

Trends in Performance Characteristics of Modern Automobile SI and Diesel Engines

John B. Heywood and Orian Z. Welling

Sloan Automotive Laboratory, Massachusetts Institute of Technology

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ABSTRACT

A prior study (Chon and Heywood, [1]) examined how the design and performance of spark-ignition engines evolved in the United States during the 1980s and 1990s. This paper carries out a similar analysis of trends in basic engine design and performance characteristics over the past decade. Available databases on engine specifications in the U.S., Europe, and Japan were used as the sources of information. Parameters analyzed were maximum torque, power, and speed; number of cylinders and engine configuration, cylinder displacement, bore, stroke, compression ratio; valvetrain configuration, number of valves and their control; port or direct fuel injection; naturally-aspirated or turbocharged engine concepts; spark-ignition and diesel engines. Design features are correlated with these engine's performance parameters, normalized by engine and cylinder displacement.

Performance improvements (expressed as brake mean effective pressure, BMEP, and specific power) in fixed-valve-timing engines over the past decade have been modest; variable-valve control engines have improved more significantly, and substantially increased their market share. The number of naturally-aspirated engines with cylinder deactivation is growing. The percentage of turbocharged engines has increased steadily. Direct-injection gasoline engines have also increased market share, often combined with turbocharging. Compression ratios for diesels have decreased as high-speed direct-injection engines replaced indirect-injection engines, and their BMEP values have increased. For gasoline engines, compression ratio has been increasing steadily, and is

about half a ratio higher in Europe (10.5) than in the U.S. (10.0) and slightly higher in Japan (10.2). Established scaling laws for normalized engine performance continue to give good correlations over the full range of engine sizes, for each different type of engine technology. The origins of such differences in performance are differences in engine breathing, compression ratio, use of direct fuel injection and steadily increasing maximum mean piston speed.

INTRODUCTION

The past decade has seen many changes in internal combustion engines—the gasoline-fueled spark-ignition engine and the diesel—used in cars and light trucks. New ideas such as cylinder deactivation and flex fuel engines have come into production. Approaches such as variable valve control and direct gasoline injection into the cylinder, and turbocharging and engine downsizing, are increasingly being used. In addition, many detailed engine and operating changes have been implemented which improve engine specific torque and power, and reduce fuel consumption and emissions. Analyzing the basic design and performance information available on current production engines allows us to quantify and explain these trends. Both the spread of new technologies (such as direct gasoline injection) and the impact of these technologies on engine performance and key design details such as engine displacement, cylinder volume and number, compression ratio, and bore/stroke ratio are of interest.

A similar study was completed by Chon and Heywood [1] of North American (NA) model year 1985 through 1999 gasoline engines. This paper updates and extends

that study by examining the engines available in model years 2000 to 2008. The primary focus is on engines available in North America. Data on engines available in Europe and Japan were also examined, and some of the major differences between engines in these different regions are identified.

The information used in this study was obtained from engine specification databases obtained from Ward's Automotive Group [2] for the year's studied for North America, and for some of these years for Europe and Japan. These databases contain information on engine geometry and design, including number and dimensions of cylinders, engine displacement, number of valves per cylinder, valvetrain configuration and control, bore and stroke, compression ratio, fuel injection technology (into the intake port or direct in-cylinder), whether the engine is naturally-aspirated, turbocharged, or supercharged, use of cylinder deactivation, whether the engine is "flex-fuel" or diesel. They also contain engine performance information: maximum brake power, maximum engine speed, and maximum torque. This information was used to calculate the maximum brake mean effective pressure, maximum specific power, and maximum mean piston speed [3] for the various different engine configurations available. Standard scaling relationships between key engine design and operating parameters are assessed.

We will first review the major engine design trends in North America since model year 2000. We then quantify the changes in basic engine size and geometry that have occurred. Engine performance trends are examined next using the standard normalized performance parameters. The performance of these recent 2000 to 2008 model year engines are then compared with the values derived for 1985-1999 engines in our previous paper [1]. Finally, this performance data is used to assess the validity of the well-established engine performance, size, and speed scaling laws. Throughout, we attempt to explain the physical reasons behind the differences in performance of these different engine designs.

ENGINE DESIGN TRENDS

DATABASE SUMMARY - The primary database (obtained from Ward's Automotive Group [2]) gave the following information on each different engine available in light-duty vehicles in North America in each of the stated model years: fuel—gasoline/diesel/flex fuel, number of cylinders, valvetrain configuration, fixed valve timing or variable valve control, breathing—naturally-aspirated, turbocharged, supercharged, fuel injection (port or direct in-cylinder), use of cylinder deactivation, engine displacement, bore, stroke, compression ratio, maximum power, speed at maximum power, maximum

torque, speed at maximum torque, vehicle in which the engine is sold.

We also have used a comparable worldwide engine database which includes North America, Europe, and Japan, for engines produced in model years 2001 to 2005 [2]. The average normalized performance parameters calculated from these two data sets matched well for the overlapping model year engines.

The number of different engine designs available in each model year for each geographic region is substantial. For example, in the North American database the number has steadily increased from 185 in 2000 to 218 in 2008. Note that what constitutes a different engine is not that well defined. Some of the different engines are relatively minor variations of the same base engine; most are significantly different. A few incorrect data entries became obvious as we worked with the database. These were either corrected or deleted. Also, we were not able to use the 2002 database in [2]; however, since data trends with model year are well behaved, that is not critical. We do not regard these minor problems with the database as significant as we quantify and explain the trends observed. However, where the number of engines in a given category is small, the variability and scatter in the trends will obviously be larger.

DESIGN TRENDS - The breakdown between gasoline, diesel, and flex-fuel engines available in each model year, 2000 to 2008, in North America is shown in Fig. 1. Gasoline engines dominate at about 90% of the available engines. Diesels have held steady at about 4%. Flex-fuel engines are rising, and at 5% now outnumber diesels (note prior to 2007, flex-fuel engines were not identified in the database). In Europe, the diesel engine percentage is, of course, much higher, about 50%, and depends on the country; in Japan the percentage is low, some 2%.

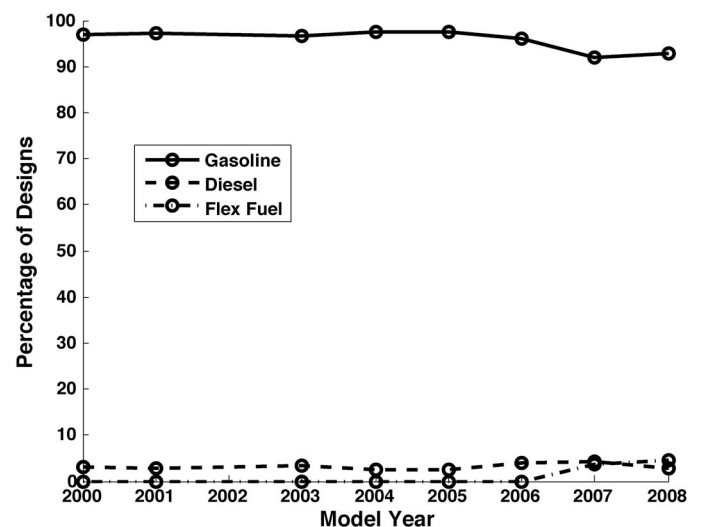


Fig. 1: Relative percentage of North American (NA) engines by fuel used versus model year.

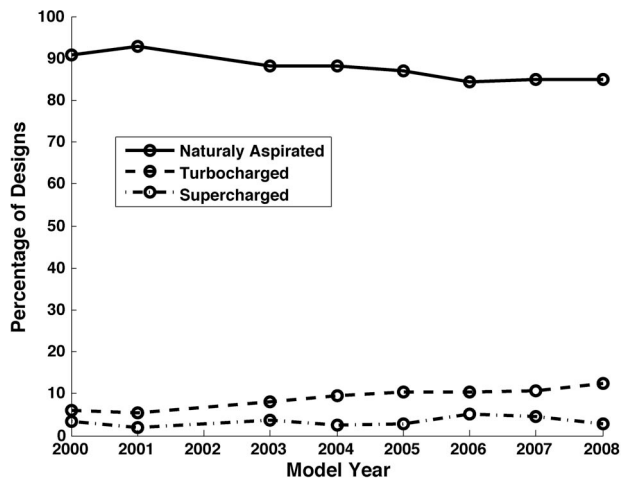


Fig. 2: Relative percentage of NA gasoline engines by breathing mode versus model year.

In North America, the percentage of gasoline engines, which are boosted, has risen steadily from 10% in model-year 2000 to 15% in 2008 (see Fig. 2). The growth is all in turbocharged gasoline engines; the number of supercharged engines is small, about 3%. In Europe the percentage of gasoline engines that are boosted in 2005 was about twice the percentage in North America: 19% turbocharged, 3.4% supercharged. The 4% of the engines that are diesel in North America are now all high-speed direct-injection turbocharged diesel engines.

In gasoline engine block design in North America, V engines increased their fraction from 60 to 67% over this eight-year period, and in-line engines have correspondingly decreased from 38 to 28%. W configured, Boxer-type opposed-piston engines now constitute about 6% of the gasoline engines available. The percentages by number of cylinders is shown in Fig. 3. In North America, 6-cylinder engines have remained at 40-45 %, while 4-cylinder engines have decreased from 34 to 26% and 8-cylinder engines increased from 22 to 27%: 5-cylinder engines have risen from less than 1% to about 2.5%. There are also similar small percentages of 10- and 12-cylinder engines (combined, in 2008, 2.5%) and there is one 3-cylinder engine.

In Europe and Japan, 4-cylinder engines now dominate the mix at 65 and 59%, respectively. In Europe, the relative percentages have changed little over the 2001-2005 period with 17% 6-cylinder and about 8% 8-cylinder engines. In Japan, 3-cylinder engines increased from 9% in 2001-2003 to 22% in 2005, with 6-cylinder engines remaining steady at 19-20% over the 2001 to 2004 period, and then decreasing to 17% in 2005. 4-cylinder engines decreased from 70% in 2003 to 59% in 2005.

The modest number of diesels in North America (4%) have evolved from 60% 8-cylinder, 20% 6- and 4-cylinder in model year 2000, to half the engines being larger displacement 6- and 8-cylinder engines and half 4-cylinder engines in 2008.

Engines with cylinder deactivation were introduced in 2004 and have risen steadily at about 1.5% per year to become 6.3% of the gasoline naturally-aspirated engines now available.

Valvetrain configurations and number of valves per cylinder have also changed significantly. In North America gasoline engines, (see Fig. 4) fixed-valve-timing engines have decreased as a percentage and variable-valve-timing engines have correspondingly increased as a percentage. The fraction of two-valve engines has steadily decreased (and is now only 13%). Four-valve per cylinder engines have continued to dominate, rising from 59% in 2000 to 70% in 2008. But the percentage of 4-valve variable control engines relative to the total number of 4-valve engines has risen from 27% to 63%. Valve actuation mechanisms are now 60% double overhead cam (DOHC) driven, 22% single overhead cam driven and 19% overhead valve push-rod systems. Use of the DOHC mechanism is steadily increasing; use of push-rod systems is decreasing.

Use of direct gasoline injection into the cylinder has also grown. Starting in 2005, DI use has risen from less than 1% to 8% of naturally-aspirated 4-valve engines in 2008, replacing some of the port-fuel-injection systems then universally used. Figure 5 shows how gasoline DI is penetrating into turbocharged engine designs, starting in model-year 2005. One-third of current turbocharged engines are using direct-injection; this constitutes about

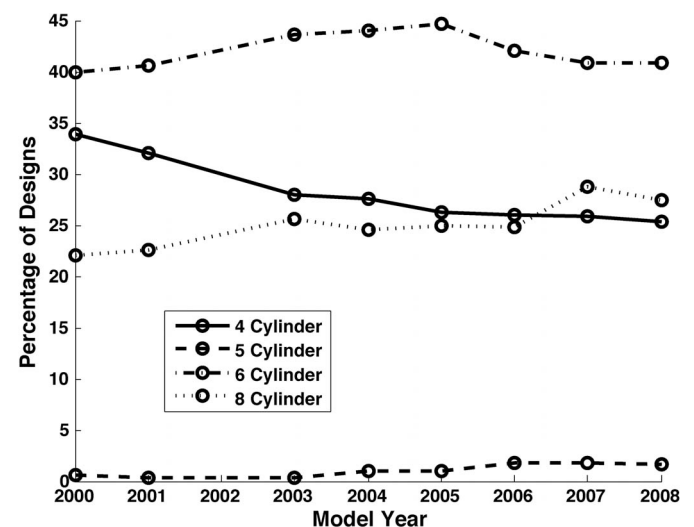


Fig. 3: Relative percentage by number of cylinders versus year: NA naturally-aspirated gasoline engines.

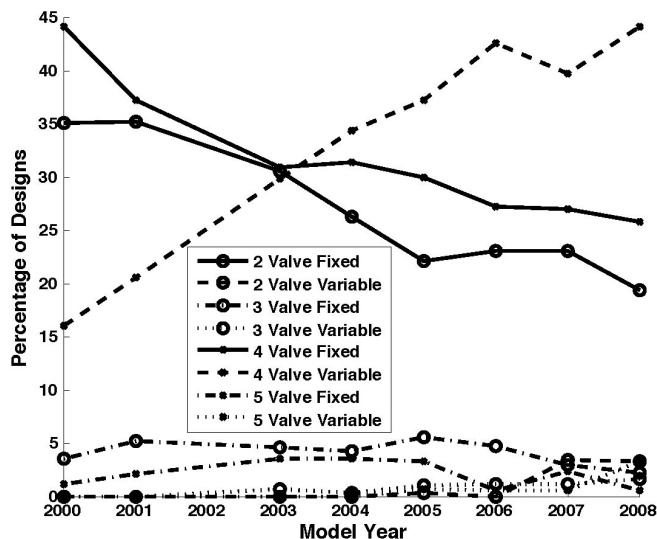


Fig. 4: Relative percentage by number of valves per cylinder, and whether fixed or variable valve control, by model year: NA naturally-aspirated gasoline engines.

two-thirds of the total current DI engines. All the high-speed automobile diesels have used direct-injection systems since 2005 model year, when use of indirect-injection diesel systems was ended.

ENGINE SIZE AND GEOMETRY - Average North American gasoline engine displacements over the time period 2000-2008 are shown in Fig. 6. Average North American diesel engine displacements are significantly larger (around 5 liters) though the number of engines is small. Gasoline engine average size has increased from 3.3 to 3.7 liters over this eight-year period: an increase of close to 1.5% per year. This trend would be expected since average vehicle performance and weight have

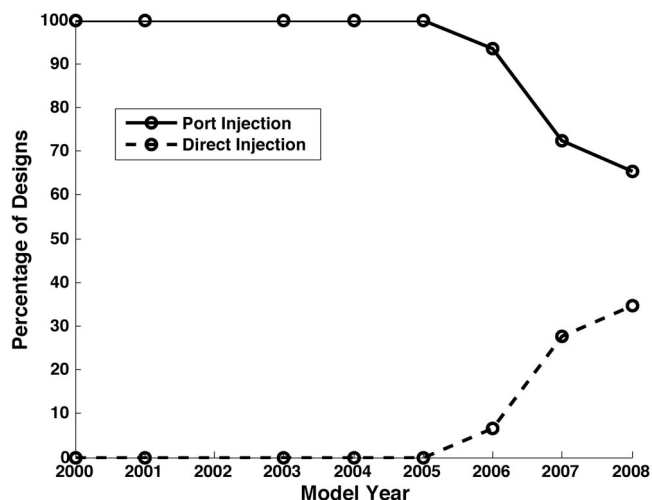


Fig. 5: Relative percentage of port and direct in-cylinder fuel injection versus model year: NA turbocharged 4-valve per cylinder gasoline engines.

both monotonically increased [4]. Average turbocharged gasoline engine displacement is smaller than that of naturally-aspirated engines, though the gap is narrowing. Supercharged engines (a small number) on average are slightly larger than the average gasoline engine size.

Figure 7 shows the trends in naturally-aspirated engine displacements for different number of cylinders. The changes over time are modest. Recent average sizes are: 4-cylinder engines, 2.1 liters; 6-cylinder engines, 3.45 liters; 8-cylinder engines, 5.05 liters. These give average cylinder volumes of 525 cm³, 575 cm³, and 630 cm³, respectively. (The small number of 5-cylinder engines causes the fluctuations in that curve.)

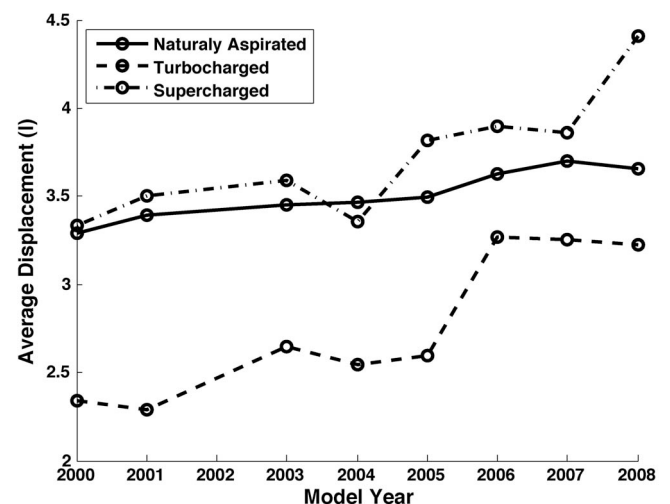


Fig. 6: Average engine displacement versus model year for NA naturally-aspirated, supercharged, and turbocharged gasoline engines.

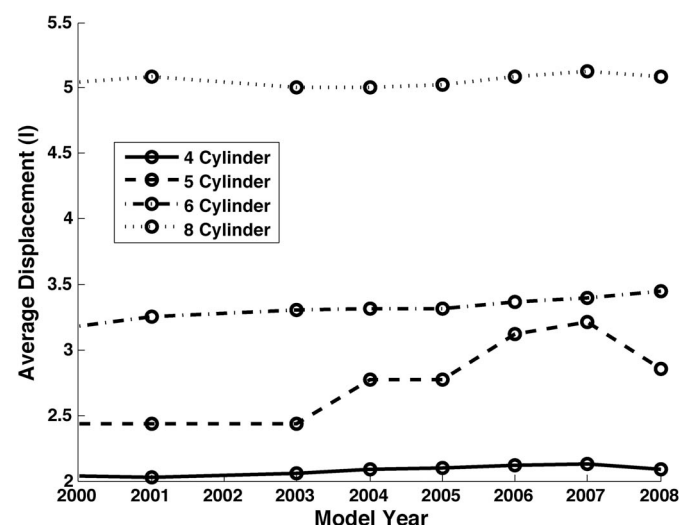


Fig. 7: Average engine displacement versus model year, by number of cylinders: NA naturally-aspirated gasoline engines.