology is used in emission control to reduce nitrogen oxides (NOx) emissions. NOx limits for vehicular emissions was introduced in Euro 5/V in 2009. However the Euro 6/VI standards introduced in 2014 significantly tightened NOx limits for diesel vehicles. Requiring maximum emission limit of no more than 80mg/km, essentially forced manufacturers to implement "lean NOx trap" technology to meet this strict regulation. Thus research trends can be observed driven by emission regulations.

The USA, Germany, and China mainly drive the publications in this area. Together, they account for 58% of the overall publications in this field. These three countries are among the top automobile manufacturing countries. China has newly emerged as one of the key players in automobile manufacturing. These countries have high stakes in emission research as it provides them with key leads for new pathways for technology development. The United States leads research on Aftertreatment technology with 259 documents (32%). The country has implemented various measures to combat air pollution. Many of the prolific authors are also from the USA. Along with research institutions and universities, firms are also involved in research in the USA, as reflected in the publication outputs. The three firms most actively involved are from the USA, namely Ford Motors and General Motors, with 19 publications each, and Cummins (which specializes in diesel and alternative fuel engines and generators, and aftertreatment systems) with 18 publications. The other dominant countries publishing in this area are Germany and China; incidentally, both of them have 104 publications.

University-industry linkages: University-industry linkages are not strong if examined through joint publications. There may be other types of linkages that may not be captured through research papers. Cummins is most actively involved in joint publications with the university. One of Cummins' interesting linkages is with the University of Virginia. This linkage is due to the author W.S. Epling, also one of the most highly cited authors. He worked in the national laboratory (Pacific Northwest National Lab), a catalyst manufacturing company (EmeraChem), and Cummins Inc. He then again shifted to academia: the University of Waterloo, then to the University of Houston, and now the University of Virginia. His research area is on diesel engine emissions reduction, catalyst degradation, and how catalyst surfaces change with reaction conditions.

Research in this area is highly interdisciplinary: The journals in which papers are published exhibit a power law distribution, with a few journals accounting for the majority of documents. The extended tail distribution shows the scattering of papers across related fields and in multidisciplinary journals. This shows the field is highly distributed across various domains. This is an indication that aftertreatment technologies need to draw from many fields of research. The most prolific publication sources are the 'International Journal of Engine Research', 'Fuel' and 'Applied Catalysis B Environmental and Environmental Science Technology' with 42, 40 and 36 research papers contributing to 14% of overall publication in this area publications.

Temporal Analysis of Aftertreatment Technology Research

Temporal analysis was undertaken to capture the research activity in key periods when emission regulations were implemented. The main themes and sub-topics of the research activity in the different periods are represented through the Strategic diagram in Figure 2. Table 1 provides the performance analysis of each theme based on citation-based impact on two indicators: total citation count and *h*-index. Closely examining the strategic diagram, i.e. Figure 3, and the performance indicators in Table 1 can provide essential insights into the identified research themes. Each identified theme within a period can also be examined in detail by identifying sub-topics that comprise the theme. The research activity in a period, overall and in granular levels were examined in the context of emission regulations.

First period (1995-2007)

The key regulations in Europe during this period were: Euro 2 adopted in 1996 placed more stringent limits for CO and HCs+NOx (this was first introduced in Euro 1 in 1991). Euro 3 adopted in 2000 introduced HCs and NOx for regulation. Euro 5 adopted in 2005, created more stringent limits for CO, HCs and NOx. Progressive

Euro regulations set stringent limits for pollutants, and more pollutants came under the ambit of regulations. This called for development of more sophisticated aftertreatment systems. For example, for gasoline engines, the Euro I limit for CO was 2.72 g/Km, Euro 3, it was 2.3 g/Km and in Euro 4 limit became more stringent at 1g/km. HC was introduced in Euro 3, setting a limit of 0.2 g/Km for subsequent Euro stages set at 0.1 g/km. Particulate Matter (PM) limit and particle number (PN) emissions were introduced only at Euro 5 and Euro 6 levels for gasoline engines. However, the PM was introduced from Euro 1 and PN from Euro 5b (in the year 2011) for Diesel engines. During this period, US introduced Tier 1, Tier II and Tier III emission regulations were introduced: Tier I in 1994, Tier II in 2000 and Tier III in 2006. Tier I standard called for light-duty vehicles to regulate CO, NOx, Particulate Matter (PM), Formaldehyde (HCHO), Non-methane organic gases (NMOG) and hydrocarbons (NMHC) emissions. For diesel engines, NOx was regulated.

Research activity could be seen pivoting in two broad research themes: ‘Aftertreatment System’ and ‘Performance’ during this period (Figure 3 and Table 1). The aftertreatment system was the most prominent in terms of research intensity and influence being in the Q1 quadrant. It is an overarching theme with 52 research papers, papers receiving good impact, and 5588 citations with an *h* index of 30. Aftertreatment research was distributed under the following major sub-topics: GPF, DPF, Particulate Matter, Vanadium, Diesel Particulate Matter, Nucleation, SCR, Biofuel, System identification, Reaction, Mathematical modelling, and Optimization. Each of the sub-topics shows the research activity in the aftertreatment system that were prominent during this period. Performance was in the Q4 quadrant, characterizing it as a primary and transversal theme. This research activity is in the following sub-topics: Hydrocarbons, Aerosol, Hydrogen, Platinum-Catalyst, and Mass Emissions. Storage/reduction catalysts and diesel particulate emission control are among the most cited articles consistent with themes. This can be partially attributed to the peak year of car manufacturing in the US around 1990. Furthermore, this is when the emission limits for NOx have been introduced, and research has primarily focused on developing catalysts for NO_x reduction.

Second period (2008-2011)

This period saw the introduction of two Euro standards: Euro 5 in 2009 and Euro 6 in 2014. More strict controls were adopted by the European Union and the US for checking that automobiles do not violate emission norms. Different countries also introduced more strict controls on emission regulations. The research activity provides interesting insight into how research was shaped by regulations (Figure 3 and Table 1). Two Motor themes can be identified in this period: ' Air Pollution’ and ‘Sensors’. Research activity under the ‘Air Pollution’ theme is in Catalytic converter, Mathematic modelling, SCR, DPF, Fuel, Engine, EGR, Heavy duty Vehicle, Platinum catalytic, Mechanism, Impact, Optimization, Thermal efficiency, etc. This theme dominates research intensity and impact: 194 documents with 9288 citations and an *h* index 54. Many sub-topics of Aftertreatment are covered within this theme.

A Sensor is installed in the exhaust gas system to recognise nitrogen oxides in the exhaust gas flow. The NOx sensor is an essential component in the aftertreatment system to reduce NOx. Sensors are often excellent indicators of pending repairs and maintenance and will point out any issues the aftertreatment system may face. This is also reflected in the thematic mapping, as this theme is centrally connected to the whole network. It also has a high citation influence of 124 despite the low research intensity of only four papers. ‘Number emissions’ is in the Q2 quadrant, implying strong internal cohesion within its sub-topics but weaker connections with other themes. ‘Hybrid vehicle’ is in the Q3 quadrant, which means it is an emerging area of research. The core functional elements of the aftertreatment system are ‘Urea’ and ‘active catalytic’. They are in the Q4 quadrant, i.e. under the primary and general themes. This is unsurprising as they are a significant component of an aftertreatment system. The formation of ammonia from urea in heavy-duty vehicles is a precursor of secondary organic aerosols. Given this, limits on ammonia emissions are also imposed for heavy-duty vehicles and those for other pollutants in Euro standards. Platinum Catalysts in Simulated Diesel Exhaust, NH_3-SCR reactions over a Cu-zeolite, and a Fe-zeolite catalyst were the key topics in the highly cited papers. This is consistent with the critical sub-topics identified. The SCR catalysts research was emerging during this period as each catalytic converter had the issue of emitting other pollutants when one was controlled. All the SCR systems researched in this period were on a pilot scale

Third period (2012-2015)

The Euro 6 norms were strongly implemented during this period. Euro 6 emission standard specifically sets the particle number (PN) limits set for gasoline direct injection (GDI) vehicles. PN are complex mixtures of volatile and non-volatile materials containing soot, organic carbon and hydrocarbons, which required manufacturers to significantly reduce the number of emitted particles. Particulate Matter (PM) emissions from gasoline direct injection (GDI) engines, particularly Particle Number (PN) emissions were found to have adverse effects of ultrafine PM emissions on human health and other environmental concerns. Euro 6 emission standards have been introduced in Europe (and similarly in China) to limit PN emissions from GDI engines. This is prompting the development and implementation of ‘gasoline particulate filter ’GPFs’ an aftertreatment device to meet these stringent standards. It is particularly used in direct injection gasoline engines, to capture and remove fine particulate matter from the exhaust gas, essentially functioning like a diesel particulate filter (DPF) but designed specifically for gasoline vehicles. It is considered a key component in modern emission control systems to meet stricter emission standards. Traps tiny soot particles present in exhaust gases from gasoline engines, preventing them from being released into the environment.

It is important to see how research shaped during this period with the advent of these stringent regulation. Research activity pivoted on ten research themes during this period (Figure 3 and Table 1). Observing the ‘number of emissions’ moving from the Q2 to the Q1 quadrant is interesting. In spite of only 14 papers, their influence is high as they account for 366 citations and have an index of 10. However, the dominating theme in this period is the ‘Aftertreatment System’ being in the Q1 quadrant. There are 304 publications under his theme with citations of 10858 and *an* impact of 55. This shows its overarching influence in terms of productivity and impact. The theme ‘Vanadium’ emerges as a motor theme (Q1) and exhibits good influence with 206 citations. It is interesting to see from the theme analysis of each theme that this was part of the Sensor theme in the earlier period. ‘Methane’ and ‘Pressure’ are in the Q4 quadrant (basic and transversal), with a high citation score of 82 and 90, respectively. ‘Microwave technology’ is the Q2 quadrant, which means well-developed interlinks (high density), but that research does not connect widely to the field, i.e. has low centrality. It has two documents and 60 citations, which shows the high reception of its papers in the community. Similar to Vanadium, this theme was part of Sensor earlier. Fast and standardized microwave heating allows delicate control of catalyst properties. Microwave-synthesized catalysts generally perform better than conventional catalysts. Highly cited papers were Diesel-engine vehicles, exhaust aftertreatment systems, low-temperature combustion, and HCCI engines with high load limits. In this period, the toxicity of emissions from diesel engines was realized, and designing catalysts for controlling emissions from diesel engines was the focus of many researchers.

Fourth period (2016-2019)

Euro 6 standards were further qualified at granular levels during this period, Euro 6a to Euro 6d. Essentially they defined with more clarity the specific characteristics of the pollutants and their emission standard limits. During this period, the Aftertreatment technology research field pivoted on eleven themes (Figure 3 and Table 1). The many themes and their position across different quadrants show the field is getting more dynamic. Researchers are working in a diversity of sub-topics. Aftertreatment technologies primarily attempt to address the challenges of air pollution. Thus, the visibility of ‘Air Pollution’ as a motor theme (Q1 quadrant) with a high research intensity of 382 publications is not surprising. Air pollution research in aftertreatment is widely spread across many sub-topics, as identified in the 2008-11 period. Researchers are also actively citing research on this theme, as papers have attracted 9124 citations with a high *h*-index of 46. Other research themes that are motor themes are ‘Particles’, ‘Sulfur Oxides’, and ‘On-board-diagnosis’. On-board diagnostics (OBD) a self-diagnostic system built into a system designed to ensure a vehicle is operating within emission standards for emission regulation. In the US, OBD became mandatory in 1996 for all light duty vehicles. In EU became mandatory for gasoline vehicles in 2001 and for diesel vehicles in 2003 and was first introduced in China in 2008. OBD being in Q1 quadrant shows this has become now one of the key prominent area of research now. ‘Propane-oxidation’ is in the basic and transversal quadrant. ‘Pressure’, ‘Water’, and ‘Computational Fluid dynamic’ are in the Q3 quadrant, signifying emerging research areas. ‘Light-duty vehicles’ and ‘Energy efficiency’ are in the Q2 quadrant. This is a crucial period as many developing countries like India leapfrogged from BS-IV to BS-VI norms, where aftertreatment technology compliance is the primary requisite. Highly cited papers covered the topics of Aerosol Formation from Gasoline and Diesel Motor Vehicle Emissions and Fuel Reforming and Copper catalysts. This was when the well-known connectivity between the oxidation of fuels and their contribution to air pollution was considered in real-time. The stringent emission standards were implemented, which urged automobile manufacturers to design advanced aftertreatment technologies to comply with the emission standards.

Fifth period (2020-2023)

US is introducing Tier 4 standards in 2024 with more stringent standards. Tier 4 standard calls for 90 percent reduction in PM and NOx emissions compared to Tier 1-3 standards. It also calls for ultra-low sulfur diesel fuel with a sulfur content of less than 15 parts per million (ppm). Euro 7 norm is to be introduced in EU with stricter limits on tailpipe emissions, more stringent testing requirements, and new standards for battery performance. It will also call for regulation of nitrous oxide (N_2O), this has not been regulated earlier. Having very effective control of vehicular emission has become a competitive edge for automobiles. The new regulatory norms to be introduced have already been published giving opportunity for vehicle manufacturers to be prepared for new aftertreatment systems that can adhere to these new norms. The implementation of Euro norms became more widespread with emerging economies like India also implementing norms adhering to the broad provisions of Euro 6. Most of the countries during this period had minimum EURO 4 norms. Manufacturers are also going for voluntary standards such as Blue Sky Standards that sets higher stringent limits then the existing standards. The new regulations is expected to further push investment in R&D in aftertreatment. Research intensity and areas of research scope is also expected to increase with the implemented and forthcoming new regulations. The intensity and broad spread of research during this period shows the influence of increasing regulation. This is similar to the previous period of 2016-19 when regulations became more stringent. The research during this period is seen to be distributed across 11 themes (Figure 3 and Table 1). Like the previous period, the themes are spread across the four quadrants. Each theme also has many sub-topics with which research is happening. The presence of ‘Air Pollution’ as a motor theme again asserts the importance of connecting research in this field to this. One can discern from the thematic map of this theme that it covers the following key domains: SCR, LNT, Aftertreatment Systems, Diesel Oxidation Catalyst, DPF, Fuel, hydrocarbons, PM, and Catalytic Converter. ‘Tailpipe’ is in the Q4, i.e. under basic and transversal themes. Only two research papers are receiving a high impact of 40 citations. The major challenge for aftertreatment systems is related to controlling tailpipe emissions. Surprisingly, this has not been used as a prominent keyword. *Plausibly, the broader term ‘aftertreatment’ or ‘air pollution’ is used instead of this*. ‘Methane’, ‘Environment’, ‘Deposition’, and ‘Radio-frequency’ are in the motor theme, indicating higher influence in the field. ‘Air pollution’ comes in the motor theme in the previous

periods, showing its pervasive influence in the field. This theme is covered under the aftertreatment system in two periods. ‘EGR’ is in Q2 quadrant. The themes ‘Marine diesel engine’ and ‘Real driving emission’, ‘Mass transfer’, and ‘Particulate Processes’ are consolidated with emerging or declining themes. Highly cited papers in this period are regulations, current status, effects, and reduction strategies of emissions for marine diesel engines and Copper Active Sites in Zeolites by Ammonia and Plasma-Driven Nitrogen Oxidation and Catalytic Reduction.
The Figure 3 below and Table 2 shows the temporal research activity of the different periods.

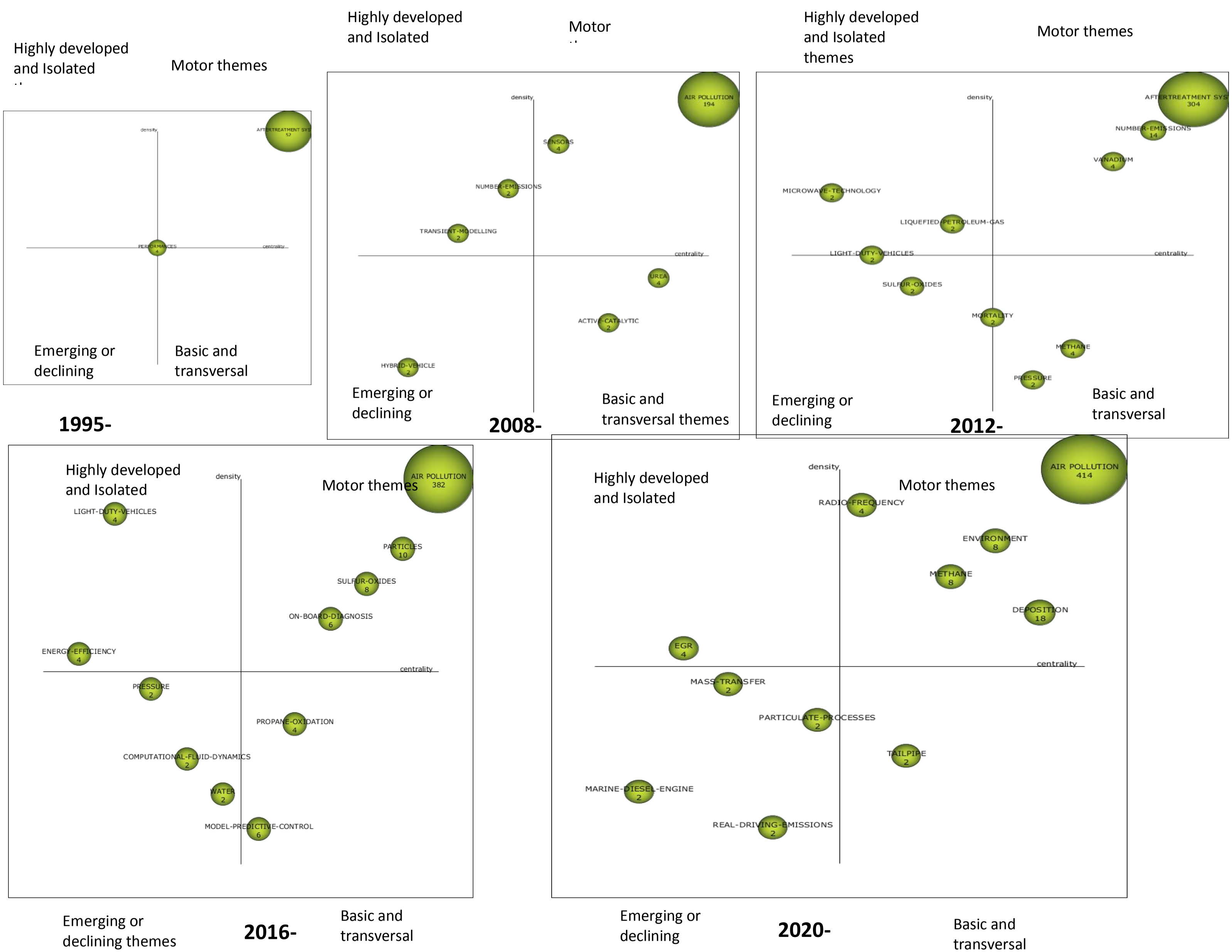

Figure 3. Strategic diagrams for the different periods in

Table 1. Performance Measurement for Different Periods.

Periods 1995-2007			
Theme	**Quadrant**	**Publications**	**Citations (*h*-Index)**
Aftertreatment System	Q1	52	5588 (30)
Performances	Q4	4	442 (4)

Periods 2008-2011			
Theme	**Quadrant**	**Publications**	**Citations (*h*-Index)**
Active Catalytic	Q4	2	42 (2)
Air Pollution	Q1	194	9288 (54)
Hybrid Vehicle	Q3	2	0 ( )
Number Emissions	Q2	2	62 (2)
Sensors	Q1	4	124 (4)
Transient-Modelling	Q2	2	32 (2)
Urea	Q4	4	298 (4)

Periods 2012-2015			
Theme	**Quadrant**	**Publications**	**Citations (*h*-Index)**
Aftertreatment System	Q1	304	10858 (55)
Light-Duty-Vehicles	Q2	2	366 (2)
Liquefied-Petroleum-Gas	Q2	2	60 (2)
Methane	Q4	4	82 (4)
Microwave-Technology	Q2	2	60 (2)
Mortality	Q4	2	86 (2)
Number-Emissions	Q1	14	366 (10)
Pressure	Q4	2	90 (2)
Sulfur-Oxides	Q3	2	156 (2)
Vanadium	Q1	4	206 (4)

Periods 2016-2019			
Theme	**Quadrant**	**Publications**	**Citations (*h*-Index)**
Air Pollution	Q1	382	9124 (46)
Computational-Fluid-Dynamics	Q3	2	18 (2)
Energy-Efficiency	Q2	4	30 (4)
Light-Duty-Vehicles	Q2	4	296 (4)
Model-Predictive-Control	Q4	6	60 (6)
On-Board-Diagnosis	Q1	6	38 (4)
Particles	Q1	10	230 (8)
Pressure	Q3	2	10 (2)
Propane Oxidation	Q4	4	136 (4)
Sulfur-Oxides	Q1	8	196 (6)
Water	Q3	2	74 (2)

Periods 2020-2023			
Theme	**Quadrant**	**Publications**	**Citations (*h*-Index)**
Air Pollution	Q1	414	9343 (29)
Deposition	Q1	18	204 (8)
EGR	Q2	4	6 (2)
Environment	Q1	8	32 (2)
Marine Diesel Engine	Q3	2	30 (2)
Mass Transfer	Q3	2	6 (2)
Methane	Q1	8	68 (4)
Particulate Process	Q3	2	8 (2)
Radio-Frequency	Q1	4	30 (2)
Real Driving Emissions	Q3	2	32 (2)
Tailpipe	Q4	2	10 (2)

The strategic diagram in Figure 3 identified key themes over different temporal periods positioned under the 4 quadrants. The overall positioning of the themes and new themes emerging in different time periods is presented in Table 2. The color codes connects to the thematic evolution of the themes leading to research areas represented in Figure 4.

Table 2. Key Research Themes in Different Periods: 1995-2023.

Themes	1995-2007	2008-2011	2012-2015	2016-2019	2020-2023
Aftertreatment System	Q1		Q1		
Performances	Q4				
Active Catalytic		Q4			
Air Pollution		Q1		Q1	Q1
Hybrid Vehicle		Q3			
Number Emissions		Q2	Q1		
Sensors		Q1			
Transient- Modelling		Q2			
Urea		Q4			
Light-Duty-Vehicles			Q2	Q2	
Liquefied-Petroleum-Gas			Q2		
Methane			Q4		
Microwave-Technology			Q2		
Mortality			Q4		
Pressure			Q4	Q3	
Sulfur-Oxides			Q3		
Vanadium			Q1		
Computational-Fluid-Dynamics				Q3	
Energy-Efficiency				Q2	
Model-Predictive-Control				Q4	
On-Board- Diagnosis				Q1	
Particles				Q1	
Propane Oxidation				Q4	
Sulfur-Oxides				Q1	
Water				Q3	
Deposition					Q1
EGR					Q2
Environment					Q1
Marine Diesel Engine					Q3
Mass Transfer					Q3
Methane					Q1
Particulate Process					Q3
Radio-Frequency					Q1
Real Driving Emissions					Q3
Tailpipe					Q4

Structural analysis of the evolution of the Aftertreatment technology scientific field

A thematic area is a set of themes that have evolved across different periods. Figure 4 provides the visualisation of the analytical analysis of the themes detected in each period. The clusters of themes about the same thematic area are identified in the figure through different colours. A solid line means that both themes share one of their central keywords, and a dotted line means that both themes share some peripheral keyword (Cobo et al., 2011a). The sphere size represents the number of documents belonging to each theme. The solid lines show that the linked themes lie in the same domain. The dotted lines are connected with themes, not from the relevant domain. The thickness of the edges is proportional to the inclusion index.

Five thematic areas were identified by examining Figure 4 and Performance measures: aftertreatment *Systems*, *Sensors*, *Number Emissions*, *Active Catalytic*, and *Light-duty vehicles*. An area is formed primarily by linking themes from different periods. This shows research cohesion in this field, with only a few topics seen as isolated. In other words, research domains have evolved over various periods, with new topics included under a theme. This is not surprising as emission regulations have also evolved in this way. Air pollution and aftertreatment systems are overlapping themes with strong connectivity with each other through their central keywords. The dominance of sub-topics has sometimes resulted in the distinction between them as air pollution or aftertreatment systems. In all the periods, it is Quadrant Q1, signifying that it was the central theme with internal solid cohesion among the sub-topics and a strong connection with other themes.

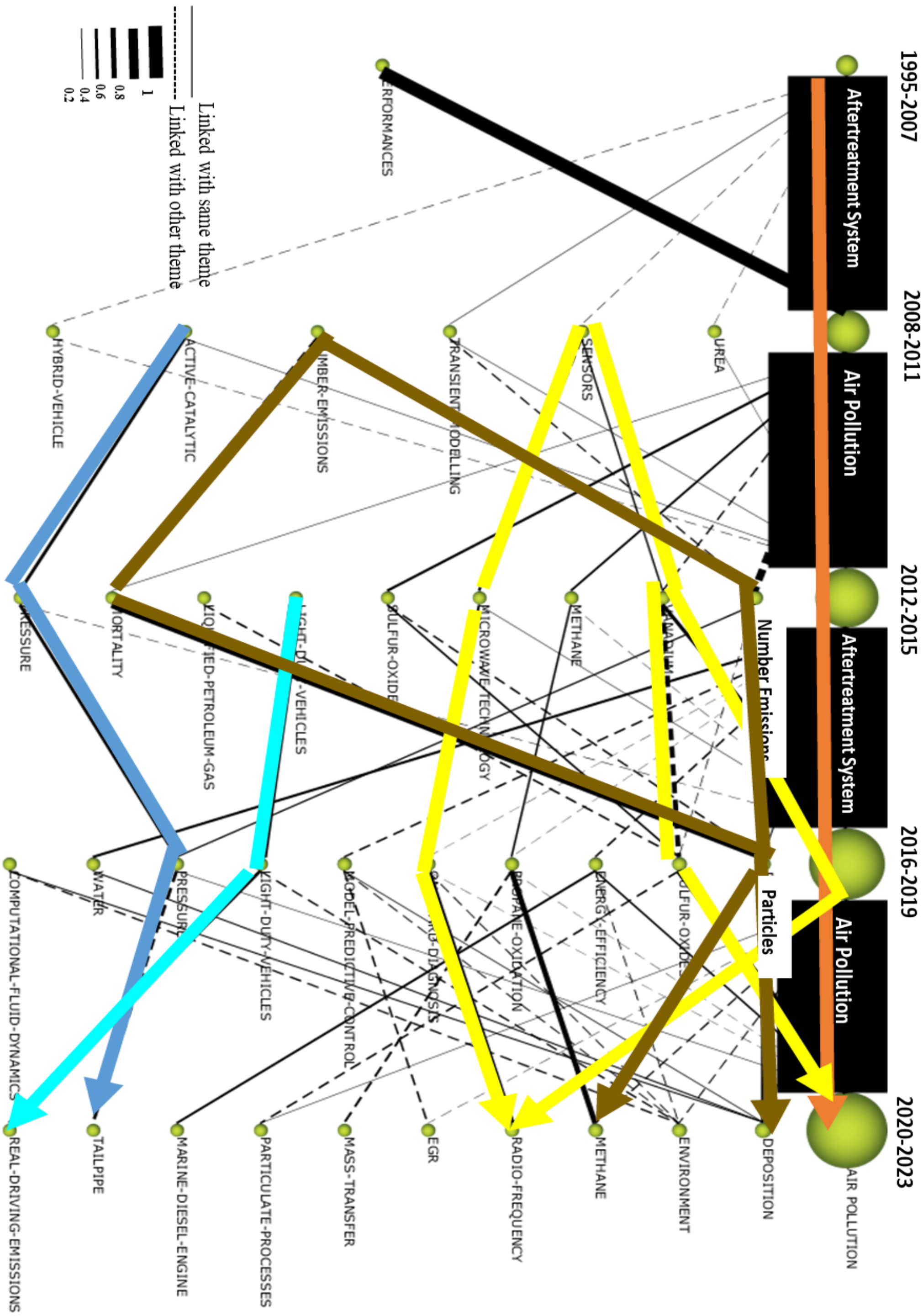

Figure 4. Thematic Evolution of Aftertreatment Technology.

The thematic area *Sensor* has evolved over different periods; research in different sub-topics related to this field has also received high citations. This theme is visible from the period 2008-2011. In the following period 92012-2015), it evolved in two thematic areas: Vanadium and Microwave technology. The theme Vanadium is in the motor theme (Q1), which shows its strong influence on research activity. Vanadium based catalysts are used in SCR processes to reduce NOx emissions. This catalyst is effective at reducing NOx at high temperatures 350-400 degree Celsius and is helping in addressing new stricter emission norms of NOx. Microwave technology is in the Q2 theme, implying strong cohesion within its different sub-topics. Microwave technology evolved from 2016 to 2019 as Onboard diagnostics (OBD). OBD is an electronic vehicle system that monitors the emissions system and critical engine components. It can usually detect a malfunction or deterioration in these components before the driver becomes aware of the problem. The regulations that called for implementing OBD and research activity happening in this domain was examined during temporal analysis. The Vanadium theme in this period is split into air pollution and sulfur oxides. Air pollution, Sulfur oxides, and OBD are in motor themes (Q1) in this period. From 2020 to 2023, Air pollution and OBD merged and evolved as Radiofrequency, and it focused on the impact on the environment. Air Pollution and Radiofrequency are in Q1 in this period. The theme particle *Number Emissions* in real-time emissions emerged in 2008-2011. It is in the Q2 quadrant, showing strong internal ties but weak external links. From 2012 to 2015, it evolved into Mortality and Number of Emission, which are in Q4 and Q1, respectively. In the next period, it evolved as Particles implies in Q1, showing the field's importance. The health effects of particulates and other vehicle emissions were analyzed in this period. From 2020 to 2023, deposition and methane evolved, which are in Q1, and show that both themes are well developed in the related field. Like other themes, the thematic area Active Catalytic shows an interesting evolutionary trend. In 2008-2011, it was in Q4 quadrant. From 2012 to 2015, it evolved as pressure in the Q4 quadrant. In the next period, the theme was in the Q3 quadrant. In the last period, it evolved as a tailpipe in Q4. The tailpipe is the last piece of the exhaust system that directs the exhaust gases out and away from the vehicle. Active catalysts are a core component of aftertreatment technologies. The period-wise thematic delineation has shown how the sub-topics have evolved in this theme. The theme Light duty vehicle evolved from 2012-2015, which is in Q2 shows the strong internal ties but weak external links. This shows that this are well-developed and isolated themes in this area. In 2016-2019, it became again in the same quadrant, as shown in Figure 4. In the last period, it evolved as a Real driving emission (RDE) in the Q3 quadrant. This quadrant can be for emerging or declining areas. It reflects an emerging area as RDE norms are now incorporated into new regulations. It primarily measures particulate matter and nitrogen oxide emission values in real traffic. Europe was the first region to introduce RDE norms, and many other countries have adopted the European regulatory emission norms. For example, RDE norms took effect in India on April 1, 2023.

Discussion and Conclusion

Regulations are becoming essential in driving innovations and technology development. There is an increasing need to study how regulations affect scientific research as newly emerging technologies are highly science-driven. It provides new understanding into the 'demand-driven model of science', the role regulations play in determining the scientific research priorities. The study has examined this in the context of aftertreatment technologies that are specifically designed to reduce harmful emissions coming from a vehicle's tailpipe emissions. Aftertreatment systems are complex systems that needs integration of various technologies that are highly science driven. There is a high demand for the development of advanced aftertreatment systems as vehicle manufacturers have to strictly comply with emission regulations of the country where their vehicles are sold. The question that has been explored in the study is how emission regulations have shaped scientific research. Bibliometrics approach was applied to capture the temporal and longitudinal assessment of scientific activity over the period 1991-2023. The study thus also provides a novel approach to look into the relationship among two key research constructs. The vehicular regulation norms of Europe and USA have identified the pollutants that need to be controlled by vehicles with later evolution stages making it more stringent in terms of particle size and incorporation of additional pollutants that has to be controlled. The emission regulations in different countries have primarily been shaped by the emission standards of these two countries. The key research themes, topics/sub-topics of research over different periods (temporal analysis), and key areas research activity over the whole study period (longitudinal analysis) were identified. The study further drawing from this examined how the research activity mapped with the emission norms and more granularly with the pollutants that need to be controlled within a period. The paper has been able to demonstrate varied influences of emission regulations that have been implemented in phases over different periods in Europe and USA with the intensity and type of research activity.

The compliance with regulations calls for substantial changes in aftertreatment systems, such as the need for newer sophisticated filters, catalysts, and, in some cases, radical changes in design configuration, among others. This pushes for investment in R&D to understand the scientific challenges with a focus on translational research. The research intensity overall and in different subcomponents, SCR, filters DPF, GPF, Lean NO_x and DOC catalysts reflects this. The introduction of newer pollutants and stringent limits imposed in later phases of the standards shows its influence on research across various key subcomponents of aftertreatment research. The key locations of research activity, the dispersion of research across different research areas, some key conferences playing a major role provides support to the argument of research activity influenced by regulations. The study identified the different types of catalysts, filters, sensors, reactants and reducing agents, specific technologies. Some of them were found to be more prominent and some newly introduced in later periods. Examination them with regulations standards demonstrated a closer correspondence with the emission regulations. It also showed contemporary areas where research is happening and where technology development is needed to address the implemented emission norms and newer norms like the Euro 7 (which is slated to be implemented soon) and Tier 4 US emissions that was implemented in 2024.

A study of this kind, however, does not capture the other aspects of research that are not reflected in research papers. In a science-driven technology field, it gives us a good indication of research influencing technology development. However, the innovation process does not simply start with pure scientific research and then progress linearly to technological development, but more of an intertwined relationship exists between science and technology throughout the innovation process (Branscomb, L. M., 2001). Patent citation studies provide a good indication of the highly mediated link between science and technology (Meyer, M. 2000). Thus, future studies on non-patent citations can help identify papers that have influenced technology development more directly than this study draws attention to. Future studies based on patents may bring some new insights into technology development influenced by regulations. However, in spite of this limitation, the study has shown how overall research has evolved over the years in aftertreatment systems for controlling tailpipe emissions. The overall research profile and at granular levels reveal to some extent the influence of regulation over different periods. The study's novelty lies in looking at regulation as a demand pull for scientific research and applying bibliometrics to capture this factor. The study inspite of its limitations has shown a tangible influence of emission regulations on scientific research.

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