

A Century of Environmental Technologies for Light-Duty Vehicles

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ABSTRACT

This paper provides a long-term view of the deployment of environmental technologies for light-duty vehicles in the United States and their implications for other vehicle attributes. It considers technologies for controlling tropospheric air pollutants, improving fuel economy, and reducing corollary greenhouse gas emissions. Since the introduction of the first controls to improve ambient air quality in the early 1960s, these technologies have gone from simple crankcase vapor recirculation and positive control valve systems and adjustments in carburetor air/fuel ratio and spark timing to systems that continuously control and monitor vehicle operations to optimize emissions reductions and fuel economy. Not only have these technologies produced major benefits for public health, the environment, and energy conservation, but they have also fundamentally altered the characteristics of the vehicles we drive today. And future regulations will reform the vehicle fleet even further. During the next 50 years, new vehicles will continue to be more fuel efficient, weigh less, be safer, emit fewer air pollutants, and cost more to purchase than current vehicles. These vehicles will also be less expensive to fuel and will have increased autonomy and consumer features. The impact of future regulatory demands is a continuation of a long-term regulatory trend toward a safer, cleaner, and more efficient vehicle fleet.

This paper relies in part on the vehicle-related reports developed by the National Academies of Sciences, Engineering, and Medicine for the U.S. Departments of Energy and Transportation and for the U.S. Environmental Protection Agency. The Academies are often called upon by federal agencies and by Congress to weigh in on critical science, technology, and policy issues, and the regulation of light-duty vehicles has been a long-term topic of interest of its sponsors. This paper also relies on the extensive set of materials reviewed during the course of Academies' studies.

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INTRODUCTION

This paper provides a long-term view of the deployment of environmental technologies for light-duty vehicles (passenger cars and light trucks) in the United States and their implications for other vehicle attributes. It considers technologies for controlling tropospheric air pollutants, improving fuel economy, and reducing corollary greenhouse gas emissions. Since the nationwide introduction of the first controls to improve ambient air quality in the early 1960s, these technologies have gone from simple vapor recirculation and positive control valve systems and adjustments in carburetor air/fuel ratio and spark timing to systems that continuously control and monitor vehicle operations to optimize emissions reductions and fuel economy. Not only have these technologies produced major benefits for public health, the environment, and energy conservation, but they have also fundamentally altered the design and technical content of the vehicles we drive today. And future regulations will change the light-duty vehicle (LDV) fleet even further. During the next 50 years, new LDVs will continue to be more fuel efficient, use a wider variety of energy sources, be lighter and safer, emit fewer air pollutants, and cost more to purchase than current vehicles. These vehicles will also be less expensive to fuel, or resupply with energy, and will have increased autonomy and consumer features. Combining these

innovations with changes in personal mobility and ownership models may create a transformational change to the vehicle fleet at the end of this time period. The impact of future regulatory demands is a continuation of a long-term regulatory trend toward a cleaner and more efficient LDV fleet.

This paper focuses on how technologies historically adopted solely or in large part due to environmental requirements not only have provided benefits to the environment and public health, but also have become part of the fabric of modern vehicles that provides consumer and performance benefits. Environmental technologies impact the shape of vehicles, their overall economy of use, their performance, and their externalities, which include energy security, global climate change, and health savings. These technologies impact customer satisfaction derived from their operation and include drivability; performance; fuel economy; ease of refueling; and noise, vibration, and harshness. They also impact a vehicle's cost to purchase and operate. Environmental regulations are one of the factors influencing the design of vehicles, interacting with consumer and safety requirements and manufacturers' capabilities. And penetrations of these technologies are influenced by external factors such as fuel prices. But there are several examples of fundamental changes to the design and operations of vehicles that have been due solely to

environmental and energy conservation requirements. This paper relies in part on the vehicle-related reports developed by the National Academies of Sciences, Engineering, and Medicine for the U.S. Departments of Energy (DOE) and Transportation (DOT) and for the U.S. Environmental Protection Agency (EPA). The Academies are often called upon by federal agencies and by Congress to weigh in on critical science, technology, and policy issues. The regulation of LDVs has been a long-term topic of interest of the Academies and has resulted in many committee reports on fuel economy standards, including several for the DOT's National Highway Traffic Safety Administration (NHTSA): *Automotive Fuel Economy: How Far Should We Go?* [1]; *Effectiveness and Impact of Corporate Average Fuel Economy (CAFE) Standards* [2]; *Assessment of Fuel Economy Technologies for Light-Duty Vehicles* [3]; and most recently, *Cost, Effectiveness, and Deployment of Fuel Economy Technologies for Light-Duty Vehicles* [4]. Other Academies' reports on vehicle technologies that are fundamental to this paper include reports developed for DOE (*Transitions to Alternative Vehicles and Fuels* [5]; *Transitions to Alternative Transportation Technologies—A Focus on Hydrogen* [6]; *Review of the Research Program of the U.S. DRIVE Partnership: Fourth Report* [7]; *Review of the 21st Century Truck Partnership: Third Report* [8]) and for EPA (*Modeling Mobile-Source Emissions* [9]; *Evaluating Vehicle Emissions Inspection and Maintenance Programs* [10]; *Managing Carbon Monoxide Pollution in Meteorological and Topographical Problem Areas* [11]; *State and Federal Standards for Mobile Source Emissions* [12]). This paper also relies on the extensive set of regulatory documents and other materials reviewed during the course of Academies' studies.

THE FIRST FIFTY YEARS

Legislative and Regulatory Setting

The first part of the story focuses on the impacts of environmental regulations that began in the early 1960s and extends to 2015. The controlling legislation and regulatory mandates separate the technologies adopted for air quality and for fuel economy. This separation was due historically to the differing pieces of legislation directed at improving ambient air quality, especially tropospheric emissions of hydrocarbons (HC), nitrogen oxides (NO_x), carbon monoxide (CO), and particulate matter (PM) (the Clean Air Act of 1963 and later amendments in 1970, 1977, and 1990), and directed at improving fuel economy (the Energy Policy and Conservation Act of 1975 and the Energy Independence and Security Act of 2007). It is also due to the nature of the different problems—fuel economy is controlled through improvements to efficiency, whereas ambient air quality is typically controlled through restrictions on tailpipe and evaporative emissions of trace gases. Although the subsequent April 2007 Supreme Court decision giving EPA authority to regulate the efficiency of vehicles through control of greenhouse gas emissions under the Clean Air Act, the fundamental natures of the problems continue to provide a degree of technological separation into the future. The capability to control greenhouse gas emissions by regulating the efficiency of vehicles stems from the fundamental relationship that combustion of 1 gallon of gasoline produces 8,887 grams of CO_2 . A further difference is that, while the primary costs for both programs are the costs for the technologies, the benefit estimates developed by the agencies for fuel economy are primarily a private

benefit through savings in operating costs; the benefits from reducing tropospheric emissions are from reducing externalities, primarily the lowering of negative population health outcomes and the resulting societal costs. The air quality and health benefits are complex and have been the subject of numerous Academies' studies, including *Rethinking the Ozone Problem in Urban and Regional Air Pollution* [13], *Estimating the Public Health Benefits of Proposed Air Pollution Regulations* [14], and *Air Quality Management in the United States* [15]. The report *Hidden Costs of Energy* [16] provides a comprehensive analysis and comparison of externalities associated with the atmospheric emissions from energy use.

Figure 1 shows the timing of fuel economy regulations and NO_x tailpipe standards for passenger cars. This figure shows how the standards for criteria pollutants and Corporate Average Fuel Economy (CAFE) were offset in time. After the initial pulse of CAFE tightening between 1975 and 1985, fuel economy remained relatively constant for LDVs until model year (MY) 2008 for light trucks (not shown in figure) and MY 2011 for the LDV fleet. During the same 1975 to 2011 time frame, tailpipe standards went through at least five separate periods of tightening. As discussed in subsequent sections, both sets of regulations impacted overall vehicle technologies but through different technologies and different timing on controls.

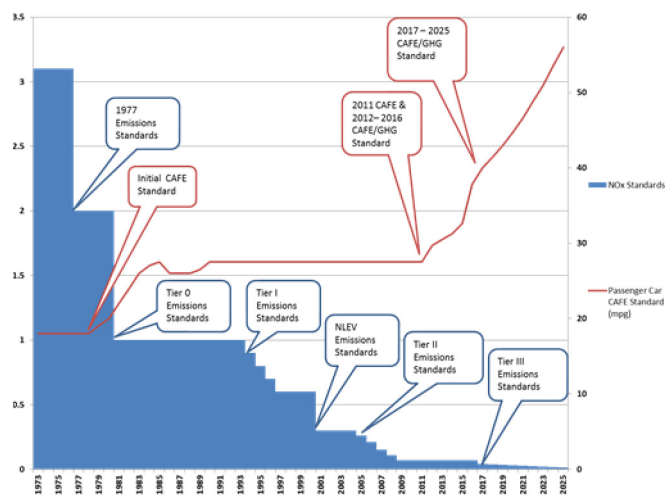


Figure 1. Passenger car CAFE and NO_x standards from 1973 to 2015. Table A1 describes the increasing durability standards associated with these progressively more stringent NO_x standards.

Air Quality Regulation and Technologies

Motivation and Regulation

The motivation for developing environmental technologies for light-duty vehicles came about with the discovery of the link between ambient air quality and automobile emissions. Prior to WWII, air pollution was typically tied to industrial or residential activities. In 1951, Arie J. Haagen-Smit explained that the formation of photochemical smog in Southern California results from the reaction of hydrocarbons and oxides of nitrogen in the presence of sunlight to form ozone [17]. This work was significant in its implication of vehicles as playing a central role in an air quality issue [5] and began

the unique role that the state of California would play in the development of automobile emissions standards for light-duty vehicles [12, 18].

A key for setting LDV emissions standards has been the concept of a “technology-forcing” standard. This is a standard requiring manufacturers to achieve an emissions limit through the use of unspecified technology or technologies that have not yet been developed for widespread commercial applications but have been shown to be feasible on an experimental or pilot-demonstration basis [12]. An example of technology-forcing standards is the new vehicle standards in the 1970 Clean Air Act Amendments. Congress wanted these standards not to be “limited by what is or appears to be technologically or economically feasible” but “to establish what the public interest requires to protect the public health of persons,” even if that means that “industries will be asked to do what seems to be impossible at the present time” [19, 20 as cited in 18]. This has brought about the coevolution of technologies and standards [12].

Table A1 summarizes the major technological eras for controlling emissions of HC, CO, NO_x, and PM. The progressive tightening of federal tailpipe standards has set off the long and sometimes contentious history of LDV emissions control among regulators, manufacturers, technology suppliers, policy-makers, and the public. Federal standards have been influenced by the California standards-setting process granted within the Clean Air Act where, in many instances, the state has adopted its tighter emissions standards a few years earlier than the federal government and in several cases pulled the national standards ahead [6]. California also pushed the deployment of zero tailpipe emissions vehicles, particularly battery-electric and fuel cell vehicles, through its zero emissions vehicle (ZEV) program. Though California’s standards-setting process requires automakers to comply with two separate standards, the U.S. Congress noted California not only had the worst air quality in the nation, but it also had been involved in motor vehicle emissions control longer than the federal government and could “offer a unique laboratory, with all the resources necessary, to develop effective control devices which can become a part of the resources of this Nation” (113 Cong. Rec. 30975 [1967]). In upholding this provision, the D.C. Circuit Court said, “Rather than being faced with 51 different standards, as they had feared, or with only one, as they had sought, manufacturers must cope with two regulatory standards under the legislative compromise” (Engine Mfrs. Ass’n v. EPA, 88 F.3d 1075, 1080 [D.C. Cir. 1996]).

Technologies

Emissions controls were grouped into three basic types (engine, evaporative, and diagnostics/durability) in the report *Evaluating Vehicle Emissions Inspection and Maintenance Programs* [10]. The initial focus was on the control of hydrocarbon emissions that leak past the piston rings and collect in the crankcase; positive crankcase ventilation systems were used to eliminate the hydrocarbon emissions through combustion by recycling them in the engine. Positive crankcase ventilation systems were required beginning with MY 1961 vehicles in California and MY 1964 vehicles nationally. The first tailpipe automobile emission standards were imposed in California in MY 1966 and nationally for MY 1968. The major approach to

emissions control over the 1968 to 1974 time period involved using engine controls, such as lean (excess air) air/fuel combustion ratios, spark timing modifications, air injection in the exhaust, and external exhaust gas recirculation. Emissions-control systems relying primarily on combustion controls usually compromised the performance and fuel economy of the engine, as it was difficult for engine design modifications alone to simultaneously control HC, CO, and NO_x emissions [10]. This National Research Council (NRC) report concluded that the use of engine design modifications coupled with exhaust aftertreatment devices represented the most successful method for meeting current and future emissions standards. As shown in Table A1, the first generation involved the development of 2-way oxidation catalyst technologies that enable further control of CO and HC, beginning in 1975. These catalysts also required the use of unleaded fuel to prevent the poisoning of the catalyst substrate.

The more fundamental modifications to vehicle technologies came about with the introduction of the 3-way catalyst technologies that allowed simultaneous control of NO_x, HC, and CO. Three-way catalysts, containing platinum and palladium for oxidation of HC and CO and rhodium for reduction of NO_x, together with cerium oxide for oxygen storage, operate efficiently within a narrow band of exhaust gas air/fuel ratios near stoichiometry, with oscillations between rich (excess fuel) and lean (excess oxygen). Implementing a system to maximize both the oxidation of HC and CO and the reduction of NO_x in the 3-way catalyst required the development of closed-loop air/fuel ratio control. Closed-loop air/fuel ratio control was needed to precisely control the air/fuel ratio at stoichiometry through all operating conditions to maximize emissions reductions. Such a system required the use of fuel injection with electronic engine control, which began as central fuel injection replacing the carburetor and later sequential port fuel injection, and exhaust gas oxygen sensors required for closed loop feedback control. In later years, as emission standards were lowered, this system also required improved fuels (e.g., reformulated gasoline, sulfur limits) and reduced oil consumption to ensure durability by reducing catalyst contamination and improving catalyst designs. Subsequent exhaust-emissions standards have primarily been met by improvements to the catalyst/controls systems, including faster catalyst light-off and improved catalyst design. Importantly, the 3-way catalyst system required the development and deployment of technologies, such as sophisticated fuel management systems and computer controls, that either had not been developed or only deployed on a small fraction of the fleet; these technologies not only enabled emissions reductions, but also increased the potential to improve vehicle performance.

During this same period, controlling emissions from LDVs also included other standards related to tailpipe emissions, evaporative emissions, and durability/inspection/OBD:

- Significant reductions in tailpipe emission to Tier 2/LEV 2 standards (Table A1),
- Increased stringency for evaporative emissions controls (Table A2),
- Development of on-board refueling vapor recovery (ORVR) systems requiring added ORVR canister and control valves with larger capacity for measuring vapor into engine (Table A2),

- Increased durability standards from 50,000 miles to 120,000 miles (150,000 miles for SULEV) and in-use testing,
- Introduction of vehicle inspection and maintenance programs [11], and
- Introduction and expansion of on-board diagnostic (OBD) systems (Table A3).

All of these required that the components of these environmental controls be married within the design and operation of the vehicle. Significantly improved performance and durability of the components resulted from these durability, inspection, and OBD requirements.

Summary of Impacts

The technologies and methods described above for controlling HC, CO, and NO_x, as well as PM emissions, can be directly linked to large improvements in ambient air quality and human health. For example, the Tier 2 emissions and gasoline sulfur control requirements estimate annualized benefit of over \$20 billion per year (1997 dollars) in year 2030, with the benefits being dominated by reduced mortality due to PM reductions [21]. While finding the importance of making such estimates, *Estimating the Public Health Benefits of Proposed Air Pollution Regulations* [14] noted the difficulty of estimating such benefits given the series of steps and assumptions that are needed to produce the analysis. Another major human health benefit has been the removal of lead from gasoline that was done at the behest of automakers to maintain the performance of catalysts. The removal of lead from gasoline has greatly reduced human exposure to lead in the ambient environment. In its retrospective study of the benefits of the Clean Air Act from 1970 to 1990, the EPA estimates that the health benefits from reducing lead exposure was second only to reducing PM [22].

Another indicator of the success of vehicle emissions controls is the improvement in ambient air quality. Figure 2 shows the three-fold reduction in ozone levels in downtown Los Angeles by 1996 from the highest level ever recorded in 1955. The reductions in ozone levels reflect reductions in vehicle hydrocarbon and oxides of nitrogen emissions, which are precursors of smog. Another example is the reduction in violations of the National Ambient Air Quality Standard for CO, for which LDVs are the dominant source. Figure 3 shows the reduction of violations for one location (Fairbanks, Alaska) that experiences severe wintertime temperature inversions. Fairbanks went from having over one hundred violations per year to zero over the period of increasing stringency of CO emissions standards. *Managing Carbon Monoxide Pollution in Meteorological and Topographical Problem Areas* [11] documents similar improvements in locations across the country that experience such inversions. Though reducing violations of ozone and PM ambient air quality standards has not progressed as fast as CO, and reductions in PM provide the vast majority of health benefits, in general, ambient air quality in the United States has improved greatly [23]. It is clear that this is partially due to the technological innovations by vehicle manufacturers and suppliers that have made quantifiable reductions in emissions and contributed to reductions in violations of ambient air quality standards. These improvements translate to significant benefits to human health.

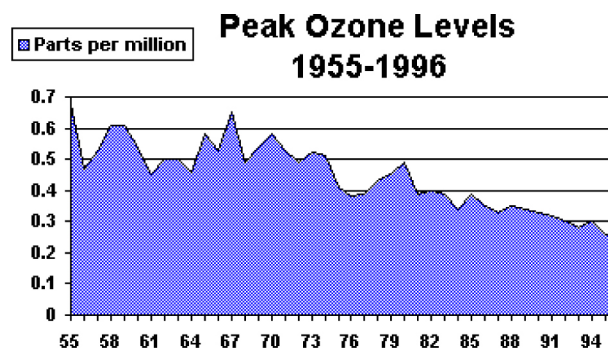


Figure 2. In 1955, when modern ozone monitoring began, downtown Los Angeles experienced the highest ozone level ever recorded—0.68 parts per million—nearly three times the highest level in 1996 [24].

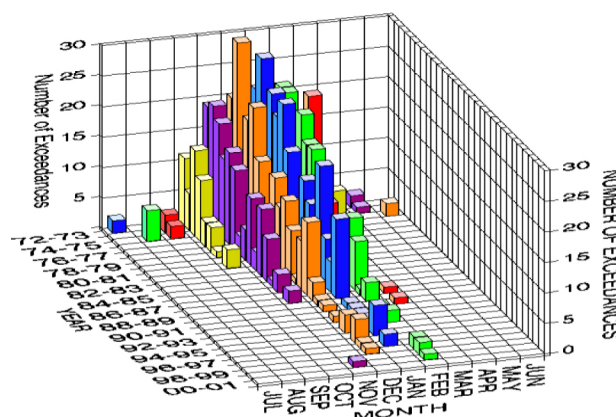


Figure 3. Reduction in number of exceedances of National Ambient Air Quality Standard for CO in Fairbanks, Alaska [11].

Some of the most fundamental changes to the design and technical content of LDVs over the past 50 years have been the fleet-wide introductions of catalytic converters and on-board computers for engine control, including fuel injection to precisely control air/fuel ratio. Their introductions were tied to the need to precisely maintain an air/fuel ratio that would allow a 3-way catalyst to maximize the reduction of tailpipe emissions of NO_x, HC, and CO. The fundamental capabilities of on-board computers for engine control have enabled other technologies such as turbocharging, variable valve timing and lift, and cylinder deactivation, for example. When combined with the use of OBD, extended durability standards, and in-use testing, consumers benefit by vehicles staying cleaner longer, requiring less routine maintenance, and providing significant improvements in drivability. Though there are other factors, these technologies contribute to the documented increase in the average age of LDVs, which has risen from 8.4 years in 1995 to 11.5 years in 2014 [25].

Fuel Economy Regulation and Technologies

Pre-Regulation of Fuel Economy

The efficiency of fuel use is a historical consideration for automotive engineering. As early as 1918, the automotive engineer Charles Kettering predicted the demise of the gasoline engine because of its inefficient fuel use: “[T]he good Lord has tolerated this foolishness of throwing away 90 percent of the energy in the fuel long enough” [26]. Over time, peak engine efficiency has improved from 10 percent