

A Study of Potential Fuel Economy Technologies to Achieve CAFE 2025 Regulations using Fleet Simulation Modeling Software

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ABSTRACT

The 2025 Corporate Average Fleet Economy (CAFE) fuel economy regulations are a significant challenge to the automotive industry. These regulations require dramatic increases in vehicle fleet fuel economy. This paper will identify and analyze a portfolio of technologies that have the potential to achieve the 2025 CAFE fuel economy targets, focusing on powertrain enhancements. The study uses a MAHLE Powertrain developed fleet modeling tool and a range of vehicle technologies and powertrain data taken from MAHLE's global research and development activities. Powertrain technologies considered include extreme engine downsizing, dilute combustion, friction reduction, hybridization, diesel and alternative fuels. The vehicle technologies analyzed include vehicle light weighting, reduced rolling resistance, advanced transmissions and improved aerodynamics.

The results of this study suggest that in order to meet CAFE 2025 fleet fuel economy regulations, a combination of advanced powertrain, drivetrain and vehicle technology changes will be required.

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INTRODUCTION

2025 CAFE regulations have forced every company connected to the automotive industry to re-think current design standards and invest in technology that pushes the boundaries of current engineering practices to improve efficiency.

New regulations also introduce new calculations, technology incentives and manufacturer specific offsets. CAFE fuel economy figures have separate calculations for passenger vehicles and light trucks based on a vehicle's "foot print" (determined by multiplying a vehicle's average track width by its wheelbase). CAFE fuel economy numbers do not reflect actual vehicle fuel economy as presented to the consumer. The fuel economy number presented to the customer on a vehicle window sticker is the Environmental Protection Agency (EPA) 2008 testing procedure that accounts for the FTP75, HWYFET, US06, SC03 and cold FTP75 laboratory drive cycle tests. For this study, the pre-2008 weighted calculation as shown in [Equation 1](#) will be utilized and uses the standard FTP-75 and HWYFET drive cycles. Differences between EPA and CAFE fuel economy calculations places the EPA "real world" published figure roughly 20% lower than the CAFE published value [1]. This is due to the CAFE calculation including specific technology credits for air conditioning, idle start/stop, electrification and solar/thermal systems that are added into the final fuel economy value for each vehicle model [1].

For example, a full-size truck with a vehicle footprint of 65 sq. ft. would be required to have a CAFE fuel economy value of 39.3 to 40.3 miles per gallon (MPG) whereas the EPA figure is only 31.4 to

32.2 MPG. For this study, only EPA calculated fuel economy and CO₂ values will be used but will be translated back to CAFE values which will then be used in the standard CAFE weighted harmonic mean calculation for a final CAFE fleet fuel economy value.

$$\text{Fuel Economy} = \frac{1}{\left(\frac{.55}{\text{FTP75}}\right) + \left(\frac{.45}{\text{HWYFET}}\right)} \quad (1)$$

The CAFE harmonic mean [equation \(2\)](#) is used to calculate the fleet average and takes into account the sales volume (n_A) for a specific model as well as the corresponding fuel economy number (f_A) for each model [2]. Due to OEMs having different numbers of models as well as sales distribution, each OEM will have a different final CAFE fleet average.

$$\frac{n_A + n_B + n_C}{\frac{n_A}{f_A} + \frac{n_B}{f_B} + \frac{n_C}{f_C}} \quad (2)$$

Industry experts have also realized that there is not one single technology that can be applied across a manufacturer's model range that will meet the 2025 CAFE standards but it will require a combination of technologies from every area of automobile design in order to meet the new legislation. [Table 1](#) demonstrates the necessary improvement in fuel economy for each vehicle class mandated by the 2025 CAFE standards.

This study will focus on using a standard OEM's 2014 Model Year vehicle fleet along with vehicle specifications and vehicle performance characteristics.

Table 1. CAFE Fleet Fuel Economy Improvement

Vehicle Class	2013 CAFE Vehicle Average [MPG]	2025 CAFE Vehicle Goal [MPG]	Percent Increase [%]
Sub-Compact Car	39.0	62.0	37.1%
Compact Car	35.5	57.0	37.7%
Mid-Size Car	38.4	52.5	26.9%
Full-Size Car	27.0	50.0	46.0%
Sports Car	24.5	55.0	55.5%
CUV A	30.0	56.5	46.9%
CUV B	25.9	50.0	48.2%
CUV Hybrid	54.0	57.0	5.3%
Small Panel Van	27.6	44.0	37.3%
SUV A	22.8	41.0	44.4%
SUV B	24.0	43.0	44.2%
SUV C	18.6	38.0	51.1%
Full-Size Truck	19.4	33.0	41.1%
Full-Size Van	17.4	33.0	47.3%

Fleet Sales Volume

CAFE 2025 standards now include a final fleet calculation that includes total yearly sales volumes by vehicle model. Figure 1 shows typical US based OEM fleet sales volumes for one OEM for one calendar year as a percentage of the OEM's total sales. These figures will be used in this paper for the baseline and final calculation of the CAFE 2025 fleet fuel economy number.

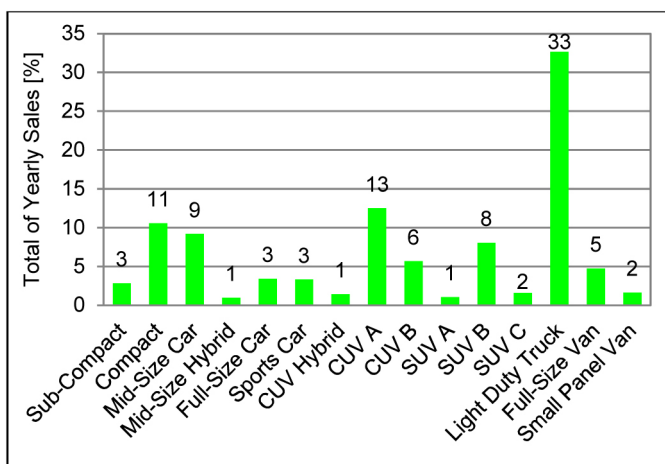


Figure 1. Typical OEM Average Yearly Sales Figures as Percentage of Total OEM Sales

ANALYSIS PACKAGE

All simulation work performed for this analysis was conducted using the MAHLE Fleet Analysis Software tool (MFAS). MAHLE Powertrain has developed the MFAS tool which can be used to analyze the fuel consumption and CO₂ burden of large fleets with a mix of vehicles and varying drive cycles. MFAS was developed for the purpose of providing commercial fleet operators a simple way of examining the impact of new technologies on their annual operating costs and CO₂ footprint.

The tool operates using backward facing calculations of individual vehicles over a given drive-cycle whereby the drive-cycle speed is imposed on the vehicle at each calculation time-step. The model then back-calculates through the driveline to determine the instantaneous engine (or motor) speed and torque requirement. If the required torque or speed is too high for the driveline, the model will determine the maximum speed that can be achieved for the current time-step. The fuel consumed (or battery state of charge) is then calculated from the speed and torque input for the current calculation step.

MFAS also includes the ability to enter an estimate of the accuracy of various user specified parameters used in the calculation, giving the ability to provide a margin of error for the calculated result. The tool can accommodate many driveline architectures, including conventional internal combustion engine (ICE) vehicles, dual fuel ICE, series hybrids, parallel hybrids and EVs. Figure 2 shows a comparison of NEDC chassis dynamometer testing against software simulation for the same mid-size passenger car. Correlation within 3% between simulated and measured fuel usage demonstrates high validity of the MFAS tool. The NEDC cycle was used as for this validation exercise as in the authors view, it exercises a wider range of the engines operating map. During development, the tool has been extensively validated against measured drive-cycle data for many vehicles.

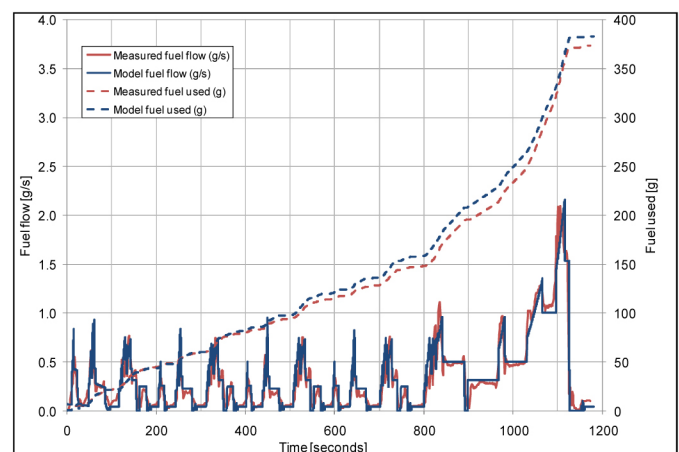


Figure 2. NEDC Drive Cycle Correlation - Chassis dynamometer results versus software simulation for a mid-sized passenger car

APPROACH

The number of new technologies currently being researched and applied to vehicles in varying combinations provides the background for the depth of this study. It was decided that technologies would be

selected based on directly measured data and published experience by MAHLE Powertrain. The first step was compiling a database comprising all the vehicles, powertrains and drivetrains contained in a typical manufacturer's fleet of vehicles using published data for all specifications to ensure accuracy. Once this database was completed, checked and verified, the process of building each vehicle/engine combination into the simulation software followed. Correlating the MFAS baseline vehicle configuration simulations against manufacturer's published data was the next step. Having correlated the simulation against published values, the margins of error defined within the tool were restricted to unquantifiable variables, such as tire rolling resistance (which is dependent on environmental conditions), vehicle aero coefficients (dependent on vehicle trim level within a specific model) and powertrains where the Brake Specific Fuel Consumption (BSFC) map was scaled from a different capacity, in order to ensure low error bands comparable to other vehicle modeling software. Once correlation was completed, the selected technologies were applied to the appropriate powertrain and vehicle combinations and the fleet simulation rerun.

Vehicle Baseline Correlation

With current OEM vehicle fleets containing multiple variants or trim levels of the same vehicle model, averages of the combined vehicle model results were used to determine the final fuel economy and emission result for each vehicle model used in the analysis of this vehicle fleet. Each individual variant was modeled with published data and then simulated in order to correlate simulated vs. published fuel economy and CO₂ results accurately [3].

Vehicle baseline fuel economy and CO₂ emissions were simulated and calculated to within $\pm 1\%$ of published values for vehicles where the BSFC map was known and $\pm 3\%$ for vehicles that were simulated with a theoretical BSFC map. Once this was complete for the entire vehicle range, new technologies were applied in different combinations depending on vehicle "footprint" and the feasibility of those technologies being applied to vehicles of that size in the future.

TECHNOLOGIES AND METHODOLOGY

Future technologies were categorized and organized into the following categories:

1. Powertrain Technology
2. Drivetrain Technology
3. Vehicle Chassis Systems Technology

Powertrain Technologies

The technologies contained in this section deal only with engine components and propulsion of the vehicle. Each technology was applied from actual testing results or taken from previous published research. The technologies chosen for this study are all single or combinations of approaches currently in development by multiple OEMs, suppliers and research centers. The data used was, as far as possible, based on MAHLE Powertrain known test data and previous

publications. There were many technologies that could have been applied but were not deemed cost effective or feasible for production by the 2025 deadlines.

Low Friction Engine Components

Much advancement is currently being made in order to reduce the mechanical energy lost to friction. Many Tier 1 manufacturers including MAHLE have lower friction components and systems available or under development. Previous work has shown an increase of up to 2% in fuel economy on the drive cycle. This was as a result of a 25% reduction in friction torque measured on a motoring engine rig after the addition of components and systems re-optimized for low friction [4]. The component changes for this study included:

- Improved piston and ring pack design
- Re-optimized crank and rod bearings
- Roller bearing camshafts
- Lightweight valves, new cam profiles and springs
- Variable oil pump and re-organized oil flow

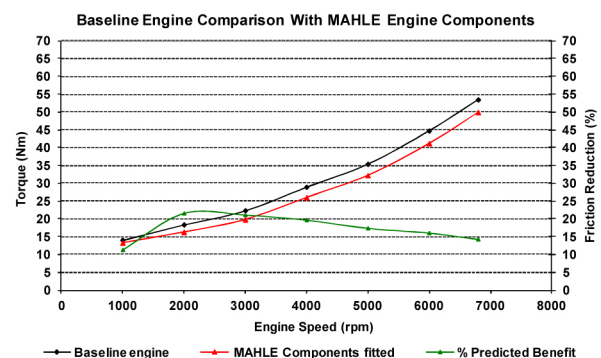


Figure 3. Friction Reduction Improvement Potential [4]

Figure 3 shows the motored friction gains measured in the engine. The referenced work included both an engine based development study leading to measured BSFC improvements and an application to a development vehicle. The vehicle was tested on the drive cycle to determine the overall fuel economy gain of 2% as stated with a further 2% potential from improved engine temperature control. For this analysis it is considered reasonable to apply a 2% vehicle fuel economy saving across the fleet.

Extreme Engine Downsizing

With the evolution of downsized gasoline turbocharged direct injected (GTDI) engines, the possibility of a production engine operating at up to 30 bar BMEP has become a future technology many companies are researching. The industry is already applying downsizing with the introduction of engines in the 20-25 bar BMEP range. It can therefore be expected that this trend will be continued within reasonable design and cost limitations. The MAHLE DI3 engine is an example of what is possible with this approach, providing 120 kW and 285 N-m, or 30bar BMEP, from a 1.2L 3-cylinder engine. Installed in a full size or D class vehicle, this engine provides equivalent performance and drivability to a production 2.4L V6 engine or to a 1.7L turbocharged engine [5]. Fuel

economy results taken from this technology demonstration prove that the 30bar BMEP downsized engine in a vehicle can achieve 30% fuel economy improvement over a V6 engine of similar performance or 10-15% over a current generation 2.0l turbo direct injection downsized engine. The research work undertaken by the authors in [4] has also demonstrated the future fuel economy improvements available when applied to this demonstrator engine. Two alternatives were considered:

1. **Aggressive Downsizing:** Development showed the capability of the engine to achieve BMEP levels, after appropriate combustion system development, of 35 bar. This study therefore takes a similarly aggressively downsized engine and applies it to the fleet. The engine capacity was scaled for each application so the existing production peak torque was met with the smaller downsized engine, see Table 2. Note: for the lower capacity variants, which are anticipated to be 2 and 3 cylinder engines, more development effort would be required to reach production readiness. Figure 4 shows the measured BSFC map.

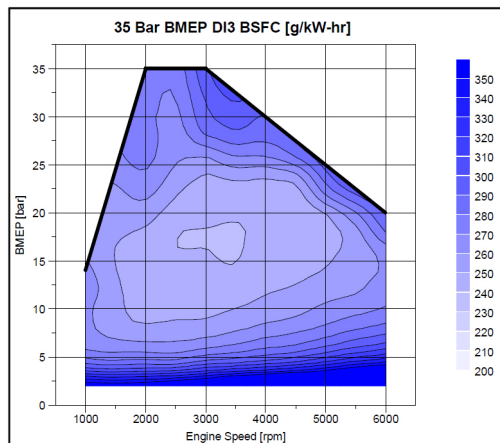


Figure 4. MAHLE DI3 Engine BSFC Map (35 Bar BMEP)

2. **Dilute Downsizing: Application of additional applicable technologies to a downsized engine:** Given the development challenges to further increased downsizing the application of additional technologies was considered based on the existing 30bar BMEP engine (see Table 3). There are a range of technologies that could be applied such as EGR, lean combustion, variable valvetrains (lift) or variable compression ratio (via variable valvetrains and Miller Cycle or via one of the many published variable compression ratio mechanisms). The measured benefits of these systems are presented in [6]. The relative differences between approaches are reasonably similar at 10 to 15% improvement over the baseline engine. For the purposes of this study, it is assumed that a combination of high and low pressure EGR is used for higher load fuel economy improvement on the downsized application plus the use of a lean combustion strategy at medium to light loads. These technologies are discussed below. The combined BSFC map is shown in Figure 8.

Table 2. 35 bar BMEP Downsized Engine Specifications

	Reduced Displacement [litre]	BMEP [bar]	Torque [Nm]
Sub-Compact Car	0.6	35	167.1
Compact Car	0.8	35	222.8
Mid-Size Car	1.0	35	278.5
Full-Size Car	1.2	35	334.2
Sports Car	1.8	35	501.3
CUV A	1.0	35	278.5
CUV B	1.8	35	501.3
Small Panel Van	0.8	35	222.8
SUV A	1.4	35	389.9
SUV B	1.8	35	501.3
SUV C	1.8	35	501.3
Full-Size Truck/Van	2.2	35	612.7

Table 3. 30 bar BMEP Downsized Engine Specifications

	Reduced Displacement [litre]	BMEP [bar]	Torque [Nm]
Sub-Compact Car	0.8	30	191.0
Compact Car	1.0	30	238.7
Mid-Size Car	1.2	30	286.5
Full-Size Car	1.4	30	334.2
Sports Car	2.2	30	525.2
CUV A	1.2	30	286.5
CUV B	2.0	30	477.5
Small Panel Van	1.0	30	238.7
SUV A	1.6	30	381.9
SUV B	2.0	30	477.5
SUV C	2.0	30	477.5
Full-Size Truck/Van	2.4	30	572.9

Lean Combustion

Lean combustion has historically been applied via stratified charge engines, made possible by gasoline direct injection. Numerous production applications have existed, most recently via Daimler using a central piezo direct injector and a multiple injection strategy. Typically around 10% fuel economy improvements have been reached. Unfortunately, operating the engine either homogeneously or in stratified regions at lambda levels between 1.2 and 1.6 results in high NO_x emissions and a subsequent need for additional aftertreatment. Beyond lambda 1.6 further fuel economy improvements can be made at considerably lower NO_x levels, provided stable combustion can be achieved. To achieve this high ignition energy is required, which is the subject of much current research. Typical methods include spark, plasma, microwave and jet ignition systems. The fuel economy savings shown in Figure 5 show the potential of a lean combustion system using a Turbulent Jet Ignition system [7]. In this case, unlike controlled auto ignition