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Life cycle energy and environmental evaluation of downsized vs. lightweight material automotive engines

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A B S T R A C T

New, stringent fuel economy and emissions regulations are putting increasing pressure on automobile manufacturers to come up with technologies that will help reach those targets. Reducing the weight of the car is one way of achieving better fuel economy during the use stage of the automobile's life cycle. This can be done by replacing the cast iron and steel in the engine with other lighter weight metals such as aluminum and magnesium. However, this change does not come without associated tradeoffs involving cost, performance, and environmental impact. Another way of increasing the fuel efficiency while maintaining the same power output is by going to a lower displacement (essentially a smaller) engine, employing direct fuel injection and turbocharging. This paper reports on a study comparing the life-cycle environmental impacts associated with the two alternatives, along with a cost analysis of the two competing technologies. A combined approach of downsizing the engine and light-weighting the entire vehicle, including the engine components, wherever feasible, is looked upon as the most preferred path to achieving greater improvements in overall lifetime energy consumption and further reductions in environmental impacts.

1. Introduction

With continued instability in gasoline prices and new fuel economy and emissions regulations that call for an average fuel economy of 35.5 miles per gallon by 2016 and 54.5 miles per gallon by 2025 (NY Times, 2012), the pressure to lightweight vehicles is stronger than ever before. Reducing the weight of the car is one way to achieve better fuel economy during the use stage of the automobile's life cycle. The engine, being one of the heaviest components, is a good candidate for weight reduction. Aluminum, which is considerably lighter in weight than cast iron, has already made phenomenal advances into the cylinder block market. Replacing the cast iron and steel with lighter weight metals such as aluminum and magnesium, however, invites the interplay of a host of factors with associated tradeoffs involving cost, performance, and environmental impact. Another way of increasing the fuel efficiency is by using lower displacement turbocharged engines, making use of technology that allows better gas mileage while maintaining the same engine power.

Turbocharging is an innovation that is based upon the internal combustion engine (ICE) powertrain and the existing fueling infrastructure (Sierzchula et al., 2012). Downsized engines, typically employing direct fuel injection and turbocharging (Petitjean et al., 2004; Zapata and Nieuwenhuis, 2010), have consistently improved in performance over the past few years. The ability of turbochargers to improve both thermal efficiency and engine specific output provides engineers improved performance or improved economy, the latter achieved not only by virtue of better thermal efficiency but also by engine downsizing, leading to vehicle weight reduction. One example of aggressive downsizing is the Mahle demonstrator engine, which is stated to have a 30% higher efficiency with 50% less displacement. For achieving its peak performance, the Mahle demonstrator engine utilizes a two-stage turbocharger design (Korte et al., 2010; Mahle, 2009). In a 2010 Automotive Engineering International Technology Report, Fred Becker of Concepts NREC states that automotive OEMs are trying to expand the operating range and effectiveness of single turbocharger, as well as two-stage systems, as they also try to understand what the next generation turbocharger design and operating characteristics will look like. Calling it a “paradigm shift” (as engine swept volumes continue to be reduced), Becker says that next generation turbos will be tailored to meet the duty cycles of four, three, and even twin-cylinder gasoline engines featuring boosting systems that integrate the turbo unit with cooled exhaust gas recirculation (EGR) and even particulate filters (AEI, 2010).

This study evaluates two different light-duty engine options, downsized vs. lightweight, and compares them to a present day,

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List of acronyms

CO_2	Carbon Dioxide
DOHC	Dual Overhead Cam
EGR	Exhaust Gas Recirculation
EOL	End-of-Life
EPA	Environmental Protection Agency
FE	Fuel Economy
GDI	Gasoline Direct Injection
GJ	Giga Joules
GWP	Global Warming Potential
HP	Horse Power
ICE	Internal Combustion Engine
IPCC	Intergovernmental Panel on Climate Change
MPCC	Magnesium Powertrain Cast Components
MPG	Miles per Gallon
NA	Naturally Aspirated
NEDC	New European Driving Cycle
OEM	Original Equipment Manufacturer
PFI	Port Fuel Injection
SF_6	Sulfur Hexafluoride
USAMP	United States Automotive Materials Partnership
VVT	Variable Valve Timing

conventional engine used in a mid-size sedan, while all maintaining the same performance level. The results are expressed in terms of the overall life-cycle impacts associated with the three options. Particular emphasis is placed on life-cycle energy and global warming impacts. The cost implications of these changes are also addressed.

2. Goals, scope, and major assumptions

The study is aimed at conducting a comparative evaluation of the energy and environmental implications of two types of light-duty vehicle engines, downsized and lightweight, with respect to a baseline engine. For this purpose, the downsized engine that utilizes gasoline direct injection (GDI) and turbocharging is a 2.0L, I4, 4-valve, dual overhead cam (DOHC), dual variable valve timing (d-VVT), turbocharged, GDI engine. The baseline is an equivalent conventional 3.0L, V6, 4-valve, DOHC, d-VVT, naturally aspirated (NA), port fuel injected (PFI) engine. Both these engine configurations are obtained from Case Study # 0102 of the US Environmental Protection Agency (EPA) Light-Duty Technology Cost Analysis report (USEPA, 2010). This study, conducted by FEV, Inc., is hereafter referred to as the EPA-FEV study. The lightweight option is a variation of the baseline engine that uses magnesium in certain engine components, wherever technically feasible.

The engine subsystem and component-level classification used in the EPA-FEV study is shown in Table 1, with the sub-subsystems and components included in our study identified in bold text. The components chosen for inclusion are based on their mass and relevance, as detailed in the assumptions that follow.

Life-Cycle Assessment (LCA) is a tool that allows us to evaluate the energy and environmental consequences of a product or manufacturing process throughout the product's life, right from the extraction of materials, through manufacturing, use, and end-of-life disposition, i.e., reuse, recycling, and/or ultimate disposal. Though the comparison is being made between the engines only, the life-cycle impacts of these engines can be assessed by including the amount of fuel consumed during the vehicle operation phase, which typically accounts for the major share of energy and environmental impacts during the automobile's life cycle. For this reason, the functional unit for LCA is taken to be an engine used in a car over its lifetime. The vehicle class defined is a mid to large size sedan that seats 4-6 passengers. The performance specifications for all three engine configurations are considered to be equivalent, with a maximum power output of approximately 225 hp and maximum torque of approximately 210 lb-ft.

The functional unit for the LCA has, therefore, been broadly defined as follows:

> *One gasoline-fueled engine with a power output of 225 hp, used in a mid-size car over its lifetime of 120,000 miles.*

The attributes of the three engines are summarized in Table 2.

As may be observed from the engine specifications provided in Table 2, the lightweight engine is assumed to be exactly the same as the baseline engine, except that certain components are made of lighter-weight magnesium instead of aluminum, thus giving it a 26 lb weight advantage over the baseline engine. The components identified for light-weighting are taken from the USAMP Magnesium Powertrain Cast Components (MPCC) project report (IBIS, 2008). These components are the Engine Block, Oil Pan, and Front Engine Cover.

Table 3 provides the details of materials contained in the components included in the assessment, and their relative contribution to the total engine weight in each of the three cases.

Table 1
Engine subsystem and component-level classification.

Engine subsystem	Sub-subsystem/components
Engine frames, mountings & brackets	Engine frames, engine mountings, hanging hardware
Crank drive	**Crankshaft**, flywheels/flexplates, connecting rods, pistons, bearing elements
Counter balance	Dynamic parts, static parts, drives
Cylinder block	**Cylinder block**, crankshaft bearing caps, bedplate, piston cooling
Cylinder head	**Cylinder head**, valve guides & seats, guides for valvetrain, camshaft bearing housing, camshaft sensors, camshaft carrier, cylinder head covers
Valvetrain	**Camshaft**, intake valves, exhaust valves, valve springs, spring retainers & keepers & seats
Timing drives	Timing wheels, **front cover**, tensioners, guides, belts, chains
Accessory drives	Pulleys, tensioners, guides, belts
Intake	**Intake manifold**, **lower intake**–**upper plenum**, air filter box, air filters, throttle housing assembly & supplies, pipes/hoses/ducting
Fuel induction	Fuel rails, fuel injectors, pressure regulators & sensors, fuel injection pumps, pipes/hoses, brackets
Exhaust	Exhaust manifold, collector pipes, catalysts, silencers (mufflers), oxygen sensors, pipes/hoses, brackets
Lubrication	**Oil pans**, oil pumps, pressure regulators& sensors, oil filters, pipes/hoses, sealing elements, heat exchangers
Cooling	Water pumps, thermostat housing, heat exchangers, pressure regulators, pipes/hoses/ducting, brackets
Induction air charging	**Turbochargers**, heat exchangers, pipes/hoses/ducting, brackets
Breather	Oil/air separator, valves, adapters, pipes/hoses/ducting
Electronic and electrical	Engine management, engine electronic, engine electrical (e.g. wiring, ignition, plugs, coils, powertrain control module)
Accessory	Starter motors, alternators, power steering pumps, air conditioning compressors

Note: Components and/or sub-subsystems in **bold** have been included for assessment in this study.