The Influence of Advanced Combustion Engine Patents Funded by the U.S. Department of Energy's Vehicle Technologies Office and Other DOE Offices

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Executive Summary

This report describes the results of an analysis tracing the technological influence of advanced combustion research funded by the U.S. Department of Energy (DOE)'s Vehicle Technologies Office (VTO) and its precursor programs, as well as advanced combustion research funded by other offices in DOE. The tracing is carried out both backwards and forwards in time, and focuses on patents filed in three systems: the U.S. Patent & Trademark Office (U.S. patents); the European Patent Office (EPO patents); and the World Intellectual Property Organization (WIPO patents). The primary period covered in this analysis is 1976 to 2018.

The main purpose of the backward tracing is to determine the extent to which VTO-funded advanced combustion research has formed a foundation for innovations patented by leading advanced combustion organizations. Meanwhile, the primary purpose of the forward tracing is to examine the broader influence of VTO-funded advanced combustion research upon subsequent technological developments, both within and outside advanced combustion technology. In addition to these VTO-based analyses, we also extend many elements of the analysis to other DOE-funded advanced combustion patents, in order to gain insights into their influence.

The main finding of this report is:

- Advanced combustion research funded by VTO, and by DOE in general, has had a significant influence on subsequent developments, especially within advanced combustion technology. This influence can be seen on innovations associated with the leading advanced combustion companies, with many of their patents linked extensively via citations to earlier advanced combustion patents associated with VTO and DOE funding.

More detailed findings from this report include:

- In advanced combustion technology, in the period 1976-2018, we identified a total of 111,546 patents (51,903 U.S. patents, 31,711 EPO patents and 27,932 WIPO patents). We grouped these patents into 76,392 patent families, with each family containing all patents resulting from the same initial application (named the 'priority application').

- 442 advanced combustion patents are confirmed to be associated with VTO funding (337 U.S. patents, 44 EPO patents, and 61 WIPO patents). We grouped these VTO-funded advanced combustion patents into 299 patent families.

- In addition, we identified a further 143 advanced combustion patents (96 U.S. patents, 18 EPO patents and 29 WIPO patents) that are associated with DOE funding. These "Other DOE-funded" patents are grouped into 81 patent families.

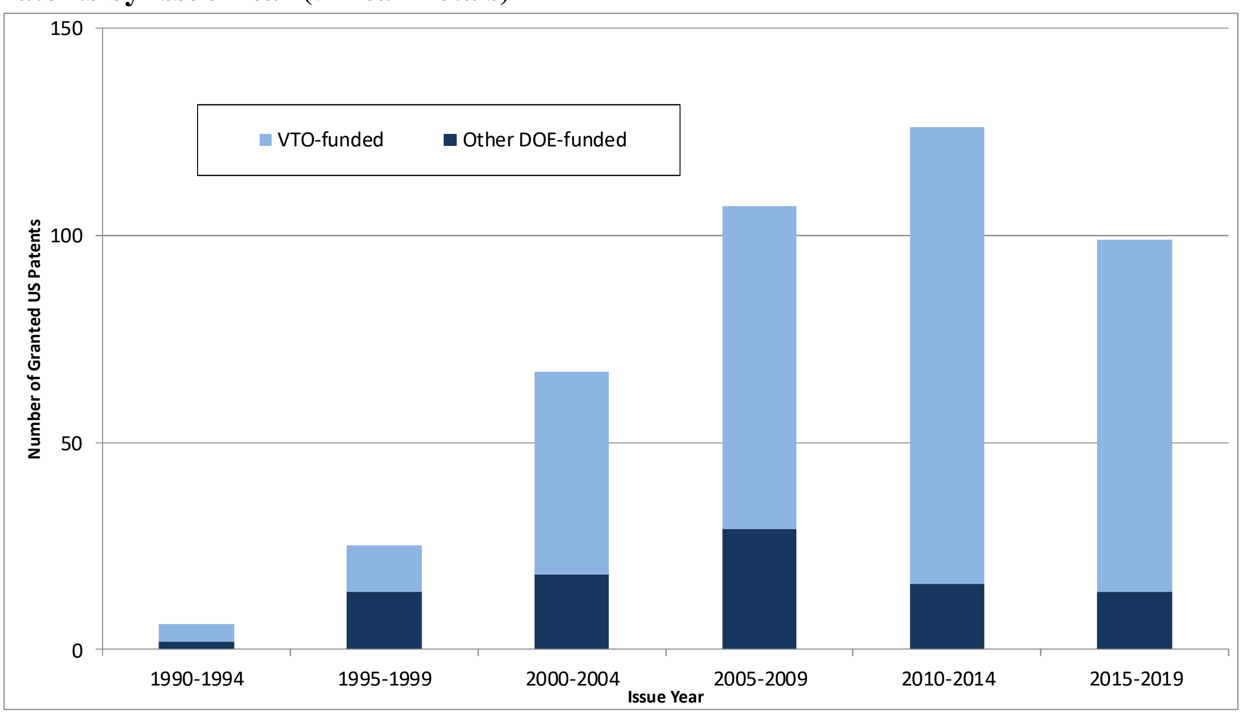
- Out of these 81 Other DOE-funded patent families, 43 are definitely not VTO-funded. These patent families were either funded by a different DOE office, or were marked as being not VTO-funded by inventors or VTO technology managers, but without specifying funding from another DOE source.

- The remaining 38 Other DOE-funded advanced combustion patent families could not be linked definitively to a specific DOE funding source, and may in fact have been VTO-funded. Hence, up to 47% (38 out of 81) of the Other DOE-funded advanced combustion patent families in this analysis may be VTO-funded. As such, the results presented in this report may understate the influence of VTO-funded advanced combustion research, relative to the influence of advanced combustion research funded by DOE in general.

- The total number of DOE-funded advanced combustion patents (VTO-funded plus Other DOE-funded) is 585, corresponding to 380 patent families. This represents 0.5% of the total number of advanced combustion patent families in the period 1976-2018.

- DOE-funded (i.e. VTO-funded plus Other DOE-funded) advanced combustion patenting was relatively sparse prior to the mid-1990s (see Figure E-1). This patenting then increased markedly throughout the period from the mid-1990s through 2010-2014. VTO funding played an increasingly prominent role during this time period. Since then, DOE-funded advanced combustion patenting has declined somewhat, although it remains at a relatively high level compared to earlier time periods.

Figure E-1 - Number of VTO/Other DOE-funded Advanced Combustion Granted U.S. Patents by Issue Year (5-Year Totals)



Note: The data collection period for this analysis ended with 2018. Any 2019 patents in the 2015-2019 column are additional patents that have been included because they are members of the same patent families as pre-2019 patents. No new patent search for 2019 was carried out.

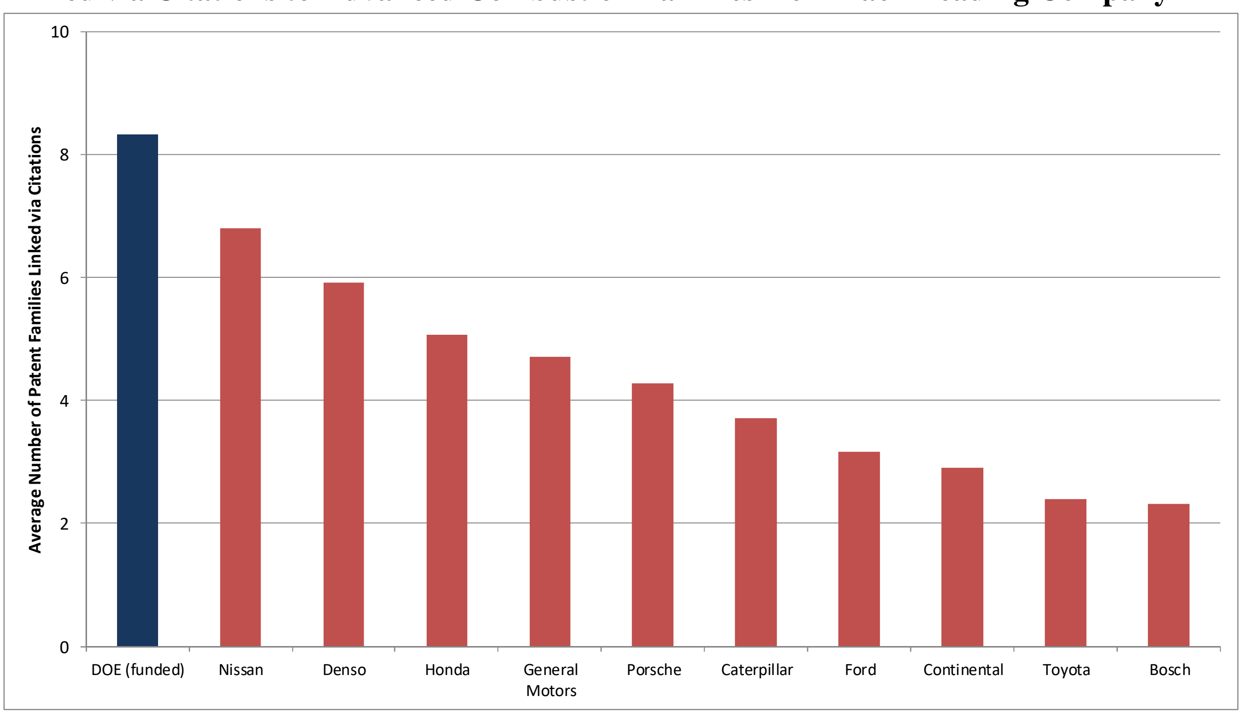
- Advanced combustion is a very active area of patenting for leading automakers, suppliers and engine companies. The ten companies with the largest advanced combustion patent portfolios are: Toyota (7,015 patent families); Bosch (6,512); Ford (3,957); General

Motors (2,581), Denso (2,293); Caterpillar (2,048); Nissan (2,012); Honda (2,010); Continental AG (1,934) and Porsche (1,839). In comparison, the portfolios of 299 VTO-funded - and 81 Other DOE-funded - advanced combustion patent families are relatively small. These size differences are taken into account in assessing the influence of the various patent portfolios.

- VTO-funded advanced combustion patents have a particular focus on exhaust feedback systems (i.e. EGR), turbochargers, selective catalytic reduction (SCR) and compression ignition. Recent years have also seen an increase in VTO-funded patenting related to exhaust valve operation, heat and magnetic exhaust treatment and turbocharger fuel supply.

- On average, DOE-funded advanced combustion patent families are each linked via citations to over eight subsequent patent families assigned to the leading advanced combustion companies (see Figure E-2). This means that, on average, more advanced combustion patent families owned by leading companies are linked via citations to earlier DOE-funded advanced combustion patents than are linked to the advanced combustion patents assigned to any other leading company. This is an impressive result and suggests that, while the portfolio of DOE-funded advanced combustion patents is much smaller than those of the leading companies, this portfolio has formed an important part of the foundation for technologies developed by these companies.

Figure E-2 - Average Number of Leading Company Advanced Combustion Patent Families Linked via Citations to Advanced Combustion Families from Each Leading Company



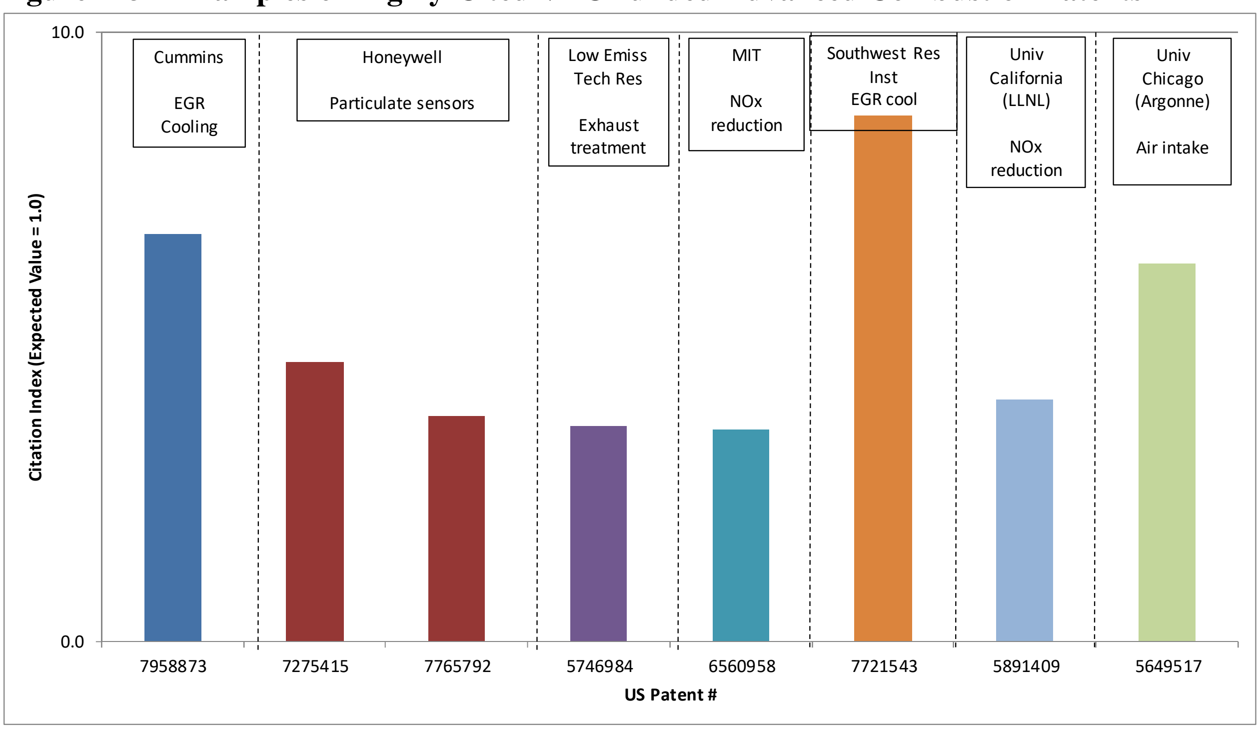
- Among the leading companies, advanced combustion patent families owned by Ford, Caterpillar, General Motors and Toyota have the most extensive citation links to earlier

VTO-funded advanced combustion patents. This suggests that VTO-funded advanced combustion research has had an especially strong influence on innovations developed by these companies.

- VTO-funded advanced combustion patents have an average Citation Index value of 1.30 (the Citation Index is a normalized citation metric with an expected value of 1.0; a value of 1.30 shows that, based on their age and technology, VTO-funded advanced combustion patents have been cited as prior art 30% more frequently than expected by subsequent patents). Meanwhile, Other DOE-funded advanced combustion patents have an average Citation Index of 1.20 (i.e. they have been 20% more frequently than expected). The influence of VTO-funded and Other DOE-funded advanced combustion patents can be seen primarily within the advanced combustion technology field, while there are also spillovers into technologies related to chemical detection, gas turbines and fluid dynamics.

- There are a number of individual high-impact VTO-funded advanced combustion patents, examples of which are shown in Figure E-3. They include Southwest Research Institute and Cummins patents related to EGR cooling, both of which have been cited as prior art by more than six times as many subsequent patents as expected, given their age and technology. They also include highly-cited Honeywell patents for particulate sensors; NOx reduction patents assigned to MIT and the University of California (through its management of LLNL); a University of Chicago (Argonne National Lab) patent for air intake systems; and a patent assigned to the USCAR Low Emissions Technologies R&D Partnership for exhaust treatment.

Figure E-3 – Examples of Highly-Cited VTO-funded Advanced Combustion Patents



1.0 Introduction

This report focuses on advanced combustion technology. Its objective is to trace the influence of advanced combustion research funded by DOE's Vehicle Technologies Office (VTO) – as well as advanced combustion research funded by DOE as a whole – upon subsequent developments both within and outside advanced combustion technology. The purpose of the report is to:

(i) Locate patents awarded for key VTO-funded (and other DOE-funded) innovations in advanced combustion technology; and

(ii) Determine the extent to which VTO-funded (and other DOE-funded) advanced combustion research has influenced subsequent technological developments both within and beyond advanced combustion.

The primary focus of the report is on the influence of VTO-funded advanced combustion patents. That said, we also extend many elements of the analysis to DOE-funded advanced combustion patents that could not be definitively linked to VTO funding. There are both evaluative and practical reasons for extending the analysis in this way. From an evaluation perspective, it is interesting to examine the influence of VTO itself upon the development of advanced combustion technology, while also tracing the influence of DOE more generally. Meanwhile, in practical terms, determining which patents were funded by VTO, versus other offices within DOE, is often very difficult.

In the U.S. patent system, applicants are required to acknowledge any government funding they have received related to the invention described in their patent application. Typically, this government support is reported at the level of the agency (e.g. Department of Energy, Department of Defense, etc.). Hence, the only way to determine which office within DOE funded a given patent is via other data resources (e.g. iEdison), or through direct input from offices, program managers and individual inventors. For older patents, such information is often unavailable, because records may be less comprehensive, and there is less access to the inventors and program managers involved.

Rather than discard patents confirmed as DOE-funded, but that could not be definitively categorized as VTO-funded, we instead included these patents in the analysis under a separate "Other DOE-funded" category. Some of these patents are confirmed as being linked to funding from other DOE offices, while for others the source of funding within DOE is unknown (see page 11). Many of these "unknown" patents may in fact have been funded by VTO, although a definitive link could not be established. Hence, the results reported here may underestimate the influence of VTO-funded advanced combustion research, relative to the influence of advanced combustion research funded by the rest of DOE.

This report contains three main sections. The first of these sections describes the project design. This section includes a brief overview of patent citation analysis, and outlines its use in the multi-generation tracing employed in this project. The second section outlines the methodology, and includes a description of the various data sets used in the analysis, and the processes through which these data sets were constructed and linked.

The third section presents the results of our analysis. Results are presented at the organizational level for both VTO-funded and Other DOE-funded patents. These results show the distribution of VTO-funded (and Other DOE-funded) patents across advanced combustion technologies (as defined by Cooperative Patent Classifications). They also evaluate the extent of VTO's influence (and DOE's influence in general) on subsequent developments in advanced combustion and other technologies. Patent level results are then presented to highlight individual VTO-funded advanced combustion patents that have been particularly influential, as well as to reveal key patents from other organizations that build extensively on VTO-funded advanced combustion research.[1]

2.0 Project Design

This section of the report outlines the project design. It begins with a brief overview of patent citation analysis, which forms the basis for much of the evaluation presented in this report. This overview is followed by a description of the techniques used to link the various patent sets in the analysis, along with a listing and description of the metrics employed in the study.

The analysis described in this report is based largely upon tracing citation links between successive generations of patents. This tracing is carried out both backwards and forwards in time. The main purpose of the backward tracing is to determine the extent to which technologies developed by leading companies in the advanced combustion industry used VTO-funded research as a foundation. Meanwhile, the primary purpose of the forward tracing is to examine how VTO-funded advanced combustion patents influenced subsequent technological developments more broadly, both within and outside advanced combustion technology. Many elements of the backward and forward tracing are extended to the Other DOE-funded patents in order to trace their influence, both overall and on the leading advanced combustion companies.[2]

Our analysis covers patents filed in three systems: the U.S. Patent & Trademark Office (U.S. patents); the European Patent Office (EPO patents); and the World Intellectual Property Organization (WIPO patents). By covering multiple generations of citations across patent systems, our analysis allows for a wide variety of possible linkages between DOE-funded advanced combustion research and subsequent technological developments. Examining all of these linkage types at the level of an entire technology involves a significant data processing effort, and requires access to specialist citation databases, such as those maintained at 1790 Analytics. As a result, this project is more ambitious than many previous attempts to trace through multiple generations of research, which have often been based on studying very specific technologies or individual products.

[1] This is one of a series of similar reports examining research portfolios across a range of DOE offices. Note that the results are not designed to be compared across portfolios, for example in terms of numbers of patents granted, number of citations received etc. The portfolios have very different profiles with respect to research risks, funding levels and time periods covered, plus there are wide variations in the propensity to patent across technologies. Hence, the results reported in the various reports should not be used for comparative analyses across portfolios.

[2] The analyses described in this report were carried out separately for VTO-funded advanced combustion patents and Other DOE-funded advanced combustion patents. However, referring repeatedly to "VTO-funded/Other DOE-funded patents" or "VTO-funded/Other DOE-funded research" in describing the analyses is lengthy, so we instead use the collective terms "DOE-funded patents" and "DOE-funded research" in the Project Design and Methodology sections of the report.

Patent Citation Analysis

In many patent systems, patent documents contain a list of references to prior art. The purpose of these prior art references is to detail the state of the art at the time of the patent application, and to demonstrate how the new invention is original over and above this prior art. Prior art references may include many different types of public documents. A large number of the references are to earlier patents, and these references form the basis for this study. Other references (not covered in this study) may be to scientific papers and other types of documents, such as technical reports, magazines and newspapers.

The responsibility for adding prior art references differs across patent systems. In the U.S. patent system, it is the duty of patent applicants to reference (or "cite") all prior art of which they are aware that may affect the patentability of their invention. Patent examiners may then reference additional prior art that limits the claims of the patent for which an application is being filed. In contrast to this, in patents filed at the European Patent Office (EPO) and World Intellectual Property Organization (WIPO), prior art references are added solely by the examiner, rather than by both the applicant and examiner. The number of prior art references on EPO and WIPO patents thus tends to be much lower than the number on U.S. patents.[3]

Patent citation analysis focuses on the links between generations of patents that are made by these prior art references. In simple terms, this type of analysis is based upon the idea that the prior art referenced by patents has had some influence, however slight, upon the development of these patents. The prior art is thus regarded as part of the foundation for the later inventions.

In assessing the influence of individual patents, citation analysis centers on the idea that highly cited patents (i.e. those cited by many later patents) tend to contain technological information of particular interest or importance. As such, they form the basis for many new innovations and research efforts, and so are cited frequently by later patents. While it is not true to say that every highly cited patent is important, or that every infrequently cited patent is necessarily trivial, many research studies have shown a correlation between patent citations and measures of technological and economic importance. For background on the use of patent citation analysis, including a summary of validation studies supporting its use, see: Breitzman A. & Mogee M. "The many applications of patent analysis", *Journal of Information Science*, 28(3), 2002, 187-205; and Jaffe A. & de Rassenfosse G. "Patent Citation Data in Social Science Research: Overview and Best Practices", NBER Working Paper No. 21868, January 2016.

Patent citation analysis has also been used extensively to trace technological developments over time. For example, in the analysis presented in this report, we use citations from patents to earlier patents to trace the influence of DOE-funded advanced combustion research. Specifically, we identify cases where patents cite DOE-funded advanced combustion patents as prior art. These represent first-generation links between DOE-funded patents and subsequent technological

[3] Note that this analysis does not cover patents from other systems, notably patents from the Chinese, Japanese and Korean patent offices. This is because patents from these systems do not typically list any prior art. Hence, it is not possible to use citation links to trace the influence of DOE research on patents from these systems. Having said this, Chinese, Japanese and Korean organizations are among the most prolific applicants in the WIPO system. Our analysis thus picks up the role of organizations from these countries via their WIPO filings.

developments. We also identify cases where patents cite patents that in turn cite DOE-funded advanced combustion patents. These represent second-generation links between technological developments and DOE-funded research.

The idea behind this analysis is that the later patents have built in some way on the earlier DOE-funded advanced combustion research. By determining how frequently DOE-funded advanced combustion patents have been cited by subsequent patents, it is thus possible to evaluate the extent to which DOE-funded research forms a foundation for various technologies both within and beyond advanced combustion.

Forward and Backward Tracing

As noted above, the purpose of this analysis is to trace the influence of DOE-funded advanced combustion research upon subsequent developments both within and beyond advanced combustion technology. There are two approaches to such a tracing study – backward tracing and forward tracing – each of which has a slightly different objective.

Backward tracing, as the name suggests, looks backwards over time. The idea of backward tracing is to take a particular technology, product, or industry, and to trace back to identify the earlier technologies upon which it has built. In the context of this project, we first identify the leading advanced combustion organizations in terms of patent portfolio size. We then trace backwards from the patents owned by these organizations. This makes it possible to determine the extent to which innovations associated with these leading advanced combustion organizations build on earlier VTO-funded and Other DOE-funded research.

The idea of forward tracing is to take a given body of research, and to trace the influence of this research upon subsequent technological developments. In the context of the current analysis, forward tracing involves identifying all advanced combustion patents resulting from research funded by DOE (i.e. VTO plus Other DOE). The influence of these patents on later generations of technology is then evaluated. This tracing is not restricted to subsequent advanced combustion patents, since the influence of a body of research may extend beyond its immediate technology. Hence, the purpose of the forward tracing element of this project is to determine the influence of DOE-funded advanced combustion patents upon developments both inside and outside this technology.

Tracing Multiple Generations of Citation Links

The simplest form of tracing study is one based on a single generation of citation links between patents. Such a study identifies patents that cite, or are cited by, a given set of patents as prior art. The analysis described in this report extends the tracing by adding a second generation of citation links.[4]

[4] As noted above, the forward and backward tracing were carried out separately for VTO-funded and Other DOE-funded advanced combustion patents. The references in this section to “DOE patents” are shorthand, and do not mean that the tracing was carried out for all DOE-funded advanced combustion patents as a single portfolio.

The backward tracing starts with patents assigned to the leading patenting organizations in advanced combustion technology. The first generation contains the patents that are cited as prior art by these starting patents. The second generation contains patents that are in turn cited as prior art by these first generation patents. In other words, the backward tracing starts with advanced combustion patents owned by leading organizations in this technology, and traces back through two generations of earlier patents to identify the technologies upon which they were built, including those funded by DOE.

The forward tracing starts with DOE-funded patents in advanced combustion technology. The first generation contains the patents that cite these DOE-funded patents as prior art. The second generation contains the patents that in turn cite these first-generation patents. In other words, the analysis starts with DOE-funded advanced combustion patents and traces forward for two generations of subsequent patents.

This means that we trace forward through two generations of citations starting from DOE-funded advanced combustion patents; and backward through two generations starting from the patents owned by leading advanced combustion organizations. Hence there are two types of links between DOE-funded patents and subsequent generations of patents:

1. **Direct Links**: where a patent cites a DOE-funded advanced combustion patent as prior art.

2. **Indirect Links**: where a patent cites an earlier patent, which in turn cites a DOE-funded advanced combustion patent. The DOE patent is thus linked indirectly to the subsequent patent.

The idea behind adding the second generation of citations is that agencies such as DOE often support basic scientific research. It may take time, and numerous generations of research, for this basic research to be used in an applied technology, for example that described in a patent owned by a leading company. Introducing a second generation of citations provides greater access to these indirect links between basic research and applied technology.

One potential problem with adding generations of citations must be acknowledged. Specifically, if one uses enough generations of links, eventually almost every node in the network will be linked. This is a problem common to many networks, whether these networks consist of people, institutions, or scientific documents, as in this case. The most famous example of this is the idea that every person is within six links of any other person in the world. By the same logic, if one takes a starting set of patents, and extends the network of prior art references far enough, almost all patents will be linked to this starting set. Hence, while including a second generation of citations provides insights into indirect links between basic research and applied technologies, adding further generations may bring in too many patents with little connection to the starting patent set.

Constructing Patent Families

The coverage of a patent is limited to the jurisdiction of its issuing authority. For example, a patent granted by the U.S. Patent & Trademark Office (a ‘U.S. patent’) provides protection only within the United States. If an organization wishes to protect an invention in multiple countries, it must file patents in each of those countries' systems. For example, a company may file to protect a given invention in the U.S., China, Germany, Japan and many other countries. This would result in multiple patent documents for the same invention.[5] In addition, in some systems – notably the U.S. – inventors may apply for a series of patents based on the same underlying invention.

In the case of this study, one or more U.S., EPO and WIPO patents may result from a single invention. To avoid counting the same inventions multiple times, it is necessary to construct "patent families". A patent family contains all of the patents and patent applications that result from the same original patent application (named the "priority application"). A family may include patents from multiple countries, and also multiple patents from the same country. In this project, we constructed patent families for DOE-funded advanced combustion patents, and also for the patents owned by leading advanced combustion organizations. We also assembled families for all patents linked via citations to DOE-funded advanced combustion patents.

To construct these patent families, we matched the priority documents of the U.S., EPO and WIPO patents, in order to group them into the appropriate families. It should be noted that the priority document need not necessarily be a U.S., EPO or WIPO application. For example, a Japanese patent application may result in U.S., EPO and WIPO patents, which are grouped in the same patent family because they share the same Japanese priority document.

Metrics Used in the Analysis

Table 1 contains a list of the metrics used in the analysis. These metrics are divided into three main groups – technology landscape metrics (trends, assignees, and technology distributions), backward tracing metrics, and forward tracing metrics. Findings for each of these three groups of metrics can be found in the Results section of the report.

[5] It also means that patents from a given country's system are not synonymous with inventions made in that country. Indeed, roughly half of all U.S. patent applications are from overseas inventors.

Table 1 – List of Metrics Used in the Analysis

Metric
Trends
• Number of VTO/Other DOE-funded advanced combustion patent families by year of priority application
• Number of VTO/Other DOE-funded granted U.S. advanced combustion patents by issue year
• Overall number of advanced combustion patent families by priority year
• Percentage of advanced combustion patents families funded by VTO/Other DOE by priority year
Assignee Metrics
• Number of advanced combustion patent families for leading patenting organizations
• Assignees with largest number of advanced combustion patent families funded by VTO/Other DOE
Technology Metrics
• Patent classification (CPC) distribution for VTO-funded advanced combustion patent families (vs Other DOE-funded, leading advanced combustion companies, all advanced combustion)
Backward Tracing Metrics
• Total/Average number of leading company advanced combustion patent families linked via citations to earlier patent families from VTO/Other DOE-funding and other leading companies
• Number of advanced combustion patent families for each leading company linked via citations to earlier VTO/Other DOE-funded patent families
• Total citation links from each leading company to VTO/Other DOE-funded patent families
• Percentage of leading company advanced combustion patent families linked via citations to earlier VTO/Other DOE-funded patent families
• VTO/Other DOE-funded advanced combustion patent families linked via citations to largest number of leading company advanced combustion patent families
• Leading company advanced combustion patent families linked via citations to largest number of VTO-funded advanced combustion patent families
• Highly cited leading company advanced combustion patent families linked via citations to earlier VTO-funded advanced combustion patent families
Forward Tracing Metrics
• Citation Index for advanced combustion patent portfolios owned by leading companies, plus portfolios of VTO/Other DOE-funded advanced combustion patents
• Number of patent families linked via citations to VTO/Other DOE-funded advanced combustion patents by patent classification
• Organizations (beyond leading advanced combustion companies) linked via citations to largest number of VTO/Other DOE-funded advanced combustion patent families
• Highly cited VTO-funded advanced combustion U.S. patents
• VTO/Other DOE-funded advanced combustion patent families linked via citations to largest number of subsequent advanced combustion/non-advanced combustion patent families
• Highly cited patents (not owned by leading companies) linked via citations to earlier VTO-funded advanced combustion patents families

3.0 Methodology

The previous section of the report outlines the objective of our analysis – that is, to determine the influence of VTO-funded (and Other DOE-funded) advanced combustion research on subsequent developments both within and outside advanced combustion technology. This section of the report describes the methodology used to implement the analysis. Particular emphasis is placed on the processes employed to construct the various data sets required for the analysis. Specifically, the backward tracing starts from the set of all advanced combustion patents owned by leading patenting organizations in this technology. Meanwhile, the forward tracing starts from the sets of advanced combustion patents funded by VTO and Other DOE. We therefore had to define these various data sets – VTO-funded advanced combustion patents; Other DOE-funded advanced combustion patents; and advanced combustion patents assigned to the leading organizations in this technology.

Identifying VTO-funded and Other DOE-funded Advanced Combustion Patents

The objective of this analysis is to trace the influence of advanced combustion research funded by VTO (plus advanced combustion research funded by the remainder of DOE) upon subsequent developments both within and outside advanced combustion technology. Outlined below are the three steps used to identify VTO-funded and Other DOE-funded advanced combustion patents. These three steps are:

(i) Defining the universe of DOE funded patents;

(ii) Determining which of these DOE funded patents are relevant to advanced combustion; and

(iii) Categorizing these DOE-funded advanced combustion patents according to whether or not they can be linked definitively to VTO funding.

Defining the Universe of DOE-Funded Patents

Identifying patents funded by government agencies is often more difficult than locating patents funded by companies. When a company funds internal research, any patented inventions emerging from this research are likely to be assigned to the company itself. In order to construct a patent set for a company, one simply has to identify all patents assigned to the company, along with all of its subsidiaries, acquisitions, etc.

Constructing a patent list for a government agency is more complicated, because the agency may fund research carried out at many different organizations. For example, DOE operates seventeen national laboratories. Patents emerging from these laboratories may be assigned to DOE. However, they may also be assigned to the organization that manages a given laboratory. For example, many patents from Sandia National Laboratory are assigned to Lockheed Martin (Sandia's former lab manager), while many Lawrence Livermore National Laboratory patents are assigned to the University of California. Lockheed Martin and the University of California are large organizations with many interests beyond managing DOE labs, so one cannot simply take all of their patents and define them as DOE-funded. A further complication is that DOE does not only fund research in its own labs and research centers, it also funds extramural research carried out by other organizations. If this research results in patented inventions, these patents are likely to be assigned to the organizations carrying out the research, rather than to DOE.

We therefore constructed a database containing all DOE-funded patents. These include patents assigned to DOE itself, and also patents assigned to individual labs, lab managers, and other organizations and companies funded by DOE. This "All DOE" patent database was constructed using a number of sources:

1. ***DOEPatents Database*** – The first source is a database of DOE-funded patents put together by DOE's Office of Scientific & Technical Information (OSTI), and available on the web at www.osti.gov/doepatents/. This database contains information on research grants provided by DOE. It also links these grants to the organizations or DOE labs that carried out the research, the sponsor organization within DOE, and the patents that resulted from these DOE grants.

2. ***iEdison Database*** – EERE staff provided us with an output from the iEdison database, which is used by government grantees and contractors to report government-funded subject inventions, patents, and utilization data to the government agency that issued the funding award.

3. ***Visual Patent Finder Database*** – EERE also provided us with an output from its Visual Patent Finder tool. This tool takes DOE-funded patents and clusters them based on word occurrence patterns. In our case, the output was a flat file containing DOE-funded patents.

4. ***Patents assigned to DOE*** – in the USPTO database, we identified a small number of U.S. patents assigned to DOE itself that were not in the any of the sources above. These patents were added to the list of DOE patents.

5. ***Patents with DOE Government Interest*** – A U.S. patent has on its front page a section entitled 'Government Interest', which details the rights that the government has in a particular invention. For example, if a government agency funds research at a private company, the government may have certain rights to patents granted based on this research. We identified all patents that refer to 'Department of Energy' or 'DOE' in their Government Interest field, including different variants of these strings. We also identified patents that refer to government contracts beginning with 'DE-' or containing the string '-ENG-'. The former string typically denotes DOE contracts and financial assistance projects, while the latter is a legacy code listed on a number of older DOE-funded patents. We manually checked all of the patents containing these strings that were not already in any of the sources above, to make sure that they are indeed DOE-funded (e.g. '-ENG-' is also used in a small number of NSF contracts). We then included any additional DOE funded patents in the database.

The "All DOE" patent database constructed from these five sources contains more than 31,000 U.S. patents issued between January 1976 and December 2018 (the end-point of the primary data collection for this analysis).

Identifying DOE-Funded Advanced Combustion Patents

Having defined the universe of DOE-funded patents, the next step was to determine which of these patents are relevant to advanced combustion technology. We designed a custom patent filter to identify advanced combustion patents, consisting of a combination of Cooperative Patent Classifications (CPCs) and keywords. Details of the patent filter are shown in Table 2. The form of the filter is (Filter A OR Filter B), so patents that qualify under either of the filters in Table 2 were included in the initial patent set.

Table 2 – Filters used to identify DOE-funded Advanced Combustion Patents

Filter A
Cooperative Patent Classification
Y02T 10/10-56 (Climate change mitigation – internal combustion engine vehicles)
Filter B
Cooperative Patent Classification
F01N (Exhaust apparatus/treatment)
F02B (Internal combustion engines)
F02D (Controlling combustion engines)
F02F (Cylinders, pistons, casings)
F02M (Fuel supply for combustion engines)
F02N (Starting combustion engines)
F02P (Ignition for combustion engines)
G01N 27/407 (Investigating or analyzing gases)
H01J 49 (Particle spectrometers)
Y02T 10 (Climate change mitigation – road transport)
AND
Title/Abstract
Compression(-)ignit* or HCCI or PCCI or RCCI or LTC or CI(-)DI or SCR or GDCI or EGR or homogenous(-)charge* or direct(-)inject* or exhaust(-)gas(-)recirculation or fuel(-)inject* or lean(-)burn* or low(-)temperature(-)combust* or selective(-)catalytic(-)reduc* or lifted(-)flame* or variable(-)compression(-)ratio*

We then manually checked the initial list of patents to determine which of them appear relevant to advanced combustion. Having constructed this draft patent list, we then sent it to VTO for review. Following this review, and based on feedback from VTO, the initial list of advanced combustion patents funded by DOE contained a total of 418 granted U.S. patents.

Defining VTO-funded vs. Other DOE-funded Advanced Combustion Patents

As noted above, linking DOE-funded patents to individual offices is often a difficult task. For this analysis, EERE staff undertook an exhaustive process to determine which of the 418 DOE-funded advanced combustion patents in the initial list could be linked definitively to VTO funding. This process involved a number of steps, which are listed below:

- (i) Linking contract numbers listed in patents to EERE project contract numbers, for financial assistance projects,
- (ii) Linking contract numbers listed in patents to EERE SBIR project agreement numbers,
- (iii) Asking VTO technology managers to verify individual patents,
- (iv) Asking VTO technology managers to send lab patents to lab POCs to get direct verification of these patents,
- (v) Contacting individual inventors listed on patents to ask them to confirm whether individual patents were funded by VTO, and
- (vi) Locating references to patents in available office annual project progress reports or patent disclosure documents with accomplishments reported by PIs.

Final List of VTO-funded and Other DOE-funded Advanced Combustion Patents

Based on the process described above, we divided the initial list of 418 DOE-funded advanced combustion U.S. patents into two categories – VTO-funded and Other DOE-funded. We then searched for equivalents of each of these patents in the EPO and WIPO systems. An equivalent is a patent filed in a different patent system covering essentially the same invention. We also searched for U.S. patents that are continuations, continuations-in-part, or divisional applications of each of the patents in the final set. We then grouped the patents into families by matching priority documents (see earlier discussion of patent families). Table 3 contains a summary of the final number of VTO-funded and Other DOE-funded advanced combustion patents and patent families.

Table 3 – Number of VTO-funded and Other DOE-funded Advanced Combustion Patents and Patent Families

	# Patent Families	# U.S. Patents	# EPO Patents	# WIPO Patents
VTO-funded	299	337	44	61
Other DOE-funded	81	96	18	29
Total DOE-funded	380	433	62	90

Table 3 shows that we identified a total of 299 VTO-funded advanced combustion patent families, containing 337 U.S. patents, 44 EPO patents, and 61 WIPO patents (see Appendix A for patent list). We also identified 81 Other DOE-funded advanced combustion patent families, containing 96 U.S. patents, 18 EPO patents, and 30 WIPO patents (see Appendix B for patent list). The patents in these DOE-funded portfolios were almost all granted from 1990 onwards.

As noted throughout this report, the approach used to define patents as VTO-funded was very stringent. Hence, a number of the 81 Other DOE-funded patent families may in fact have been funded by VTO, but are not categorized as such because a definite link could not be established. To get a better sense of how many of these Other DOE-funded patents (and patent families) may in fact be VTO-funded, we divided them into two groups.

The first group contains DOE-funded patent families that were definitely not funded by VTO. These include families linked specifically to funding from an office other than VTO, or that the inventor or VTO technology manager said were not funded by VTO (but without specifying funding from a different office). There are 43 such patent families.

The second group contains DOE-funded patent families where the funding source within DOE could not be established, and inventors and VTO technology managers could not state categorically whether or not they were funded by VTO. There are 38 such patent families. Hence, up to 47% (38 out of 81) of the Other DOE-funded patent families included in this analysis may in fact be VTO-funded. As a result, the findings in this analysis may understate the influence of VTO-funded advanced combustion patents, relative to the influence of the remainder of DOE patents.

Identifying Advanced Combustion Patents Assigned to Leading Organizations

The purpose of the backward tracing element of our analysis is to evaluate the influence of VTO-funded (and Other DOE-funded) research upon advanced combustion innovations produced by leading organizations in this technology. To identify such organizations, we first defined the universe of advanced combustion patents in the period 1976-2018 using the patent filter detailed earlier in Table 2. Based on this filter, we identified a total of 51,903 advanced combustion U.S. patents; 27,932 advanced combustion WIPO patents; and 31,711 advanced combustion EPO patents. We grouped these patents into 76,392 patent families by matching priority documents.

We then located the most prolific patenting organizations in this overall advanced combustion patent universe, based on number of patent families. The ten organizations with the largest number of advanced combustion patent families are shown in Table 4.[6]

The companies in Table 4 include many of the largest automakers and suppliers worldwide. The number of patent families listed in this table includes all variant names under which these companies have patents, taking into account including all subsidiaries and acquisitions. The advanced combustion patent families of these ten companies in Table 4 form the starting point for the backward tracing element of the analysis. As such, this analysis evaluates the influence of DOE-funded advanced combustion research on technologies developed by leading companies in the auto industry.

[6] All ten of these organizations are companies. For clarity, they are referred to in the results section of the report as the leading combustion companies, rather than organizations. Also, note that they are selected based on patent portfolio size, which does not necessarily reflect number of units sold or revenues, profits etc. A fuller description would be the leading patenting advanced combustion companies, but this is a cumbersome description to use throughout the results section of the report.

Table 4 – Top 10 Patenting Advanced Combustion Companies

Company	# Advanced Combustion Patent Families
Toyota	7015
Bosch	6512
Ford	3957
General Motors	2581
Denso	2293
Caterpillar	2048
Nissan	2012
Honda	2010
Continental	1934
Porsche	1839

Constructing Citation Links

Through the processes described above, we constructed starting patent sets for both the backward forward tracing elements of the analysis. The patent set for the backward tracing consisted of patent families assigned to the leading patenting organizations in advanced combustion technology. The patent sets for the forward tracing consisted of VTO-funded (and, separately, Other DOE-funded) advanced combustion patent families.

Having defined these patent sets, we then traced backward through two generations of citations from the leading organizations' advanced combustion patents, and forward through two generations of citations from the VTO/Other DOE-funded advanced combustion patents. These included citations listed on U.S., EPO and WIPO patents, and required extensive data cleaning to account for differences in referencing formats across these systems. The citation linkages identified, along with characteristics of the starting patent sets, form the basis for the results described in the next section of this report.

4.0 Results

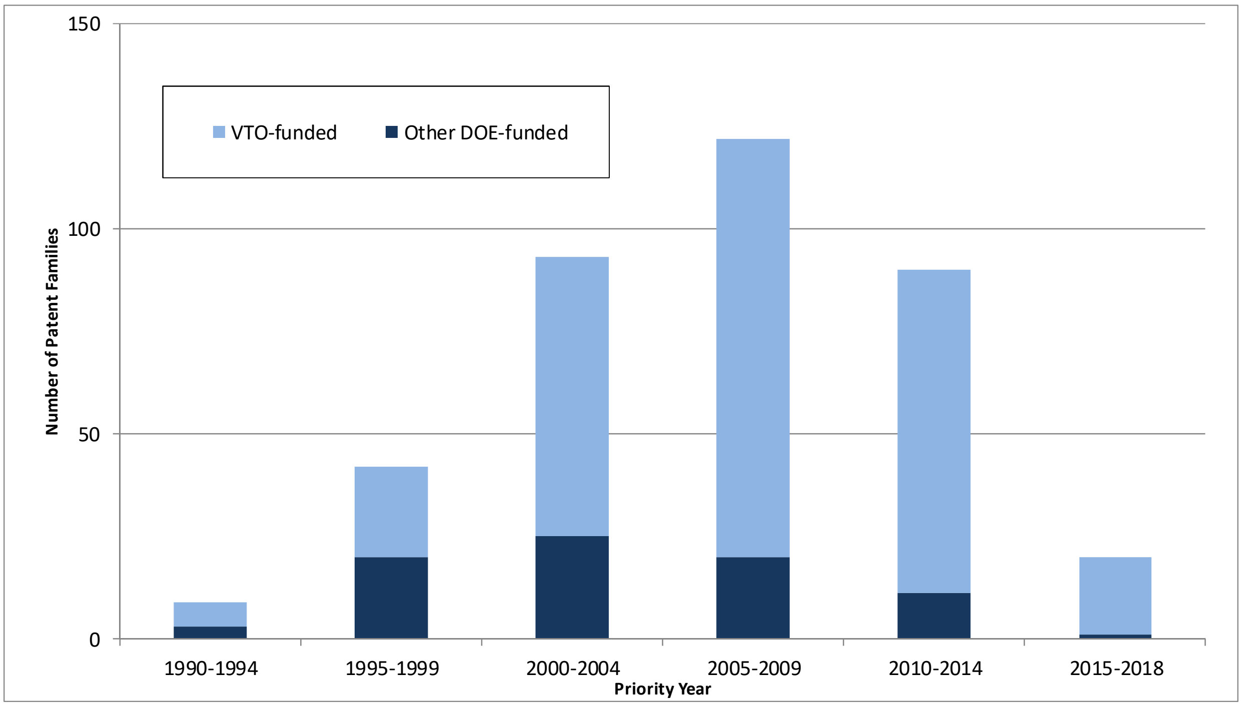
This section of the report outlines the results of our analysis tracing the influence of VTO-funded and Other DOE-funded advanced combustion research on subsequent developments both within and beyond advanced combustion technology. The results are divided into three main sections. In the first section, we examine trends in patenting over time in advanced combustion technology, and assess the distribution of VTO-funded and Other DOE-funded patents across advanced combustion technologies. The second section then reports the results of an analysis tracing backwards from advanced combustion patents owned by the leading companies in this technology. The purpose of this analysis is to determine the extent to which advanced combustion innovations developed by leading companies build upon earlier advanced combustion research funded by VTO (plus advanced combustion research funded by the remainder of DOE). In the third section, we report the results of an analysis tracing forwards from VTO-funded (and Other DOE-funded) advanced combustion patents. The purpose of this analysis is to assess the broader influence of DOE-funded research upon subsequent developments within and beyond advanced combustion technology.

Overall Trends in Advanced Combustion Patenting

Trends in Advanced Combustion Patenting over Time

Figure 1 shows the number of DOE-funded advanced combustion patent families by priority year – i.e. the year of the first application in each patent family. For presentation purposes, this figure concentrates on the period since 1990. That said, it should be noted that there are also three VTO-funded and three Other DOE-funded advanced combustion patent families scattered across the time period 1976-1989. These patent families are included in the analysis, even though they are not shown here.

Figure 1 - Number of VTO/Other DOE-funded Advanced Combustion Patent Families by Priority Year (5-Year Totals)



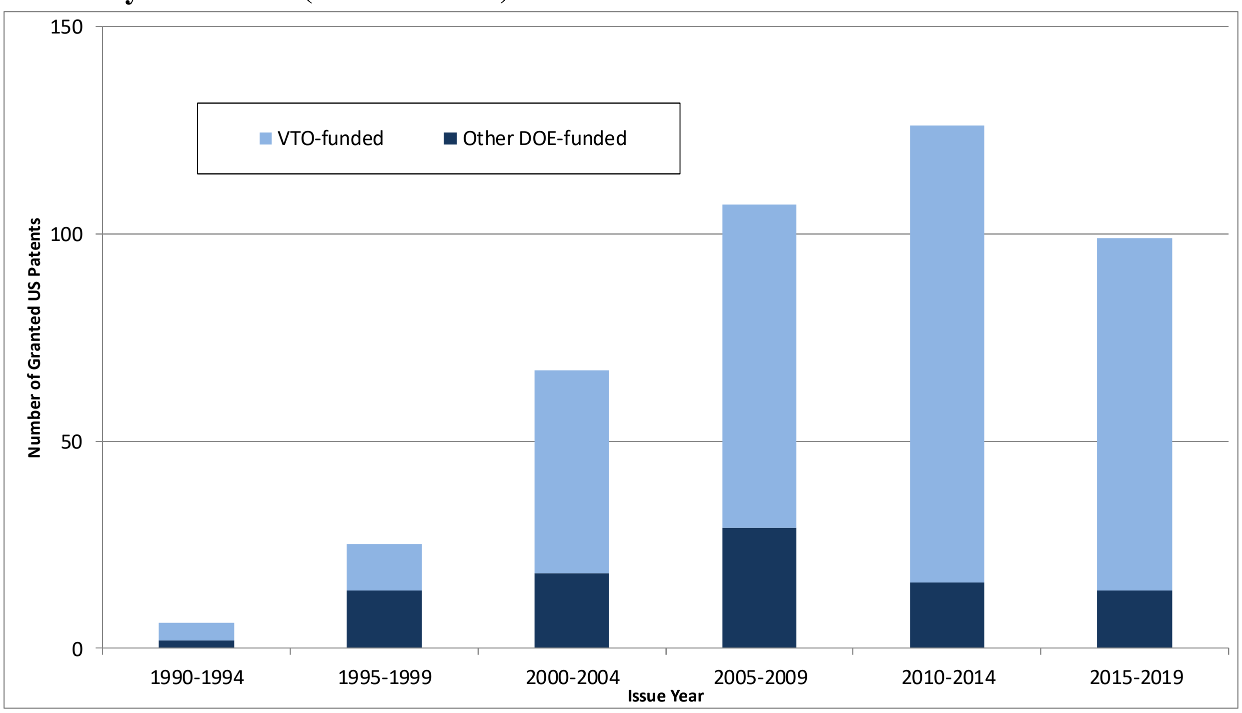
Note: The final time period in this figure is 2015-2018, and is shown for completeness, although data for this time period are incomplete. Our primary data collection covered only patents issued through 2018. Due to time lags associated with the patenting process, only a fraction of the patent families from 2015-2018 will be included.

Figure 1 separates VTO-funded and Other DOE-funded patent families, and reveals an interesting pattern in terms of DOE-funded patent activity in advanced combustion technology. During the 1990s, there was a marked increase in patent activity, albeit from a low base, with nine patent families filed in 1990-94 and 42 filed in 1995-99. These patent families were relatively evenly distributed between VTO and Other DOE funding.

The next decade saw a continued increase in DOE-funded advanced combustion patenting, with 93 patent families filed in 2000-04 and 122 filed in 2005-09. It is notable that much of this increase was associated with VTO funding. Out of the 215 DOE-funded patent families filed between 2000 and 2009, 170 (79%) were funded by VTO. The dominance of VTO funding continued in 2010-2014, with 88% (79 out of 90) of DOE-funded patent families in this time period being funded by VTO. However, 2010-2014 also marked the start of a decline in overall DOE-funded advanced combustion patenting. Patenting within this period is skewed towards the early years, with the number of patent families peaking in 2011 and declining thereafter. This decline continued in 2015-2018 (although data for this time period are incomplete).

Figure 1 suggests that DOE-funded advanced combustion patenting increased throughout the period from 1990-2009, with VTO-funded patents playing an increasingly prominent role. After that time, there was then a decline in DOE-funded advanced combustion patenting. This pattern is also reflected in Figure 2, which shows the number of advanced combustion granted U.S. patents funded by DOE since 1990. As in Figure 1, there is an increase in DOE-funded patenting over time, peaking at 126 U.S. patents granted in 2010-14, with the percentage of patents funded by VTO growing throughout. There is then a slight decline in the most recent time period, with 99 U.S. patents granted in granted in 2015-19 (with this decline partially explained by the incomplete data for this time period).

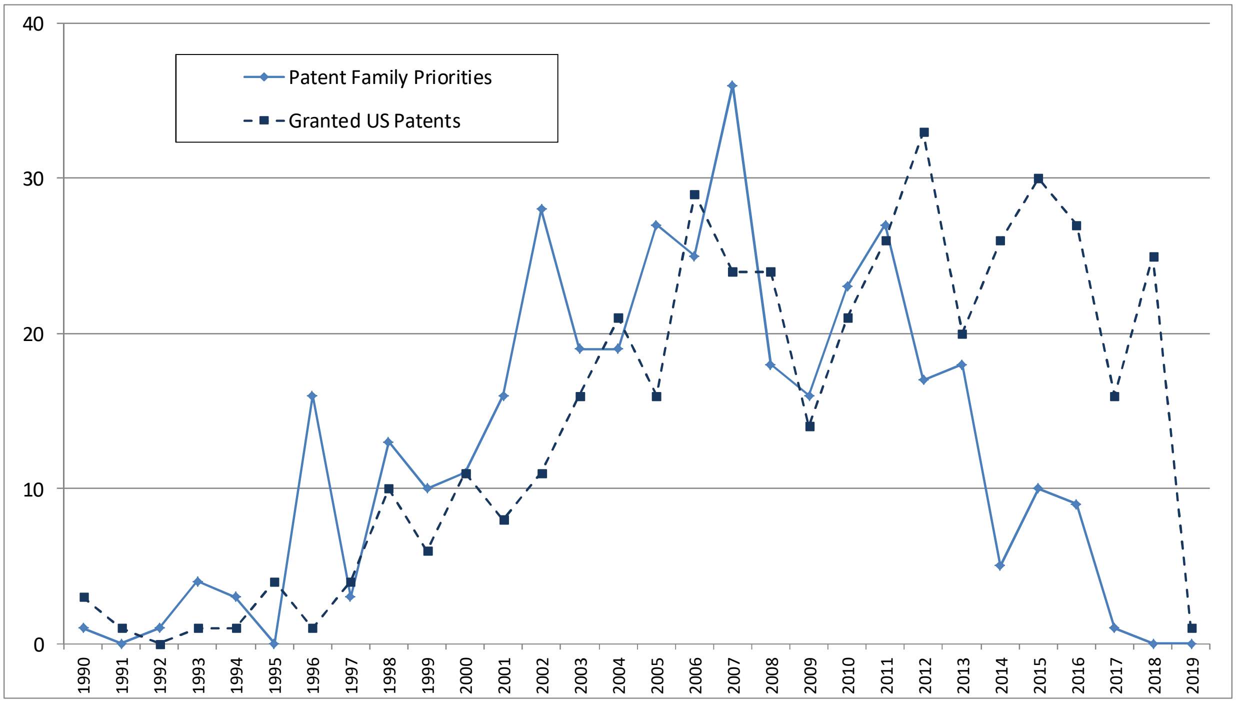
Figure 2 - Number of VTO/Other DOE-Funded Advanced Combustion Granted U.S. Patents by Issue Year (5-Year Totals)



Note: The data collection period for this analysis ended with 2018. Any 2019 patents in the 2015-2019 column are additional patents that have been included because they are members of the same patent families as pre-2019 patents. No new patent search for 2019 was carried out.

Comparing Figures 1 and 2 shows the effect of time lags in the patenting process, with many of the patent families with priority dates in 2005-09 and 2010-14 (Figure 1) resulting in granted U.S. patents in 2010-14 and 2015-19 (Figure 3). These time lags can also be seen in Figure 3, which shows advanced combustion patent family priority years alongside issue years for granted U.S. advanced combustion patents (in this figure, VTO and Other DOE are combined, in order to simplify the presentation). In this figure, the peak in patent family priorities is in 2007, with the peak in granted U.S. patents occurring in 2012. More recently, patent family priorities dropped away sharply in the period after 2013, although the number of U.S. granted remained high until 2018 (note that, due to the primary data collection for this analysis ending in 2018, the number of patent families and granted U.S. patents declines sharply in 2019).

Figure 3 - Number of DOE-funded Advanced Combustion Patent Families (by Priority Year) and Granted U.S. Patents (by Issue Year)

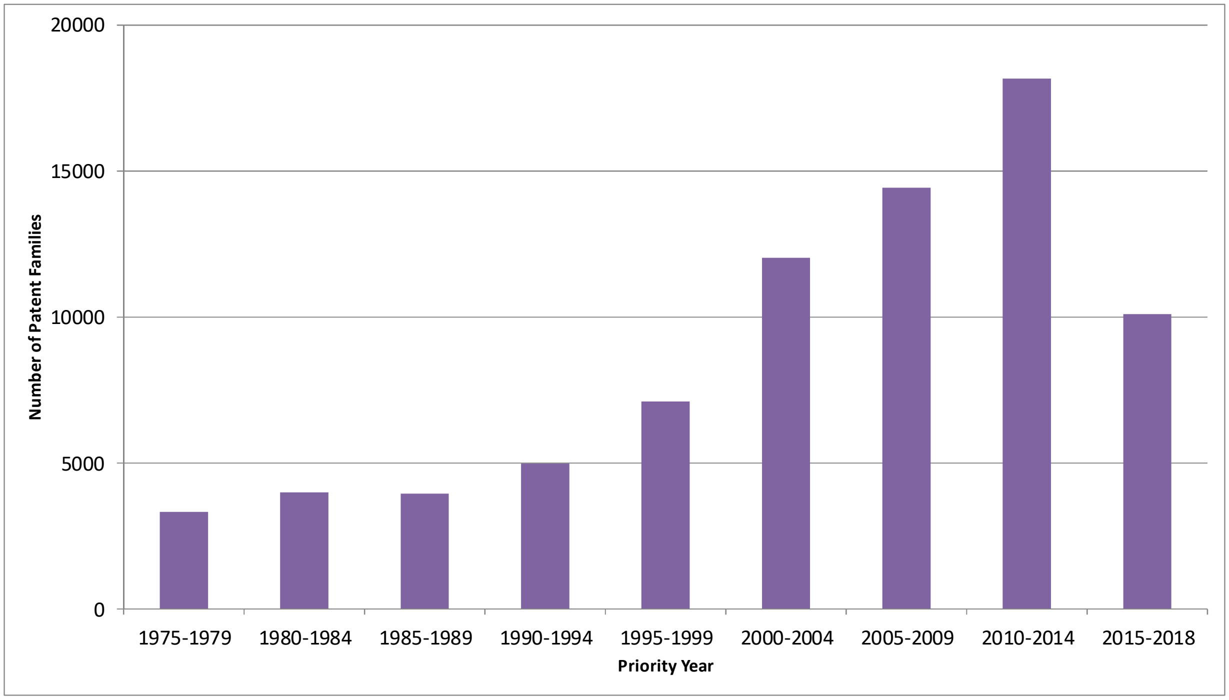


Note: The data collection period for this analysis ended with 2018. Any 2019 patents in the 2015-2019 column are additional patents that have been included because they are members of the same patent families as pre-2019 patents. No new patent search for 2019 was carried out.

Figures 1-3 focus on DOE-funded advanced combustion patent families. Figure 4 broadens the scope, and shows the overall number of advanced combustion patent families by priority year (based on USPTO, EPO, and WIPO filings). This chart covers the period back to 1975. It follows a relatively similar pattern to Figure 1, which focused solely on DOE-funded advanced combustion patent families. Overall patenting started to increase in the 1990s, and continued to grow throughout the next two decades, before peaking at 18,149 patent families in 2010-14. The overall number of patent families declined in 2015-19, although data for this period are incomplete. Hence, the trend in DOE-funded advanced combustion patenting is in line with the broader trend in this technology in general.

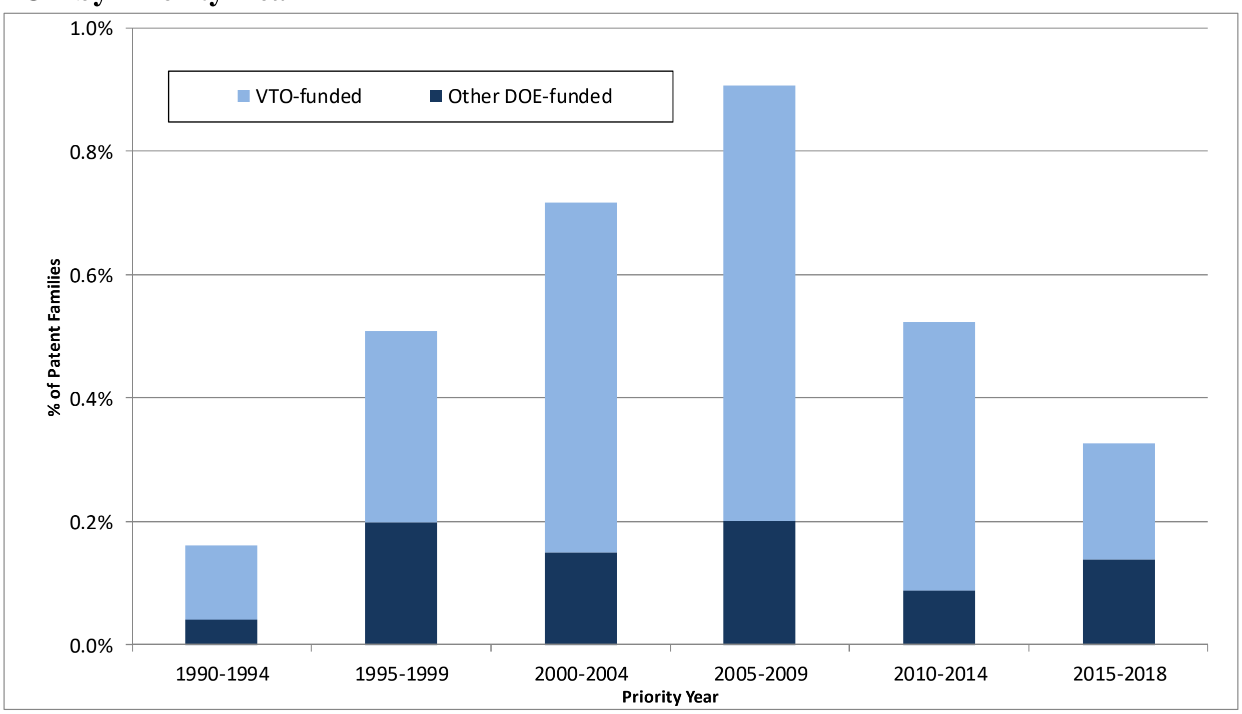
The overall number of advanced combustion patent families is very high, showing that this has been an important technology for very large companies over a significant period of time. Within this highly active patent landscape, DOE-funded patent families represent only a small percentage of the overall total, as reflected in Figure 5. This figure shows the percentage of advanced combustion patent families that were funded by DOE (VTO plus Other DOE). The percentage has never been above 1% of the total, peaking at 0.91% in 2005-09. Overall, 0.5% of advanced combustion patent families in the period 1976-2018 were funded by DOE. The small DOE-funded patent portfolio, relative to the overall advanced combustion patent landscape, should be kept in mind in assessing the results of this analysis.

Figure 4 - Total Number of Advanced Combustion Patent Families by Priority Year (5-Year Totals)



Note: The final time period in this figure is 2015-2018, and is shown for completeness, although data for this time period are incomplete. Our primary data collection covered only patents issued through 2018. Due to time lags associated with the patenting process, only a fraction of the patent families from 2015-2018 will be included.

Figure 5 - Percentage of Advanced Combustion Patent Families Funded by VTO/Other DOE by Priority Year



Leading Advanced Combustion Assignees

The ten leading patenting companies in advanced combustion technology are listed above in Table 4, along with their number of advanced combustion patent families. Figure 6 shows the same information in graphical form, while also including DOE-funded patent families. These top ten companies are the basis for the backward tracing element of the analysis, as outlined below.

Figure 6 – Top 10 Advanced Combustion Companies (based on number of patent families)

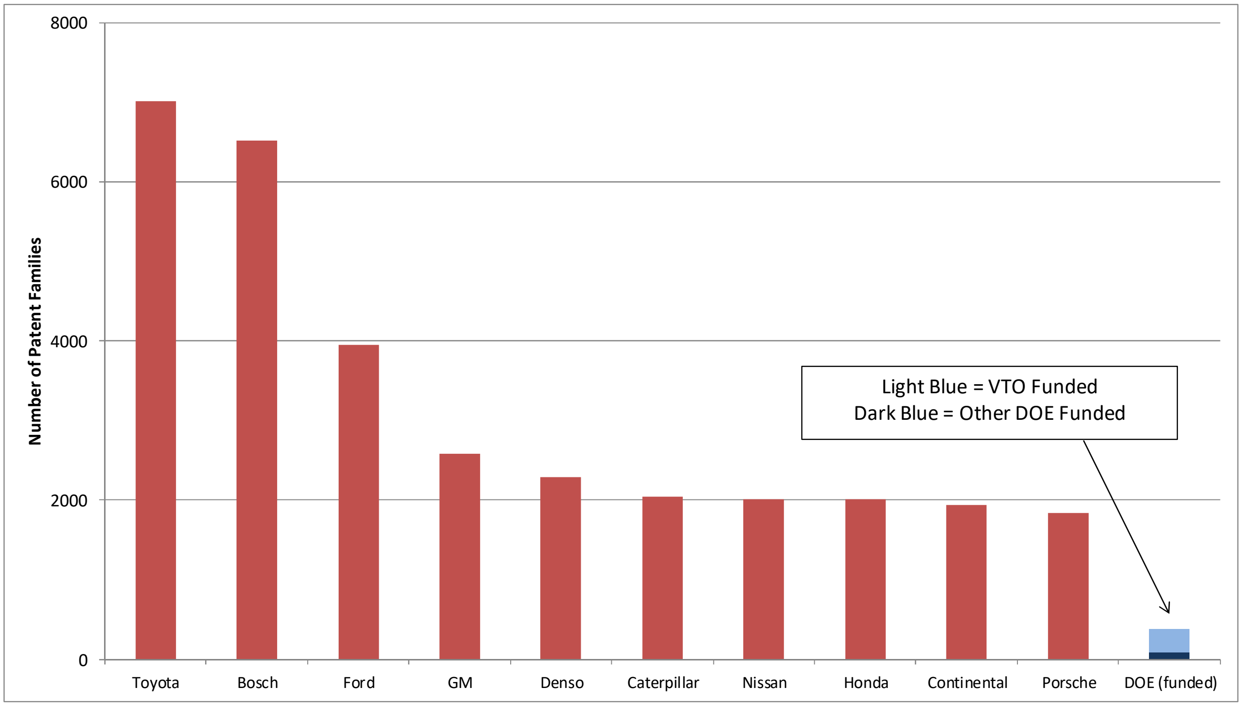


Figure 6 shows that the DOE-funded advanced combustion patent portfolio is much smaller than those assigned to the leading companies. For example, while Toyota has over 7,000 advanced combustion patent families, there are only 382 DOE-funded advanced combustion patent families (299 of which are associated with VTO funding). In assessing the impact of VTO-funded and Other DOE-funded advanced combustion patents, versus the impact of the patent portfolios associated with the leading companies, we therefore take into account this difference in portfolio size.

It should be noted that there is some double-counting of patent families in Figure 6, specifically where innovations developed by a leading company were funded in whole or in part by VTO (or another office within DOE). For example, Bosch, Caterpillar, Ford and General Motors all have advanced combustion patent families that were partially or fully funded by VTO. In Figure 6, these patent families are thus counted in both the VTO segment of the DOE column, and in the respective company column. This double-counting is appropriate, since these patent families are both funded by VTO and assigned to a leading company.

Assignees of VTO/Other DOE-funded Advanced Combustion Patents

The DOE-funded advanced combustion patent portfolios are constructed somewhat differently from the portfolios of the top ten companies listed in Figure 6. Specifically, DOE's 382 patent families are those funded by DOE, but they are not necessarily assigned to the agency. For example, VTO (or another DOE office) may have partially or fully funded research projects at DOE labs or companies. In such cases, the assignees of any resulting patents will be the respective companies or DOE lab managers (as in the case of the General Motors, Caterpillar, Ford and Bosch patent families discussed above).

Figure 7 shows the leading assignees on VTO-funded patent families. This chart is headed by General Motors (67 patent families), Caterpillar (58 families) and Cummins (49 families). The remaining assignees in Figure 8 include large automobile and engine companies, such as Detroit Diesel, Ford and Delphi, showing that VTO has funded research at some of the leading companies in the industry. There are also patent families assigned to the University of Wisconsin and the University of California, the latter in large part due to its management of the Lawrence Livermore National Laboratory (LLNL) and the Lawrence Berkeley National Laboratory (LBNL), plus UT-Battelle, the manager of Oak Ridge National Laboratory (ORNL). This reflects VTO's funding of advanced combustion research in academic and DOE lab settings.

Figure 7 - Assignees with Largest Number of VTO-Funded Advanced Combustion Patent Families

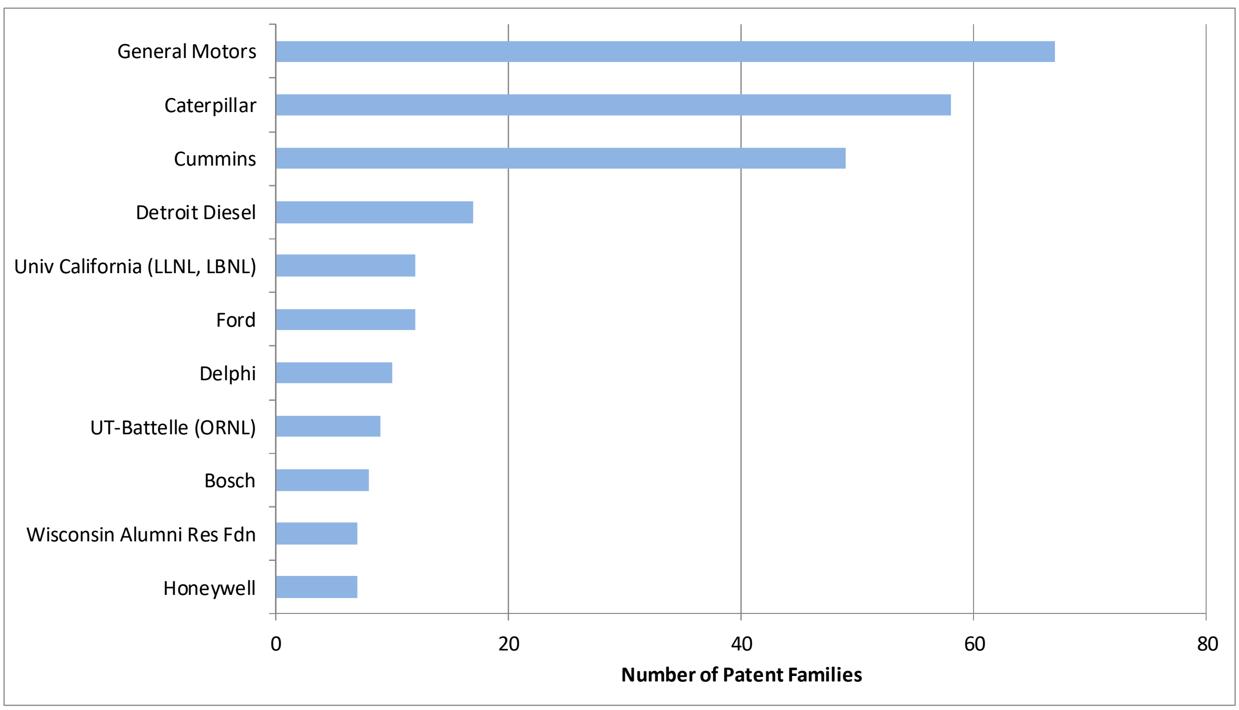
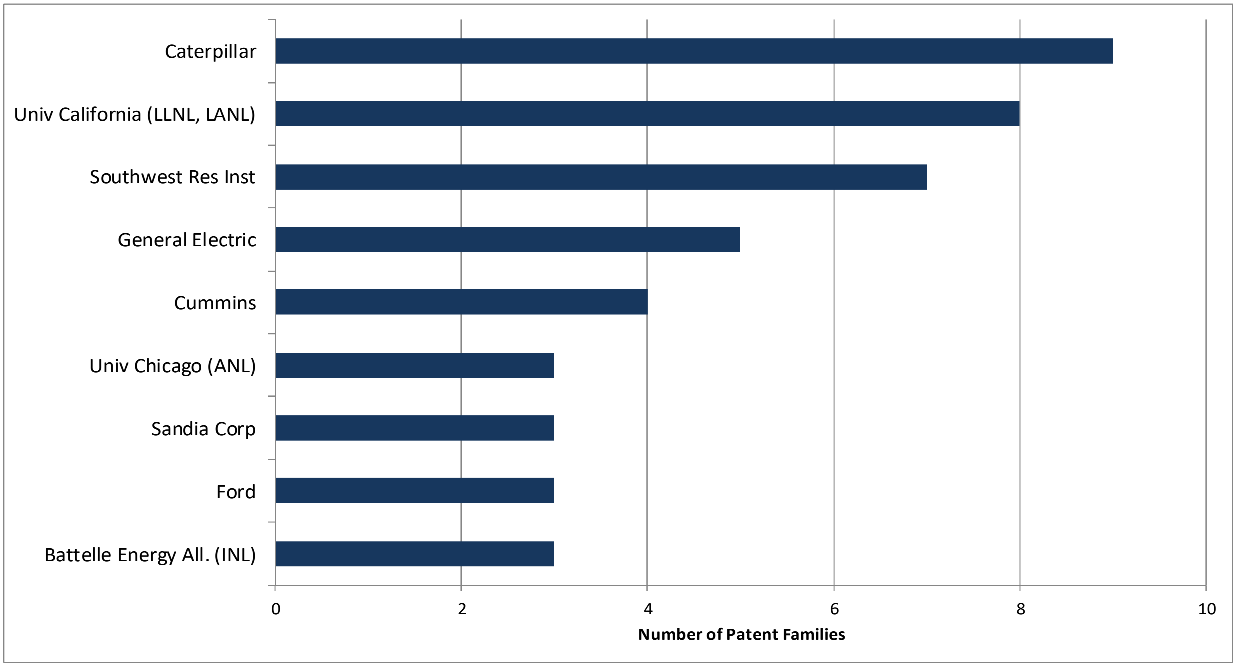


Figure 8 shows the leading assignees on Other DOE-funded advanced combustion patent families. The numbers of patent families in this figure are lower than for the VTO-funded assignees in Figure 7, reflecting the fact that there are fewer Other DOE-funded patent families in general. There is some overlap in the assignees in the two figures, notably Caterpillar, Ford and the University of California, the latter through its management of LLNL and Los Alamos National Laboratory (LANL). Beyond these organizations, there is more of a focus on non-profits and DOE lab managers among the Other DOE-funded patent families, although the numbers are relatively low.

Figure 8 - Assignees with Largest Number of Other DOE-funded Advanced Combustion Patent Families



Distribution of Advanced Combustion Patents across Patent Classifications

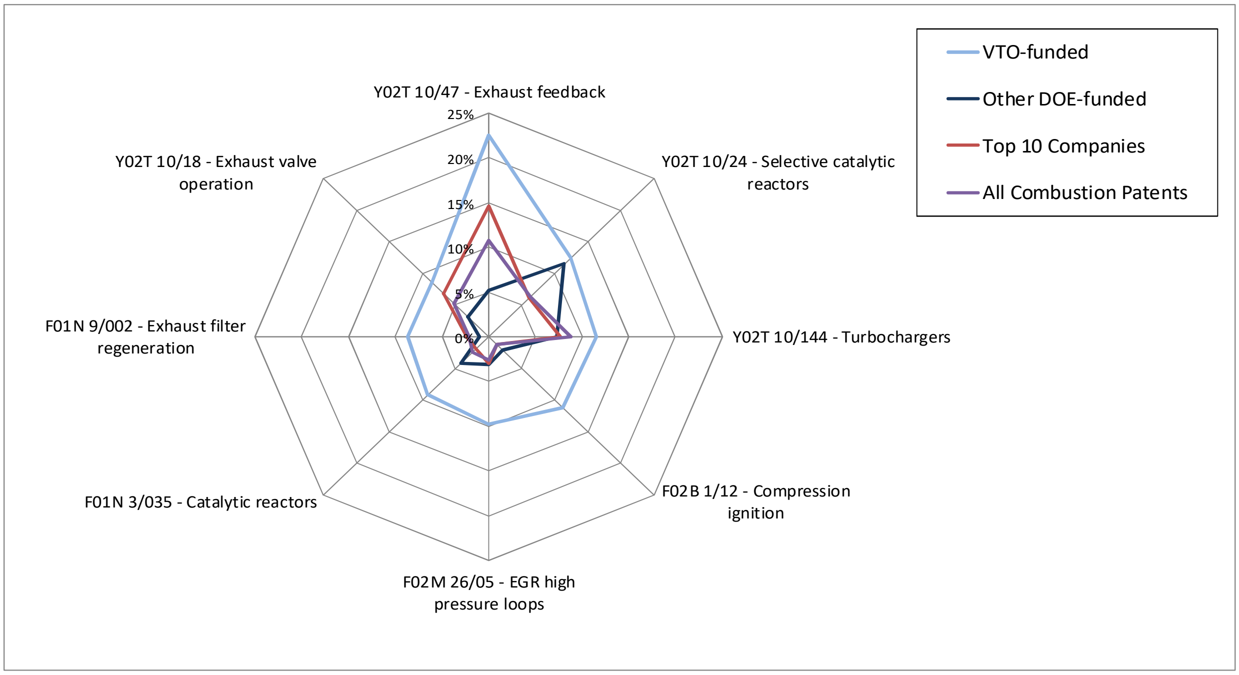
We analyzed the distribution of VTO-funded advanced combustion U.S. patents across Cooperative Patent Classifications (CPCs).[7] We then compared this distribution to those associated with Other DOE-funded advanced combustion patents; advanced combustion patents assigned to the ten leading companies; and the universe of all advanced combustion patents. This analysis provides insights into the technological focus of VTO funding in advanced combustion, versus the focus of the remainder of DOE, leading advanced combustion companies, and advanced combustion technology in general.

The results from this CPC analysis are shown in two separate charts, each from a different perspective. The first chart (Figure 9) is based on the eight CPCs that are most prevalent among VTO-funded advanced combustion patents. The purpose of this chart is thus to show the main focus areas of VTO-funded advanced combustion research, and the extent to which these areas translate to other portfolios (Other DOE-funded; leading advanced combustion companies; all advanced combustion).

[7] The CPC is a patent classification system. Patent offices attach numerous CPC classifications to a patent, covering the different aspects of the subject matter in the claimed invention. In generating these charts, all CPCs associated with each patent are included.

This figure shows that VTO-funded research includes relatively balanced coverage across the eight CPCs (which is not particularly surprising, since the VTO-funded patent portfolio forms the basis for the CPCs included in the chart). The CPC Y02T 10/47, which is concerned with exhaust feedback for engine management systems, is the most common CPC among VTO-funded advanced combustion U.S. patents. Over 22% of VTO-funded advanced combustion U.S. patents include this CPC, suggesting that exhaust feedback systems (i.e. EGR) have been a significant research focus for recipients of VTO funding. Turbochargers (CPC Y02T 10/144), selective catalytic reduction (SCR) systems (CPC Y02T 10/24) and compression ignition (CPC F02B 1/12) are also areas of major interest among VTO-funded patents.

Figure 9 - Percentage of Advanced Combustion U.S. Patents in Most Common Cooperative Patent Classifications (Among VTO-Funded Patents)



The Other DOE-funded patents share the focus on selective catalytic reduction systems (CPC Y02T 10/24) and, to a lesser degree, turbochargers (CPC Y02T 10/144). Meanwhile, the CPC distributions for the leading companies - and for advanced combustion patents in general - are similar to each other, and mirror those for VTO-funded patents to some degree. Again, there is a focus on exhaust feedback, SCR and turbochargers. That said, the percentage of patents with CPCs directed to these technologies is lower than for VTO-funded patents, which is not surprising, given that they are much larger patent portfolios. As such, they are unlikely to be as focused as the smaller VTO-funded portfolio.

Figure 10 is similar to Figure 9, except that it is from the perspective of the most common CPCs among all advanced combustion patents. Hence, the purpose of this chart is to show the main research areas within advanced combustion as a whole, and how these areas are represented in selected advanced combustion portfolios (VTO-funded; Other DOE-funded; leading advanced combustion companies). The biggest difference between the CPCs in the two figures is the presence of CPCs related to fuel injection (Y02T 10/146) and ignition control (Y02T 10/46) in Figure 10. VTO-funded patents have very little presence in these CPCs, especially ignition control, suggesting that these technologies have not been a major focus for recipients of VTO advanced combustion funding.

Figure 10 - Percentage of Advanced Combustion U.S. Patents in Most Common Cooperative Patent Classifications (Among All Advanced Combustion Patents)

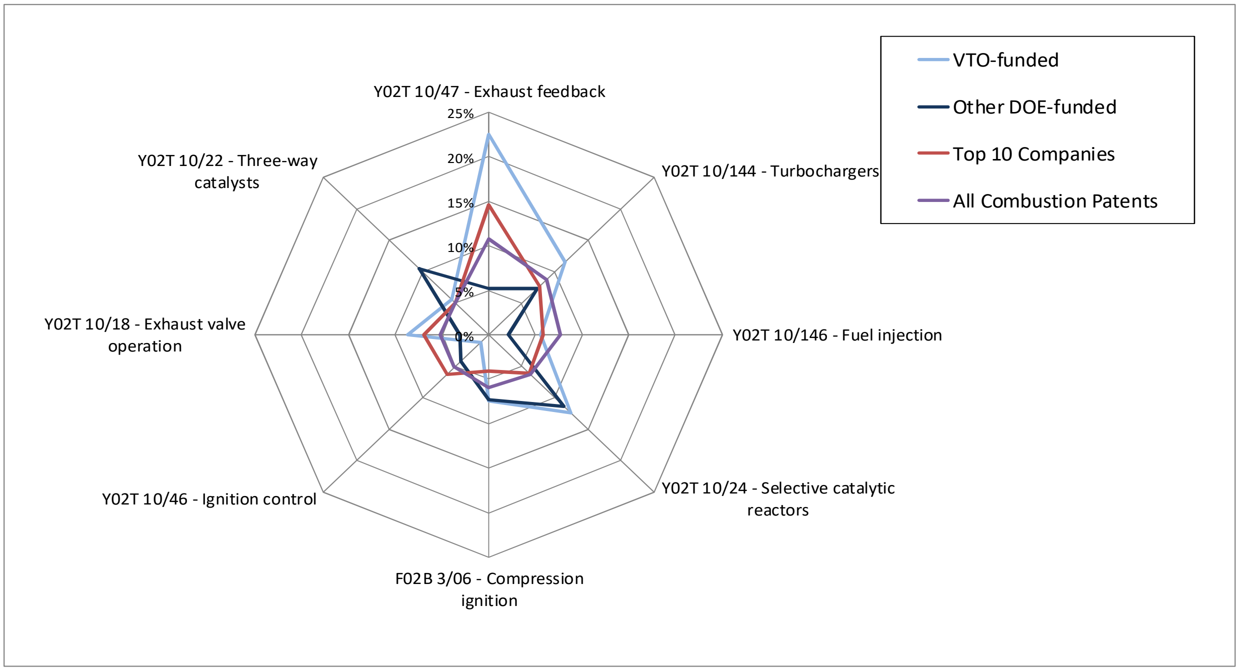
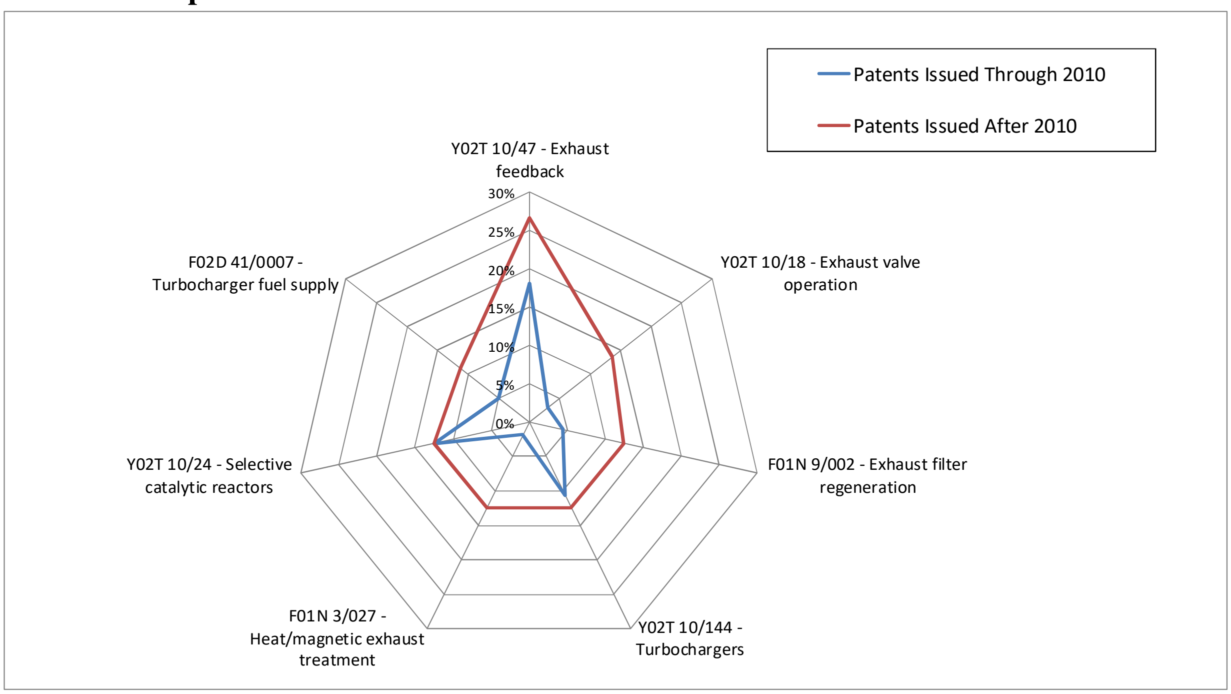


Figure 11 compares the CPC distribution of VTO-funded advanced combustion U.S. patents across two time periods – patents issued through 2010, and those issued from 2011 onwards.

Figure 11 - Percentage of VTO-funded Advanced Combustion U.S. Patents in Most Common Cooperative Patent Classifications across Two Time Periods



This figure shows that the three technology areas highlighted in Figure 9 (exhaust feedback, SCR, turbochargers) can be seen in patents from both time periods, suggesting that these have been a long-term focus for recipients of VTO funding. Meanwhile, CPCs related to exhaust valve operation (Y02T 10/18), heat and magnetic exhaust treatment (F01N 3/027) and turbocharger fuel supply (F02D 41/0007) are more concentrated among patents issued after 2010. As such, these appear to be areas of increasing focus for recipients of VTO funding.

Tracing Backwards from Advanced Combustion Patents Owned by Leading Companies

This section reports the results of an analysis tracing backwards from advanced combustion patents owned by leading companies in this technology to earlier research, including that funded by DOE. The results in this section are examined at two levels. First, we report results at the organizational level. These results reveal the extent to which VTO-funded (and Other DOE-funded) research forms a foundation for subsequent innovations associated with leading advanced combustion companies. Second, we drill down to the level of individual patents, with a particular focus on VTO-funded advanced combustion patents. These patent-level results highlight specific VTO-funded patents that have had a particularly strong influence on subsequent patents owned by leading companies. They also highlight which advanced combustion patents owned by these leading companies are linked particularly extensively to earlier VTO-funded research.

Organizational Level Results

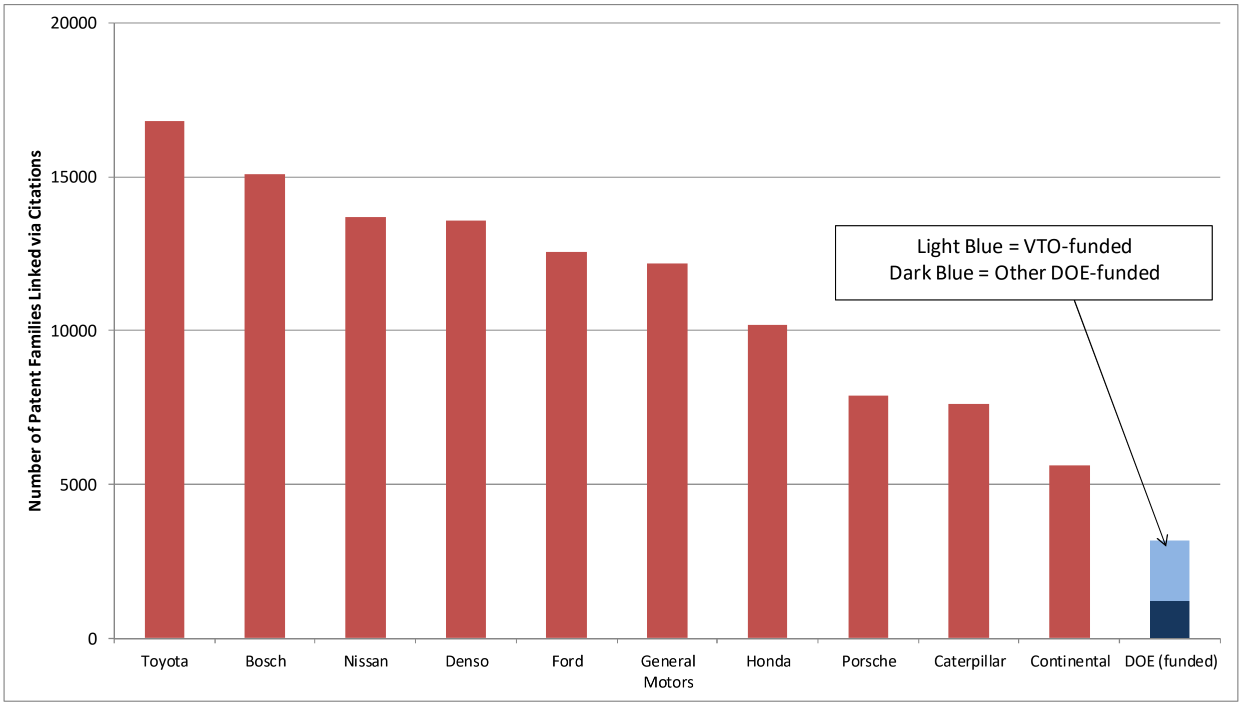
In the organizational level results, we first compare the influence of VTO-funded and Other DOE-funded advanced combustion research against the influence of leading companies in this technology. We then look at which of these leading companies build particularly extensively on DOE-funded advanced combustion research.

Figure 12 compares the influence of DOE-funded advanced combustion research to the influence of research carried out by the top ten advanced combustion companies. Specifically, this figure shows the number of advanced combustion patent families owned by the leading companies that are linked via citations to earlier advanced combustion patent families assigned to each of these leading companies (plus patent families funded by DOE). In other words, this figure shows the companies whose patents have had the strongest influence upon subsequent developments made by leading companies in advanced combustion technology.[8]

[8] This figure compares the influence of patents *funded* by VTO/DOE against patents *owned* by (i.e. assigned to) organizations. Such a comparison is reasonable, since patents funded by organizations through their R&D budgets will be assigned to those organizations. Also, organizations cannot choose to reference the patents of a non-competitor (such as DOE) rather than the patents of a competitor in order to reduce the "credit" given to that competitor. Such an omission could lead to the invalidation of their patents. Note that, as in Figure 6, there is some double-counting in Figure 12 and Figure 13, as some patent families assigned to Bosch, Caterpillar, Ford and General Motors were also funded by DOE. Also, in Figures 12 and 14-16, leading company patent families linked to both VTO-funded and Other DOE-funded patents are allocated to the VTO-funded segment of the DOE column, in order to avoid double-counting these families.

In total, 3,184 leading company advanced combustion patent families (i.e. 13.8% of their 23,125 families) are linked via citations to earlier DOE-funded advanced combustion patents, out of which 1,985 are linked to VTO-funded advanced combustion patents. This finding puts DOE-funded patents at the bottom of Figure 12. In comparison, 16,831 leading company patent families are linked via citations to earlier Toyota patent families.

Figure 12 - Number of Leading Company Advanced Combustion Patent Families Linked via Citations to Earlier Advanced Combustion Patents from each Leading Company
e.g. 3,184 leading company families are linked to earlier VTO/Other DOE-funded families

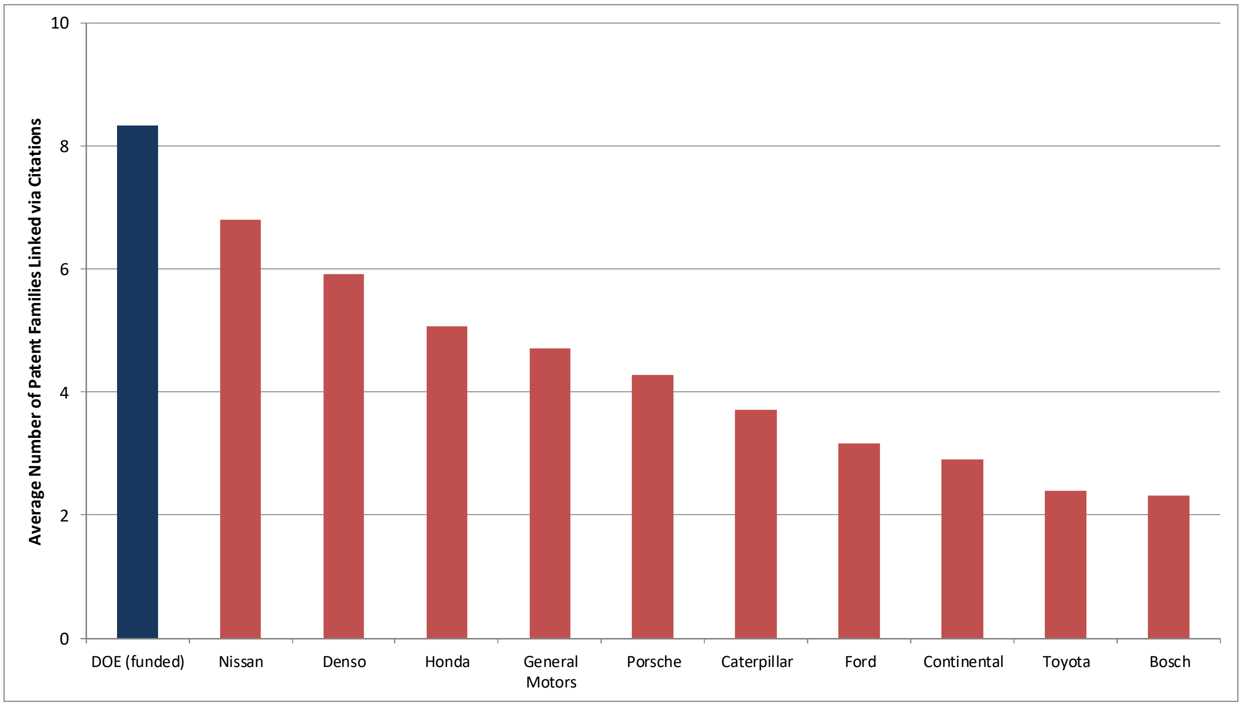


At first glance, the finding in Figure 12 does not appear promising in terms of DOE's influence on advanced combustion technology. However, this figure does not take into account the different sizes of the patent portfolios associated with the various companies. For example, it is not surprising that many more patent families are linked via citations to Toyota than to DOE, since Toyota has almost twenty times as many patent families available to be cited as prior art.

Figure 13 takes into account the differences in patent portfolio size. It shows the average (mean) number of leading company patent families linked to patent families associated with each of the companies (plus DOE) in Figure 12. For example, on average, DOE-funded advanced combustion patent families (the majority of which are VTO-funded) are each linked to over eight patent families assigned to the leading companies. This puts DOE at the head of Figure 13, ahead of Nissan, Denso and Honda. It means that, on average, more advanced combustion patent families owned by leading companies are linked via citations to each DOE-funded advanced combustion patent family than are linked to the advanced combustion patent families assigned to any other leading company.

Figure 13 suggests that, taking into account its relatively small size, the portfolio of DOE-funded advanced combustion patents has helped form an important part of the foundation for advanced combustion research carried out by the leading companies. Indeed, this figure may underestimate the influence of VTO-funded advanced combustion research (relative to Other DOE-funded research), since some of the Other DOE-funded advanced combustion patent families may in fact have been funded by VTO, as discussed earlier.

Figure 13 – Average Number of Leading Company Advanced Combustion Patent Families Linked via Citations to Advanced Combustion Families from Each Leading Company
e.g. on average, each DOE-funded patent family is linked to over eight subsequent patent families assigned to leading companies



Figures 14 through 16 examine which of the leading companies build particularly extensively on earlier DOE-funded patents. Figure 14 shows how many advanced combustion patent families owned by each of the leading companies are linked via citations to at least one earlier DOE-funded advanced combustion patent. Out of the ten leading advanced combustion companies, four are linked particularly strongly to earlier DOE-funded patents. As such, they build most extensively on earlier DOE-funded advanced combustion research. Ford heads this list, with 810 patent families linked to DOE-funded patents, 639 of which are linked to VTO. Caterpillar is second in Figure 14, with 446 patent families linked to DOE-funded patents (336 linked to VTO), followed by General Motors (394 families linked to DOE; 325 to VTO) and Toyota (340 families linked to DOE; 271 to VTO).

Figure 15 counts the total number of citation links from leading companies to earlier DOE-funded patents. This differs slightly from the count of linked families in Figure 14, since a single patent family can be linked to multiple earlier DOE-funded patents. The same four companies are prominent in Figure 15, reinforcing their close links to earlier DOE-funded advanced combustion research. Ford is again at the head of this chart, with a total of 1,639 citation links to DOE-funded advanced combustion patents, 1,222 of which are links to VTO-funded patents. Caterpillar is in second place, with 1,115 citation links to DOE, 820 of which are links to VTO, followed by General Motors (941 links to DOE; 717 to VTO) and Toyota (671 links to DOE; 518 to VTO).

Figure 14 – Number of Patent Families Linked via Citations to Earlier VTO/Other DOE-funded Advanced Combustion Patents for each Leading Advanced Combustion Company

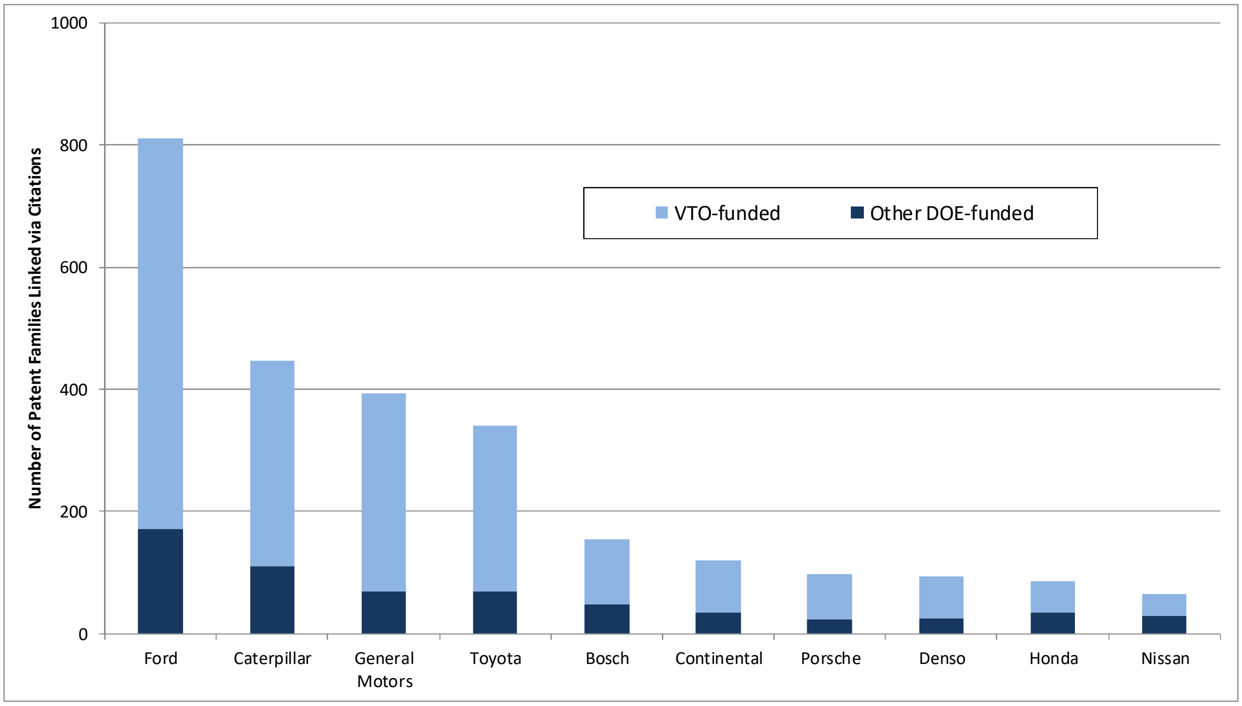
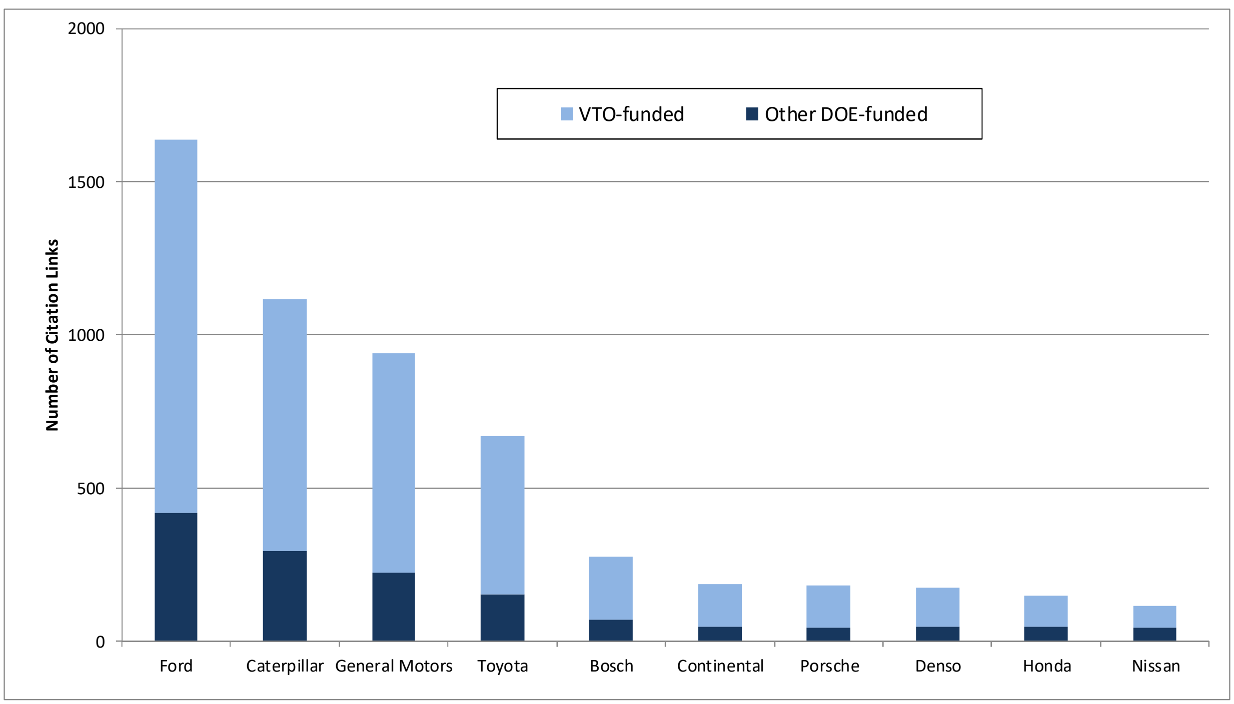


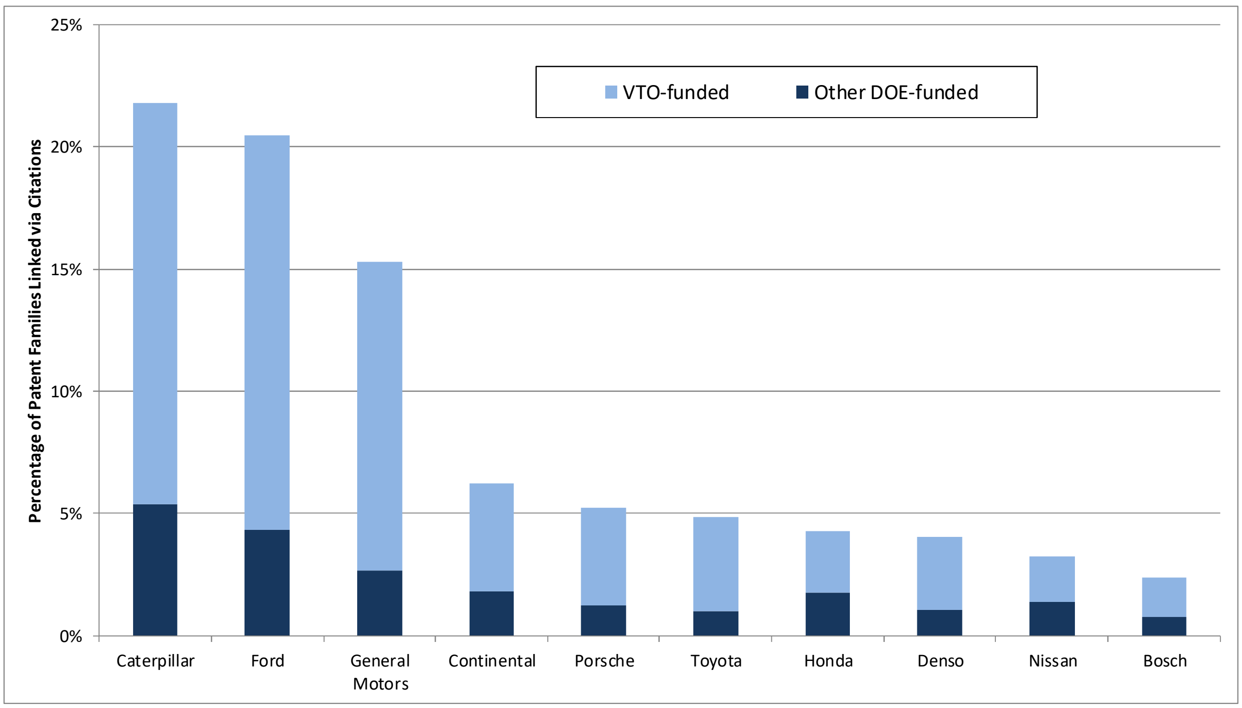
Figure 15 - Number of Citation Links from Leading Advanced Combustion Company Patent Families to Earlier VTO/Other DOE-funded Advanced Combustion Patents



There is an element of portfolio size bias in the patent family counts in Figures 14 and 15. Companies with larger advanced combustion patent portfolios are likely to have more patent families linked to DOE, simply because they have more families overall. Figure 16 accounts for this portfolio size bias by calculating the percentage of each leading company's advanced combustion patent families that are linked via citations to earlier DOE-funded advanced combustion patents, rather than their absolute number. This is a measure of how extensively each company builds on DOE-funded research, relative to their overall patent output.

Figure 16 reveals that three leading companies have more than 15% of their advanced combustion patent families linked via citations to earlier DOE-funded advanced combustion patents – Caterpillar (21.8%), Ford (20.5%) and General Motors (15.3%). Toyota is less prominent in this figure than in Figures 14 and 15. While Toyota's absolute number of patent families linked to DOE-funded families is among the highest, this results in part from its large patent portfolio, and its percentage of families linked to DOE is around the average.

Figure 16 - Percentage of Leading Advanced Combustion Company Patent Families Linked via Citations to Earlier VTO/Other DOE-funded Advanced Combustion Patents



Patent Level Results

The previous section of the report examined results at the level of entire patent portfolios. The purpose of this section is to drill down to identify individual DOE-funded advanced combustion patent families (in particular VTO-funded families) that have had a particularly strong influence on subsequent advanced combustion patents owned by leading companies in this technology. Looking in the opposite direction, it also identifies individual advanced combustion patents owned by leading companies that have extensive links to earlier VTO-funded research.

Table 5 shows the VTO-funded advanced combustion patent families linked via citations to the largest number of subsequent patent families owned by leading companies in this technology. Many of the patents in this table are relatively old. This is not surprising, since older patents have had a longer time period to become connected to subsequent generations of technology. As such, most of the patent families in Table 5 represent older foundational technologies that are linked to subsequent innovations associated with leading companies in the advanced combustion industry.

The two VTO-funded patent families linked to the most leading company families are both assigned to the University of California, through its management of Livermore and Berkeley Labs respectively. The first family (whose representative patent[9] is US #5,711,147) describes a selective catalytic reduction system for decreasing the NOx output of exhausts. It is linked to 241 patent families owned by the leading companies. The second family (representative patent US #4,924,828) describes a pulsed jet combustion system designed to reduce emissions, and is linked to 200 patent families owned by the leading companies. In both of these cases, all ten of the leading companies have patent families linked to the VTO-funded patents, showing the breadth of their influence.

Table 5 – VTO-Funded Advanced Combustion Patent Families Linked via Citations to Most Subsequent Leading Company Advanced Combustion Patent Families

Patent Family #	Representative Patent #	Priority Year	# Linked Families	Assignee	Title
24809071	5711147	1996	241	Univ California (LLNL)	Plasma-assisted catalytic reduction system
23224258	4924828	1989	200	Univ California (LBNL)	Method and system for controlled combustion engines
23495413	6560958	1998	197	MIT	Emission abatement system
27106405	5891409	1996	144	Univ California (LLNL)	Pre-converted nitric oxide gas in catalytic reduction system
22802680	6116026	1998	121	Detroit Diesel	Engine air intake manifold having built-in intercooler
33300281	6981375	2003	107	Detroit Diesel	Turbocharged internal combustion engine with EGR flow
24702304	5746984	1996	99	Low Emissions Tech Res	Exhaust system with emissions storage device and plasma reactor
23135832	6119451	1999	98	Univ California (LLNL)	Nitrogen oxide removal using diesel fuel and a catalyst
34632722	6923167	2003	95	Univ California (LLNL)	Controlling and operating homogeneous charge compression ignition (HCCI) engines
41342695	7869930	2008	87	Ford	Approach for reducing overheating of direct injection fuel injectors
29250210	6637205	2002	86	Honeywell	Electric assist and variable geometry turbocharger

There are also more recent VTO-funded patent families in Table 5. These include a Ford patent family (representative patent US #7,869,930) describing a fuel supply method for reducing overheating of direct injection fuel injectors, and a Detroit Diesel patent family (representative patent US #6,981,375) outlining a turbocharged engine incorporating exhaust gas recirculation.

[9] The representative patent is a single patent from a family, but it is not necessarily the priority filing.

These represent somewhat more recent VTO-funded technologies that have had a strong influence on subsequent generations of technology developed by the leading advanced combustion companies.

Table 5 lists VTO-funded patents linked to large numbers of subsequent advanced combustion patent families owned by leading companies. Table 6 looks in the opposite direction, and lists advanced combustion patent families owned by leading companies that are linked particularly extensively to earlier patents funded by VTO.

Table 6 - Leading Company Advanced Combustion Patent Families Linked via Citations to Largest Number of VTO-Funded Advanced Combustion Patent Families

Patent Family #	Representative Patent #	Priority Year	# VTO Fams	Assignee	Title
38710555	7743602	2006	11	Caterpillar Inc.	Reformer assisted lean NOx catalyst aftertreatment system and method
49995653	9151241	2012	11	Caterpillar Inc.	Reactivity controlled compression ignition engine operating on a Miller cycle
48288131	8826652	2011	10	General Motors Corp	Power system and method for energizing an electrically heated catalyst
50879601	8978602	2012	10	Caterpillar Inc.	Six-stroke engine power density matching system and method
55488146	9689354	2016	9	Ford Motor Co.	Engine exhaust gas recirculation system with at least one exhaust recirculation treatment device
39154390	9249752	2006	9	Caterpillar Inc.	System implementing low-reductant engine operation mode
41265746	8161731	2008	8	Caterpillar Inc.	Selective catalytic reduction using controlled catalytic deactivation
39187132	8006481	2006	8	General Motors Corp	Method and apparatus to selectively reduce NOx in an exhaust gas feedstream
56800645	9745927	2015	8	Denso Corp	Emissions reduction system for an internal combustion engine
44223969	8042527	2010	8	Ford Motor Co.	Coordination of HP and LP EGR
56887529	9903323	2016	8	Denso Corp	Emissions reduction system for an internal combustion engine
43853731	8661791	2009	8	General Motors Corp	Systems and methods for controlling regeneration of nitrogen oxide adsorbers

Caterpillar has a number of patent families among those with the most links to VTO-funded advanced combustion patents. These Caterpillar families cover a range of combustion technologies, including exhaust treatment (representative patent US #7,743,602), multi-fuel engines (representative patent US #9,151,241) and six-stroke engine control (representative patent US #8,978,602). General Motors, Denso, and Ford also have multiple patent families in Table 6, covering technologies such as NOx reduction (General Motors; representative patent US #8,006,481); air supply systems (Denso; representative patent US #9,745,927); and exhaust gas recirculation (Ford; representative patent US #9,689,354). Many of the patent families in Table 6 are relatively new, and are examples of how VTO-funded advanced combustion research has helped form part of the foundation for recent advances made by leading companies.

We also identified high-impact advanced combustion patents owned by leading companies that have citation links back to VTO-funded patents.[10] The idea is to highlight important technologies owned by leading companies that are linked to earlier advanced combustion research funded by VTO. Table 7 lists advanced combustion patents owned by leading companies that have Citation Index values of five or over (i.e. they have been cited at least five times as frequently as expected), and that are linked via citations to earlier VTO-funded advanced combustion patents.

Table 7 - Highly Cited Leading Company Advanced Combustion Patents Linked via Citations to Earlier VTO-funded Advanced Combustion Patents

Patent	Issue Year	# Cites Received	Citation Index	Assignee	Title
8080494	2011	77	14.6	Nissan	Catalyst, exhaust gas purifying catalyst, and method of producing the catalyst
7063062	2006	130	13.0	Ford	Valve selection for an engine operating in a multi-stroke cylinder mode
6959693	2005	107	12.2	Toyota	Fuel injection system and method
7032581	2006	80	10.2	Ford	Engine air-fuel control for an engine with valves that may be deactivated
7406947	2008	50	8.4	Ford	System and method for tip-in knock compensation
8103428	2012	46	7.4	Ford	Method for controlling an engine
8479511	2013	31	7.2	Ford	Method and system for a turbocharged engine
8103425	2012	37	6.7	Caterpillar	Simulation-based control for HCCI power systems
6928806	2005	93	6.3	Ford	Exhaust gas aftertreatment systems
7367319	2008	33	5.5	General Motors	Method and apparatus to determine magnitude of combustion chamber deposits
7400967	2008	62	5.0	Honda	Control system for internal combustion engine

The patents in this table are listed in descending order according to their Citation Index values. The list is headed by a 2011 Nissan patent (US #8,080,494) describing an exhaust purifying catalyst. This patent has been cited as prior art by 77 subsequent patents, which is more than fourteen times as many citations as expected for a patent of its age and technology. In turn, the Nissan patent is linked to earlier VTO-funded patents describing lean NOx catalysts.

[10] High-impact patents are identified using 1790's Citation Index metric. This metric is derived by first counting the number of times a patent is cited as prior art by subsequent patents. This number is then divided by the mean number of citations received by peer patents from the same issue year and technology (as defined by their first listed Cooperative Patent Classification). For example, the number of citations received by a 2010 patent in CPC H01J 49 (Particle Spectrometers) is divided by the mean number of citations received by all patents in that CPC issued in 2010. The expected Citation Index for an individual patent is one. The extent to which a patent's Citation Index is greater or less than one reveals whether it has been cited more or less frequently than expected, and by how much. For example, a Citation Index of 1.5 shows that a patent has been cited 50% more frequently than expected. Meanwhile a Citation Index of 0.7 reveals that a patent has been cited 30% less frequently than expected. By extension, the expected Citation Index for a portfolio of patents is also one, with values above one showing that a portfolio has been cited more than expected, and values below one showing that a portfolio has not been cited as frequently as expected. Note that the Citation Index is calculated for U.S. patents only, since citation rates differ across patent systems.

Table 7 also includes a number of highly-cited patents assigned to Ford. The most highly-cited of these (US #7,063,062) is a 2006 patent describing valve control to improve engine performance and reduce emissions. This Ford patent has been cited as prior art by 130 subsequent patents, thirteen times as many citations as expected for a patent of its age and technology. In turn, this Ford patent is linked to earlier VTO-funded patents describing combustion timing control. Ford also has a number of other highly-cited patents in Table 7 outlining engine control, a subject also covered by highly-cited patents assigned to Caterpillar and Honda. All of these patents are linked to earlier VTO-funded patents, showing the influence of VTO research on high-impact technologies developed by the leading companies.

While the patent-level results focus on VTO-funded advanced combustion patent families, we also identified Other DOE-funded advanced combustion families linked to the largest number of subsequent patent families owned by leading companies in this technology. These families, listed in Table 8, are headed by a patent family assigned to Ford (and funded by DOE), describing a turbocharged engine with exhaust gas recirculation. This patent family (representative patent US #6,035,640) is linked to 233 patent families owned by the leading combustion companies, with all ten of the companies represented among these linked families.

Table 8 - Other DOE-Funded Advanced Combustion Patent Families Linked via Citations to Most Subsequent Leading Company Advanced Combustion Families

Patent Family #	Representative Patent #	Priority Year	# Linked Families	Assignee	Title
22893288	6035640	1999	233	Ford	Control method for turbocharged diesel engines having exhaust gas recirculation
24207238	4543930	1983	173	Southwest Res Inst	Staged direct injection diesel engine
30114483	6742335	2002	121	Clean Air Power Inc	EGR control system and method for an internal combustion engine
24954384	5735245	1996	119	Southwest Res Inst	Method and apparatus for controlling fuel/air mixture in a lean burn engine
25007921	5715677	1996	106	Univ California (LLNL)	Diesel NOx reduction by plasma-regenerated absorbend beds
23279357	6742328	2001	82	Southwest Res Inst	Systems and methods for controlling diesel engine emissions
23862190	6347511	1999	64	Ford	Exhaust gas purification system for lean burn engine
22843172	6612269	2000	54	Univ California (UC Riverside)	Apparatus and method for operating internal combustion engines from variable mixtures of gaseous fuels
21791452	5526641	1993	41	Univ Chicago (ANL)	NOx reduction method
24912929	5671716	1996	25	Ford	Fuel injection system and strategy

Table 8 also contains a number of patent families assigned to Southwest Research Institute. These include an early patent family (representative patent US #4,543,930) filed in 1983, and describing a direct injection diesel engine. This patent family is linked to 173 patent families assigned to the leading companies, including at least one family from each of these companies. There are also more recent Southwest Research Institute patent families in Table 8 related to exhaust filters and controlling fuel-air mixtures.

Overall, the backward tracing element of the analysis suggests that VTO-funded and Other DOE-funded advanced combustion patents have had a strong influence on subsequent innovations associated with the leading advanced combustion companies. This influence can be seen both over time, and across these leading companies, with a number of DOE-funded patent families linked via citations to patents assigned to all ten of the leading companies.

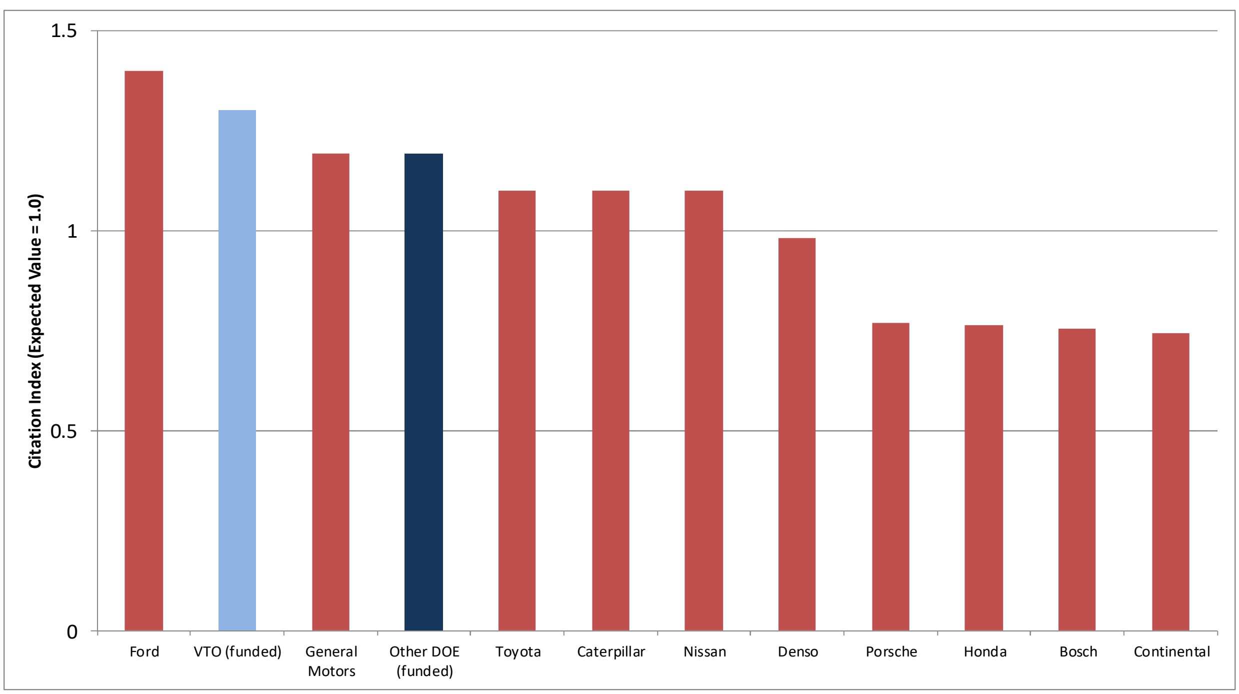
Tracing Forwards from DOE-funded Advanced Combustion Patents

The previous section of the report examines the influence of DOE-funded advanced combustion research upon technological developments associated with leading advanced combustion companies. That analysis was based on tracing backwards from the patents of leading companies to previous generations of research. This section reports the results of an analysis tracing in the opposite direction – starting with VTO-funded (and Other DOE-funded) advanced combustion patents, and tracing forwards in time through two generations of citations. Hence, while the previous section of the report focuses on DOE's influence upon a specific patent set (i.e. patents owned by leading advanced combustion companies), this section of the report focuses on the broader influence of VTO-funded (and Other DOE-funded) advanced combustion research, both within and beyond the advanced combustion industry. Also, in order to avoid repeating earlier results, the forward tracing concentrates primarily on patents that are linked to DOE-funded advanced combustion research, but are not owned by leading advanced combustion companies.

Organizational Level Results

We first generated Citation Index values for the portfolios of VTO-funded and Other DOE-funded advanced combustion patents. We then compared these Citation Indexes against those of the ten leading advanced combustion companies. The results are shown in Figure 17.

Figure 17 - Citation Index for Leading Companies' Advanced Combustion Patents, plus VTO-funded and Other DOE-funded Advanced Combustion Patents



This figure reveals that VTO-funded advanced combustion patents have an average Citation Index of 1.30, showing they have been cited 30% more frequently than expected. The Citation Index for Other DOE-funded advanced combustion patents is slightly lower at 1.19, but this means that these patents have still been cited 19% more frequently than expected. Overall, VTO ranks second in Figure 17, behind only Ford, while Other DOE is fourth. The Citation Index accounts for the size of different patent portfolios, so this finding again reflects the relatively strong influence of the DOE-funded advanced combustion patent portfolio, given its small size compared to those of the leading companies.

The Citation Index measures the overall influence of the DOE-funded advanced combustion patent portfolios, but does not necessarily address the breadth of this influence across technologies. To analyze this question, we therefore identified the Cooperative Patent Classifications (CPCs) of the patent families linked via citations to earlier DOE-funded advanced combustion patent families.[11] These CPCs reflect the influence of DOE-funded research across technologies.

Figure 18 shows the CPCs with the largest number of patent families linked to VTO-funded advanced combustion patents. Typically, a figure such as this shows CPCs in two different colors – i.e. those related to advanced combustion technology and those beyond advanced combustion technology. The former represent the influence of VTO-funded patents on advanced combustion technology itself, while the latter represent spillovers of the influence of VTO-funded advanced combustion research into other technology areas.

In this case, all of the CPCs are shown in a single color, since they are all related to advanced combustion. This suggests that combustion is a relatively self-contained technology, with successive generations of technology building upon earlier research. That said, there are a number of different combustion technologies represented in Figure 18, ranging from fuel supply, to engine control, to exhaust treatment. This reflects the influence of VTO-funded patents across many different areas of combustion technology.

Figure 19 is similar to Figure 18, but is based on patent families linked to Other DOE-funded advanced combustion patents, rather than VTO-funded advanced combustion patents. Again, all of these CPCs are related to combustion, and their distribution is similar to that of the families linked to VTO-funded patents. There are CPCs covering all stages of combustion, from fuel supply to engine control to exhaust treatment.

[11] Patents typically have numerous CPCs attached to them, reflecting different aspects of the invention they describe. In this analysis, we include all CPCs attached to the patents linked to earlier DOE-funded advanced combustion patent families.

Figure 18 - Number of Patent Families Linked via Citations to Earlier VTO-Funded Advanced Combustion Patents by CPC

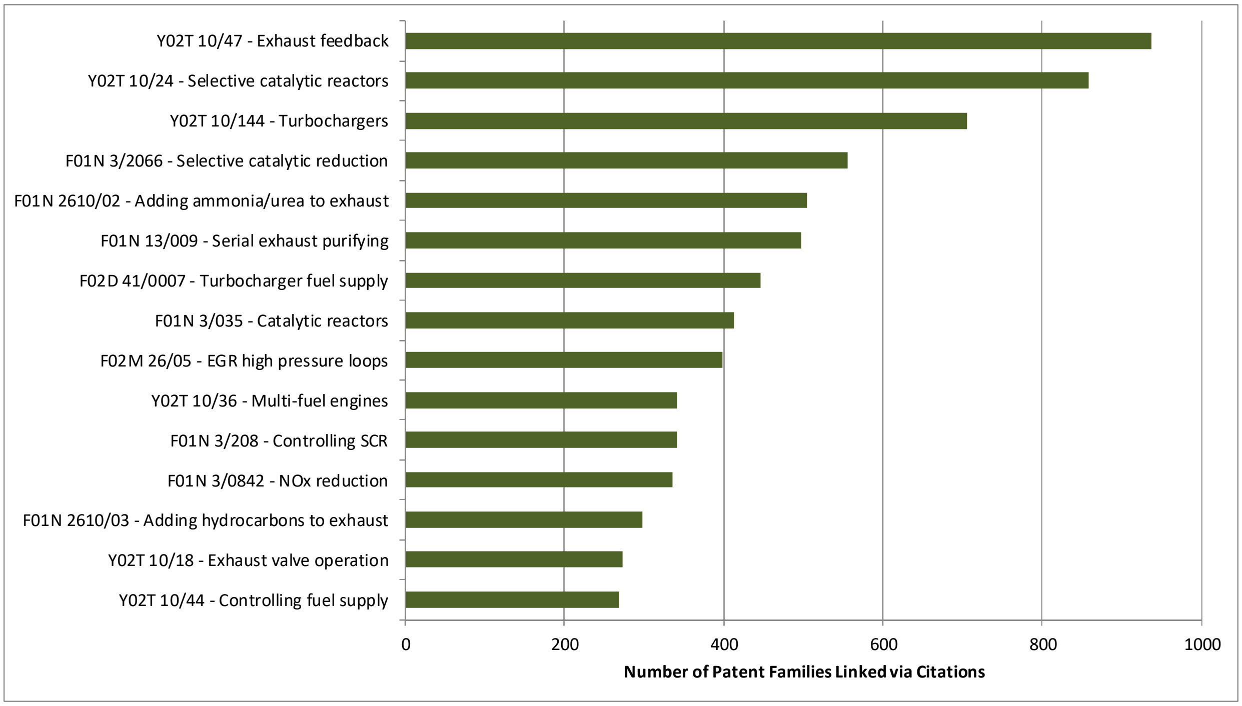
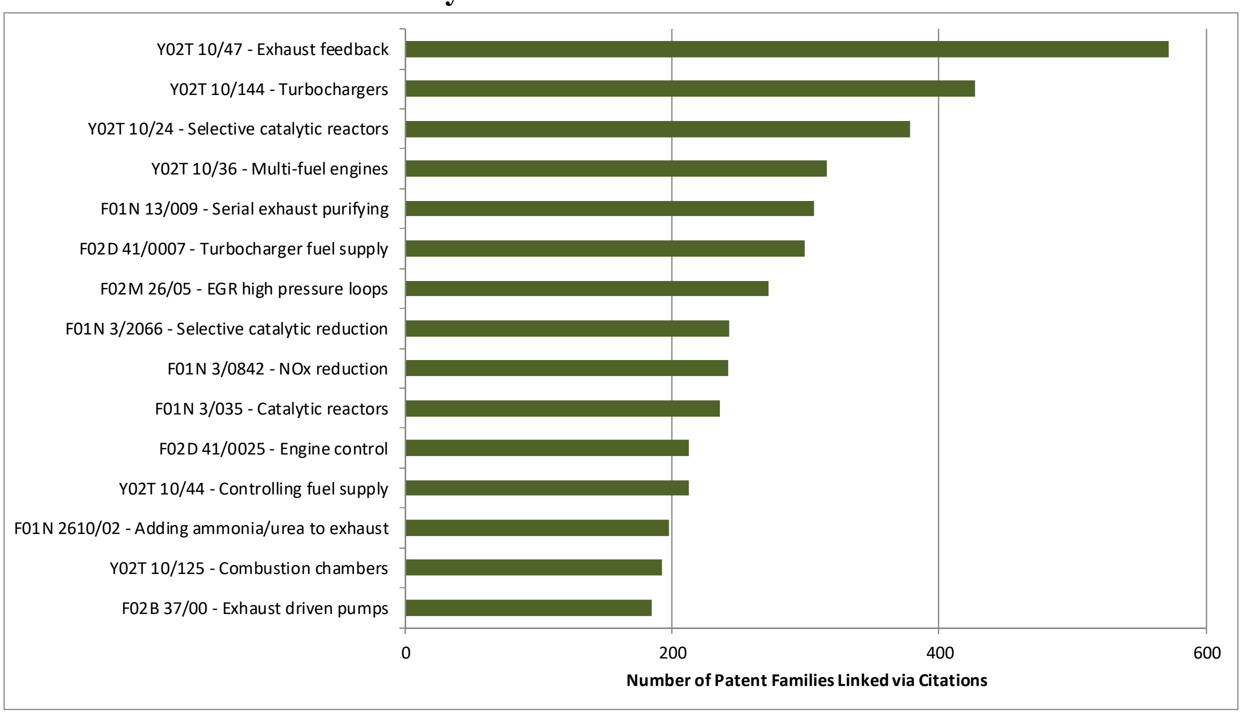
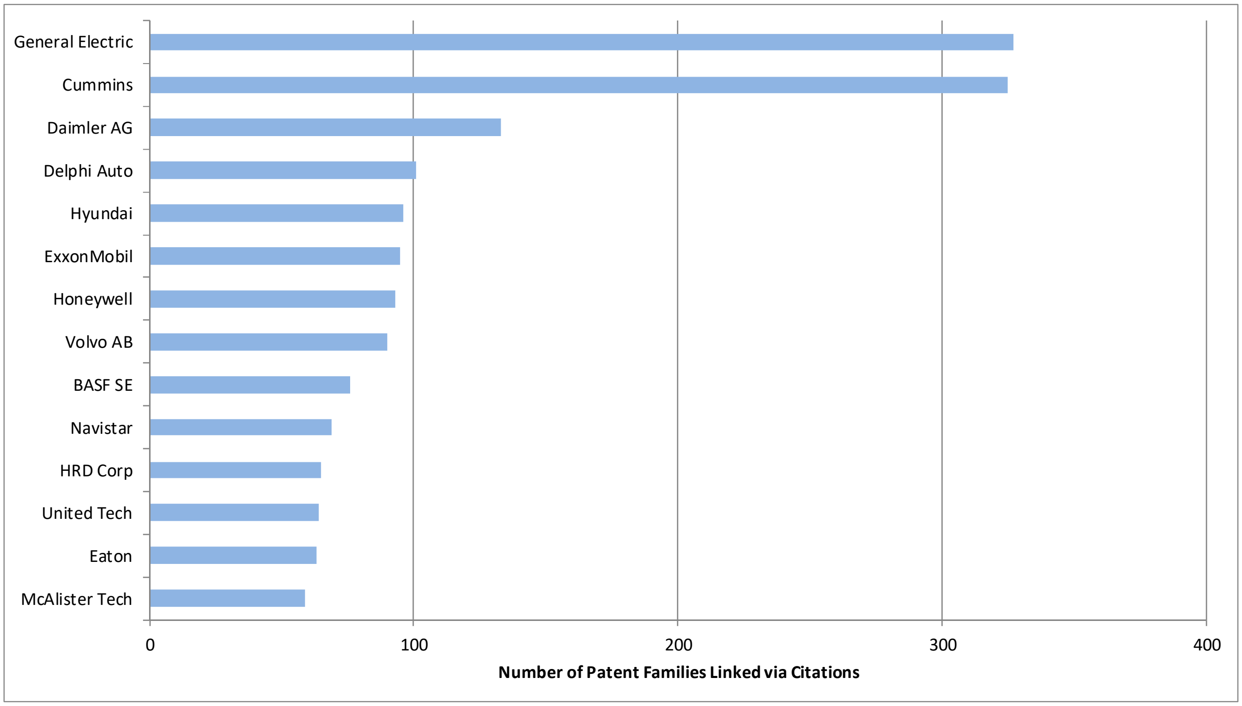


Figure 19 - Number of Patent Families Linked via Citations to Earlier Other DOE-Funded Advanced Combustion Patents by CPC



The organizations with the largest number of patent families linked via citations to earlier VTO-funded advanced combustion patents are shown in Figure 20. To avoid repeating the results from earlier, this figure excludes the ten leading advanced combustion companies used in the backward tracing element of the analysis. Also, note that Figure 20 includes all patent families assigned to these organizations, not just their patent families describing advanced combustion technology.

Figure 20 - Organizations with Largest Number of Patent Families Linked via Citations to VTO-funded Advanced Combustion Patents (excluding leading advanced combustion companies)

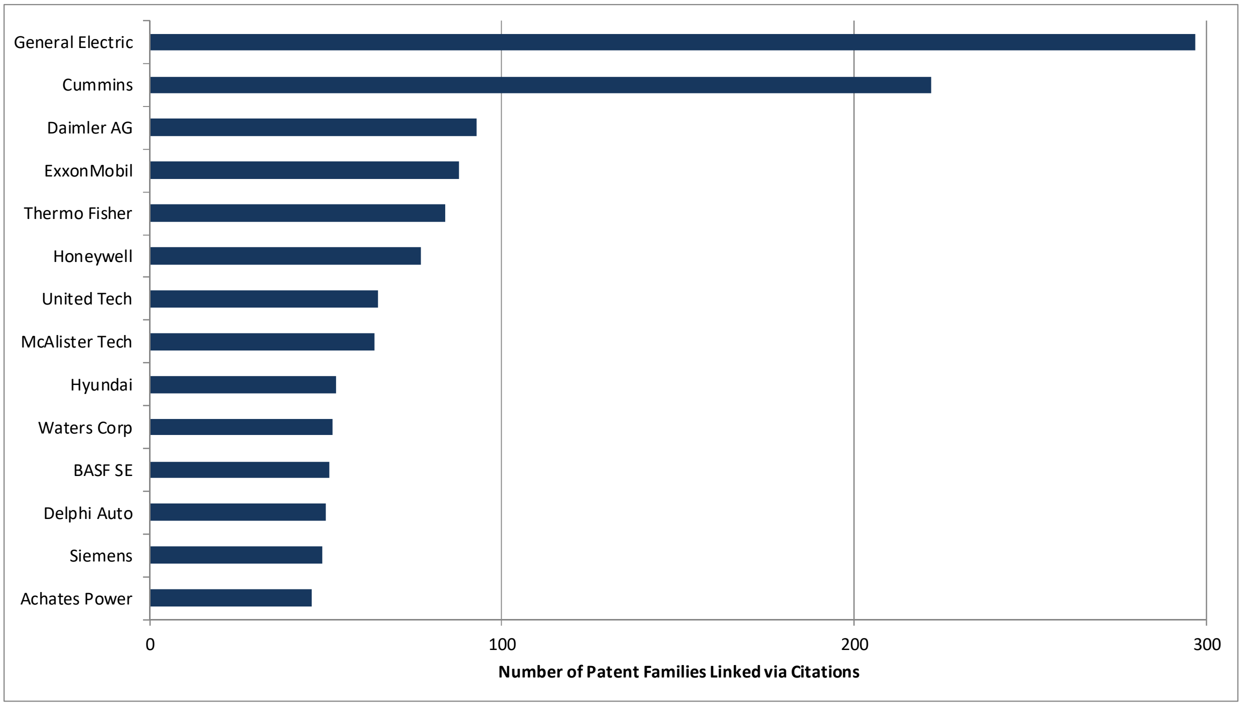


Two companies stand out in Figure 20 – General Electric and Cummins. The former has 327 patent families linked to VTO-funded advanced combustion patents, while the latter has 325 such patent families. The General Electric patent families describe a variety of technologies, including combustion-related subjects (such as fuel supply, turbochargers and exhaust gas recirculation), plus other subjects (such as gas turbines and fluid dynamics). The Cummins patent families, meanwhile, focus on both engine control and exhaust treatment, through technologies such as EGR and SCR.

Beyond General Electric and Cummins, Figure 20 contains a number of other automakers and suppliers, such as Daimler, Hyundai, Volvo and Delphi. It also includes large companies with interests beyond the auto industry, such as Honeywell, BASF and United Technologies. This reflects the breadth of influence of VTO-funded advanced combustion research on technologies developed by a wide range of organizations.

Figure 21 shows the organizations with the largest number of patent families linked to earlier Other DOE-funded advanced combustion patents. This figure contains many of the same companies as Figure 20, which focused on patent families linked to earlier VTO-funded advanced combustion patents. General Electric and Cummins are again at the head of Figure 21, with automakers and suppliers Daimler, Hyundai and Delphi also present in both figures. There are some differences, notably the presence of Thermo Fisher Scientific among the companies with the strongest links to Other DOE-funded advanced combustion patents. The Thermo Fisher patent families describe analyte and compound detection and measurement, and are linked to earlier Sandia patents (e.g. US #5,789,745) describing monitoring exhaust gases, hazardous waste and other chemicals.

Figure 21 - Organizations with Largest Number of Patent Families Linked via Citations to Other DOE-funded Advanced Combustion Patents (excluding leading advanced combustion companies)



Patent Level Results

This section of the report drills down to identify individual DOE-funded (and particularly VTO-funded) advanced combustion patents whose influence on subsequent technological developments has been particularly strong. It also highlights patents that have extensive citation links to earlier VTO-funded advanced combustion research.

The simplest way of identifying high-impact VTO-funded advanced combustion patents is via overall Citation Indexes. The VTO-funded patents with the highest Citation Index values are shown in Table 9, with selected patents also presented in Figure 22. The patents in this table are a mix of older patents that have received large numbers of citations from subsequent generations of patents, and more recent patents that have attracted more citations than expected. One advantage of using Citation Indexes is that these two groups of patents can be compared directly, since each is benchmarked against peer patents of the same age and technology.

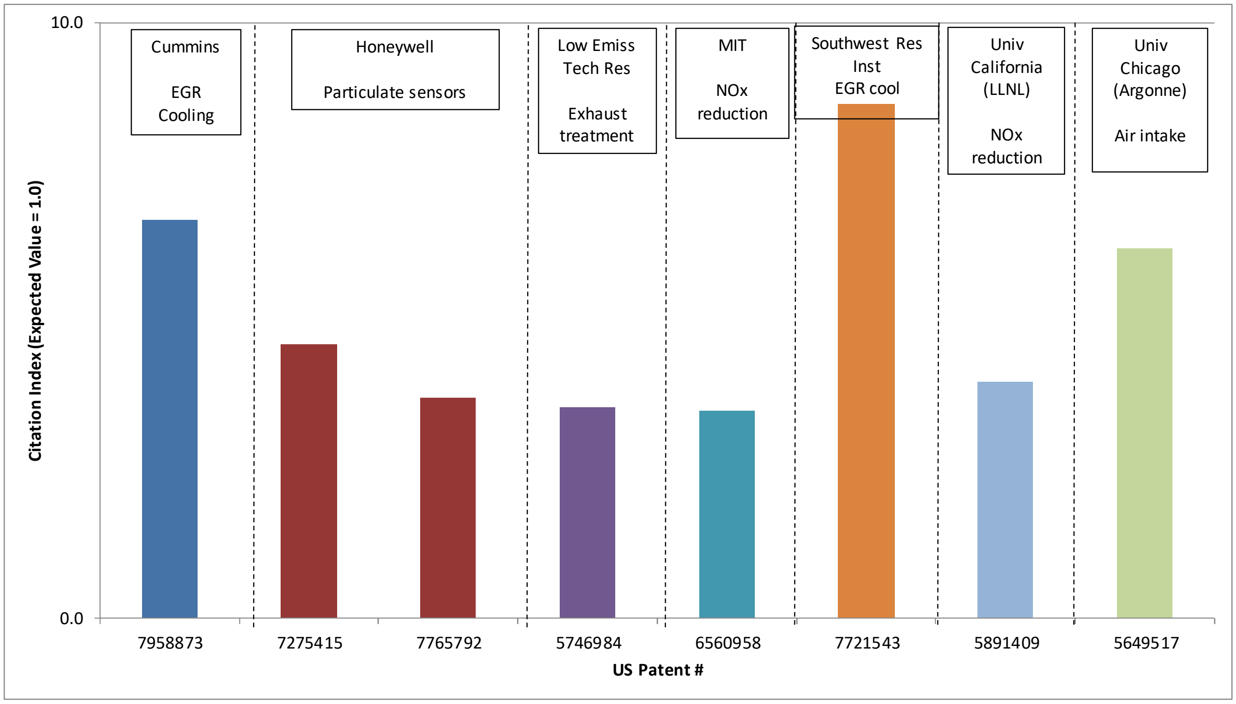
Table 9 – List of Highly Cited VTO-Funded Advanced Combustion Patents

Patent #	Issue Year	# Cites Received	Citation Index	Assignee	Title
7721543	2010	75	8.63	Southwest Res Inst	System and method for cooling a combustion gas charge
7958873	2011	31	6.69	Cummins Inc	Open loop Brayton cycle for EGR cooling
5649517	1997	97	6.20	Univ Chicago (ANL)	Variable oxygen/nitrogen enriched intake air system for internal combustion engine applications
7275415	2007	36	4.58	Honeywell	Particulate-based flow sensor
5891409	1999	60	3.97	Univ California (LLNL)	Pre-converted nitric oxide gas in catalytic reduction system
6038854	2000	83	3.71	Univ California (LLNL)	Plasma regenerated particulate trap and NOx reduction system
7765792	2010	30	3.69	Honeywell	System for particulate matter sensor signal processing
5746984	1998	106	3.53	Low Emissions Tech Res	Exhaust system with emissions storage device and plasma reactor
6560958	2003	58	3.48	MIT	Emission abatement system
6769635	2004	43	3.33	Caterpillar	Mixed mode fuel injector with individually moveable needle valve members
5636619	1997	46	2.94	Univ Chicago (ANL)	Method and apparatus for reducing cold-phase emissions by utilizing oxygen-enriched intake air
7869930	2011	21	2.90	Ford	Approach for reducing overheating of direct injection fuel injectors
7174714	2007	29	2.72	Caterpillar	Electric turbocompound control system
6701707	2004	38	2.62	Ford	Exhaust emission diagnostics
5711147	1998	72	2.32	Univ California (LLNL)	Plasma-assisted catalytic reduction system
6981375	2006	29	2.25	Detroit Diesel	Turbocharged internal combustion engine with EGR flow

The patent at the head of Table 9 (US #7,721,543) was issued in 2010, and assigned to Southwest Research Institute. It describes a method for cooling gas, especially exhaust gas in an EGR system, and has been cited by 75 subsequent patents, more than eight times as many citations as expected. Table 9 also contains other highly-cited VTO-funded patents that are concerned with EGR, including patents assigned to Cummins and Detroit Diesel.

Table 9 contains a number of highly-cited patents assigned to the University of California, through its management of LLNL. These patents (e.g. US #6,038,854) focus on NOx reduction methods, especially for lean-burn and diesel engines. There are also patents (e.g. US #5,649,517) assigned to the University of Chicago (ANL) describing air intake systems for combustion engines, using oxygen enrichment to reduce emissions. In terms of raw citation counts, the most highly-cited patent in Table 9 (US #5,746,984) is assigned to USCAR’s Low Emissions Technologies Research and Development Partnership. This 1998 patent, which has been cited by over 100 subsequent patents, describes a method for storing harmful emissions, and then destroying these emissions using a plasma reactor.

Figure 22 – Examples of Highly-Cited VTO-funded Advanced Combustion Patents



The Citation Indexes in Table 9 are based on a single generation of citations to VTO-funded advanced combustion patents. Tables 10 and 11 extend this by examining a second generation of citations – i.e. they show the VTO-funded advanced combustion patents linked directly or indirectly to the largest number of subsequent patent families.[12] These subsequent families are divided into two groups, according to whether they are within or beyond advanced combustion technology. This provides insights into which VTO-funded patent families have been particularly influential within advanced combustion technology, and which have had a broader impact beyond advanced combustion.

Table 10 contains older VTO-funded advanced combustion patent families (i.e. with priority dates prior to 2000) linked to the largest number of subsequent patent families. The patent family at the head of this figure (representative patent US #5,711,147) is assigned to the University of California through its management of LLNL. This patent family, which was highlighted earlier in the backward tracing element of the analysis, describes a system for reducing NOx emissions. It is linked to 1,145 subsequent patent families, more than half of which are within advanced combustion technology. It is one of a number of patent families in Table 10 assigned to the University of California through its management of LLNL.

The University of Chicago also has a number of patent families in Table 10, through its association with Argonne National Lab. These patent families describe air intake systems, and include the highly-cited patents highlighted earlier in the discussion of Table 9. Also appearing again is the plasma-enhanced emissions treatment patent family assigned to USCAR's Low

[12] The VTO-funded patent families are divided into two tables based on their age, since older patents tend to be connected to larger numbers of subsequent patents, simply because there has been more time for them to become linked to future generations of technology.

Emissions Technologies Research and Development Partnership. Table 10 also includes an MIT patent family for NOx reduction (representative patent US #6,560,958) and a Detroit Diesel patent family describing a turbocharged engine (representative patent #6,116,026).

Table 10 - Pre-2000 VTO-funded Advanced Combustion Patent Families Linked via Citations to Largest Number of Subsequent Advanced Combustion/Other Patent Families

Family #	Priority Year	Rep. Patent #	# Linked Families	# Linked Comb Fams	Assignee	Title
24809071	1996	5711147	1145	673	Univ California (LLNL)	Plasma-assisted catalytic reduction system
24702304	1996	5746984	776	315	Low Emissions Tech Res	Exhaust system with emissions storage device and plasma reactor
27106405	1996	5891409	767	414	Univ California (LLNL)	Pre-converted nitric oxide gas in catalytic reduction system
23495413	1998	6560958	748	473	MIT	Emission abatement system
23224258	1989	4924828	681	520	Univ California	Method and system for controlled combustion engines
46251117	1993	5649517	472	192	Univ Chicago (ANL)	Variable oxygen/nitrogen enriched intake air system for internal combustion engine applications
22802680	1998	6116026	436	347	Detroit Diesel	Engine air intake manifold having built-in intercooler
22543513	1998	6173567	345	183	Univ Chicago (ANL)	Method to reduce diesel engine exhaust emissions
26691853	1993	5636619	317	138	Univ Chicago (ANL)	Method and apparatus for reducing cold-phase emissions by utilizing oxygen-enriched intake air
22288814	1998	6055808	303	161	Univ Chicago (ANL)	Method and apparatus for reducing particulates and NOx emissions from diesel engines utilizing oxygen enriched combustion air
46256513	1999	6202407	294	177	Univ California (LLNL)	NOx reduction system utilizing pulsed hydrocarbon injection

Table 11 contains newer VTO-funded patent families, with priority dates from 2000 onwards. That said, most of these families are still relatively old, dating from the very start of this century. The patent family at the head of Table 11 (representative patent US #6,637,205) is assigned to Honeywell, and describes a method for controlling intake and exhaust from an internal combustion engine. It is linked to 243 subsequent patent families, 175 of which are related to combustion technology. This is one of two Honeywell patents in Table 11, with the other (representative patent US #6,971,258) describing a sensor for detecting particles, for example in exhaust gas.

Caterpillar has a number of patent families in Table 11, describing a variety of combustion-related technologies. These include catalysts for NOx reduction (representative patents US #6,706,660 and US #6,703,343) and mixed-mode fuel injectors (representative patent US #6,769,635). Other highly-linked VTO-funded patent families include a University of California

(LLNL) family describing HCCI engine control (representative patent US #6,923,167) and a Detroit Diesel family for a turbocharged engine (representative patent US #6,981,375).

Table 11 - Post-1999 VTO-funded Advanced Combustion Patent Families Linked via Citations to Largest Number of Subsequent Advanced Combustion/Other Patent Families

Family #	Priority Year	Rep. Patent #	# Linked Families	# Linked Comb Fams	Assignee	Title
29250210	2002	6637205	243	175	Honeywell	Electric assist and variable geometry turbocharger
34632722	2003	6923167	188	155	Univ California (LLNL)	Controlling and operating homogeneous charge compression ignition (HCCI) engines
33300281	2003	6981375	181	163	Detroit Diesel	Turbocharged internal combustion engine with EGR flow
21820545	2001	6706660	166	36	Caterpillar	Metal/metal oxide doped oxide catalysts having high deNOx selectivity for lean NOx exhaust aftertreatment systems
34711078	2003	6971258	161	74	Honeywell	Particulate matter sensor
31886175	2002	6701707	159	141	Ford	Exhaust emission diagnostics
31998166	2002	6769635	149	131	Caterpillar	Mixed mode fuel injector with individually moveable needle valve members
21809880	2001	6703343	135	37	Caterpillar	Method of preparing doped oxide catalysts for lean NOx exhaust
41342695	2008	7869930	123	101	Ford	Approach for reducing overheating of direct injection fuel injectors
34274902	2004	6866030	119	54	Detroit Diesel	Model based exhaust gas recirculation control algorithm
22494863	2002	6516787	111	91	Caterpillar	Use of exhaust gas as sweep flow to enhance air separation membrane performance

One notable feature of both Table 10 and Table 11 is the high percentage of patent families linked via citations to VTO-funded advanced combustion patents that are themselves related to combustion. For most of the patent families in these tables, more than half of the later families linked to them are from within combustion. As in the earlier discussion of patent classifications (see Figures 18 and 19), this suggests that combustion is a relatively self-contained technology, and much of the influence of DOE-funded combustion research can be seen within the bounds of this technology.

The tables above identify VTO-funded patent families linked particularly strongly to subsequent technological developments. Table 12 looks in the opposite direction, and identifies highly-cited patents linked to earlier VTO-funded advanced combustion patents. As such, these are examples where VTO-funded advanced combustion research has formed part of the foundation for subsequent high-impact technologies. This table focuses on patent families not owned by the leading advanced combustion companies, since those families were examined in the backward tracing element of the analysis.

Table 12 - Highly Cited Patents (not from leading advanced combustion companies) Linked via Citations to Earlier VTO-funded Advanced Combustion Patents

Patent #	Issue Year	# Cites Received	Citation Index	Assignee	Title
7709414	2010	79	14.99	Nanostellar Inc	Engine exhaust catalysts containing palladium-gold
8291891	2012	57	12.04	Southwest Res Inst	EGR system with dedicated EGR cylinders
6561157	2003	115	10.61	Cummins Inc	Multiple operating mode engine and method of operation
6276334	2001	153	9.85	Cummins Inc	Premixed charge compression ignition engine with optimal combustion control
7721543	2010	75	8.63	Southwest Res Inst	System and method for cooling a combustion gas charge
6874453	2005	64	8.62	RWE Ag	Two stroke internal combustion engine
6742507	2004	80	8.37	Xebec Adsorption	Feed composition modification for internal combustion engines
6994073	2006	62	8.35	Woodward Inc	Method and apparatus for detecting ionization signal in diesel and dual mode engines with plasma discharge system
7610752	2009	73	7.79	Eaton Corp	Devices and methods for reduction of NOx emissions from lean burn engines
7275374	2007	86	7.57	Honeywell	Coordinated multivariable control of fuel and air in engines

The patent at the head of Table 12 is assigned to Nanostellar Inc., which developed nano-engineered catalyst materials for reducing exhaust emissions, especially in diesel engines. This patent (US #7,709,414) has been cited as prior art by 79 subsequent patents, almost fifteen times as many citations as expected given its age and technology. Beyond this Nanostellar patent, the next four patents are assigned to Southwest Research Institute (for EGR systems and coolers) and Cummins (for engine control and optimization). Table 12 also includes patents from a range of other companies, including energy companies such as RWE and Xerbec Adsorption, plus industrial companies such as Woodward and Eaton. The highly-cited patents of these various companies in Table 12 are linked to earlier VTO-funded combustion research, showing the influence of this research on subsequent technological developments across a range of companies.

As with the backward tracing element of the analysis, the patent-level results from the forward tracing focus on VTO-funded advanced combustion patents. However, within the forward tracing, we did also identify Other DOE-funded advanced combustion patent families linked to the largest number of subsequent patent families within and beyond advanced combustion technology. These Other DOE-funded advanced combustion families are shown in Table 13.

The patent family at the head of Table 13 (representative patent US #6,035,640) is assigned to Ford and describes describing a turbocharged engine with exhaust gas recirculation. It is linked to 695 subsequent patent families, 529 of which are related to combustion (with many of these combustion families associated with the leading combustion companies, as noted earlier in the backward tracing element of the analysis). Table 13 also includes a number of patent families assigned to the University of California describing fuel injectors and NOx reduction in exhausts; plus Southwest Research Institute patent families for engine control and emissions reduction.

Table 13 - Other DOE-funded Advanced Combustion Patent Families Linked via Citations to Largest Number of Subsequent Advanced Combustion/Other Patent Families

Family #	Priority Year	Rep. Patent #	# Linked Families	# Linked Comb Fams	Assignee	Title
22893288	1999	6035640	695	529	Ford	Control method for turbocharged diesel engines having exhaust gas recirculation
25502261	1997	5789745	603	2	Sandia Corp	Ion mobility spectrometer using frequency-domain separation
25007921	1996	5715677	558	279	Univ California (LLNL)	Diesel NOx reduction by plasma-regenerated absorbent beds
24207238	1983	4543930	449	398	Southwest Res Inst	Staged direct injection diesel engine
21791452	1993	5526641	414	162	Univ Chicago (ANL)	NOx reduction method
30114483	2002	6742335	349	274	Clean Air Power Inc	EGR control system and method for an internal combustion engine
24954384	1996	5735245	281	193	Southwest Res Inst	Method and apparatus for controlling fuel/air mixture in a lean burn engine
23684161	1982	4493297	274	100	Geo-Centers Inc	Plasma jet ignition device
23279357	2001	6742328	255	190	Southwest Res Inst	Systems and methods for controlling diesel engine emissions
46204872	2002	6880344	244	71	UTC Power LLC	Combined rankine and vapor compression cycles
25338129	1997	5769621	225	22	Univ California (LANL)	Laser ablation based fuel ignition
22303010	1998	6199519	188	45	Sandia Corp	Free-piston engine
22843172	2000	6612269	170	95	Univ California (UC Riverside)	Apparatus and method for operating internal combustion engines from variable mixtures of gaseous fuels

Similar to the VTO-funded patent families listed in Tables 10 and 11, one feature of many of the Other DOE-funded families in Table 13 is that the later families linked to them via citations are largely combustion-related. That said, there are exceptions to this in Table 13. Notably, the Sandia patent family listed second (representative patent US #5,789,745) is linked to 603 subsequent families, only two of which are within combustion. This Sandia family, highlighted earlier in the report, describes chemical detection and analysis (e.g. in exhaust emissions). Many of the subsequent patent families linked to it describe chemical detection and measurement, rather than combustion.

Overall, the forward tracing element of the analysis shows that VTO-funded and Other DOE-funded advanced combustion research has had a strong influence on subsequent technologies. This influence can be seen most strongly within advanced combustion technology, with combustion patents from a range of companies linked to earlier DOE-funded patents.

5.0 Conclusions

This report describes the results of an analysis tracing links between advanced combustion research funded by DOE (VTO plus Other DOE) and subsequent developments both within and beyond advanced combustion technology. This tracing is carried out both backwards and forwards in time. The purpose of the backward tracing is to determine the extent to which VTO-funded (and Other DOE-funded) research forms a foundation for the technologies developed by leading advanced combustion companies. The purpose of the forward tracing is to examine the influence of VTO-funded (and Other DOE-funded) advanced combustion patents upon subsequent developments, both within and outside advanced combustion technology.

The backward tracing element of the analysis shows that VTO-funded and Other DOE-funded advanced combustion patents have had a strong influence on subsequent innovations associated with the leading advanced combustion companies. This influence can be seen both over time, and across these leading companies. Meanwhile, the forward tracing shows that, although DOE-funded patents were a small percentage of all advanced combustion patents over the time period 1976 to 2018, they have had a strong influence on subsequent technologies. This influence can be seen both within advanced combustion technology, and in other technologies such as gas turbines, chemical detection and fluid dynamics.

Overall, the analysis presented in this report reveals that advanced combustion research funded by VTO, and by DOE in general, has had a significant influence on subsequent developments, both within and beyond advanced combustion technology. This influence can be seen on innovations associated with the leading advanced combustion companies, plus innovations associated with large companies across a range of other technologies.

Appendix A. VTO-funded Advanced Combustion Patents used in the Analysis

Patent #	Application Year	Issue / Publication Year	Original Assignees	Title
4924828	1989	1990	UNIVERSITY OF CALIFORNIA	METHOD AND SYSTEM FOR CONTROLLED COMBUSTION ENGINES
4926818	1989	1990	UNIVERSITY OF CALIFORNIA	PULSED JET COMBUSTION GENERATOR FOR PREMIXED CHARGE ENGINES
4974571	1989	1990	UNIVERSITY OF CALIFORNIA	PULSED JET COMBUSTION GENERATOR FOR NON-PREMIXED CHARGE ENGINES
WO1990010143	1990	1990	UNIVERSITY OF CALIFORNIA	METHOD AND SYSTEM FOR CONTROLLED COMBUSTION ENGINES
WO1990010152	1990	1990	UNIVERSITY OF CALIFORNIA	PULSED JET COMBUSTION GENERATOR FOR PREMIXED CHARGE ENGINES
WO1990010153	1990	1990	UNIVERSITY OF CALIFORNIA	PULSED JET COMBUSTION GENERATOR FOR NON-PREMIXED CHARGE ENGINES
EP0460059	1990	1991	UNIVERSITY OF CALIFORNIA	METHOD AND SYSTEM FOR CONTROLLED COMBUSTION ENGINES.
EP0460061	1990	1991	UNIVERSITY OF CALIFORNIA	PULSED JET COMBUSTION GENERATOR FOR NON-PREMIXED CHARGE ENGINES.
EP0460077	1990	1991	UNIVERSITY OF CALIFORNIA	PULSED JET COMBUSTION GENERATOR FOR PREMIXED CHARGE ENGINES.
5271365	1992	1993	US DEPT OF ENERGY	JET PLUME INJECTION AND COMBUSTION SYSTEM FOR INTERNAL COMBUSTION ENGINES
5474036	1994	1995	HANSEN ENGINE CORP	INTERNAL COMBUSTION ENGINE WITH ROTARY VALVE ASSEMBLY HAVING VARIABLE INTAKE VALVE TIMING
WO1995023279	1995	1995	HANSEN ENGINE CORP	INTERNAL COMBUSTION ENGINE ROTARY VALVE ASSEMBLY HAVING VARIABLE INTAKE VALVE TIMING
EP0745179	1995	1996	HANSEN ENGINE CORP	INTERNAL COMBUSTION ENGINE ROTARY VALVE ASSEMBLY HAVING VARIABLE INTAKE VALVE TIMING
5636619	1996	1997	UNIVERSITY OF CHICAGO	METHOD AND APPARATUS FOR REDUCING COLD-PHASE EMISSIONS BY UTILIZING OXYGEN-ENRICHED INTAKE AIR
5640845	1995	1997	UNIVERSITY OF CHICAGO	NITROGEN SPARK DENOXER
5649517	1996	1997	UNIVERSITY OF CHICAGO	VARIABLE OXYGEN/NITROGEN ENRICHED INTAKE AIR SYSTEM FOR INTERNAL COMBUSTION

				ENGINE APPLICATIONS
5711147	1996	1998	UNIVERSITY OF CALIFORNIA	PLASMA-ASSISTED CATALYTIC REDUCTION SYSTEM
5746783	1995	1998	MARTIN MARIETTA ENERGY SYSTEMS INC	LOW EMISSIONS DIESEL FUEL
5746984	1996	1998	LOW EMISSIONS TECH R&D PARTNERSHIP	EXHAUST SYSTEM WITH EMISSIONS STORAGE DEVICE AND PLASMA REACTOR
WO1998000221	1997	1998	LOW EMISSIONS TECH R&D PARTNERSHIP	EXHAUST SYSTEM WITH EMISSIONS STORAGE DEVICE AND PLASMA REACTOR
WO1998009699	1997	1998	UNIVERSITY OF CALIFORNIA	PLASMA-ASSISTED CATALYTIC REDUCTION SYSTEM
5858030	1997	1999	AIR PRODUCTS & CHEMICALS INC	DIESEL FUEL COMPOSITION COMPRISING DIALKOXY ALKANES FOR INCREASED CETANE NUMBER
5891409	1997	1999	UNIVERSITY OF CALIFORNIA	PRE-CONVERTED NITRIC OXIDE GAS IN CATALYTIC REDUCTION SYSTEM
5893267	1997	1999	UNIVERSITY OF CALIFORNIA	CATALYTIC REDUCTION SYSTEM FOR OXYGEN-RICH EXHAUST
5921221	1998	1999	FORD GLOBAL TECHNOLOGIES LLC	METHOD OF CONTROLLING CYCLIC VARIATION IN ENGINE COMBUSTION
EP0903395	1998	1999	AIR PRODUCTS & CHEMICALS INC	DIESEL FUEL COMPOSITION COMPRISING DIALKOXY ALKANES FOR INCREASED CETANE NUMBER
EP0946256	1997	1999	UNIVERSITY OF CALIFORNIA	PLASMA-ASSISTED CATALYTIC REDUCTION SYSTEM
WO1999067508	1999	1999	UNIVERSITY OF CHICAGO	METHOD AND APPARATUS FOR REDUCING PARTICULATES AND NOX EMISSIONS FROM DIESEL ENGINES UTILIZING OXYGEN ENRICHED COMBUSTION AIR
6038853	1998	2000	UNIVERSITY OF CALIFORNIA	PLASMA-ASSISTED CATALYTIC STORAGE REDUCTION SYSTEM
6038854	1998	2000	UNIVERSITY OF CALIFORNIA	PLASMA REGENERATED PARTICULATE TRAP AND NO.SUB.X REDUCTION SYSTEM
6055808	1998	2000	UNIVERSITY OF CHICAGO	METHOD AND APPARATUS FOR REDUCING PARTICULATES AND NO.SUB.X EMISSIONS FROM DIESEL ENGINES UTILIZING OXYGEN ENRICHED COMBUSTION AIR
6062178	1998	2000	SOUTHWEST RESEARCH INSTITUTE	METHOD OF OPERATING UNI-FLOW TWO-CYCLE ENGINE DURING REDUCED LOAD CONDITIONS
6103080	1998	2000	UNIVERSITY OF CALIFORNIA	HYDROCARBON SENSORS AND MATERIALS THEREFOR
6116026	1998	2000	DETROIT DIESEL	ENGINE AIR INTAKE MANIFOLD

			CORP	HAVING BUILT-IN INTERCOOLER
6119451	1999	2000	UNIVERSITY OF CALIFORNIA	NITROGEN OXIDE REMOVAL USING DIESEL FUEL AND A CATALYST
6156162	1998	2000	LOW EMISSIONS TECH R&D PARTNERSHIP	POWER SUPPLY FOR DIELECTRIC BARRIER DISCHARGE PLASMA
EP1010889	1999	2000	DETROIT DIESEL CORP	ENGINE AIR INTAKE MANIFOLD HAVING BUILT-IN INTERCOOLER
WO2000015951	1999	2000	UNIVERSITY OF CHICAGO	METHOD TO REDUCE DIESEL ENGINE EXHAUST EMISSIONS
6173567	1998	2001	UNIVERSITY OF CHICAGO	METHOD TO REDUCE DIESEL ENGINE EXHAUST EMISSIONS
6190507	1999	2001	US DEPT OF ENERGY	METHOD FOR GENERATING A HIGHLY REACTIVE PLASMA FOR EXHAUST GAS AFTERTREATMENT AND ENHANCED CATALYST REACTIVITY
6202407	1999	2001	UNIVERSITY OF CALIFORNIA	NOX REDUCTION SYSTEM UTILIZING PULSED HYDROCARBON INJECTION
6311668	2000	2001	CATERPILLAR INC	MONOVALVE WITH INTEGRATED FUEL INJECTOR AND PORT CONTROL VALVE, AND ENGINE USING SAME
6330875	1999	2001	CATERPILLAR INC	ENGINE WITH HYDRAULIC FUEL INJECTION AND ABS CIRCUIT USING A SINGLE HIGH PRESSURE PUMP
WO2001014698	2000	2001	MASSACHUSETTS INSTITUTE OF TECHNOLOGY	EMISSION ABATEMENT SYSTEM
WO2001057368	2001	2001	CUMMINS INC	VALVE TRAIN WITH A SINGLE CAMSHAFT
6354270	2000	2002	CATERPILLAR INC	HYDRAULICALLY ACTUATED FUEL INJECTOR INCLUDING A PILOT OPERATED SPOOL VALVE ASSEMBLY AND HYDRAULIC SYSTEM USING SAME
6363913	2000	2002	CATERPILLAR INC	SOLID STATE LIFT FOR MICROMETERING IN A FUEL INJECTOR
6374595	2000	2002	UNIVERSITY OF CALIFORNIA	PLASMA-ASSISTED CATALYTIC STORAGE REDUCTION SYSTEM
6378497	1999	2002	CATERPILLAR INC	ACTUATION FLUID ADAPTER FOR HYDRAULICALLY-ACTUATED ELECTRONICALLY-CONTROLLED FUEL INJECTOR AND ENGINE USING SAME
6390046	2000	2002	CUMMINS INC	VALVE TRAIN WITH A SINGLE CAMSHAFT
6422002	2000	2002	US DEPT OF ENERGY	METHOD FOR GENERATING A HIGHLY REACTIVE PLASMA FOR EXHAUST GAS AFTERTREATMENT AND ENHANCED CATALYST REACTIVITY

6422198	2000	2002	DELPHI TECHNOLOGIES INC	PRESSURE ATOMIZER HAVING MULTIPLE ORIFICES AND TURBULENT GENERATION FEATURE
6443121	2000	2002	CATERPILLAR INC	HYDRAULICALLY ACTUATED GAS EXCHANGE VALVE ASSEMBLY AND ENGINE USING SAME
6474295	2001	2002	CATERPILLAR INC	MONOVALVE WITH INTEGRATED FUEL INJECTOR AND PORT CONTROL VALVE, AND ENGINE USING SAME
EP1212520	2000	2002	MASSACHUSETTS INSTITUTE OF TECHNOLOGY	EMISSION ABATEMENT SYSTEM
WO2002088535	2002	2002	WISCONSIN ALUMNI RESEARCH FOUNDATION	DIESEL ENGINE EMISSIONS REDUCTION BY MULTIPLE INJECTIONS HAVING INCREASING PRESSURE
6516787	2002	2003	CATERPILLAR INC	USE OF EXHAUST GAS AS SWEEP FLOW TO ENHANCE AIR SEPARATION MEMBRANE PERFORMANCE
6523529	2001	2003	CATERPILLAR INC	INTEGRATION OF AIR SEPARATION MEMBRANE AND COALESCING FILTER FOR USE ON AN INLET AIR SYSTEM OF AN ENGINE
6526939	2001	2003	WISCONSIN ALUMNI RESEARCH FOUNDATION	DIESEL ENGINE EMISSIONS REDUCTION BY MULTIPLE INJECTIONS HAVING INCREASING PRESSURE
6560958	1999	2003	MASSACHUSETTS INSTITUTE OF TECHNOLOGY	EMISSION ABATEMENT SYSTEM
6564772	2001	2003	CATERPILLAR INC	INJECTOR TIP FOR AN INTERNAL COMBUSTION ENGINE
6601549	2001	2003	CATERPILLAR INC	TWO STROKE HOMOGENOUS CHARGE COMPRESSION IGNITION ENGINE WITH PULSED AIR SUPPLIER
6637205	2002	2003	HONEYWELL INTERNATIONAL INC	ELECTRIC ASSIST AND VARIABLE GEOMETRY TURBOCHARGER
6659056	2002	2003	CUMMINS INC	VALVE TRAIN WITH A SINGLE CAMSHAFT
6666201	2002	2003	FORD GLOBAL TECHNOLOGIES LLC	SYSTEM AND METHOD FOR DIAGNOSING EGR PERFORMANCE USING NOX SENSOR
6668788	2001	2003	CATERPILLAR INC	HOMOGENOUS CHARGE COMPRESSION IGNITION ENGINE HAVING A CYLINDER INCLUDING A HIGH COMPRESSION SPACE
6668789	2001	2003	WISCONSIN ALUMNI RESEARCH FOUNDATION	INTERNAL COMBUSTION ENGINE USING PREMIXED COMBUSTION OF STRATIFIED CHARGES

WO2003027005	2002	2003	MASSACHUSETTS INSTITUTE OF TECHNOLOGY	PLASMATRON-CATALYST SYSTEM
6685897	2000	2004	UNIVERSITY OF CALIFORNIA	HIGHLY-BASIC LARGE-PORE ZEOLITE CATALYSTS FOR NOX REDUCTION AT LOW TEMPERATURES
6700662	2001	2004	UNIVERSITY OF CHICAGO	PORTABLE LII BASED INSTRUMENT AND METHOD FOR PARTICULATE CHARACTERIZATION IN COMBUSTION EXHAUST
6701707	2002	2004	FORD GLOBAL TECHNOLOGIES LLC	EXHAUST EMISSION DIAGNOSTICS
6703343	2001	2004	CATERPILLAR INC	METHOD OF PREPARING DOPED OXIDE CATALYSTS FOR LEAN NOX EXHAUST
6706660	2001	2004	CATERPILLAR INC	METAL/METAL OXIDE DOPED OXIDE CATALYSTS HAVING HIGH DENOX SELECTIVITY FOR LEAN NOX EXHAUST AFTERTREATMENT SYSTEMS
6708655	2002	2004	CATERPILLAR INC	VARIABLE COMPRESSION RATIO DEVICE FOR INTERNAL COMBUSTION ENGINE
6718753	2002	2004	MASSACHUSETTS INSTITUTE OF TECHNOLOGY	EMISSION ABATEMENT SYSTEM UTILIZING PARTICULATE TRAPS
6736106	2002	2004	WISCONSIN ALUMNI RESEARCH FOUNDATION	ENGINE VALVE ACTUATION FOR COMBUSTION ENHANCEMENT
6752104	2001	2004	CATERPILLAR INC	SIMULTANEOUS DUAL MODE COMBUSTION ENGINE OPERATING ON SPARK IGNITION AND HOMOGENOUS CHARGE COMPRESSION IGNITION
6758870	2002	2004	AIR PRODUCTS & CHEMICALS INC	METHOD OF PRODUCING A DIESEL FUEL BLEND HAVING A PRE-DETERMINED FLASH-POINT AND PRE-DETERMINED INCREASE IN CETANE NUMBER
6769392	2001	2004	CATERPILLAR INC	VARIABLE VALVE TIMING IN A HOMOGENOUS CHARGE COMPRESSION IGNITION ENGINE
6769635	2003	2004	CATERPILLAR INC	MIXED MODE FUEL INJECTOR WITH INDIVIDUALLY MOVEABLE NEEDLE VALVE MEMBERS
6793899	2001	2004	MASSACHUSETTS INSTITUTE OF TECHNOLOGY	PLASMATRON-CATALYST SYSTEM
6802285	2002	2004	CATERPILLAR INC	ENGINE HAVING A VARIABLE VALVE ACTUATION SYSTEM
6820600	2003	2004	DETROIT DEISEL CORP	METHOD FOR CONTROLLING AN ENGINE WITH AN EGR SYSTEM

6824661	2001	2004	CERAMPHYSICS INC	COMBINED OXYGEN AND NOX SENSOR
EP1381767	2002	2004	WISCONSIN ALUMNI RESEARCH FOUNDATION	DIESEL ENGINE EMISSIONS REDUCTION BY MULTIPLE INJECTIONS HAVING INCREASING PRESSURE
WO2004011791	2003	2004	HONEYWELL INTERNATIONAL INC	ELECTRICALLY ASSISTED AND VARIABLE GEOMETRY TURBOCHARGER
WO2004093294	2003	2004	HONEYWELL INTERNATIONAL INC	ELECTRIC MOTOR CARTRIDGE FOR AN ELECTRICALLY ASSISTED TURBOCHARGER
WO2004109095	2004	2004	CATERPILLAR INC	FUEL INJECTOR NOZZLE FOR AN INTERNAL COMBUSTION ENGINE
6843231	2003	2005	CATERPILLAR INC	CYLINDER TO CYLINDER BALANCING USING INTAKE VALVE ACTUATION
6843239	2001	2005	CATERPILLAR INC	HIGH SPEED EXHAUST GAS RECIRCULATION VALVE
6843434	2003	2005	CATERPILLAR INC	DUAL MODE FUEL INJECTOR WITH ONE PIECE NEEDLE VALVE MEMBER
6866030	2004	2005	DETROIT DIESEL CORP	MODEL BASED EXHAUST GAS RECIRCULATION CONTROL ALGORITHM
6923167	2003	2005	UNIVERSITY OF CALIFORNIA	CONTROLLING AND OPERATING HOMOGENEOUS CHARGE COMPRESSION IGNITION (HCCI) ENGINES
6945475	2002	2005	CATERPILLAR INC	DUAL MODE FUEL INJECTION SYSTEM AND FUEL INJECTOR FOR SAME
6948482	2003	2005	CATERPILLAR INC	ENGINE CYLINDER TEMPERATURE CONTROL
6971258	2003	2005	HONEYWELL INTERNATIONAL INC	PARTICULATE MATTER SENSOR
6971378	2002	2005	CUMMINS INC	CYLINDER HEAD HAVING AN INTERNAL EXHAUST GAS RECIRCULATION PASSAGE
6973921	2003	2005	CATERPILLAR INC	FUEL PUMPING SYSTEM AND METHOD
6978760	2003	2005	CATERPILLAR INC	MIXED MODE FUEL INJECTOR AND INJECTION SYSTEM
EP1540159	2003	2005	HONEYWELL INTERNATIONAL INC	ELECTRICALLY ASSISTED AND VARIABLE GEOMETRY TURBOCHARGER
EP1588040	2004	2005	WISCONSIN ALUMNI RESEARCH FOUNDATION	ENGINE VALVE ACTUATION FOR COMBUSTION ENHANCEMENT
WO2005066611	2004	2005	HONEYWELL INTERNATIONAL INC	PARTICULATE MATTER SENSOR
WO2005068809	2004	2005	WISCONSIN ALUMNI	ENGINE VALVE ACTUATION FOR COMBUSTION ENHANCEMENT

			RESEARCH FOUNDATION	
WO2005124113	2005	2005	CUMMINS INC	METHOD FOR MODIFYING TRIGGER LEVEL FOR ADSORBER REGENERATION
6981370	2002	2006	CATERPILLAR INC	METHOD AND APPARATUS FOR PM FILTER REGENERATION
6981375	2003	2006	DETROIT DIESEL CORP	TURBOCHARGED INTERNAL COMBUSTION ENGINE WITH EGR FLOW
7018442	2003	2006	CATERPILLAR INC	METHOD AND APPARATUS FOR REGENERATING NOX ADSORBERS
7032566	2003	2006	CATERPILLAR INC	FUEL INJECTOR NOZZLE FOR AN INTERNAL COMBUSTION ENGINE
7051956	2004	2006	SANDIA CORP	EJECTOR DEVICE FOR DIRECT INJECTION FUEL JET
7055469	2003	2006	CATERPILLAR INC	COMBUSTION ENGINE VARIABLE COMPRESSION RATIO APPARATUS AND METHOD
7069918	2004	2006	CUMMINS INC	CYLINDER HEAD HAVING AN INTERNAL EXHAUST GAS RECIRCULATION PASSAGE
7076945	2004	2006	DETROIT DIESEL CORP	METHOD AND SYSTEM FOR CONTROLLING TEMPERATURES OF EXHAUST GASES EMITTED FROM AN INTERNAL COMBUSTION ENGINE TO FACILITATE REGENERATION OF A PARTICULATE FILTER
7080511	2005	2006	DETROIT DIESEL CORP	METHOD FOR CONTROLLING ENGINE AIR/FUEL RATIO
7094722	2002	2006	CATERPILLAR INC	NOX CATALYST AND METHOD OF SUPPRESSING SULFATE FORMATION IN AN EXHAUST PURIFICATION SYSTEM
7128046	2005	2006	SANDIA CORP	FUEL MIXTURE STRATIFICATION AS A METHOD FOR IMPROVING HOMOGENEOUS CHARGE COMPRESSION IGNITION ENGINE OPERATION
7134273	2002	2006	FORD GLOBAL TECHNOLOGIES LLC	EXHAUST EMISSION CONTROL AND DIAGNOSTICS
7134615	2002	2006	CATERPILLAR INC	NOZZLE INSERT FOR MIXED MODE FUEL INJECTOR
7143580	2004	2006	DETROIT DIESEL CORP	VIRTUAL COMPRESSOR OUTLET TEMPERATURE SENSING FOR CHARGE AIR COOLER OVERHEATING PROTECTION
7150268	2005	2006	CATERPILLAR INC	FUEL PUMPING SYSTEM AND METHOD
7153810	2004	2006	CATERPILLAR INC	SILVER DOPED CATALYSTS FOR TREATMENT OF EXHAUST
EP1614207	2003	2006	HONEYWELL INTERNATIONAL INC	ELECTRIC MOTOR CARTRIDGE FOR AN ELECTRICALLY ASSISTED TURBOCHARGER

EP1706722	2004	2006	HONEYWELL INTERNATIONAL INC	PARTICULATE MATTER SENSOR
WO2006052918	2005	2006	CUMMINS INC	MASS SPECTROMETRY SYSTEM AND METHOD
WO2006096220	2005	2006	CATERPILLAR INC	NOX ADSORBER AND METHOD OF REGENERATING THE SAME
7168243	2005	2007	CATERPILLAR INC	NOX ADSORBER AND METHOD OF REGENERATING SAME
7174714	2004	2007	CATERPILLAR INC	ELECTRIC TURBOCOMPOUND CONTROL SYSTEM
7182074	2005	2007	DETROIT DIESEL CORP	MANIFOLD ASSEMBLY FOR AN INTERNAL COMBUSTION ENGINE
7185614	2004	2007	CATERPILLAR INC	DOUBLE BOWL PISTON
7185642	2005	2007	DETROIT DIESEL CORP	MANIFOLD BODY FOR AN INTERNAL COMBUSTION ENGINE
7198024	2006	2007	CATERPILLAR INC	LOW EMISSIONS COMPRESSION IGNITED ENGINE TECHNOLOGY
7201137	2005	2007	CATERPILLAR INC	MIXED MODE CONTROL METHOD AND ENGINE USING SAME
7210286	2004	2007	DETROIT DIESEL CORP	METHOD AND SYSTEM FOR CONTROLLING FUEL INCLUDED WITHIN EXHAUST GASES TO FACILITATE REGENERATION OF A PARTICULATE FILTER
7211793	2004	2007	CUMMINS INC	MASS SPECTROMETRY SYSTEM AND METHOD
7212908	2005	2007	DETROIT DIESEL CORP	SYSTEM AND METHOD FOR REDUCING COMPRESSION IGNITION ENGINE EMISSIONS
7219649	2005	2007	CATERPILLAR INC	ENGINE SYSTEM AND METHOD OF OPERATING SAME OVER MULTIPLE ENGINE LOAD RANGES
7235221	2006	2007	CATERPILLAR INC	NO _X CATALYST AND METHOD OF SUPPRESSING SULFATE FORMATION IN AN EXHAUST PURIFICATION SYSTEM
7247383	2004	2007	US DEPT OF ENERGY	INTEGRATED SELF-CLEANING WINDOW ASSEMBLY FOR OPTICAL TRANSMISSION IN COMBUSTION ENVIRONMENTS
7257945	2003	2007	UT-BATTELLE LLC	STRIPPING ETHANOL FROM ETHANOL-BLENDED FUELS FOR USE IN NO _X SCR
7275415	2005	2007	HONEYWELL INTERNATIONAL INC	PARTICULATE-BASED FLOW SENSOR
7277790	2006	2007	UT-BATTELLE LLC	COMBUSTION DIAGNOSTIC FOR ACTIVE ENGINE FEEDBACK CONTROL
7279143	2004	2007	MASSACHUSETTS INSTITUTE OF TECHNOLOGY	PLASMATRON-CATALYST SYSTEM
7281518	2007	2007	DETROIT DIESEL CORP	METHOD AND SYSTEM OF DIESEL ENGINE SETPOINT

				COMPENSATION FOR TRANSIENT OPERATION OF A HEAVY DUTY DIESEL ENGINE
7287372	2005	2007	CATERPILLAR INC	EXHAUST AFTER-TREATMENT SYSTEM WITH IN-CYLINDER ADDITION OF UNBURNT HYDROCARBONS
7287506	2006	2007	CATERPILLAR INC	THERMOELECTRIC SYSTEM
7290520	2006	2007	CATERPILLAR INC	FUEL INJECTOR NOZZLE FOR AN INTERNAL COMBUSTION ENGINE
EP1753942	2005	2007	CUMMINS INC	METHOD FOR MODIFYING TRIGGER LEVEL FOR ADSORBER REGENERATION
EP1831913	2005	2007	CUMMINS INC	MASS SPECTROMETRY SYSTEM AND METHOD
WO2007008282	2006	2007	CATERPILLAR INC	MIXED MODE CONTROL METHOD AND ENGINE USING SAME
WO2007015995	2006	2007	HONEYWELL INTERNATIONAL INC	PARTICULATE-BASED FLOW SENSOR
WO2007021336	2006	2007	CATERPILLAR INC	ENGINE SYSTEM AND METHOD OF OPERATING SAME OVER MULTIPLE ENGINE LOAD RANGES
WO2007050384	2006	2007	HONEYWELL INTERNATIONAL INC	SYSTEM FOR PARTICULATE MATTER SENSOR SIGNAL PROCESSING
WO2007075594	2006	2007	HONEYWELL INTERNATIONAL INC	ONBOARD DIAGNOSTICS FOR ANOMALOUS CYLINDER BEHAVIOR
WO2007097944	2007	2007	CUMMINS INC	METHOD FOR CONTROLLING TURBINE OUTLET TEMPERATURES IN A DIESEL ENGINE
7320219	2006	2008	DETROIT DIESEL CORP	METHOD FOR CONTROLLING AN INTERNAL COMBUSTION ENGINE USING MODEL BASED VGT/EGR CONTROL
7322183	2006	2008	DETROIT DIESEL CORP	METHOD AND SYSTEM FOR CONTROLLING TEMPERATURES OF EXHAUST GASES EMITTED FROM AN INTERNAL COMBUSTION ENGINE TO FACILITATE REGENERATION OF A PARTICULATE FILTER
7337763	2004	2008	WISCONSIN ALUMNI RESEARCH FOUNDATION	ENGINE VALVE ACTUATION FOR COMBUSTION ENHANCEMENT
7370613	2004	2008	CATERPILLAR INC	ECCENTRIC CRANK VARIABLE COMPRESSION RATIO MECHANISM
7371353	2005	2008	CATERPILLAR INC	EXHAUST PURIFICATION WITH ON-BOARD AMMONIA PRODUCTION
7377254	2006	2008	CATERPILLAR	EXTENDING OPERATING RANGE

			INC	OF A HOMOGENEOUS CHARGE COMPRESSION IGNITION ENGINE VIA CYLINDER DEACTIVATION
7377270	2006	2008	CATERPILLAR INC	EXHAUST GAS RECIRCULATION IN A HOMOGENEOUS CHARGE COMPRESSION IGNITION ENGINE
7380540	2007	2008	CATERPILLAR INC	DYNAMIC CONTROL OF A HOMOGENEOUS CHARGE COMPRESSION IGNITION ENGINE
7418816	2005	2008	FORD GLOBAL TECHNOLOGIES LLC	EXHAUST GAS AFTERTREATMENT SYSTEMS
7431011	2007	2008	UT-BATTELLE LLC	METHOD AND DEVICE FOR DIAGNOSING AND CONTROLLING COMBUSTION INSTABILITIES IN INTERNAL COMBUSTION ENGINES OPERATING IN OR TRANSITIONING TO HOMOGENEOUS CHARGE COMBUSTION IGNITION MODE
7441403	2004	2008	DETROIT DIESEL CORP	METHOD AND SYSTEM FOR DETERMINING TEMPERATURE SET POINTS IN SYSTEMS HAVING PARTICULATE FILTERS WITH REGENERATION CAPABILITIES
7444980	2007	2008	CATERPILLAR INC	FUEL INJECTOR NOZZLE FOR AN INTERNAL COMBUSTION ENGINE
7458214	2003	2008	HONEYWELL INTERNATIONAL INC	ELECTRIC MOTOR CARTRIDGE FOR AN ELECTRICALLY ASSISTED TURBOCHARGER
7464540	2006	2008	CATERPILLAR INC	AMMONIA PRODUCING ENGINE UTILIZING OXYGEN SEPARATION
7464690	2007	2008	WISCONSIN ALUMNI RESEARCH FOUNDATION	ADAPTIVE ENGINE INJECTION FOR EMISSIONS REDUCTION
7469181	2007	2008	CATERPILLAR INC	HIGH LOAD OPERATION IN A HOMOGENEOUS CHARGE COMPRESSION IGNITION ENGINE
7469532	2005	2008	GENERAL MOTORS CORP	DIESEL PARTICULATE FILTER (DPF) REGENERATION BY ELECTRICAL HEATING OF RESISTIVE COATINGS
7469693	2007	2008	UT-BATTELLE LLC	ADVANCED ENGINE MANAGEMENT OF INDIVIDUAL CYLINDERS FOR CONTROL OF EXHAUST SPECIES
EP1907801	2006	2008	HONEYWELL INTERNATIONAL INC	PARTICULATE-BASED FLOW SENSOR
EP1913248	2006	2008	CATERPILLAR INC	ENGINE SYSTEM AND METHOD OF OPERATING SAME OVER MULTIPLE ENGINE LOAD RANGES
EP1943414	2006	2008	HONEYWELL INTERNATIONAL INC	SYSTEM FOR PARTICULATE MATTER SENSOR SIGNAL PROCESSING

EP1992808	2008	2008	DEERE & CO	POWER SYSTEM AND METHOD
WO2008036797	2007	2008	BASF CORP	CATALYST, METHOD FOR ITS PREPARATION AND SYSTEM TO REDUCE NOX IN AN EXHAUST GAS STREAM
WO2008036803	2007	2008	BASF CATALYSTS LLC; GEN MOTORS CORP	CATALYSTS TO REDUCE NOX IN AN EXHAUST GAS STREAM AND METHODS OF PREPARATION
WO2008036813	2007	2008	BASF CORP	CATALYSTS TO REDUCE NOX IN AN EXHAUST GAS STREAM AND METHODS OF PREPARATION
WO2008051315	2007	2008	CATERPILLAR INC	EXHAUST GAS RECIRCULATION IN A HOMOGENEOUS CHARGE COMPRESSION IGNITION ENGINE
WO2008066594	2007	2008	CATERPILLAR INC	LOW PRESSURE EGR SYSTEM HAVING FULL RANGE CAPABILITY
WO2008088554	2007	2008	MACK TRUCKS INC	HYBRID INTERNAL COMBUSTION ENGINE AND AIR MOTOR SYSTEM AND METHOD
WO2008094230	2007	2008	CATERPILLAR INC	HIGH LOAD OPERATION IN A HOMOGENEOUS CHARGE COMPRESSION IGNITION ENGINE
WO2008094231	2007	2008	CATERPILLAR INC	DYNAMIC CONTROL OF A HOMOGENEOUS CHARGE COMPRESSION IGNITION ENGINE
WO2008127249	2007	2008	CATERPILLAR INC	ENGINE PISTON HAVING AN INSULATING AIR GAP
7497138	2006	2009	FORD GLOBAL TECHNOLOGIES LLC	SYSTEM AND METHOD FOR IMPROVING PERFORMANCE OF A FLUID SENSOR FOR AN INTERNAL COMBUSTION ENGINE
7523606	2005	2009	CATERPILLAR INC	PARASITIC LOAD CONTROL SYSTEM FOR EXHAUST TEMPERATURE CONTROL
7540279	2007	2009	DEERE & CO	HIGH EFFICIENCY STOICHIOMETRIC INTERNAL COMBUSTION ENGINE SYSTEM
7541010	2003	2009	CATERPILLAR INC	SILVER DOPED CATALYSTS FOR TREATMENT OF EXHAUST
7549317	2007	2009	HONEYWELL INTERNATIONAL INC	PARTICLE-BASED FLOW SENSOR
7552583	2004	2009	CATERPILLAR INC	EXHAUST PURIFICATION WITH ON-BOARD AMMONIA PRODUCTION
7555945	2007	2009	MICHIGAN STATE UNIVERSITY	MASS AIR FLOW SENSOR HAVING OFF AXIS CONVERGING AND DIVERGING NOZZLES
7591131	2006	2009	CATERPILLAR INC	LOW PRESSURE EGR SYSTEM HAVING FULL RANGE CAPABILITY
7591132	2006	2009	GENERAL MOTORS CORP	APPARATUS AND METHOD TO INJECT A REDUCTANT INTO AN EXHAUST GAS FEEDSTREAM

7594940	2007	2009	GENERAL MOTORS CORP	ELECTRICALLY HEATED PARTICULATE FILTER DIAGNOSTIC SYSTEMS AND METHODS
7614231	2007	2009	DETROIT DIESEL CORP	METHOD AND SYSTEM TO OPERATE DIESEL ENGINE USING REAL TIME SIX DIMENSIONAL EMPIRICAL DIESEL EXHAUST PRESSURE MODEL
7628007	2006	2009	HONEYWELL INTERNATIONAL INC	ONBOARD DIAGNOSTICS FOR ANOMALOUS CYLINDER BEHAVIOR
EP2018469	2006	2009	HONEYWELL INTERNATIONAL INC	ONBOARD DIAGNOSTICS FOR ANOMALOUS CYLINDER BEHAVIOR
EP2022963	2008	2009	HONEYWELL INTERNATIONAL INC	VARIABLE-GEOMETRY TURBOCHARGER WITH ASYMMETRIC DIVIDED VOLUTE FOR ENGINE EXHAUST GAS PULSE OPTIMIZATION
EP2025871	2008	2009	DEERE & CO	CENTRIPETAL TURBINE AND INTERNAL COMBUSTION ENGINE WITH SUCH A TURBINE
EP2053208	2008	2009	DEERE & CO	LOW EMISSION TURBO COMPOUND ENGINE SYSTEM
EP2069051	2007	2009	BASF CORP	CATALYST, METHOD FOR ITS PREPARATION AND SYSTEM TO REDUCE NOX IN AN EXHAUST GAS STREAM
EP2069052	2007	2009	BASF CATALYSTS LLC; GEN MOTORS CORP	CATALYSTS TO REDUCE NOX IN AN EXHAUST GAS STREAM AND METHODS OF PREPARATION
EP2069053	2007	2009	BASF CORP	CATALYSTS TO REDUCE NOX IN AN EXHAUST GAS STREAM AND METHODS OF PREPARATION
EP2101047	2009	2009	DEERE & CO	INTERNAL COMBUSTION ENGINE AND METHOD
EP2106360	2007	2009	MACK TRUCKS INC	HYBRID INTERNAL COMBUSTION ENGINE AND AIR MOTOR SYSTEM AND METHOD
WO2009067787	2008	2009	WESTPORT POWER INC	METHOD AND APPARATUS FOR DETERMINING A NORMAL COMBUSTION CHARACTERISTIC FOR AN INTERNAL COMBUSTION ENGINE FROM AN ACCELEROMETER SIGNAL
WO2009067804	2008	2009	WESTPORT POWER INC	METHOD AND APPARATUS FOR USING AN ACCELEROMETER SIGNAL TO DETECT MISFIRING IN AN INTERNAL COMBUSTION ENGINE
WO2009075917	2008	2009	GENERAL ELECTRIC CO	FUEL INJECTION SYSTEM AND METHOD OF OPERATING THE SAME FOR AN ENGINE
WO2009085429	2008	2009	CUMMINS INC	SYSTEM AND METHOD FOR

				ADJUSTING FUEL INJECTOR ON-TIMES
WO2009102500	2009	2009	CUMMINS INC	SYSTEM AND METHOD FOR ON-BOARD WASTE HEAT RECOVERY
7650781	2007	2010	DETROIT DIESEL CORP	METHOD FOR VERIFYING THE FUNCTIONALITY OF THE COMPONENTS OF A DIESEL PARTICULATE FILTER SYSTEM
7654079	2006	2010	CUMMINS INC	DIESEL OXIDATION CATALYST FILTER HEATING SYSTEM
7654240	2006	2010	CATERPILLAR INC	ENGINE PISTON HAVING AN INSULATING AIR GAP
7655065	2006	2010	GENERAL MOTORS CORP	HYDROCARBON-ENHANCED PARTICULATE FILTER REGENERATION VIA MICROWAVE IGNITION
7685809	2005	2010	CATERPILLAR INC	ON-BOARD AMMONIA GENERATION AND EXHAUST AFTER TREATMENT SYSTEM USING SAME
7694518	2007	2010	DEERE & CO	INTERNAL COMBUSTION ENGINE SYSTEM HAVING A POWER TURBINE WITH A BROAD EFFICIENCY RANGE
7721535	2006	2010	CUMMINS INC	METHOD FOR MODIFYING TRIGGER LEVEL FOR ADSORBER REGENERATION
7721543	2006	2010	SOUTHWEST RESEARCH INSTITUTE	SYSTEM AND METHOD FOR COOLING A COMBUSTION GAS CHARGE
7739994	2007	2010	CATERPILLAR INC	THERMOELECTRIC SYSTEM FOR AN ENGINE
7759280	2006	2010	BASF CORP	CATALYSTS, SYSTEMS AND METHODS TO REDUCE NOX IN AN EXHAUST GAS STREAM
7765792	2005	2010	HONEYWELL INTERNATIONAL INC	SYSTEM FOR PARTICULATE MATTER SENSOR SIGNAL PROCESSING
7770565	2008	2010	CUMMINS INC	SYSTEM AND METHOD FOR CONTROLLING AN EXHAUST GAS RECIRCULATION SYSTEM
7788907	2007	2010	FORD GLOBAL TECHNOLOGIES LLC	EXHAUST INJECTOR SPRAY TARGET
7805235	2008	2010	CUMMINS INC	SYSTEM AND METHOD FOR CONTROLLING A FLOW OF INTAKE AIR ENTERING AN INTERNAL COMBUSTION ENGINE
7810318	2007	2010	GENERAL MOTORS CORP	ELECTRICALLY HEATED PARTICULATE FILTER REGENERATION METHODS AND SYSTEMS FOR HYBRID VEHICLES
7811527	2008	2010	CATERPILLAR INC	EXHAUST PURIFICATION WITH ON-BOARD AMMONIA PRODUCTION
7828517	2007	2010	HONEYWELL	VARIABLE-GEOMETRY

			INTERNATIONAL INC	TURBOCHARGER WITH ASYMMETRIC DIVIDED VOLUTE FOR ENGINE EXHAUST GAS PULSE OPTIMIZATION
7839492	2008	2010	UT-BATTELLE LLC	LASER-INDUCED FLUORESCENCE FIBER OPTIC PROBE MEASUREMENT OF OIL DILUTION BY FUEL
EP2169196	2009	2010	DEERE & CO	INTERNAL COMBUSTION ENGINE, WORKING MACHINE AND METHOD
EP2220472	2008	2010	WESTPORT POWER INC	METHOD AND APPARATUS FOR DETERMINING A NORMAL COMBUSTION CHARACTERISTIC FOR AN INTERNAL COMBUSTION ENGINE FROM AN ACCELEROMETER SIGNAL
EP2220473	2008	2010	WESTPORT POWER INC	METHOD AND APPARATUS FOR USING AN ACCELEROMETER SIGNAL TO DETECT MISFIRING IN AN INTERNAL COMBUSTION ENGINE
WO2010014202	2009	2010	CUMMINS INC	EMISSIONS REDUCTIONS THROUGH MULTIPLE FUEL INJECTION EVENTS
WO2010036417	2009	2010	ROBERT BOSCH GMBH	FUEL COMPOSITION RECOGNITION AND ADAPTATION SYSTEM
7869930	2008	2011	FORD GLOBAL TECHNOLOGIES LLC	APPROACH FOR REDUCING OVERHEATING OF DIRECT INJECTION FUEL INJECTORS
7877987	2007	2011	GENERAL MOTORS CORP	ELECTRICALLY HEATED PARTICULATE FILTER REGENERATION USING HYDROCARBON ADSORBENTS
7885754	2007	2011	GENERAL ELECTRIC CO	FUEL INJECTION SYSTEM AND METHOD OF OPERATING THE SAME FOR AN ENGINE
7886529	2007	2011	GENERAL MOTORS CORP	ELECTRICALLY HEATED DPF/SCR 2-WAY SYSTEM
7891185	2007	2011	DEERE & CO	TURBO-GENERATOR CONTROL WITH VARIABLE VALVE ACTUATION
7909271	2008	2011	CATERPILLAR INC	FUEL INJECTOR NOZZLE FOR AN INTERNAL COMBUSTION ENGINE
7943548	2006	2011	BASF CORP	CATALYSTS TO REDUCE NO _X IN AN EXHAUST GAS STREAM AND METHODS OF PREPARATION
7945372	2007	2011	CUMMINS INC	SYSTEM AND METHOD FOR ADJUSTING FUEL INJECTOR ON-TIMES
7950231	2007	2011	DEERE & CO	LOW EMISSION TURBO COMPOUND ENGINE SYSTEM
7958723	2007	2011	GENERAL MOTORS CORP	ELECTRICALLY HEATED PARTICULATE FILTER

				PROPAGATION SUPPORT METHODS AND SYSTEMS
7958873	2008	2011	CUMMINS INC	OPEN LOOP BRAYTON CYCLE FOR EGR COOLING
7975469	2007	2011	GENERAL MOTORS CORP	ELECTRICALLY HEATED PARTICULATE FILTER RESTART STRATEGY
7997069	2007	2011	GENERAL MOTORS CORP	ASH REDUCTION SYSTEM USING ELECTRICALLY HEATED PARTICULATE MATTER FILTER
8006481	2006	2011	GENERAL MOTORS CORP	METHOD AND APPARATUS TO SELECTIVELY REDUCE NO _X IN AN EXHAUST GAS FEEDSTREAM
8037673	2007	2011	GENERAL MOTORS CORP	SELECTIVE CATALYST REDUCTION LIGHT-OFF STRATEGY
8057581	2007	2011	GENERAL MOTORS CORP	ZONED ELECTRICAL HEATER ARRANGED IN SPACED RELATIONSHIP FROM PARTICULATE FILTER
8065878	2008	2011	DEERE & CO	TWO PHASE EXHAUST FOR INTERNAL COMBUSTION ENGINE
8071504	2008	2011	CATERPILLAR INC	EXHAUST SYSTEM HAVING A GOLD-PLATINUM GROUP METAL CATALYST
8078386	2011	2011	FORD GLOBAL TECHNOLOGIES LLC	APPROACH FOR REDUCING OVERHEATING OF DIRECT INJECTION FUEL INJECTORS
8078389	2010	2011	WESTPORT POWER INC	METHOD AND APPARATUS FOR DETERMINING A NORMAL COMBUSTION CHARACTERISTIC FOR AN INTERNAL COMBUSTION ENGINE FROM AN ACCELEROMETER SIGNAL
WO2011011868	2010	2011	WESTPORT POWER INC	METHOD AND APPARATUS FOR RECONSTRUCTING IN-CYLINDER PRESSURE AND CORRECTING FOR SIGNAL DECAY
WO2011037926	2010	2011	CUMMINS INC	SYSTEM AND METHOD FOR ESTIMATING EGR MASS FLOW RATES
WO2011038340	2010	2011	CUMMINS INC	ENGINE EXHAUST MANIFOLD PRESSURE CONTROL OF INTAKE FLOW
WO2011038345	2010	2011	CUMMINS INC	EGR FLOW COMPENSATION FOR A DIESEL AIR HANDLING SYSTEM
WO2011053905	2010	2011	CUMMINS INC	ENGINE CONTROL TECHNIQUES TO ACCOUNT FOR FUEL EFFECTS
WO2011100027	2010	2011	WISCONSIN ALUMNI RESEARCH FOUNDATION	ENGINE COMBUSTION CONTROL VIA FUEL REACTIVITY STRATIFICATION
WO2011153486	2011	2011	CUMMINS INC	FRESH AIR FLOW ESTIMATION
8100116	2009	2012	GENERAL MOTORS CORP	DIESEL EMISSION REDUCTION USING INTERNAL EXHAUST GAS

				RECIRCULATION
8103427	2009	2012	CUMMINS INC	EGR FLOW COMPENSATION FOR A DIESEL AIR HANDLING SYSTEM
8104270	2007	2012	GENERAL MOTORS CORP	ELECTRICALLY HEATED PARTICULATE FILTER PREPARATION METHODS AND SYSTEMS
8105417	2008	2012	GENERAL MOTORS CORP	FACE CRACK REDUCTION STRATEGY FOR PARTICULATE FILTERS
8108131	2010	2012	WESTPORT POWER INC	METHOD AND APPARATUS FOR USING AN ACCELEROMETER SIGNAL TO DETECT MISFIRING IN AN INTERNAL COMBUSTION ENGINE
8112990	2008	2012	GENERAL MOTORS CORP	LOW EXHAUST TEMPERATURE ELECTRICALLY HEATED PARTICULATE MATTER FILTER SYSTEM
8146350	2008	2012	GENERAL MOTORS CORP	VARIABLE POWER DISTRIBUTION FOR ZONED REGENERATION OF AN ELECTRICALLY HEATED PARTICULATE FILTER
8151557	2007	2012	GENERAL MOTORS CORP	ELECTRICALLY HEATED DPF START-UP STRATEGY
8156737	2007	2012	GENERAL MOTORS CORP	ELEVATED EXHAUST TEMPERATURE, ZONED, ELECTRICALLY-HEATED PARTICULATE MATTER FILTER
8165786	2010	2012	HONEYWELL INTERNATIONAL INC	SYSTEM FOR PARTICULATE MATTER SENSOR SIGNAL PROCESSING
8171900	2010	2012	GENERAL MOTORS CORP	ENGINE INCLUDING HYDRAULICALLY ACTUATED VALVETRAIN AND METHOD OF VALVE OVERLAP CONTROL
8173574	2007	2012	BASF CORP	CATALYSTS TO REDUCE NO _X IN AN EXHAUST GAS STREAM AND METHODS OF PREPARATION
8177016	2007	2012	MACK TRUCKS INC	HYBRID INTERNAL COMBUSTION ENGINE AND AIR MOTOR SYSTEM AND METHOD
8185293	2009	2012	ROBERT BOSCH GMBH	FUEL COMPOSITION RECOGNITION AND ADAPTATION SYSTEM
8186151	2009	2012	GENERAL MOTORS CORP	METHOD TO MONITOR HC-SCR CATALYST NOX REDUCTION PERFORMANCE FOR LEAN EXHAUST APPLICATIONS
8195378	2009	2012	CUMMINS INC	EMISSIONS REDUCTIONS THROUGH MULTIPLE FUEL INJECTION EVENTS
8201442	2009	2012	CUMMINS INC	SYSTEM AND METHOD FOR ESTIMATING EGR MASS FLOW RATES

8205439	2009	2012	GENERAL MOTORS CORP	ELECTRICALLY HEATED PARTICULATE FILTER WITH ZONED EXHAUST FLOW CONTROL
8205441	2006	2012	GENERAL MOTORS CORP	ZONE HEATED INLET IGNITED DIESEL PARTICULATE FILTER REGENERATION
8209962	2005	2012	DETROIT DIESEL CORP	DIESEL PARTICULATE FILTER SOOT PERMEABILITY VIRTUAL SENSORS
8236261	2011	2012	CATERPILLAR INC	EXHAUST SYSTEM HAVING A GOLD-PLATINUM GROUP METAL CATALYST
8248612	2010	2012	UT-BATTELLE LLC	OXYGEN CONCENTRATION SENSORS AND METHODS OF RAPIDLY MEASURING THE CONCENTRATION OF OXYGEN IN FLUIDS
8252077	2007	2012	GENERAL MOTORS CORP	ELECTRICALLY HEATED PARTICULATE FILTER HEATER INSULATION
8256220	2009	2012	GENERAL MOTORS CORP, GENERAL ELECTRIC CO	EXHAUST GAS BYPASS VALVE CONTROL FOR THERMOELECTRIC GENERATOR
8286424	2010	2012	GENERAL MOTORS CORP	THERMOELECTRIC GENERATOR COOLING SYSTEM AND METHOD OF CONTROL
8291694	2007	2012	GENERAL MOTORS CORP	ELECTRICALLY HEATED PARTICULATE FILTER ENHANCED IGNITION STRATEGY
8291872	2009	2012	UT-BATTELLE LLC	HIGHLY EFFICIENT 6-STROKE ENGINE CYCLE WITH WATER INJECTION
8297238	2010	2012	GENERAL MOTORS CORP	VARIABLE COOLING CIRCUIT FOR THERMOELECTRIC GENERATOR AND ENGINE AND METHOD OF CONTROL
8322129	2006	2012	CUMMINS INC	METHOD FOR CONTROLLING TURBINE OUTLET TEMPERATURES IN A DIESEL ENGINE
EP2459980	2010	2012	WESTPORT POWER INC	METHOD AND APPARATUS FOR CONTROLLING AN ENGINE BASED ON A RECONSTRUCTED IN-CYLINDER PRESSURE SIGNAL CORRECTED FOR SENSOR SIGNAL DECAY
EP2495408	2012	2012	DELPHI TECHNOLOGIES INC	VALVE TRAIN SYSTEM FOR AN INTERNAL COMBUSTION ENGINE
EP2505811	2012	2012	ROBERT BOSCH GMBH	ADJUSTING THE SPECIFICITY OF AN ENGINE MAP BASED ON THE SENSITIVITY OF AN ENGINE CONTROL PARAMETER RELATIVE TO A PERFORMANCE VARIABLE
EP2505812	2012	2012	ROBERT BOSCH	PERTURBING ENGINE

			GMBH	PERFORMANCE MEASUREMENTS TO DETERMINE OPTIMAL ENGINE CONTROL SETTINGS
EP2505813	2012	2012	ROBERT BOSCH GMBH	DEFINING REGION OF OPTIMIZATION BASED ON ENGINE USAGE DATA
EP2505814	2012	2012	ROBERT BOSCH GMBH	CONCURRENTLY ADJUSTING INTERRELATED CONTROL PARAMETERS TO ACHIEVE OPTIMAL ENGINE PERFORMANCE
EP2534352	2010	2012	WISCONSIN ALUMNI RESEARCH FOUNDATION	ENGINE COMBUSTION CONTROL VIA FUEL REACTIVITY STRATIFICATION
WO2012019161	2011	2012	CUMMINS INC	EMISSIONS-CRITICAL CHARGE COOLING USING AN ORGANIC RANKINE CYCLE
WO2012047649	2011	2012	BASF CORP	HYDROCARDON SELECTIVE CATALYTIC REDUCTION CATALYST FOR NOX EMISSIONS CONTROL
WO2012088532	2011	2012	CUMMINS INC	SYSTEM AND METHOD FOR REGULATING EGR COOLING USING A RANKINE CYCLE
WO2012092481	2011	2012	CUMMINS INC	SYSTEM AND METHOD FOR MONITORING AND DETECTING FAULTS IN A CLOSED-LOOP SYSTEM
WO2012100212	2012	2012	CUMMINS INC	RANKINE CYCLE WASTE HEAT RECOVERY SYSTEM AND METHOD WITH IMPROVED EGR TEMPERATURE CONTROL
WO2012118858	2012	2012	CUMMINS INC	SYSTEM AND METHOD OF DPF PASSIVE ENHANCEMENT THROUGH POWERTRAIN TORQUE-SPEED MANAGEMENT
WO2012134612	2012	2012	WISCONSIN ALUMNI RESEARCH FOUNDATION	ENGINE COMBUSTION CONTROL AT LOW LOADS VIA FUEL REACTIVITY STRATIFICATION
WO2012173688	2012	2012	CATERPILLAR INC	COMPRESSION IGNITION ENGINE HAVING FUEL SYSTEM FOR NON-SOOTING COMBUSTION, AND METHOD
8347607	2009	2013	GENERAL MOTORS CORP	INTEGRATED EXHAUST AND ELECTRICALLY HEATED PARTICULATE FILTER REGENERATION SYSTEMS
8396649	2012	2013	WESTPORT POWER INC	METHOD AND APPARATUS FOR RECONSTRUCTING IN-CYLINDER PRESSURE AND CORRECTING FOR SIGNAL DECAY
8431043	2009	2013	CUMMINS INC	SYSTEM AND METHOD FOR ON-BOARD WASTE HEAT RECOVERY
8443594	2010	2013	GENERAL MOTORS CORP	METHOD OF CONTROLLING TEMPERATURE OF A

				THERMOELECTRIC GENERATOR IN AN EXHAUST SYSTEM
8443784	2011	2013	GENERAL MOTORS CORP	INTERNAL COMBUSTION ENGINE AND METHOD FOR CONTROL
8443789	2010	2013	GENERAL MOTORS CORP	EXHAUST GAS RECIRCULATION SYSTEM FOR AN INTERNAL COMBUSTION ENGINE
8463495	2010	2013	GENERAL MOTORS CORP	METHOD FOR CONTROLLING EXHAUST GAS HEAT RECOVERY SYSTEMS IN VEHICLES
8473181	2012	2013	CUMMINS INC	EMISSIONS REDUCTIONS THROUGH MULTIPLE FUEL INJECTION EVENTS
8474258	2008	2013	DEERE & CO	STOICHIOMETRIC COMPRESSION IGNITION ENGINE WITH INCREASED POWER OUTPUT
8478476	2010	2013	GENERAL MOTORS CORP	SYSTEM FOR DETECTING OPERATING ERRORS IN A VARIABLE VALVE TIMING ENGINE USING PRESSURE SENSORS
8517137	2012	2013	MACK TRUCKS INC	HYBRID INTERNAL COMBUSTION ENGINE AND AIR MOTOR SYSTEM AND METHOD
8517664	2010	2013	FORD GLOBAL TECHNOLOGIES LLC	TURBOCHARGER
8549846	2006	2013	GENERAL MOTORS CORP	DIESEL PARTICULATE FILTER REGENERATION VIA RESISTIVE SURFACE HEATING
8554407	2011	2013	GENERAL MOTORS CORP	BYPASS VALVE AND COOLANT FLOW CONTROLS FOR OPTIMUM TEMPERATURES IN WASTE HEAT RECOVERY SYSTEMS
8602002	2010	2013	GENERAL MOTORS CORP	SYSTEM AND METHOD FOR CONTROLLING ENGINE KNOCK USING ELECTRO-HYDRAULIC VALVE ACTUATION
8602007	2010	2013	GENERAL MOTORS CORP	INTEGRATED EXHAUST GAS RECIRCULATION AND CHARGE COOLING SYSTEM
8615988	2005	2013	GENERAL MOTORS CORP	ELECTRICAL DIESEL PARTICULATE FILTER (DPF) REGENERATION
8616177	2010	2013	WISCONSIN ALUMNI RESEARCH FOUNDATION	ENGINE COMBUSTION CONTROL VIA FUEL REACTIVITY STRATIFICATION
EP2665907	2012	2013	CUMMINS INC	RANKINE CYCLE WASTE HEAT RECOVERY SYSTEM AND METHOD WITH IMPROVED EGR TEMPERATURE CONTROL
WO2013116122	2013	2013	CUMMINS INC	SYSTEM, METHOD, AND APPARATUS FOR DETERMINING SOLID STORAGE MEDIA QUALITY FOR A NOX REDUCTANT

WO2013177119	2013	2013	CUMMINS INC	AFTERTREATMENT SYSTEM HAVING TWO SCR CATALYSTS
8621864	2010	2014	CUMMINS INC	ENGINE EXHAUST MANIFOLD PRESSURE CONTROL OF INTAKE FLOW
8627654	2011	2014	GENERAL MOTORS CORP	METHOD OF TREATING EMISSIONS OF A HYBRID VEHICLE WITH A HYDROCARBON ABSORBER AND A CATALYST BYPASS SYSTEM
8667954	2011	2014	GENERAL MOTORS CORP	SIMULTANEOUSLY FIRING TWO CYLINDERS OF AN EVEN FIRING CAMLESS ENGINE
8677748	2011	2014	CUMMINS INC	FRESH AIR FLOW ESTIMATION
8689767	2011	2014	SANDIA CORP	METHOD FOR OPERATING HOMOGENEOUS CHARGE COMPRESSION IGNITION ENGINES USING CONVENTIONAL GASOLINE
8700360	2010	2014	CUMMINS INC	SYSTEM AND METHOD FOR MONITORING AND DETECTING FAULTS IN A CLOSED-LOOP SYSTEM
8713914	2009	2014	GENERAL MOTORS CORP	METHOD AND APPARATUS FOR MONITORING A HYDROCARBON-SELECTIVE CATALYTIC REDUCTION DEVICE
8727064	2013	2014	MACK TRUCKS INC	HYBRID INTERNAL COMBUSTION ENGINE AND AIR MOTOR SYSTEM AND METHOD
8776517	2011	2014	CUMMINS INC	EMISSIONS-CRITICAL CHARGE COOLING USING AN ORGANIC RANKINE CYCLE
8800285	2012	2014	CUMMINS INC	RANKINE CYCLE WASTE HEAT RECOVERY SYSTEM
8806868	2011	2014	GENERAL MOTORS CORP	SECONDARY AIR INJECTION SYSTEM AND METHOD
8813690	2010	2014	CUMMINS INC	ENGINE CONTROL TECHNIQUES TO ACCOUNT FOR FUEL EFFECTS
8820058	2012	2014	CUMMINS INC	SYSTEM, METHOD, AND APPARATUS FOR DETERMINING SOLID STORAGE MEDIA QUALITY FOR A NO(SUB)X REDUCTANT
8826662	2011	2014	CUMMINS INC	RANKINE CYCLE SYSTEM AND METHOD
8839750	2010	2014	GENERAL MOTORS CORP	SYSTEM AND METHOD FOR CONTROLLING HYDRAULIC PRESSURE IN ELECTRO-HYDRAULIC VALVE ACTUATION SYSTEMS
8851045	2011	2014	WISCONSIN ALUMNI RESEARCH FOUNDATION	ENGINE COMBUSTION CONTROL AT LOW LOADS VIA FUEL REACTIVITY STRATIFICATION
8869770	2011	2014	CATERPILLAR INC	COMPRESSION IGNITION ENGINE HAVING FUEL SYSTEM FOR NON-SOOTING COMBUSTION AND

				METHOD
8874351	2012	2014	ROBERT BOSCH GMBH	ADJUSTING THE SPECIFICITY OF AN ENGINE MAP BASED ON THE SENSITIVITY OF AN ENGINE CONTROL PARAMETER RELATIVE TO A PERFORMANCE VARIABLE
8887693	2011	2014	CUMMINS INC	SYSTEM AND METHOD FOR ESTIMATING TURBOCHARGER COMPRESSOR INLET AIR FLOW RATE
8892332	2011	2014	CUMMINS INC	SYSTEM AND METHOD FOR ESTIMATING TURBOCHARGER OPERATING SPEED
8919099	2011	2014	GENERAL MOTORS CORP	SYSTEM AND METHOD FOR DETERMINING AN AMMONIA GENERATION RATE IN A THREE-WAY CATALYST
8919119	2011	2014	FORD GLOBAL TECHNOLOGIES LLC	SLIDING VANE GEOMETRY TURBINES
8919328	2012	2014	CUMMINS INC	RANKINE CYCLE WASTE HEAT RECOVERY SYSTEM AND METHOD WITH IMPROVED EGR TEMPERATURE CONTROL
8920770	2013	2014	CUMMINS INC	SYSTEM AND METHOD FOR ON-BOARD WASTE HEAT RECOVERY
8924125	2012	2014	ROBERT BOSCH GMBH	PERTURBING ENGINE PERFORMANCE MEASUREMENTS TO DETERMINE OPTIMAL ENGINE CONTROL SETTINGS
EP2691626	2012	2014	WISCONSIN ALUMNI RESEARCH FOUNDATION	ENGINE COMBUSTION CONTROL AT LOW LOADS VIA FUEL REACTIVITY STRATIFICATION
WO2014093643	2013	2014	PURDUE RESEARCH FOUNDATION	PREMIXED CHARGE COMPRESSION IGNITION COMBUSTION TIMING CONTROL USING NONLINEAR MODELS
8935917	2013	2015	GENERAL MOTORS CORP	PARTIALLY INTEGRATED EXHAUST MANIFOLD
8967129	2011	2015	CATERPILLAR INC	DUCTED COMBUSTION CHAMBER FOR DIRECT INJECTION ENGINES AND METHOD
8997461	2012	2015	CUMMINS INC	AFTERTREATMENT SYSTEM HAVING TWO SCR CATALYSTS
8997698	2013	2015	DELPHI TECHNOLOGIES INC	ADAPTIVE INDIVIDUAL-CYLINDER THERMAL STATE CONTROL USING PISTON COOLING FOR A GDCI ENGINE
9000374	2013	2015	UT-BATTELLE LLC	EGR DISTRIBUTION AND FLUCTUATION PROBE BASED ON CO(SUB)2 MEASUREMENTS
9002623	2012	2015	GENERAL MOTORS CORP	FULLY FLEXIBLE EXHAUST VALVE ACTUATOR CONTROL SYSTEMS AND METHODS
9046051	2011	2015	GENERAL	METHOD FOR OPERATING A

			MOTORS CORP	SPARK-IGNITION, DIRECT-INJECTION INTERNAL COMBUSTION ENGINE
9062635	2011	2015	CUMMINS INC	SYSTEM AND METHOD FOR ESTIMATING ENGINE EXHAUST MANIFOLD OPERATING PARAMETERS
9068933	2013	2015	UT-BATTELLE LLC	EGR DISTRIBUTION AND FLUCTUATION PROBE BASED ON CO2 MEASUREMENTS
9080501	2013	2015	WISCONSIN ALUMNI RESEARCH FOUNDATION	ENGINE COMBUSTION CONTROL VIA FUEL REACTIVITY STRATIFICATION
9097174	2012	2015	DELPHI TECHNOLOGIES INC	SYSTEM AND METHOD FOR CONDITIONING INTAKE AIR TO AN INTERNAL COMBUSTION ENGINE
9097197	2012	2015	ROBERT BOSCH GMBH	DEFINING A REGION OF OPTIMIZATION BASED ON ENGINE USAGE DATA
9109546	2009	2015	CUMMINS INC	SYSTEM AND METHOD FOR OPERATING A HIGH PRESSURE COMPRESSOR BYPASS VALVE IN A TWO STAGE TURBOCHARGER SYSTEM
9127601	2012	2015	GENERAL MOTORS CORP	CYLINDER TO CYLINDER BALANCING USING FULLY FLEXIBLE VALVE ACTUATION AND CYLINDER PRESSURE FEEDBACK
9133793	2010	2015	GENERAL MOTORS CORP	BOOSTING DEVICES WITH INTEGRAL FEATURES FOR RECIRCULATING EXHAUST GAS
9140159	2007	2015	GENERAL MOTORS CORP	HIGH EXHAUST TEMPERATURE, ZONED, ELECTRICALLY-HEATED PARTICULATE MATTER FILTER
9140168	2010	2015	GENERAL MOTORS CORP	EXHAUST BYPASS FLOW CONTROL FOR EXHAUST HEAT RECOVERY
9140199	2012	2015	ROBERT BOSCH GMBH	COMBUSTION MODE SWITCHING WITH A TURBOCHARGED/SUPERCHARGED ENGINE
9140209	2012	2015	CUMMINS INC	RANKINE CYCLE WASTE HEAT RECOVERY SYSTEM
9175644	2013	2015	GENERAL MOTORS CORP	ENGINE WITH EXHAUST GAS RECIRCULATION SYSTEM AND VARIABLE GEOMETRY TURBOCHARGER
9188071	2012	2015	GENERAL MOTORS CORP	SYSTEM AND METHOD FOR CONTROLLING AN ENGINE BASED ON AMMONIA STORAGE IN MULTIPLE SELECTIVE CATALYTIC REDUCTION CATALYSTS
9194318	2012	2015	CUMMINS INC	SYSTEM AND METHOD OF DPF

				PASSIVE ENHANCEMENT THROUGH POWERTRAIN TORQUE-SPEED MANAGEMENT
9200583	2012	2015	ROBERT BOSCH GMBH	CONCURRENTLY ADJUSTING INTERRELATED CONTROL PARAMETERS TO ACHIEVE OPTIMAL ENGINE PERFORMANCE
9217338	2011	2015	CUMMINS INC	SYSTEM AND METHOD FOR REGULATING EGR COOLING USING A RANKINE CYCLE
9217396	2010	2015	GENERAL MOTORS CORP	BOOSTING DEVICES WITH INTEGRAL FEATURES FOR RECIRCULATING EXHAUST GAS
9222389	2012	2015	CUMMINS INC	SYSTEMS AND METHODS FOR CONTROLLING REDUCTANT DELIVERY TO AN EXHAUST STREAM
9222432	2012	2015	ROBERT BOSCH GMBH	PATH PLANNING DURING COMBUSTION MODE SWITCH
9228527	2012	2016	ROBERT BOSCH GMBH	DYNAMIC ESTIMATOR FOR DETERMINING OPERATING CONDITIONS IN AN INTERNAL COMBUSTION ENGINE
9239015	2012	2016	GENERAL MOTORS CORP	CYLINDER PRESSURE BASED PUMP CONTROL SYSTEMS AND METHODS
9284870	2008	2016	GENERAL MOTORS CORP	ELECTRICALLY HEATED PARTICULATE MATTER FILTER SOOT CONTROL SYSTEM
9308497	2011	2016	BASF CORP	HYDROCARBON SELECTIVE CATALYTIC REDUCTION CATALYST FOR NO(SUB)X EMISSIONS CONTROL
9328674	2014	2016	CUMMINS INC	CONTROLS FOR PERFORMANCE OPTIMIZATION OF INTERNAL COMBUSTION ENGINE SYSTEMS
9334760	2014	2016	CUMMINS INC	RANKINE CYCLE WASTE HEAT RECOVERY SYSTEM
9334778	2014	2016	CUMMINS INC	SOLID AMMONIA DELIVERY SYSTEM
9334811	2012	2016	GENERAL MOTORS CORP	VALVE CONTROL SYSTEMS AND METHODS FOR HOMOGENOUS CHARGE COMPRESSION IGNITION OPERATION
9359968	2014	2016	CUMMINS INC	AIR-FUEL-RATIO DITHERING USING A DUAL FUEL PATH SOURCE
9359976	2013	2016	GENERAL MOTORS CORP	ENGINE WITH PULSE-SUPPRESSED DEDICATED EXHAUST GAS RECIRCULATION
9376955	2015	2016	WISCONSIN ALUMNI RESEARCH FOUNDATION	ENGINE COMBUSTION CONTROL VIA FUEL REACTIVITY STRATIFICATION
9376979	2012	2016	ROBERT BOSCH GMBH,	FUEL GOVERNOR FOR CONTROLLED AUTOIGNITION

			UNIVERSITY OF MICHIGAN	ENGINES
9410509	2013	2016	DELPHI TECHNOLOGIES INC	ADAPTIVE INDIVIDUAL-CYLINDER THERMAL STATE CONTROL USING INTAKE AIR HEATING FOR A GDCI ENGINE
9429096	2012	2016	ROBERT BOSCH GMBH, UNIVERSITY OF WISCONSIN	PREDICTIVE MODELING AND REDUCING CYCLIC VARIABILITY IN AUTOIGNITION ENGINES
9435298	2013	2016	GENERAL MOTORS CORP	DEDICATED EGR ENGINE WITH DYNAMIC LOAD CONTROL
9441520	2015	2016	CUMMINS INC	AFTERTREATMENT SYSTEM HAVING TWO SCR CATALYSTS
9453468	2014	2016	CUMMINS INC	SYSTEM AND METHOD FOR ESTIMATING TURBOCHARGER OPERATING SPEED
9512793	2012	2016	GENERAL MOTORS CORP	COMBUSTION DRIVEN AMMONIA GENERATION STRATEGIES FOR PASSIVE AMMONIA SCR SYSTEM
9518497	2014	2016	CUMMINS INC	SYSTEM AND METHOD FOR DETERMINING THE NET OUTPUT TORQUE FROM A WASTE HEAT RECOVERY SYSTEM
WO2016054436	2015	2016	SANDIA CORP	DUCTED FUEL INJECTION
9556778	2013	2017	CUMMINS INC	WASTE HEAT RECOVERY SYSTEM INCLUDING A CLUTCHED FEEDPUMP
9556779	2014	2017	CUMMINS INC	LEAK DETECTION AND MITIGATION IN REDUCTANT DELIVERY SYSTEMS
9567888	2014	2017	CUMMINS INC	SYSTEMS AND METHODS TO REDUCE REDUCTANT CONSUMPTION IN EXHAUST AFTERTREAMENT SYSTEMS
9624857	2015	2017	CUMMINS INC	SYSTEM AND METHOD OF DPF PASSIVE ENHANCEMENT THROUGH POWERTRAIN TORQUE-SPEED MANAGEMENT
9683515	2014	2017	CUMMINS INC	WASTE HEAT RECOVERY SYSTEM INCLUDING A MECHANISM FOR COLLECTION, DETECTION AND REMOVAL OF NON-CONDENSABLE GAS
9702272	2014	2017	CUMMINS INC	RANKINE CYCLE SYSTEM AND METHOD
9714625	2011	2017	GENERAL MOTORS CORP	SYSTEM AND METHOD FOR CONTROLLING AMMONIA LEVELS IN A SELECTIVE CATALYTIC REDUCTION CATALYST USING A NITROGEN OXIDE SENSOR
9726091	2014	2017	CUMMINS INC	ACTIVE CONTROL OF ONE OR MORE EGR LOOPS
9745869	2015	2017	CUMMINS INC	SYSTEM AND METHOD FOR REGULATING EGR COOLING USING A RANKINE CYCLE

9765658	2011	2017	DELPHI TECHNOLOGIES INC	VALVE TRAIN SYSTEM FOR AN INTERNAL COMBUSTION ENGINE
9778143	2015	2017	CUMMINS INC	SYSTEM AND METHOD FOR ESTIMATING ENGINE EXHAUST MANIFOLD OPERATING PARAMETERS
9822671	2016	2017	FORD GLOBAL TECHNOLOGIES LLC	COMPOSITE HYBRID CAM CARRIER
9845772	2015	2017	CUMMINS INC	SYSTEM AND METHOD FOR MANAGING CONDENSATION IN EGR SYSTEMS
9850812	2014	2017	WISCONSIN ALUMNI RESEARCH FOUNDATION	ENGINE COMBUSTION CONTROL AT LOW LOADS VIA FUEL REACTIVITY STRATIFICATION
9850872	2014	2017	CUMMINS INC	SYSTEM AND METHOD FOR ADJUSTING ON-TIME CALIBRATION OF A FUEL INJECTOR IN INTERNAL COMBUSTION ENGINE
EP3201446	2015	2017	SANDIA CORP	DUCTED FUEL INJECTION
EP3214296	2012	2017	CUMMINS INC	RANKINE CYCLE WASTE HEAT RECOVERY SYSTEM AND METHOD WITH IMPROVED EGR TEMPERATURE CONTROL
9863305	2016	2018	DELPHI TECHNOLOGIES INC	LOW-COST HIGH-EFFICIENCY GDCI ENGINES FOR LOW OCTANE FUELS
9863306	2015	2018	DELPHI TECHNOLOGIES INC	ENGINE RESTART AID
9879580	2015	2018	CUMMINS INC	DIAGNOSTIC METHODS FOR A HIGH EFFICIENCY EXHAUST AFTERTREATMENT SYSTEM
9890717	2016	2018	CUMMINS INC	SYSTEM AND METHOD FOR ESTIMATING TURBOCHARGER OPERATING SPEED
9909517	2016	2018	CUMMINS INC	MULT-MODE CONTROLS FOR ENGINES SYSTEMS INCLUDING SCR AFTERTREATMENT
9909549	2015	2018	SANDIA CORP	DUCTED FUEL INJECTION
9915221	2016	2018	GENERAL MOTORS CORP	SYSTEM AND METHOD FOR ENGINE COMBUSTION
9915222	2015	2018	CUMMINS INC	DIESEL PISTON WITH SEMI-HEMISPHERICAL CROWN
9957911	2016	2018	GENERAL MOTORS CORP, US DEPT OF ENERGY	DEDICATED EXHAUST GAS RECIRCULATION CONTROL SYSTEMS AND METHODS
10012185	2016	2018	DELPHI TECHNOLOGIES INC	FAST GDCI HEATED AIR INTAKE SYSTEM
10018128	2016	2018	GENERAL MOTORS CORP	VARIABLE-SPEED SUPERCHARGER FOR HIGHLY

				DILUTED INTERNAL COMBUSTION ENGINES
10022667	2017	2018	CUMMINS INC	SYSTEMS AND METHODS FOR INCREASING NITROGEN DIOXIDE FRACTION IN EXHAUST GAS AT LOW TEMPERATURE
10036356	2016	2018	CATERPILLAR INC	DUCTED COMBUSTION SYSTEMS UTILIZING DUCT-EXIT TABS
10047692	2015	2018	DELPHI TECHNOLOGIES INC	GDCI COLD START MISFIRE PREVENTION
10066568	2016	2018	ROBERT BOSCH GMBH	LEARNING AN INTAKE OXYGEN CONCENTRATION OF AN ENGINE
10077727	2016	2018	GENERAL MOTORS CORP	ENGINE CONTROL SYSTEMS AND METHODS FOR NITROGEN OXIDE REDUCTION
10094306	2013	2018	PURDUE RESEARCH FOUNDATION	NONLINEAR MODEL-BASED CONTROLLER FOR PREMIXED CHARGE COMPRESSION IGNITION COMBUSTION TIMING IN DIESEL ENGINES
10100719	2016	2018	DELPHI TECHNOLOGIES INC	GDCI INTAKE AIR TEMPERATURE CONTROL SYSTEM AND METHOD
10107296	2013	2018	FORD GLOBAL TECHNOLOGIES LLC	TURBOCHARGER SYSTEMS AND METHOD TO PREVENT COMPRESSOR CHOKE
10113465	2016	2018	CUMMINS INC	SYSTEMS AND METHODS TO REDUCE REDUCTANT CONSUMPTION IN EXHAUST AFTERTREATMENT SYSTEMS
10119456	2017	2018	CATERPILLAR INC	DUCTED COMBUSTION SYSTEMS UTILIZING FLOW FIELD PREPARATION
10138855	2016	2018	NATIONAL TECH & ENG SOLUTIONS OF SANDIA LLC	DUCTED FUEL INJECTION WITH IGNITION ASSIST
10161626	2016	2018	NATIONAL TECH & ENG SOLUTIONS OF SANDIA LLC	DUCTED FUEL INJECTION
EP3299608	2017	2018	DELPHI TECHNOLOGIES INC	GASOLINE DIRECT-INJECTION COMPRESSION-IGNITION ENGINE FOR LOW OCTANE FUELS
EP3396143	2012	2018	CUMMINS INC	INTERNAL COMBUSTION ENGINE WITH RANKINE CYCLE WASTE HEAT RECOVERY SYSTEM
10202927	2012	2019	ROBERT BOSCH GMBH; UNIV MICHIGAN	FUELING STRATEGY FOR CONTROLLED-AUTOIGNITION ENGINES

Appendix B. Other DOE-Funded Advanced Combustion Patents used in the Analysis

Patent #	Application Year	Issue / Publication Year	Original Assignees	Title
4141324	1976	1979	US DEPT OF ENERGY	LOW EMISSION INTERNAL COMBUSTION ENGINE
4493297	1982	1985	GEO-CENTERS INC	PLASMA JET IGNITION DEVICE
4543930	1983	1985	SOUTHWEST RESEARCH INSTITUTE	STAGED DIRECT INJECTION DIESEL ENGINE
5061513	1990	1991	GENERAL ELECTRIC CO	PROCESS FOR DEPOSITING HARD COATING IN A NOZZLE ORIFICE
WO1991015611	1990	1991	GENERAL ELECTRIC CO	PROCESS FOR DEPOSITING HARD COATING IN A NOZZLE ORIFICE
EP0474796	1990	1992	GENERAL ELECTRIC CO	PROCESS FOR DEPOSITING HARD COATING IN A NOZZLE ORIFICE.
5373993	1992	1994	GENERAL ELECTRIC CO	APPARATUS AND PROCESS FOR DEPOSITING HARD COATING IN A NOZZLE ORIFICE
5391233	1994	1995	GENERAL ELECTRIC CO	APPARATUS FOR DEPOSITING HARD COATING IN A NOZZLE ORIFICE
5451781	1994	1995	UNIVERSITY OF CALIFORNIA	MINI ION TRAP MASS SPECTROMETER
5477046	1995	1995	UNIVERSITY OF CALIFORNIA	ELECTRON SOURCE FOR A MINI ION TRAP MASS SPECTROMETER
5526641	1993	1996	UNIVERSITY OF CHICAGO	NO.SUB.X REDUCTION METHOD
5671716	1996	1997	FORD GLOBAL TECHNOLOGIES INC	FUEL INJECTION SYSTEM AND STRATEGY
WO1997045678	1997	1997	UNIVERSITY OF CALIFORNIA	LASER PREHEAT ENHANCED IGNITION
5715677	1996	1998	UNIVERSITY OF CALIFORNIA	DIESEL NO.SUB.X REDUCTION BY PLASMA-REGENERATED ABSORBEND BEDS
5735245	1996	1998	SOUTHWEST RESEARCH INSTITUTE	METHOD AND APPARATUS FOR CONTROLLING FUEL/AIR MIXTURE IN A LEAN BURN ENGINE
5769621	1997	1998	UNIVERSITY OF CALIFORNIA	LASER ABLATION BASED FUEL IGNITION
5778664	1996	1998	BATTELLE MEMORIAL INSTITUTE	APPARATUS FOR PHOTOCATALYTIC DESTRUCTION OF INTERNAL COMBUSTION ENGINE EMISSIONS DURING COLD START
5789745	1997	1998	SANDIA CORP	ION MOBILITY SPECTROMETER USING FREQUENCY-DOMAIN SEPARATION
5803983	1996	1998	LOCKHEED MARTIN ENERGY SYSTEMS INC	METHOD FOR REMOVING SOLID PARTICULATE MATERIAL FROM WITHIN LIQUID FUEL INJECTOR

				ASSEMBLIES
5830421	1996	1998	LOW EMISSIONS TECH R&D PARTNERSHIP	MATERIAL AND SYSTEM FOR CATALYTIC REDUCTION OF NITROGEN OXIDE IN AN EXHAUST STREAM OF A COMBUSTION PROCESS
WO1998000222	1997	1998	LOW EMISSIONS TECH R&D PARTNERSHIP	MATERIAL AND SYSTEM FOR CATALYTIC REDUCTION OF NITROGEN OXIDE IN AN EXHAUST STREAM OF A COMBUSTION PROCESS
WO1998002233	1997	1998	BATTELLE MEMORIAL INSTITUTE	METHOD AND APPARATUS FOR PROCESSING EXHAUST GAS WITH CORONA DISCHARGE
5876195	1996	1999	UNIVERSITY OF CALIFORNIA	LASER PREHEAT ENHANCED IGNITION
5914015	1996	1999	BATTELLE MEMORIAL INSTITUTE	METHOD AND APPARATUS FOR PROCESSING EXHAUST GAS WITH CORONA DISCHARGE
EP0939219	1998	1999	DELPHI TECHNOLOGIES, INC.	FUEL INJECTOR
6033641	1996	2000	UNIVERSITY OF PITTSBURGH	CATALYST FOR PURIFYING THE EXHAUST GAS FROM THE COMBUSTION IN AN ENGINE OR GAS TURBINES AND METHOD OF MAKING AND USING THE SAME
6035640	1999	2000	FORD GLOBAL TECHNOLOGIES INC	CONTROL METHOD FOR TURBOCHARGED DIESEL ENGINES HAVING EXHAUST GAS RECIRCULATION
6165934	1998	2000	LOW EMISSIONS TECH R&D PARTNERSHIP	MATERIAL AND SYSTEM FOR CATALYTIC REDUCTION OF NITROGEN OXIDE IN AN EXHAUST STREAM OF A COMBUSTION PROCESS
EP1024263	2000	2000	FORD GLOBAL TECHNOLOGIES INC	CONTROL METHOD FOR TURBOCHARGED DIESEL ENGINES HAVING EXHAUST GAS RECIRCULATION
6192870	1999	2001	DELPHI TECHNOLOGIES, INC.	FUEL INJECTOR
6199519	1998	2001	SANDIA CORP	FREE-PISTON ENGINE
6260532	1999	2001	ENVERA LLC	RIGID CRANKSHAFT CRADLE AND ACTUATOR
EP1111212	2000	2001	FORD GLOBAL TECHNOLOGIES INC	EXHAUST GAS PURIFICATION SYSTEM FOR LEAN BURN ENGINE
WO2001023722	2000	2001	ENVERA LLC	RIGID CRANKSHAFT CRADLE AND ACTUATOR
WO2001030696	2000	2001	UNIVERSITY OF CALIFORNIA	CATALYSTS FOR LEAN BURN ENGINE EXHAUST ABATEMENT
6347511	1999	2002	FORD GLOBAL TECHNOLOGIES INC	EXHAUST GAS PURIFICATION SYSTEM FOR LEAN BURN ENGINE

6379411	2000	2002	BECHTEL BWXT IDAHO LLC	TWO STROKE ENGINE EXHAUST EMISSIONS SEPARATOR
EP1205235	2001	2002	CATERPILLAR INC, BATTELLE MEMORIAL INSTITUTE	METHOD AND SYSTEM FOR DIESEL ENGINE EXHAUST TREATMENT USING A COMBINATION OF NON-THERMAL PLASMA AND METAL DOPED GAMMA-ALUMINA CATALYSTS
EP1216348	2000	2002	ENVERA LLC	VARIABLE COMPRESSION RATIO ENGINE WITH AN ADJUSTABLE VALVE TIMING
WO2002014661	2001	2002	UNIVERSITY OF CALIFORNIA	APPARATUS AND METHOD FOR OPERATING INTERNAL COMBUSTION ENGINES FROM VARIABLE MIXTURES OF GASEOUS FUELS
6514470	2000	2003	UNIVERSITY OF CALIFORNIA	CATALYSTS FOR LEAN BURN ENGINE EXHAUST ABATEMENT
6551385	2001	2003	BECHTEL BWXT IDAHO LLC	TWO STROKE ENGINE EXHAUST EMISSIONS SEPARATOR
6592731	2000	2003	CERAMPHYSICS INC	AMPEROMETRIC OXYGEN SENSOR
6612269	2001	2003	UNIVERSITY OF CALIFORNIA	APPARATUS AND METHOD FOR OPERATING INTERNAL COMBUSTION ENGINES FROM VARIABLE MIXTURES OF GASEOUS FUELS
6668763	2002	2003	UNIVERSITY OF CHICAGO	PROCESS FOR IN-SITU PRODUCTION OF HYDROGEN (H2) BY ALCOHOL DECOMPOSITION FOR EMISSION REDUCTION FROM INTERNAL COMBUSTION ENGINES
WO2003031780	2002	2003	SOUTHWEST RESEARCH INSTITUTE	SYSTEMS AND METHOD FOR CONTROLLING DIESEL ENGINE EMISSIONS
WO2003044434	2002	2003	UNIVERSITY OF CALIFORNIA	MULTI-STAGE COMBUSTION USING NITROGEN-ENRICHED AIR
6708666	2001	2004	SOUTHWEST RESEARCH INSTITUTE	MULTI-ZONE COMBUSTION CHAMBER FOR COMBUSTION RATE SHAPING AND EMISSIONS CONTROL IN PREMIXED-CHARGE COMBUSTION ENGINES
6716783	2002	2004	UNIVERSITY OF CALIFORNIA	CATALYSTS FOR LEAN BURN ENGINE EXHAUST ABATEMENT
6742328	2002	2004	SOUTHWEST RESEARCH INSTITUTE	SYSTEMS AND METHODS FOR CONTROLLING DIESEL ENGINE EMISSIONS
6742335	2002	2004	CLEAN AIR POWER INC	EGR CONTROL SYSTEM AND METHOD FOR AN INTERNAL COMBUSTION ENGINE
6790030	2002	2004	UNIVERSITY OF CALIFORNIA	MULTI-STAGE COMBUSTION USING NITROGEN-ENRICHED AIR
WO2004007925	2003	2004	CLEAN AIR POWER INC	EGR CONTROL SYSTEM AND METHOD FOR AN INTERNAL COMBUSTION ENGINE
WO2004027236	2003	2004	LAWRENCE	STAGED COMBUSTION WITH

			LIVERMORE NATIONAL SECURITY LLC	PISTON ENGINE AND TURBINE ENGINE SUPERCHARGER
WO2004046520	2003	2004	WESTPORT RESEARCH INC	DIRECT INJECTION GASEOUS FUEL ENGINE WITH IGNITION ASSIST
6848408	2003	2005	UNASSIGNED	INTAKE PORT
6855303	2003	2005	SANDIA CORP	METHOD FOR SELECTIVE CATALYTIC REDUCTION OF NITROGEN OXIDES
6880344	2003	2005	UTC POWER LLC	COMBINED RANKINE AND VAPOR COMPRESSION CYCLES
6918941	2002	2005	BATTELLE ENERGY ALLIANCE LLC	CERMET MATERIALS, SELF-CLEANING CERMET FILTERS, APPARATUS AND SYSTEMS EMPLOYING SAME
6969851	2004	2005	UNIVERSITY OF CHICAGO	ION-MOBILITY SPECTROMETRY SENSOR FOR NOX DETECTION
7007472	2004	2006	CUMMINS INC	SYSTEM FOR LIMITING TURBOCHARGER ROTATIONAL SPEED
7007669	2004	2006	CATERPILLAR INC	DISTRIBUTED IGNITION METHOD AND APPARATUS FOR A COMBUSTION ENGINE
7018524	2003	2006	US DEPT OF ENERGY	REFORMULATED DIESEL FUEL
7022647	2002	2006	BATTELLE ENERGY ALLIANCE LLC	METHODS OF FABRICATING CERMET MATERIALS AND METHODS OF UTILIZING SAME
7032376	2003	2006	SOUTHWEST RESEARCH INSTITUTE	DIESEL FUEL BURNER FOR DIESEL EMISSIONS CONTROL SYSTEM
7040094	2003	2006	LAWRENCE LIVERMORE NATIONAL SECURITY LLC	STAGED COMBUSTION WITH PISTON ENGINE AND TURBINE ENGINE SUPERCHARGER
7044103	2004	2006	DRESSER INC	FUEL QUANTITY MODULATION IN PILOT IGNITED ENGINES
7077115	2005	2006	WESTPORT RESEARCH INC	DIRECT INJECTION GASEOUS FUEL ENGINE WITH IGNITION ASSIST
7081231	2000	2006	CATERPILLAR INC, BATTELLE MEMORIAL INSTITUTE	METHOD AND SYSTEM FOR THE COMBINATION OF NON-THERMAL PLASMA AND METAL/METAL OXIDE DOPED .GAMMA.-ALUMINA CATALYSTS FOR DIESEL ENGINE EXHAUST AFTERTREATMENT SYSTEM
7083765	2004	2006	UNIVERSITY OF CALIFORNIA	CATALYSTS FOR LEAN BURN ENGINE EXHAUST ABATEMENT
7096123	2003	2006	US DEPT OF ENERGY	REFORMULATED DIESEL FUEL AND METHOD
7100375	2005	2006	CUMMINS INC	SYSTEM FOR LIMITING ROTATIONAL SPEED OF A TURBOCHARGER
7153401	2003	2006	UNIVERSITY OF	CURRENT-BIASED

			CALIFORNIA	POTENTIOMETRIC NOX SENSOR FOR VEHICLE EMISSIONS
WO2006023256	2005	2006	DRESSER INC	FUEL QUANTITY MODULATION IN PILOT IGNITED ENGINES
WO2006039452	2005	2006	SOUTHWEST RESEARCH INSTITUTE	CLOSED LOOP ENGINE CONTROL FOR REGULATING NOX EMISSIONS, USING TWO-DIMENSIONSAL FUEL-AIR CURVE
7168411	2005	2007	SOUTHWEST RESEARCH INSTITUTE	CLOSED LOOP ENGINE CONTROL FOR REGULATING NOX EMISSIONS, USING A TWO-DIMENSIONAL FUEL-AIR CURVE
7278412	2005	2007	CATERPILLAR INC	COMBUSTION-GAS RECIRCULATION SYSTEM
7287522	2005	2007	CATERPILLAR INC	ENGINE SYSTEM HAVING CARBON FOAM EXHAUST GAS HEAT EXCHANGER
EP1784568	2005	2007	DRESSER INC	FUEL QUANTITY MODULATION IN PILOT IGNITED ENGINES
EP1789761	2005	2007	UNIV COLORADO STATE	LASER SPARK DELIVERY SYSTEM WITH OPTIONAL INTEGRATED OPTICAL DIAGNOSTICS
EP1801907	2006	2007	DELAVAN INC	FUEL INJECTION AND MIXING SYSTEMS AND METHODS OF USING THE SAME
EP1845252	2007	2007	DELAVAN INC	FUEL INJECTION AND MIXING SYSTEMS HAVING PIEZOELECTRIC ELEMENTS AND METHODS OF USING THE SAME
WO2007011361	2005	2007	UNIV COLORADO STATE	LASER SPARK DELIVERY SYSTEM WITH OPTIONAL INTEGRATED OPTICAL DIAGNOSTICS
WO2007075185	2006	2007	CATERPILLAR INC	ENGINE SYSTEM HAVING CARBON FOAM EXHAUST GAS HEAT EXCHANGER
7412129	2005	2008	UNIV COLORADO STATE	FIBER COUPLED OPTICAL SPARK DELIVERY SYSTEM
7420662	2005	2008	UNIV COLORADO STATE	OPTICAL DIAGNOSTICS INTEGRATED WITH LASER SPARK DELIVERY SYSTEM
7455046	2006	2008	UCHICAGO ARGONNE LLC	NITROGEN ENRICHED COMBUSTION OF A NATURAL GAS INTERNAL COMBUSTION ENGINE TO REDUCE NO _X EMISSIONS
7467621	2006	2008	CATERPILLAR INC	ENGINE AND METHOD FOR OPERATING AN ENGINE
7468089	2005	2008	BATTELLE ENERGY ALLIANCE LLC	CERMET MATERIALS
7470393	2005	2008	BATTELLE ENERGY ALLIANCE LLC	METHODS OF PRODUCING CERMET MATERIALS AND METHODS OF UTILIZING SAME
WO2008030293	2007	2008	EXXONMOBIL CO, CATERPILLAR INC	REFORMER ASSISTED LEAN NOX CATALYST AFTERTREATMENT APPARATUS AND METHOD

WO2008054568	2007	2008	CATERPILLAR INC	ENGINE AND METHOD FOR OPERATING AN ENGINE
7488462	2006	2009	OHIO STATE UNIVERSITY	MULTI-STAGE CATALYST SYSTEMS AND USES THEREOF
7625531	2005	2009	LOS ALAMOS NATIONAL SECURITY LLC	FUEL INJECTOR UTILIZING NON-THERMAL PLASMA ACTIVATION
7699033	2007	2010	UCHICAGO ARGONNE LLC	METHOD AND SYSTEM TO DISTRIBUTE HIGH-ENERGY PULSES TO MULTIPLE CHANNELS
7743602	2006	2010	EXXONMOBIL CO, CATERPILLAR INC	REFORMER ASSISTED LEAN NO _X CATALYST AFTERTREATMENT SYSTEM AND METHOD
7766251	2005	2010	DELAVAN INC	FUEL INJECTION AND MIXING SYSTEMS AND METHODS OF USING THE SAME
WO2010062457	2009	2010	CATERPILLAR INC	ENGINE CONTROL SYSTEM HAVING SPEED-BASED TIMING
WO2010062458	2009	2010	CATERPILLAR INC	ENGINE CONTROL SYSTEM HAVING FUEL-BASED ADJUSTMENT
WO2010062459	2009	2010	CATERPILLAR INC	ENGINE CONTROL SYSTEM HAVING FUEL-BASED TIMING
WO2010120533	2010	2010	DRESSER INC	CONTROLLING EXHAUST GAS RECIRCULATION IN A COMBUSTION ENGINE
7866147	2006	2011	SOUTHWEST RESEARCH INSTITUTE	SIDE BRANCH ABSORBER FOR EXHAUST MANIFOLD OF TWO-STROKE INTERNAL COMBUSTION ENGINE
7905206	2008	2011	CATERPILLAR INC	ENGINE CONTROL SYSTEM HAVING FUEL-BASED ADJUSTMENT
8074505	2008	2011	WISCONSIN ALUMNI RESEARCH FOUNDATION	INTERNAL COMBUSTION ENGINE EXHAUST FILTRATION ANALYSIS SYSTEM
8074895	2007	2011	DELAVAN INC	FUEL INJECTION AND MIXING SYSTEMS HAVING PIEZOELECTRIC ELEMENTS AND METHODS OF USING THE SAME
RE042875	2009	2011	LAWRENCE LIVERMORE NATIONAL SECURITY LLC	STAGED COMBUSTION WITH PISTON ENGINE AND TURBINE ENGINE SUPERCHARGER
RE042876	2010	2011	UNIVERSITY OF CALIFORNIA	APPARATUS AND METHOD FOR OPERATING INTERNAL COMBUSTION ENGINES FROM VARIABLE MIXTURES OF GASEOUS FUELS
8108128	2009	2012	DRESSER INC	CONTROLLING EXHAUST GAS RECIRCULATION
8113173	2008	2012	CATERPILLAR INC	ENGINE CONTROL SYSTEM HAVING SPEED-BASED TIMING
8150603	2008	2012	CATERPILLAR	ENGINE CONTROL SYSTEM

			INC	HAVING FUEL-BASED TIMING
8181891	2009	2012	GENERAL ELECTRIC CO	MONOLITHIC FUEL INJECTOR AND RELATED MANUFACTURING METHOD
EP2414659	2010	2012	DRESSER INC	CONTROLLING EXHAUST GAS RECIRCULATION IN A COMBUSTION ENGINE
EP2469065	2011	2012	CATERPILLAR INC	INTEGRATED CONTROL SYSTEM AND METHOD
8397482	2008	2013	GENERAL ELECTRIC CO	DRY 3-WAY CATALYTIC REDUCTION OF GAS TURBINE NO(SUB)X
8567355	2010	2013	CATERPILLAR INC	INTEGRATED CONTROL SYSTEM AND METHOD
WO2013003363	2012	2013	ROLLS ROYCE FUEL CELL SYSTEMS US INC	ENGINE SYSTEMS AND METHODS OF OPERATING AN ENGINE
WO2013049335	2012	2013	CONTINENTAL CONTROLS CORP	AUTOMATIC SET POINT ADJUSTMENT SYSTEM AND METHOD FOR ENGINE AIR-FUEL RATIO CONTROL SYSTEM
WO2013141984	2013	2013	UNITED TECHNOLOGIES CORP	CATALYTIC REACTION IN CONFINED FLOW CHANNEL
8771402	2012	2014	UT-BATTELLE LLC	MEMBRANE BASED APPARATUS FOR MEASUREMENT OF VOLATILE PARTICLES
EP2726188	2012	2014	LG FUEL CELL SYSTEMS INC	ENGINE SYSTEMS AND METHODS OF OPERATING AN ENGINE
EP2761154	2012	2014	CONTINENTAL CONTROLS CORP	AUTOMATIC SET POINT ADJUSTMENT SYSTEM AND METHOD FOR ENGINE AIR-FUEL RATIO CONTROL SYSTEM
WO2014032052	2013	2014	CUMMINS INC	REDUCTANT INJECTION AND MIXING SYSTEM
WO2014043563	2013	2014	CUMMINS INC	EXHAUST SYSTEM FOR SPARK-INGNITED GASEOUS FUEL ENGINE
8987161	2010	2015	UT-BATTELLE LLC	ZEOLITE-BASED SCR CATALYSTS AND THEIR USE IN DIESEL ENGINE EMISSION TREATMENT
8991149	2011	2015	GENERAL ELECTRIC CO	DRY 3-WAY CATALYTIC REDUCTION OF GAS TURBINE NOX
9118048	2011	2015	LG FUEL CELL SYSTEMS INC	ENGINE SYSTEMS AND METHODS OF OPERATING AN ENGINE
EP2828503	2013	2015	UNITED TECHNOLOGIES CORP	CATALYTIC REACTION IN CONFINED FLOW CHANNEL
EP2895713	2013	2015	CUMMINS INC	EXHAUST SYSTEM FOR SPARK-INGNITED GASEOUS FUEL ENGINE
WO2015153799	2015	2015	OREGON STATE UNIVERSITY	INTERNAL COMBUSTION ENGINE FOR NATURAL GAS COMPRESSOR OPERATION
9260994	2013	2016	CUMMINS INC	REDUCTANT INJECTION AND MIXING SYSTEM
9279394	2015	2016	CUMMINS INC	EXHAUST SYSTEM FOR SPARK-IGNITED GASEOUS FUEL

				INTERNAL COMBUSTION ENGINE
9295960	2012	2016	UNITED TECHNOLOGIES CORP	CATALYTIC REACTION IN CONFINED FLOW CHANNEL
9303575	2012	2016	CONTINENTAL CONTROLS CORP	AUTOMATIC SET POINT ADJUSTMENT SYSTEM AND METHOD FOR ENGINE AIR-FUEL RATIO CONTROL SYSTEM
9316178	2014	2016	OREGON STATE UNIVERSITY	INTERNAL COMBUSTION ENGINE FOR NATURAL GAS COMPRESSOR OPERATION
9347359	2013	2016	CUMMINS INC	AIR DITHERING FOR INTERNAL COMBUSTION ENGINE SYSTEM
9403156	2015	2016	UT-BATTELLE LLC	ZEOLITE-BASED SCR CATALYSTS AND THEIR USE IN DIESEL ENGINE EMISSION TREATMENT
9528465	2015	2016	OREGON STATE UNIVERSITY	INTERNAL COMBUSTION ENGINE FOR NATURAL GAS COMPRESSOR OPERATION
9574533	2013	2017	GENERAL ELECTRIC CO	FUEL INJECTION NOZZLE AND METHOD OF MANUFACTURING THE SAME
EP3126649	2015	2017	OREGON STATE UNIVERSITY	INTERNAL COMBUSTION ENGINE FOR NATURAL GAS COMPRESSOR OPERATION
WO2017087062	2016	2017	GENERAL ELECTRIC CO	SYSTEM AND METHOD FO EXHAUST GAS RECIRCULATION
9874158	2015	2018	LG FUEL CELL SYSTEMS INC	ENGINE SYSTEMS AND METHODS OF OPERATING AN ENGINE
9926891	2015	2018	GENERAL ELECTRIC CO	SYSTEM AND METHOD OF EXHAUST GAS RECIRCULATION
EP3346106	2013	2018	CUMMINS INC	EXHAUST SYSTEM FOR SPARK-INGNITED GASEOUS FUEL ENGINE

An Analysis of the Influence of VTO-funded Advanced Combustion Patents

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