Lubricants’ contribution to fuel economy

Final report for ATIEL EEIG

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Executive summary

The Association Technique de l'Industrie Européenne des Lubrifiants (ATIEL) commissioned Ricardo to assess the historic and potential future CO_2 savings enabled by advancements in engine lubricant technology. Recent years have seen many technological improvements to lubricants leading to a positive effect on emissions. The work in this report quantifies these effects, and their overall impact across the EU vehicle fleet (using Ricardo's SULTAN model), based on research carried out by Ricardo.

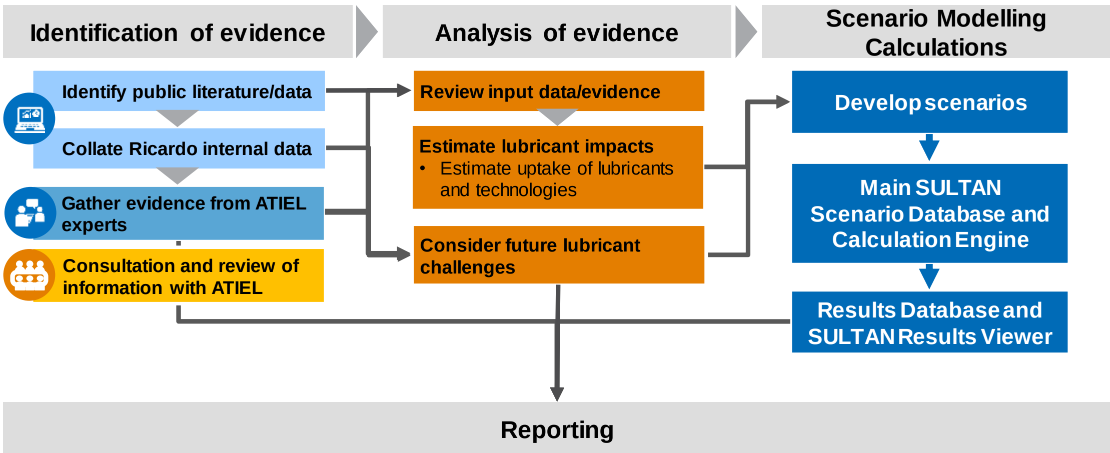
Advanced lubricants can have a number of impacts on the fuel efficiency of the vehicle and therefore the emissions of the transport system. These impacts can be considered as either direct or indirect.

Adjustments to the lubricant that have enabled a reduction in engine losses, such as friction, which reduce the engine fuel consumption are classified as direct impacts. Reduction of lubricant viscosity through base stock changes, viscosity modifiers or the addition of friction modifiers have proven to be routes to achieve this.

The indirect impacts are changes in engine technology with a fuel economy or emissions reducing effect, which would not be possible without lubricant formulation changes.

These direct and indirect impacts have been analysed for a backward-looking case (from 2005-2020) and a forward-looking case (2020-2030) in order to understand the long term impacts the lubricant industry has had on GHG emissions in the road transport sector. See Figure E1 for an overview of the methodology of the study.

Figure E1: Summary of the methodology



Ricardo has undertaken an extensive review of the literature to quantify these direct and indirect benefits, finding 212 papers for review. This, along with Ricardo proprietary information and consultation with ATIEL, fed into analysis of the direct and indirect benefits.

This analysis has shown that, for both gasoline and diesel light-duty vehicles, a wide range in the potential direct improvements is seen. Both the Ricardo and lubricant industry trend lines indicate a better fuel consumption improvement than the minimum ACEA requirements. Light commercial vehicles have similar direct lubricant impacts as these often have the same diesel engines as passenger cars.

However, for heavy-duty vehicles (trucks, buses and coaches), a narrower variation in fuel consumption for a given viscosity is seen, and there is less variation between the minimum and maximum trend lines.

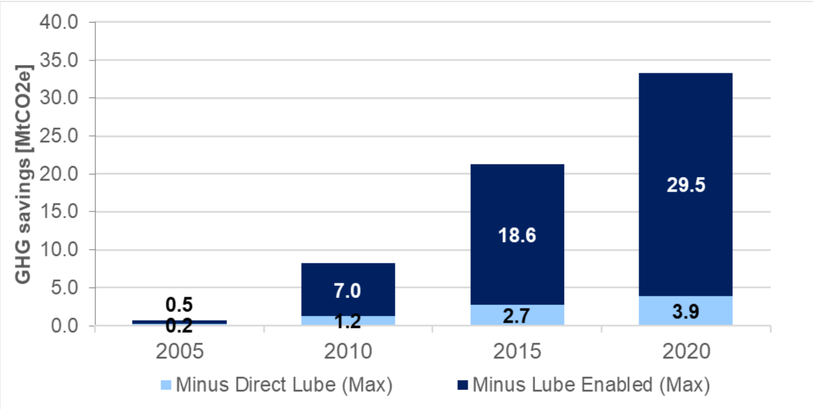
The technologies which have had, and are expected to have, an important indirect effect on light-duty CO_2 emissions include downsizing and hybridisation, ranging from stop start to full hybridisation. Low Speed Pre-Ignition (LSPI) control may enable further downsizing, and is achieved by altering lubricant additives, in particular the amount, type and ratio of calcium and magnesium detergents. Water injection and cooled Exhaust Gas Recirculation (EGR) also impact the lubricant and reduce fuel consumption.

The key indirect impacts for CO_2 reduction in heavy-duty engines are focused around increased power density and downsizing. Downsizing is only applicable for a modest part of the market (for vehicles with a payload limited by the volume rather than their mass). Other technologies which have required lubricant changes to enable their introduction are steel pistons and variable displacement oil pumps.

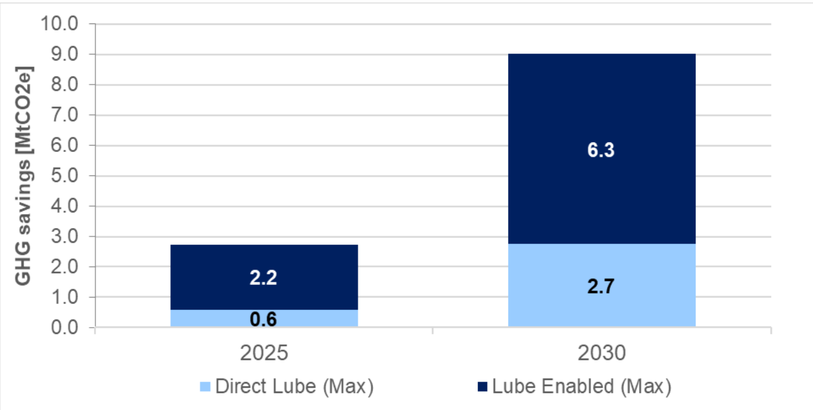
The outputs from the analysis of lubricant direct and indirect impacts on the fuel efficiency of different vehicle types, were fed directly into the SULTAN scenario modelling analysis. The amended fuel efficiency values were then used within the stock modelling process aligned to the relevant year, consequently feeding through into the overall fuel consumption of the EU vehicle parc. The results of this are shown in Figure E2.

Figure E2: Forward- and backward-looking GHG emissions reductions due to advancements in the lubrication industry

Backward-looking direct (TTW) GHG emission savings



Forward-looking direct (TTW) GHG emission savings



Note: TTW is 'tank-to-wheel', i.e. direct emissions from the vehicle exhaust.

From the road vehicle fleet scenario, it has been estimated that the direct benefit from engine lubricant technologies has led to 1.2 – 3.9 $MtCO_2e$/year of avoided emissions in 2020 (compared to 2005 lubricant technology) and will continue to reduce emissions by a further 0.9 – 2.7 $MtCO_2e$/year in 2030.

When indirect benefits are also considered, total avoided emissions have been estimated to increase by 17.8–33.4 $MtCO_2e$/year in 2020 and further reductions beyond 2020 could reach 6.0–9.0 $MtCO_2e$/year by 2030.

The backward-looking aspect of this modelling suggests that lubricants have constituted an important portion of the decarbonisation of the EU; avoided emissions indicated above account for a 2.0–4.0% reduction in GHG emissions in the year 2020 for the road transport sector, a figure which equates to almost 1% of the decarbonisation of the entire EU economy (for the 2016 EU emission figures from road transport).

The resulting cost savings from the direct and lube-enabled improvements to vehicle efficiency have been estimated to result in average annual cost saving per vehicle reaching €37–€67/year for passenger cars and €720–€1282/year for heavy trucks by 2020. Future potential *additional* annual cost savings per vehicle are estimated between €16–€25/year for cars, and €164–€207/year for heavy trucks by 2030.

The internal combustion engine is unlikely to be completely phased out soon and continues to see widespread use. In this context, it is important to see that the advancement of lubricant design has enabled a material emission reduction for a major part of the transport sector, seen since 2005, and will continue to have an impact on the wider EU emissions reduction targets through 2030 and potentially beyond.

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Abbreviation	
ACEA	European Automobile Manufacturers' Association
ASTM	American Society for Testing and Materials
ATC	Technical Committee of Petroleum Additive Manufacturers in Europe
ATIEL	Association Technique de l'Industrie Européenne des Lubrifiants
ASC	Ammonia Slip Catalyst
BAU	Business as Usual
BEV	Battery Electric Vehicle (fully electric)
BMEP	Brake Mean Effective Pressure
CAC	Charge Air Cooler
CEC	Coordinating European Council
CGI	Compacted Graphite Iron
CMP	Clean Mobility Package
CNG	Compressed Natural Gas
CO_2	Carbon Dioxide
CO_2e	Carbon Dioxide equivalent
DLC	Diamond-like Carbon
DOC	Diesel Oxidation Catalyst
DPF	Diesel Particulate Filter
EC	European Commission
EEIG	European Economic Interest Grouping
EELQMS	ATIEL European Engine Lubricants Quality Management System
EGR	Exhaust Gas Recirculation
ELR	Drive Cycle - European Load Response
ESC	Drive Cycle - European Stationary Cycle
ETC	Drive Cycle - European Transient Cycle
ETS	Emissions Trading System
EU	European Union
EV	Electric Vehicle
FAME	Fatty Acid Methyl Ester
FCEV	Fuel Cell Electric Vehicle (running on hydrogen)
FGT	Fixed Geometry Turbocharger
FIE	Fuel Injection Equipment
FQD	Fuel Quality Directive (98/70/EC)
GHG	Greenhouse Gases
GPF	Gasoline Particulate Filter
GVW	Gross Vehicle Weight

Abbreviation	
H_2	Hydrogen
HD	Heavy-Duty
HDD	Heavy-Duty Diesel
HDV	Heavy-Duty Vehicle (trucks, buses and coaches)
HEV	Hybrid Electric Vehicle
HTHS	High Temperature High Shear
HV	High Voltage
ICE	Internal Combustion Engine
ICEV	Internal Combustion Engine Vehicle
ISO	International Organisation for Standardisation
LCV	Light Commercial Vehicle (van)
LDV	Light-Duty Vehicle (Car or LCV)
LEV	Low Emission Vehicles (includes BEVs, PHEVs, REEVs and FCEVs)
LNT	Lean NOx Trap
LSPI	Low Speed Pre-Ignition
LV	Low Viscosity
MS	Member State
Mt	Mega ton (million tonnes)
NEDC	New European Drive Cycle
OEM	Original Equipment Manufacturer
PC	Passenger car
PEMS	Portable emission testing systems
PHEV	Plug-in Hybrid Electric Vehicle
PM	Particulate Matter
PN	Particle Number
POC	Particle Oxidation Catalysts
RES	Renewable Energy Sources
REEV	Range Extended Electric Vehicle
RW	Real world
SAPS	Sulphated Ash, Phosphorous and Sulphur
SCR	Selective Catalytic Reduction
SCRF	Selective Catalytic Reduction on Filter (i.e. DPF)
TC	Test cycle
TRL	Technology readiness Level
TTW	Tank-to-Wheel
TWC	Three Way Catalyst
TWLNT	Three Way Lean NOx Trap
VGT	Variable Geometry Turbocharger

Abbreviation	
WHSC	World Harmonized Stationary Cycle
WHTC	World Harmonized Transient Cycle
WLTC	Worldwide Harmonised Light Vehicle Test Cycle
WLTP	World harmonised Light-duty vehicle Test Procedure
WNTE	World-harmonised Not-To-Exceed
WTT	Well-to-Tank
WTW	Well-to-Wheel
xEV	Electric vehicles (includes BEVs, PHEVs, REEVs and FCEVs)
ZEV	Zero Emission Vehicle (includes BEV and FCEV)

1 Introduction

The Association Technique de l'Industrie Européenne des Lubrifiants (ATIEL) commissioned Ricardo to assess the historic and potential future CO_2 savings enabled by advancements in lubricant technology. In recent years, there have been many technological improvements made to lubricants resulting in a significant positive effect on emissions. These effects have been quantified using a bespoke model using Ricardo's SULTAN tool, with inputs based on research carried out by Ricardo.

The lubricant industry is aligned with the major European Union (EU) goals and policies to reduce CO_2 emissions and other greenhouse gases (GHG). Fuel efficiency improvements enabled by the industry are therefore contributing to the wider policy direction of the EU. The EU has targeted progressive GHG reduction targets by 2050, a date which a carbon neutral economy is expected. This target is enabled by the '2020 climate & energy package' adopted in 2009 (European Commission, 2009) which sets three key targets: 20% reduction in greenhouse gas emissions (compared to 1990 levels), 20% of EU energy from renewable sources, 20% improvement in energy efficiency by 2020.

More recently, the EU's climate and energy policy framework for 2030 (European Commission, 2013), agreed by Member States (MS), sets an economy-wide GHG reduction target of 40% compared to 1990 levels by 2030 (as well as a 32% share of renewable energy and a 32.5% improvement in energy efficiency). This GHG reduction target is split between the Emissions Trading System (ETS) (European Commission, 2005) and non-ETS sectors and translates to a reduction of 30% for non-ETS sectors by 2030 (compared to 2005). The Commission's White Paper on Transport (European Commission, 2011) sets out two targets for transport emissions: a 20% reduction from 2008 levels by 2030, and a 60% reduction from 1990 levels by 2050.

Road transport is a key source of emissions which must be addressed to achieve these targets. In 2016, transport contributed to 27% of the EU's total GHG emissions, with road transport accounting for 72% of these (European Commission, 2016). In this context, any reduction in fuel usage from the road transport sector has a large effect on overall system emissions.

In November 2017, the European Commission launched the 2nd Clean Mobility Package (CMP) (European Commission, 2017), setting out CO_2 standards for new cars and vans for 2021 to 2030. Since then, the revised CO_2 regulations have been finalised, meaning that average CO_2 emissions for new cars/vans would have to be 37.5%/31% lower than in 2021 (respectively) in 2030 (European Commission, 2019)[1]. Similar CO_2 standards for heavy-duty lorries/trucks, requiring 30% reduction by 2030 (versus 2019 levels), are also near finalisation (European Commission, 2018).

Advanced lubricants can have a number of impacts on the fuel efficiency of the vehicle and therefore the transport system emissions. The lubricant contributions to improving engine fuel economy (and thereby also reducing fuel costs to end-users) can be considered as either direct or indirect.

The direct impacts are those changes to the lubricant which have enabled a reduction in engine losses such as friction which reduce the engine fuel consumption. These are achieved mainly through changes to the lubricant viscosity, through either the lubricant base stock, viscosity modifiers, the addition of friction modifiers or other formulation effects to reduce engine efficiency losses.

The indirect impacts are changes in engine technology with a fuel economy or emissions reducing effect, which would not be possible without lubricant formulation changes. These may require more significant changes to the base stock, additives or formulation.

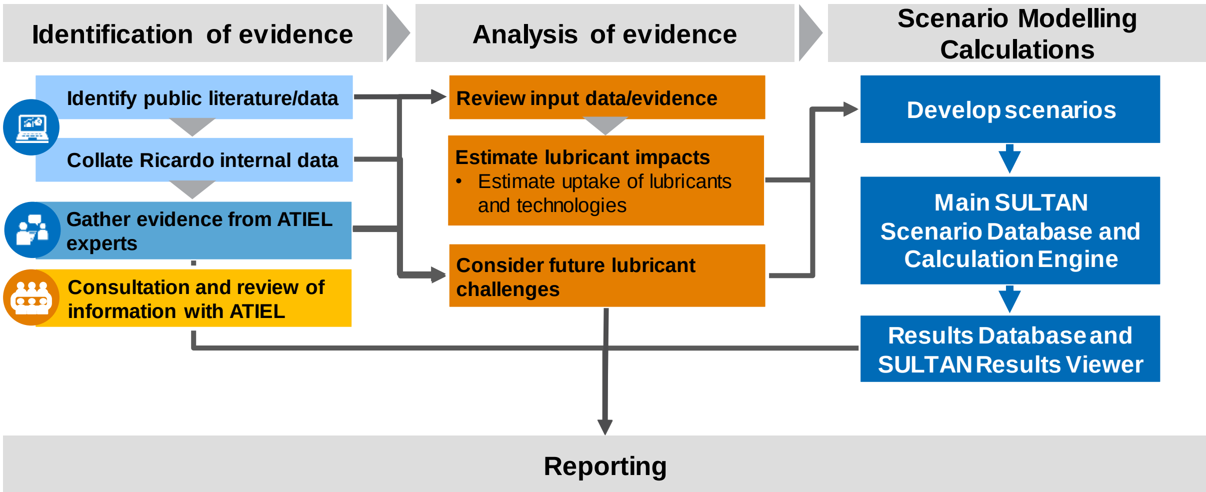
This report examines the historic and future impacts of direct and indirect contributions to fuel efficiency arising from advanced engine lubricants; an outline for the project methodology is provided in Figure 1.1.

The report is structured as follows: Chapter 2 provides a summary of the background to ATIEL and the lubricants industry. Chapter 3 provides a summary of the benefits of engine lubricants: the background legislation and technology trends is provided in Section 3.1, followed by a detailed presentation and discussion of the direct and indirect benefits of engine lubricants in Section 3.2. Finally, a discussion of the future challenges in the industry are presented in Section 3.3. This information is then used to inform

[1] A transition has been taking place in the regulatory test-cycle / test procedures from the NEDC (upon which the 2020/21 targets are based) to WLTP (Worldwide Harmonised Light-duty vehicle Test Procedure). Due to the uncertainty in the correlation between NEDC and WLTP at 2021, the post-2020 CO_2 targets will be set relative to the final WLTP values. There is therefore uncertainty on what the final gCO_2/km targets will be.

the SULTAN scenario modelling analysis, the methodology and results of which are presented in Section 3.4. A summary and conclusions drawn from this analysis is provided in the final Chapter 4, with references and technical appendices presented at the end of the report. A general overview of the methodology followed in the study is shown in Figure 1.1.

Figure 1.1: Outline of the methodology



2 Overview of ATIEL and European lubricants industry

2.1 ATIEL

ATIEL is a European Economic Interest Grouping (EEIG) representing the combined knowledge and experience of leading European and international engine oil manufacturers and marketers.

Its collective expertise in engine lubricants technology has helped establish best practices and quality standards for the benefit of both vehicle manufacturers and consumers.

ATIEL's members include the major European oil companies, as well as major global oil companies with a European presence. These companies have extensive experience in the manufacture and marketing of engine oils, often through their lubricant brands.

By drawing on the technical know-how of its membership, ATIEL promotes consensus on key technical issues, ensuring that engine oils continue to contribute to improved wear protection, deposit control, lower emissions and fuel economy.

This is achieved by publication of the *ATIEL Code of Practice* and the *ATIEL European Engine Lubricants Quality Management System* (EELQMS) Committee (ATIEL, 2019). The EELQMS has been jointly developed by the European Automobile Manufacturers' Association (ACEA), the Technical Committee of Petroleum Additive Manufacturers in Europe (ATC) and ATIEL. It aims to ensure that the lubricants on the market meet the performance claims being made about them by combining different standards, codes of practice and test methods in one system. This provides assurance that the needs of vehicle Original Equipment Manufacturers (OEMs) and consumers are met. The ATIEL Code of Practice is one element of EELQMS along with the ACEA European Oil Sequences, SAE International Standards and Coordinating European Council (CEC) Test Methods amongst others. ATIEL administers EELQMS and the ATIEL EELQMS Committee supports and promotes EELQMS, including auditing requirements, provision of training and guidance as well as monitoring lubricant field samples to assess conformance and promoting continuous improvement.

As of April 2019, 222 European companies, and a further 140 headquartered in other regions, have registered to the EELQMS Marketers' *Letter of Conformance*. This means they can make claims for their products to meet the performance requirements of ACEA.

2.2 European lubricants industry and market

2.2.1 Overview of European lubricants industry

The European lubricants industry supplied lubricants to a European passenger car parc of circa 260 million passenger cars, circa 32 million vans and 6 million trucks in 2018 (ACEA, 2018). The lubricants industry produced an estimated 3 million tonnes of automotive lubricants in 2017 (Lindemann, 2018).

The industry supply chain is split between base oil suppliers, additive suppliers and finished lubricant marketers. Base oil suppliers supply the base stock which is the bulk of on road engine lubricant by volume. Additive suppliers develop and manufacture a wide range of chemical additives with a variety of purposes which are vital for ensuring a modern lubricant satisfies the engine and customer requirements. Finished lubricant marketers blend, store and distribute the lubricants. ATIEL represents the base oil suppliers and the finished lubricant marketers, while the additive suppliers are represented by the ATC.

It is the combined technical developments of all three parts of the supply chain which result in the development of lubricants that enabled reduced emissions of CO_2 and improved fuel economy.

There are over 220 companies involved in the marketing and blending of engine lubricants, with approximately 12 companies in Europe involved in the development and production of additives.

There are many standards that a high-quality lubricant should meet; ACEA and SAE International both provide lubricant standards. ACEA provides *European Oil Sequences* (ACEA, 2019) for service-fill oils which define the minimum quality level of a lubricant for use with their member automotive manufacturers. SAE International provides standards for passenger cars, including SAE J300, *Engine Oil Viscosity Classification* (SAE International, 2015), which defines mono- and multi-grade engine oils and is used throughout the European lubricant industry. CEC, together with ASTM (American Society for Testing and Materials) and ISO (International Organisation for Standardisation), develops the *Test Methods* for performance testing of automotive engine oils.

2.2.2 The lubricants market and specification

Lubricant market

The viscosity grade of a lubricant required to be used by the OEM can vary significantly between vehicles, with a mix of different viscosities and specifications across new vehicle categories, manufacturers and engines in a given vehicle model year. Therefore, the European vehicle market at a given time point is made up of a wide mix of lubricants. This is modelled and illustrated in later Section 3.2.1 on the direct benefits of lubricants.

Lubricant specifications

There are a variety of lubricant viscosity specifications, with many OEMs having their own standards. Throughout this report multi-grade lubricants are referred to by their SAE viscosity grades (SAE International, 2015), for example 5W-30. The first number is related to the "winter viscosity", with the second number the "summer viscosity". The lower the number the lower the viscosity, which generally results in lower frictional engine losses and therefore lower fuel consumption. However, this is also dependant on the engine having been designed and manufactured for lower viscosity lubricants.

The direct lubricant contributions (a change in viscosity) are provided by changes to the component base stock, viscosity modifiers and the blending of the lubricant.

The specification of lubricant viscosity is often determined by the OEM in partnership with the lubricant manufacturer for their factory fill lubricants.

The indirect contributions to fuel economy improvement are predominately enabled by additive development together with changes in base stock (i.e. refined mineral oil versus synthetic).

ACEA

ACEA provides *European Oil Sequences* (ACEA, 2019) for service-fill oils that define different categories of lubricant. For light-duty vehicle engines (i.e. for cars and vans), the A/B class are "High SAPS" (Sulphated Ash, Phosphorous and Sulphur), while the C class are "Low SAPS" compatible with engines containing diesel or gasoline particulate filters (DPF/GPF). The E class is for heavy-duty engine oils (i.e. used in buses, coaches and trucks). Within each class there are several numbered categories, for which sequences (or specifications) are provided.

The ACEA *European Oil Sequences* specify the minimum requirements for fuel consumption improvement (i.e. direct contributions) for particular classes and categories of 2.5% for A5/B5-16 or 3.0% for C5-16 (using the CEC L-054-96 fuel economy test with the Mercedes Benz M111 engine versus a 15W-40 reference lubricant tested over the New European Driving Cycle).

The vehicle OEMs switching from A/B to C classes is an example of an indirect contribution of the lubricant to reduce emissions: the A/B class lubricants are not compatible with DPFs or GPFs; changes to the lubricant additives for the C class have allowed compatibility with these vehicle technologies and enabled them to be fitted to vehicles. The ACEA sequences are comprehensive, covering minimum viscosities at 150 ºC and 100 ºC, through to lubricant foaming tendency, oxidation, cleanliness, sludge, wear and biofuel effects.

3 The benefits of engine lubricants

3.1 Legislation and technology trends roadmap

To represent the majority of the European vehicle parc in the analysis for this study, four vehicle categories were considered, as shown in Table 3.1 below.

Table 3.1: Vehicle categories

	Category	Fuel type	Segment	Example
1	Average passenger car	Gasoline	C-segment	Citroen C4
2	Large passenger car	Diesel	D-segment	VW Passat
3	Long-haul truck	Diesel	Circa 40 tonnes gross vehicle weight (GVW)	Volvo FH12
4	Light commercial vehicle	Diesel	Delivery van	Ford Transit

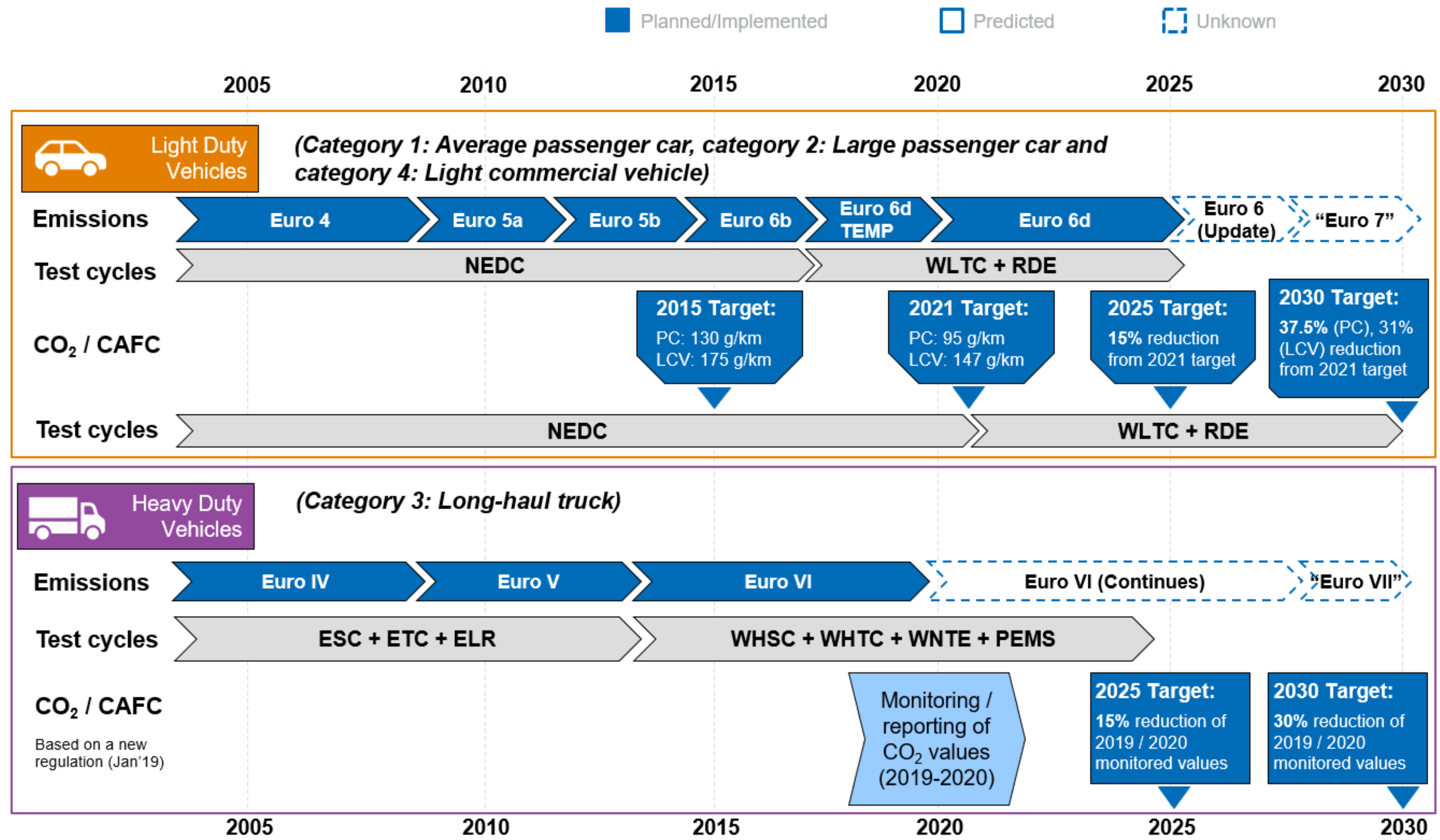
The direct benefits attributable to engine lubricant changes are discussed and analysed for these four vehicle categories, together with the indirect benefits due to the engine technologies which would not have been possible without changes to the lubricant. The assessment of impacts for the vehicle parc was considered for the years 2005, 2018 and 2030; therefore, to feed into this the technical analysis of lubricant impacts in this section considers new vehicles for the time periods of 2000, 2005, 2010, 2018 and also with predictions for 2025 and 2030.

A significant market driver for improvements to engine fuel consumption and emissions is EU legislation. Figure 3.1 shows the emissions and CO_2 reduction requirements for the different vehicle categories between 2005 and 2030, together with the vehicle test cycles for these requirements.

Throughout the 2005-2030 period a significant number of engine technology changes have or are expected to be implemented. A high-level set of roadmaps in Figure 3.2 and Figure 3.3 show the technologies for light-duty gasoline and diesel vehicles. Note that 'category 4' light commercial vehicle broadly aligns with the light-duty diesel roadmap as both categories typically share similar engines and technologies.

Figure 3.4 shows the technologies for the long-haul truck (heavy-duty diesel, HDD) category. The roadmaps show the period of a technology's mainstream deployment, which is defined as adoption by several OEMs in more than one model, or significant prominence with a single OEM. The colour of the technology indicates whether that technology is enabled by the lubricant changes since 2000 for either a CO_2 or emissions benefits. This is discussed further in Section 3.2.1.2.

Figure 3.1: Legislation roadmap for light and heavy-duty vehicles



Source: Ricardo Analysis, ICCT LD Policy Update January 2019, ICCT HD Policy Update April 2019, Transport & Environment HD Current Targets

Figure 3.2: Key engine technologies for light-duty gasoline (Category 1: Average passenger car)

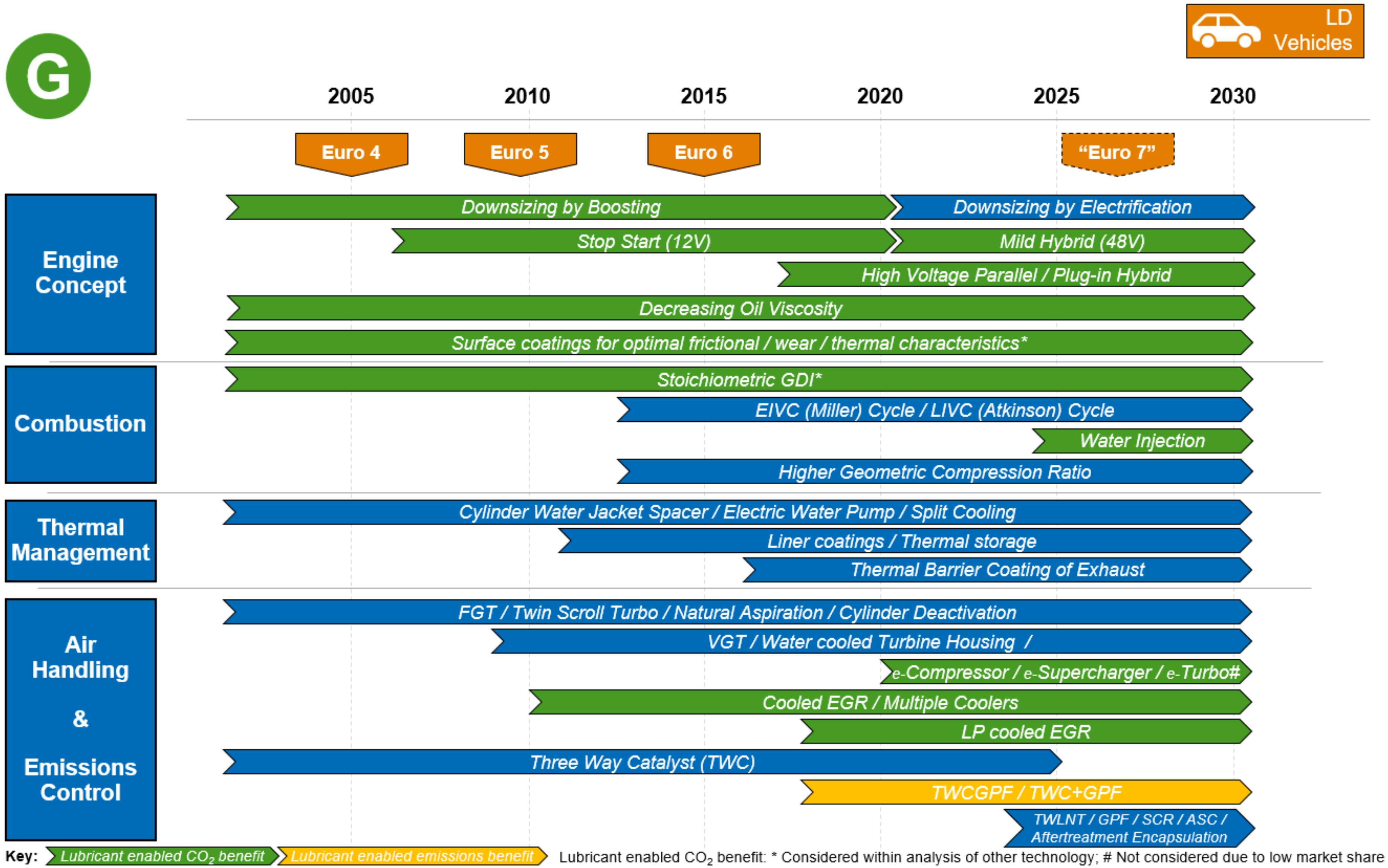


Figure 3.3: Key engine technologies for light-duty diesel (Category 2: Large passenger car and Category 4: Light commercial vehicle)

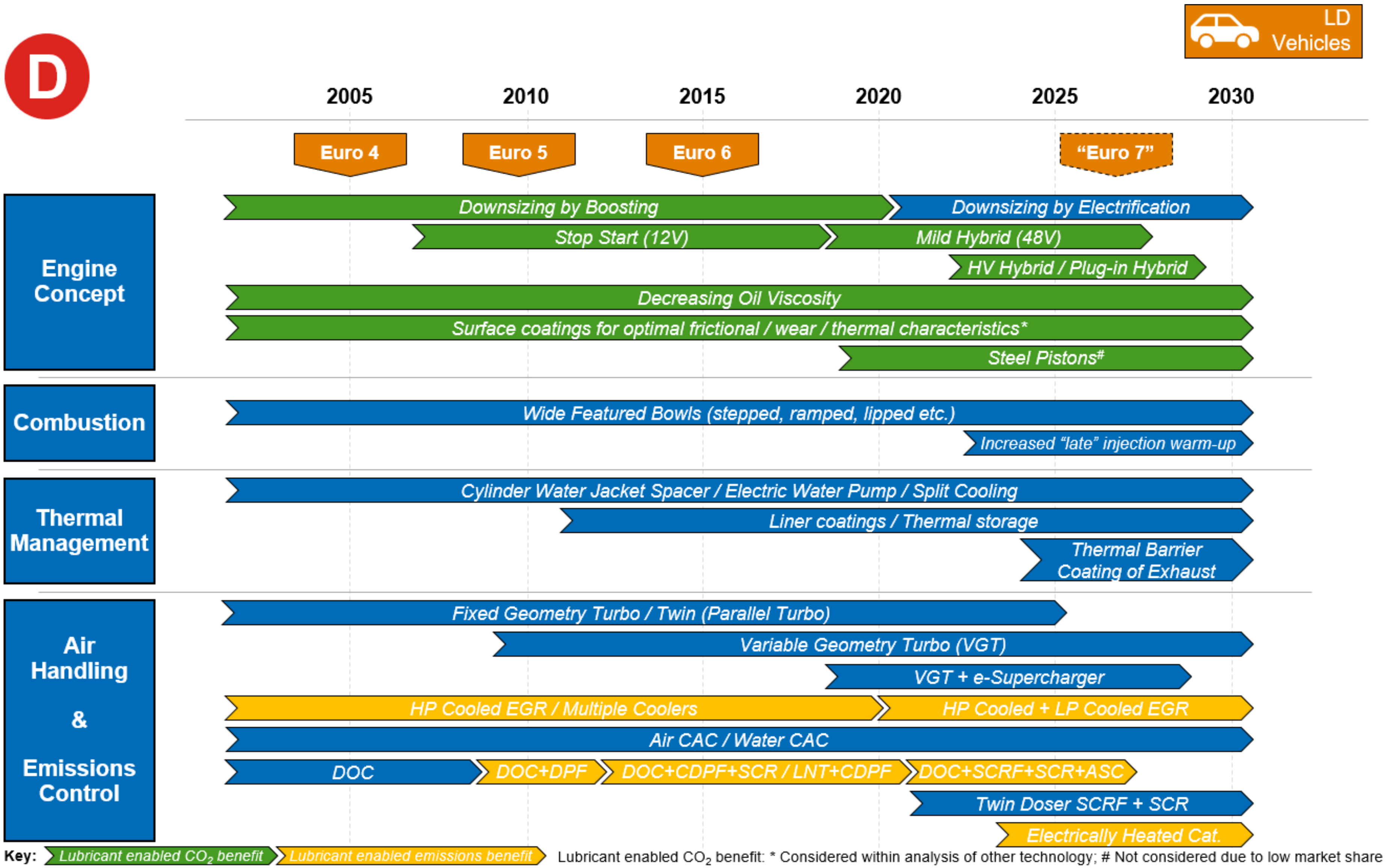
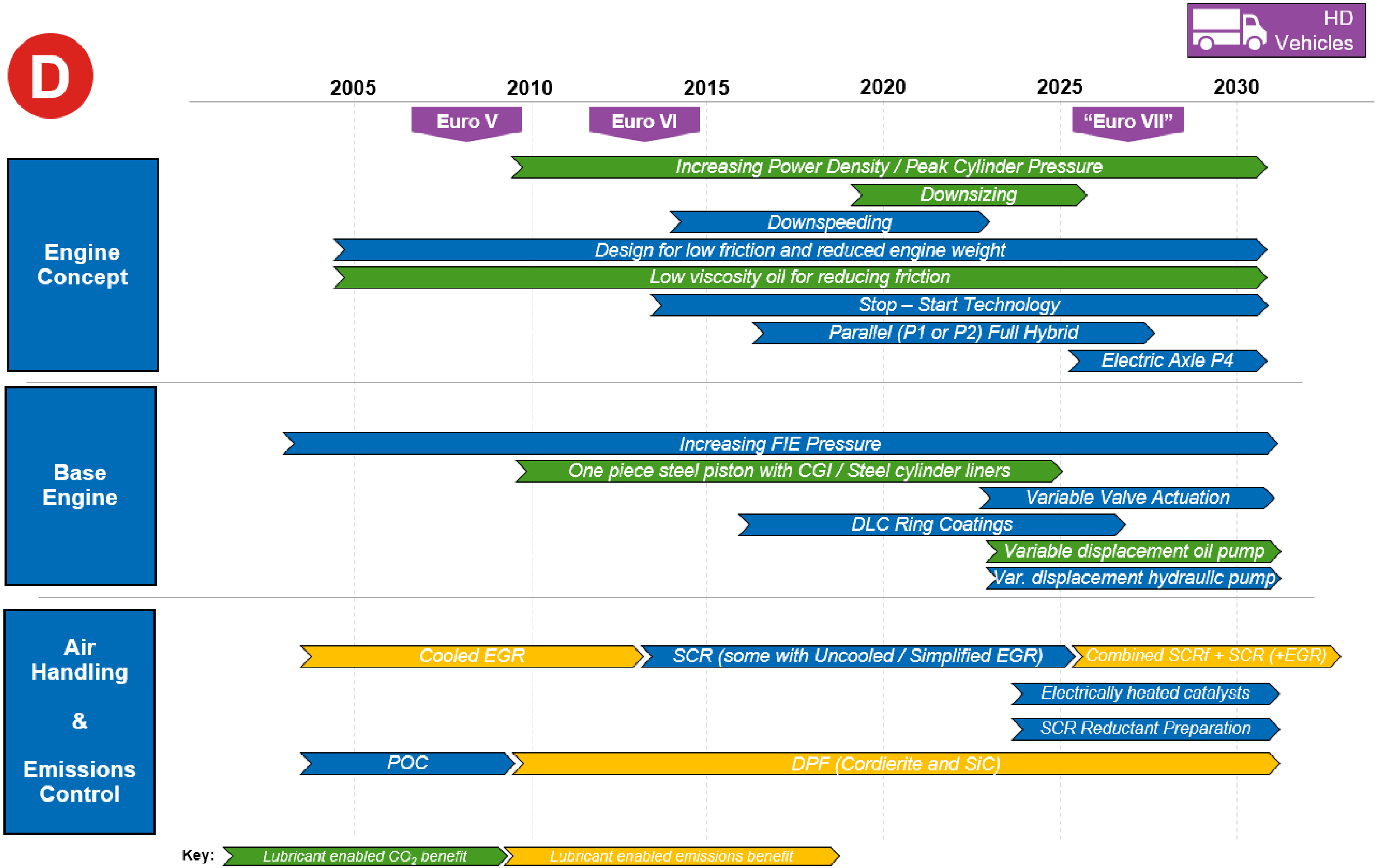


Figure 3.4: Key engine technologies for heavy-duty diesel (Category 3: Long-haul truck)



3.2 Benefits of lubricants

High level quantitative CO_2 benefits were estimated for the four vehicle classes, considering both the direct benefits attributable to changes in engine lubricant viscosity in new vehicles since the year 2000, and the indirect benefits attributable to changes in engine technology that have been enabled by lubricant changes since 2000. Throughout this study it was assumed that a reduction in CO_2 emissions is achieved directly by a reduction in fuel consumption. Potential changes in tailpipe emissions of other greenhouse gases (e.g. methane – CH_4, nitrous oxide – N_2O) were not considered.

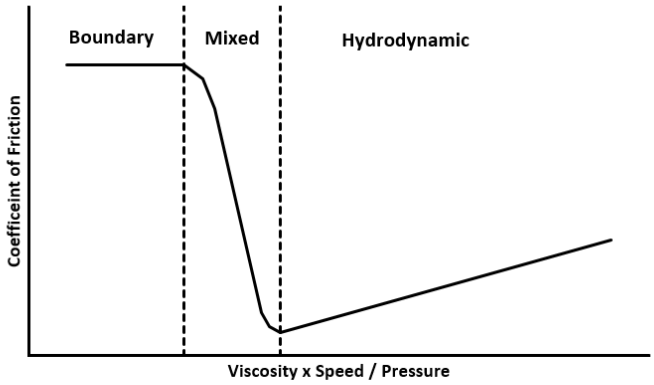
Although not quantified in this study, it should be noted that driveline lubricants also play an important role in helping to improve vehicle fuel economy and therefore in meeting CO_2 emission standards.

3.2.1 Direct benefits

The direct impacts analysed in this section are those changes to the lubricant which have enabled a reduction in engine losses, such as friction, which reduce the engine fuel consumption. These are achieved primarily through changes to lubricant viscosity, through either lubricant base stock or viscosity modifiers or through the addition of friction modifiers.

The majority of engine fuel consumption reduction is achieved by a reduction in engine friction. Engine friction is a highly complex topic, so for simplicity an engine's plain bearings can be considered a significant contribution to friction reduction due to lubricant viscosity reduction. Plain bearings in an engine include the main bearings and crankshaft bearings. The Stribeck Curve (Figure 3.5) defines the friction coefficient between two fluid lubricated surfaces, such as plain bearings. Ideally plain bearings operate in the hydrodynamic lubrication regime, where Figure 3.5 shows that a reduction in viscosity reduces the engine friction. There is little surface wear in the hydrodynamic regime. However, different bearings and different engine operation can cause time spent in the mixed regime, where sufficient fluid film is required to prevent excessive wear of the surfaces and ultimately premature engine failure. To achieve a thicker fluid film means a higher lubricant viscosity. Lubricant additives can be added to prevent wear, but these may have an undesirable effect by increasing friction. Therefore, reducing lubricant viscosity is a complex task for additive manufacturers and finished lubricant marketers, requiring significant development and engine testing to ensure the friction reduction and fuel consumption benefit does not adversely impact engine durability.

Figure 3.5: Stribeck Curve (schematic)



The direct benefits considered in this study for quantitative analysis include only changes to the lubricant viscosity, as captured by the lubricant SAE grade (such as 5W-30). Assessment of fuel economy changes due to friction modifiers is not possible; due to the confidentiality surrounding additive development, lubricant companies are not willing to divulge what additives are present in a specific lubricant when it is tested. Similarly, the uptake of additives used in the lubricants supplied to European vehicles could not be quantified either.

Therefore, there are potentially greater direct CO_2 benefits than those calculated where friction modifiers have been developed and included within lubricants since 2000.

3.2.1.1 Literature review

Ricardo undertook a comprehensive literature review to source and evaluate published literature related to engine technologies, oil properties and CO_2 benefits. The focus on this literature review was to determine data for the direct CO_2 benefits due to lubricant viscosity changes. Two industry leading powertrain sources were included in the review: the Ricardo Powerlink Database, which is the most comprehensive collection of powertrain related material in the world with over 300,000 publications, together with SAE Mobilus which contains over 200,000 publications. It should be noted, however, that these publications are not all related to lubricants.

To identify which papers were relevant to determine the direct CO_2 benefits due to lubricant viscosity changes, this literature review made use of the following search terms: 'engine lubricant', 'engine lubricant viscosity', 'engine oil', 'HTHS' and several combinations of these terms plus qualifiers (like 'friction'), totalling 30 search terms. Using those terms, and restricting the search to papers published after 2008, Ricardo experts then analysed the abstracts of the records identified and 212 relevant papers were found for review. This then resulted in 43 papers which contained quantitative fuel consumption information for the study.

Of these, only the results with a direct quantitative relationship between viscosity and fuel consumption, which were focused on commercial lubricants and applicable to the four vehicle categories, were suitable and included in the data analysed. There were seven sources suitable for inclusion in the light-duty gasoline dataset, four in the light-duty diesel dataset and five for the heavy-duty dataset. These are data points are plotted in Figure 3.10, Figure 3.11 and Figure 3.12 shown in Section 3.2.1.2.

In addition, both lubricant industry and Ricardo test data has been used to increase the number of data points. For example, this added circa 150 additional data points to form the trends plotted on the gasoline viscosity versus fuel consumption graph.

3.2.1.2 Estimates of direct CO_2 benefits

Direct benefits for new vehicles were quantified by determining and then combining two sets of trends:

1. Lubricant viscosity breakdown in the market at intervals across the 2000 to 2030 period.
2. Relative CO_2 (or fuel consumption) across the lubricant viscosity range.

The result of this analysis was an estimate of the average new vehicle contribution to fuel economy attributable to the lubricant.

This approach was taken for the three different engine types which fit the four vehicle categories:

1. Light-duty gasoline (Category 1: Average passenger car).
2. Light-duty diesel (Category 2: Large passenger car and Category 4: Light commercial vehicle).
3. Heavy-duty diesel (Category 3: Long haul diesel truck).

Lubricant viscosity breakdown across the 2000 to 2030 period

Figure 3.6 shows a summary of the approach used by Ricardo: this approach considered historical and forecast market data of the number of installed engines in Europe by OEMs to determine the key engines. Although only engines with significant production volumes were considered, circa 80% of the engine market is included in this method and it represents the mainstream. For each key engine the oil grade was determined; oil retailer recommendations and Ricardo databases were used for historical viscosity, OEM specified grades for current viscosity and Ricardo's expectations for future viscosity. Combining these gives an estimation of the viscosity split across each new vehicle market.

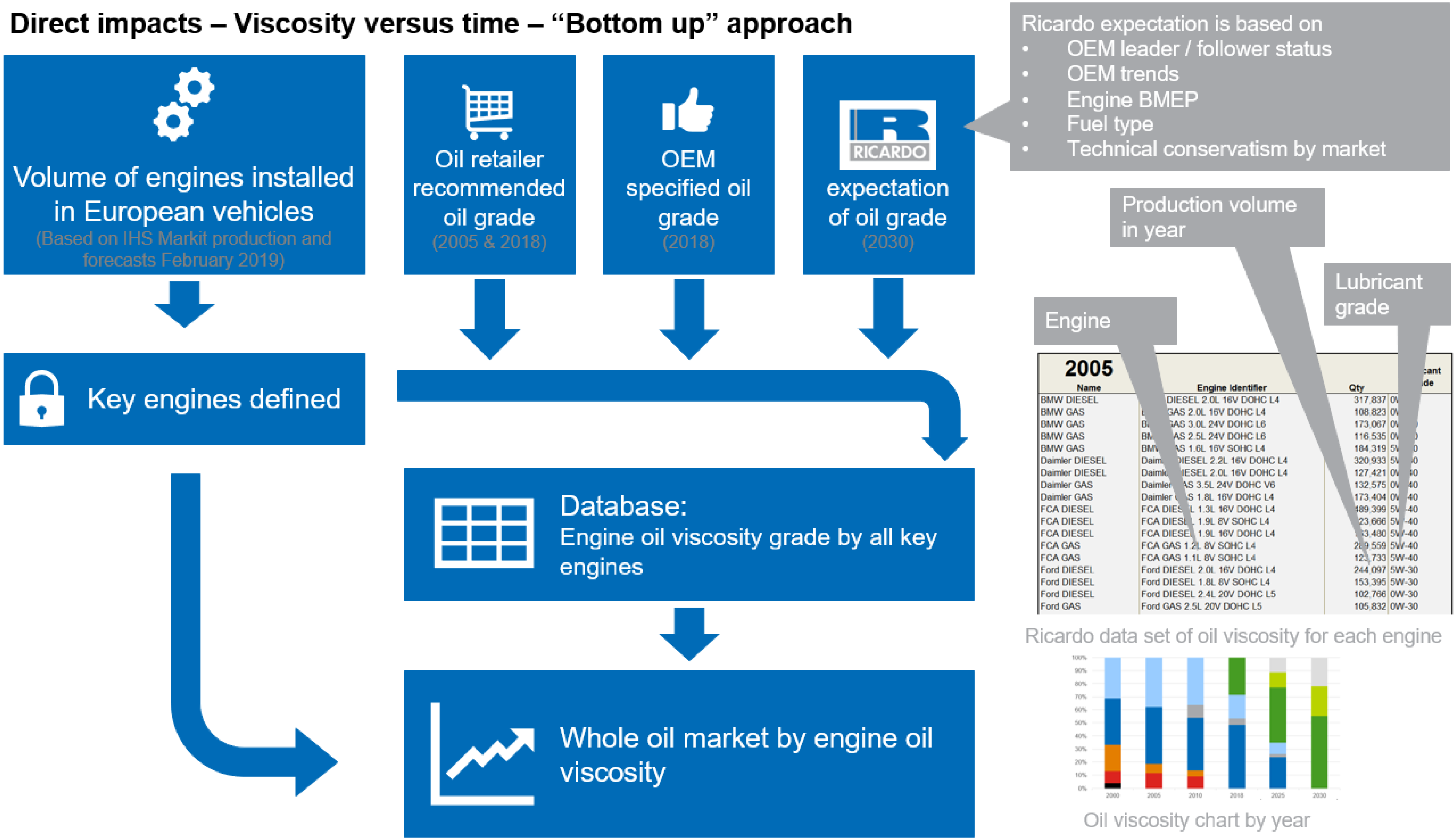
Further details on the specific assumptions made are included in Appendix A1.1. These include the number of engines produced within an engine family for it to qualify as a key engine, and the engine range considered applicable to the long-haul truck category.

Ricardo has categorised future lubricants with viscosities lower than 0W-20 into two categories:

- Low viscosity 1 (LV1), which is 0W-16.
- Low viscosity 2 (LV2), which is 0W-12 or 0W-8.

For LV2 there is uncertainty which viscosity grade will become mainstream towards 2030, as products with these viscosities are not yet available in the mainstream European market. For simplicity the same average CO_2 benefit is assumed to apply for both 0W-12 or 0W-8 in the analysis (i.e. based on the average saving for the two grades).

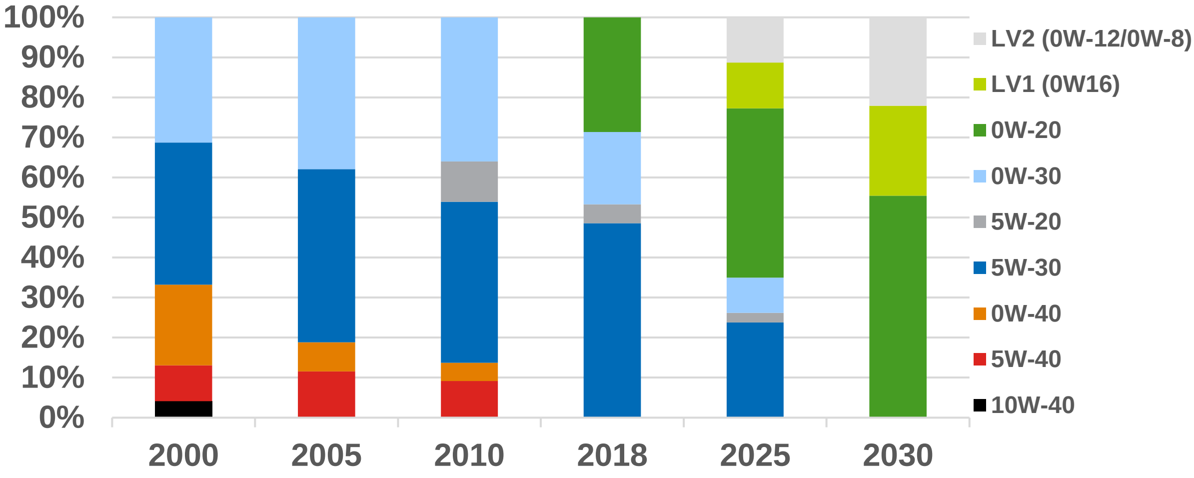
Figure 3.6: Ricardo approach to calculate lubricant specification versus time



Light-duty viscosity breakdown

The mainstream engine lubricants for new gasoline engines show a general historical trend to lower viscosity lubricants (Figure 3.7), which is expected to continue towards 2030. The 5W-40, 0W-40 and 10W-40 grades of lubricant which were specified for a third of new mainstream gasoline engines in 2000 were no longer specified by 2018. The 0W-20 grade of lubricant represents 29% of the engines in 2018, having not been present in the mainstream at 2010. The adoption of new lower viscosity lubricants by the mainstream is expected to continue towards 2030 with mainstream adoptions of 0W-16.

Figure 3.7: Estimated share of new gasoline engine lubricant viscosity by vehicle production year (Europe)

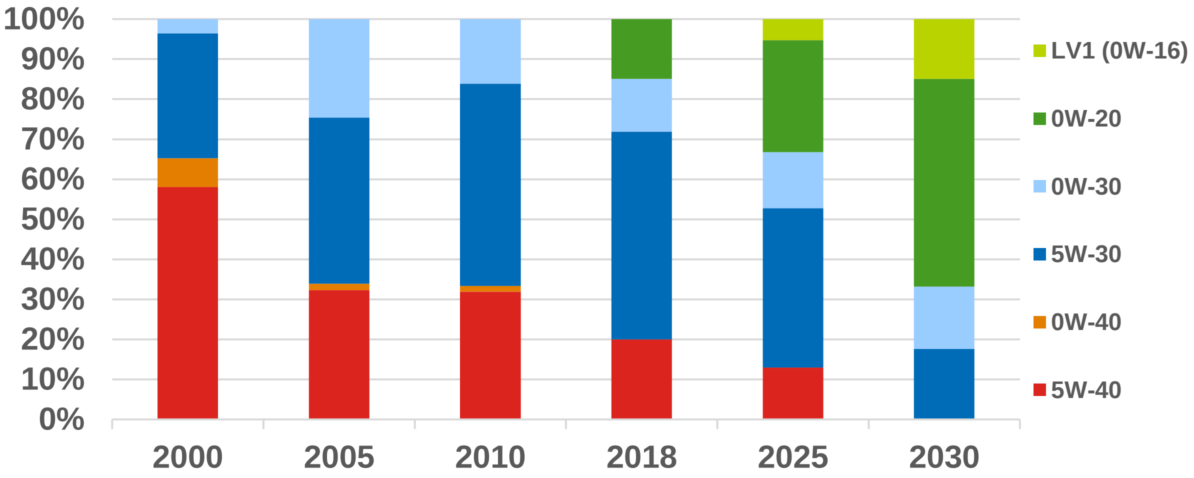


Note: 2025 and 2030 are predictions.

The adoption of LV2 lubricants (0W-12 or 0W-8) is uncertain. Significant engine design changes may be required, including to ensure sufficient film thickness for hydrodynamic operation of bearings at these low viscosities. There is some uncertainty which OEMs will follow this approach for 2030. However, given the 37.5% fleet wide passenger car CO_2 reduction required between 2021 and 2030 OEMs are expected to have to consider all possibilities to reduce fuel consumption.

Diesel passenger car and light commercial vehicle engines have a larger share of higher viscosity lubricants (Figure 3.8). They also follow a trend in the reduction of viscosity. Therefore, the future share of 0W-20 and 0W-16 lubricants is expected to be lower than for gasoline.

Figure 3.8: Estimated share of new light-duty diesel engine lubricant viscosity by vehicle production year (Europe)

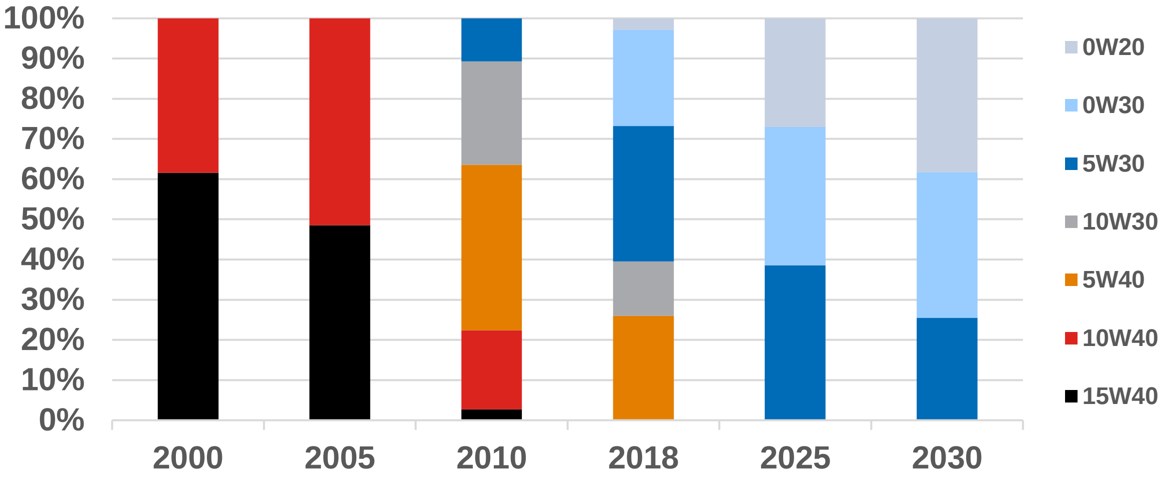


Note: 2025 and 2030 are predictions.

Heavy-duty engine viscosity breakdown

HDD engine lubricant viscosity for new long-haul trucks (Figure 3.9) shows a significant shift in lubricant viscosity. The viscosity grades of 15W-40 and 10W-40 which dominated the market in 2000 were completely replaced by lower viscosities by 2018. By 2030 the new engine specifications are expected to be split between 0W-20, 0W-30 and 5W-30 grades.

Figure 3.9: Estimated share of new heavy-duty diesel engine lubricant viscosity by vehicle production year (Europe)



Note: 2025 and 2030 are predictions.

Relative fuel consumption across the lubricant viscosity range

The relative fuel consumption change was assessed for each engine class, considering engine test data. There are a variety of datasets, with lubricants run in different engines and across different test cycles.

Each dataset includes a reference lubricant operated in a given engine over a particular engine or vehicle test cycle. The lubricant is changed to a different viscosity specification and the same test is repeated, using the same engine and the same engine or vehicle test cycle. The data is plotted by SAE lubricant viscosity grade for light-duty and High Temperature High Shear (HTHS) viscosity for heavy-duty engines. The ACEA fuel economy requirement is referenced in the charts, with the industry data of commercial lubricants aligning with or exceeding the ACEA requirements.

The data presented is the public domain data, sourced as referenced in earlier Section 3.2.1.1 of this report, together with Ricardo and lubricant industry data. While the datapoints for the public domain data are shown, due to confidentiality of the data, neither the lubricant industry or Ricardo datapoints can be displayed. However, the "data range" shows the minimum and maximum spread of the data from all three sources. Both the lubricant industry and Ricardo data trend lines are shown.

The fuel consumption is normalised back to the baseline which is 15W-40. This is an industry standard baseline and is the highest viscosity seen in the mainstream European market in the period 2000 to 2030. The fuel consumption of 15W-40 is given as 100%, with the percentage fuel consumption relative to 15W-40 given for each data point.

For light duty engine classes, the upper and lower 90% confidence interval lines are used to read off the change in fuel consumption when moving from one viscosity grade to another. For heavy-duty engines, due to a smaller variation in fuel consumption at a given viscosity, the upper and lower data range lines are used. The viscosity grades change between years, so the minimum and maximum fuel consumption changes can be calculated. A weighting factor is also applied dependant on the market share of lubricant grade at each year. The result is the fuel consumption change between years, and this is fed into the SULTAN model for the fleet-level analysis – see later Section 3.4.

Light-duty fuel consumption variation with lubricant viscosity

The general trend for both gasoline and diesel engines is that as viscosity reduces (reducing SAE grade) the fuel consumption also reduces, as shown in Figure 3.10 and Figure 3.11. The industry trend line aligns with the ACEA specification for gasoline, while for diesel it meets or exceeds it. The Ricardo trend line meets or exceeds the ACEA specification.

These trends include the data from the literature, the lubricant industry and Ricardo. The actual literature data points are presented on the graphs, but due to confidentiality only lubricant industry and Ricardo data trend lines are presented. All the data points (including those not presented) were used to calculate the full data range (shaded blue) and the upper and lower 90% confidence intervals.

In total circa 150 data points were used to inform the analysis. Regardless of whether additional data points were available, a range of fuel consumption (and therefore CO_2) reduction will be present for a given viscosity change. The reasons for this are explained in the following paragraphs.

Passenger car real world light-duty driving is highly variable. As well as the variation between urban, highway and rural driving there is significant difference in both driving style and journey length. The latter impacts the proportion of cold engine operation for a journey. Similarly, the different test cycles of the data, such as the New European Driving Cycle (NEDC) and Worldwide Harmonised Light Vehicle Test Cycle (WLTC), have different proportions of cold engine operation. Therefore, the viscosity versus fuel consumption needs to consider multigrade lubricants. This means that the viscosity effectively becomes two variables. However, due to the recording of most test data, especially public domain data, it is not possible to split the fuel consumption between the impact of the cold and warm viscosity grade changes. Additionally, the actual percentage of cold operation in real world driving throughout Europe is unknown. As a result, the light-duty variation in fuel consumption for a given multigrade viscosity is significant, but also representative of the variation of real-world driving.

There is significant variation in the fuel consumption value for a given viscosity grade, due to several different reasons:

- Different test cycles have different proportions of cold and warm operation depending on the ambient temperature and the duration of the cycle.
- Different engine designs respond differently to changes in lubricant viscosity and formulation, depending on several factors including the tolerancing and surface finishes of bearing surfaces.
- There is a variation in engine builds for the same engine design which may result in engine to engine differences. The Ricardo datasets are tested with the same physical engine, but it is not clear if this is the case with all the public domain datasets.
- Different lubricant formulations, including different friction modifiers and other surface-active additives may be present, all of which impart different lubricant frictional behaviour in the multiple engine operating conditions, despite being the same dataset. Where stated datasets with consistent friction modifiers were used.
- Within a given SAE lubricant viscosity grade there is a finite range of the viscosity specification, and even broader range of dynamic viscosity (HTHS). This is especially true for 5W-30 and 0W-20 lubricant specifications where some lubricant products are more focused on fuel economy than others.

This study aims to represent the actual fuel consumption change seen across the European vehicle parc. All these variations are representative of the real world, where individual vehicles have significant differences ranging from use cycle through to the build variation and actual lubricant used. Therefore, there will always be some uncertainty. To represent this, the upper and lower 90% confidence interval trend lines are used in the calculation of the European fuel consumption changes. The range of the data is represented by a blue shaded region, although it should be noted that real world variations may lie outside of this region.

The same factors apply to light-duty diesel engines (Figure 3.11), and again a significant variation in fuel consumption is seen for a given SAE viscosity grade. The diesel spread of data is larger.

Light commercial vehicles typically have similar diesel engines to passenger cars, although the drive cycles are different. This is highly dependent on the usage which ranges from a high utilisation lightly loaded delivery van with frequent stop-starts, to a low utilisation, heavily loaded trade van. However, there is very limited drive cycle data available which considers the fuel consumption variation with lubricant viscosity. Therefore, the diesel light-duty passenger car fuel consumption versus oil viscosity trends are used for light commercial vehicles.

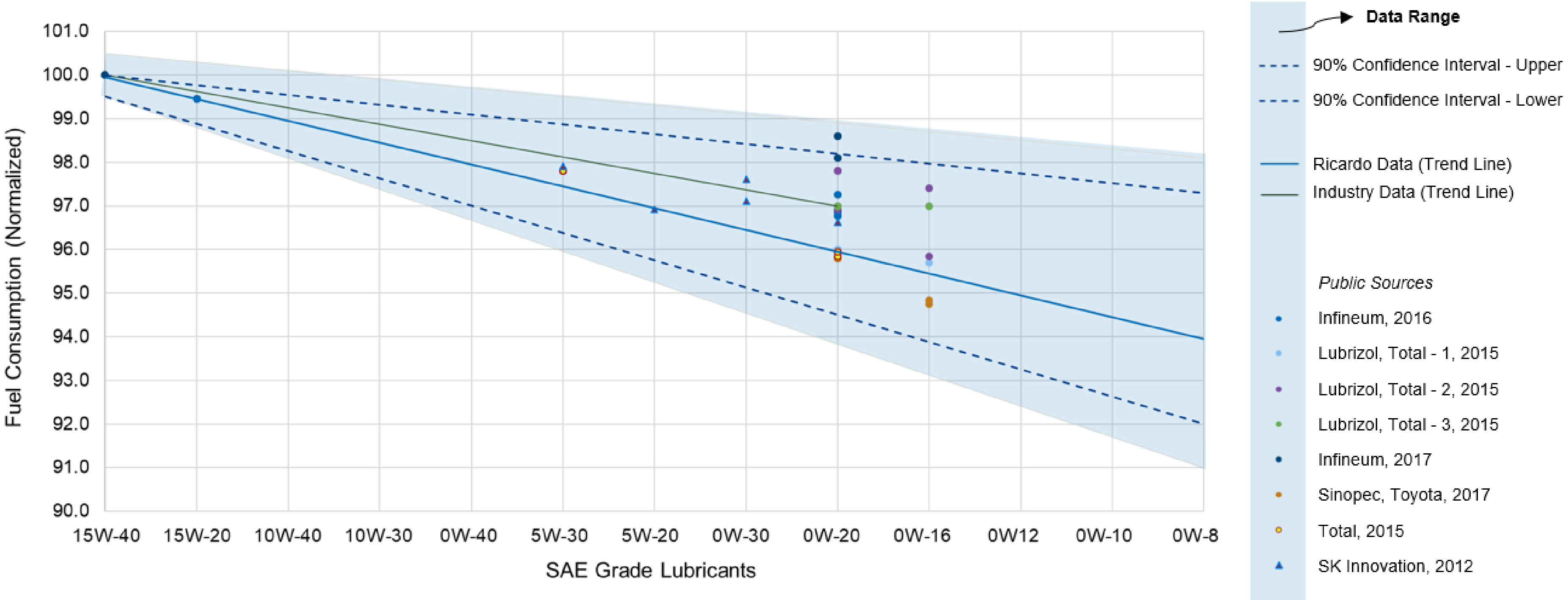
Heavy-duty fuel consumption variation with lubricant viscosity

The long haul, heavy-duty vehicle category, operates a more predictable driving type than passenger cars, being predominately express way driving (motorway) and at a cruise condition. The cold start element is only a very small proportion of the overall real-world drive cycle, so consequently only warm operation is considered in this analysis. Therefore, only the warm engine viscosity is plotted which is represented by the HTHS viscosity. The equivalent SAE grades are indicated. The result is that the variation in fuel consumption for a given viscosity is much narrower, and there is less variation between the minimum and maximum trend lines used for the European fuel consumption changes. Some variations do exist, and these are due to:

- Some differences in representative test cycles.
- The different response of engine designs to changes in viscosity.
- The variation in engine builds for the same engine design which may result in engine-to-engine differences. The Ricardo datasets are tested with the same physical engine, but it is not clear if this is the case with all the public domain datasets.
- The presence of different lubricant formulations, including friction modifiers, for the different viscosity specifications present. Where stated datasets with consistent friction modifiers were used.

Figure 3.12 shows the reduction in fuel consumption as HTHS reduces.

Figure 3.10: Light-duty gasoline engine normalised fuel consumption variation with lubricant viscosity

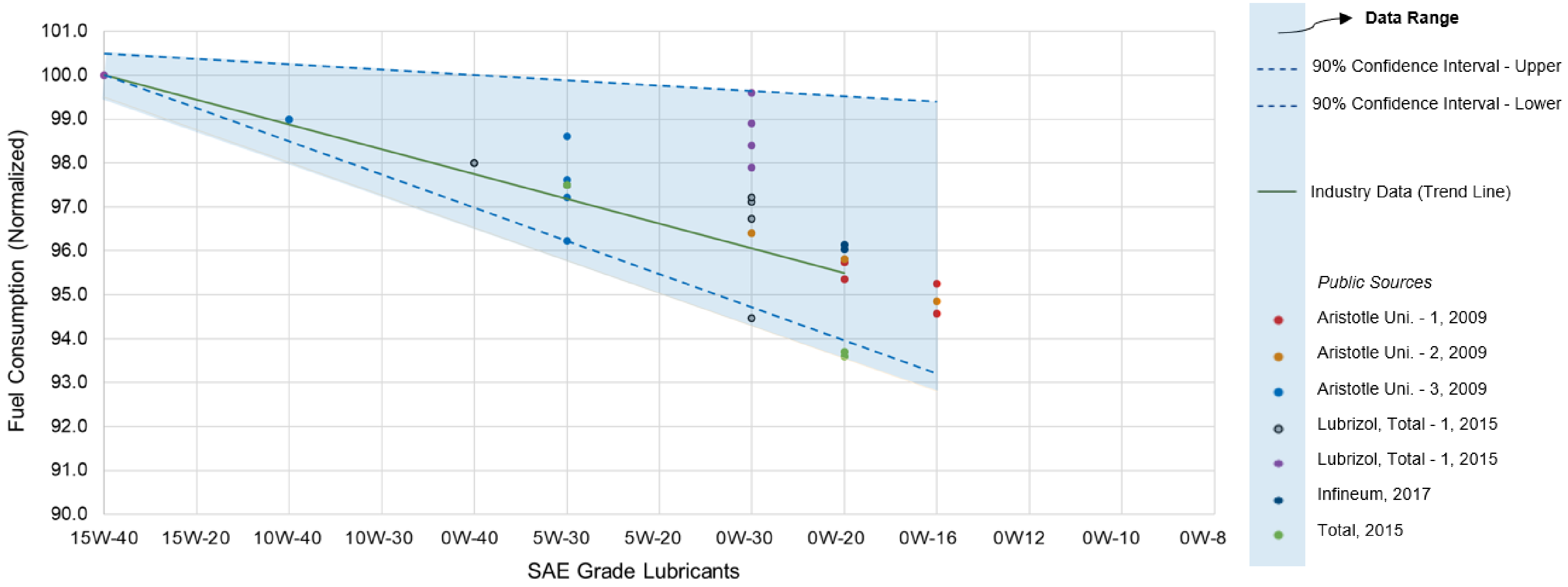


Source: Ricardo analysis from the following data sources: literature available in the public domain, data supplied by the lubricant industry / ATIEL and Ricardo data.

Note 1: Trend lines are based on circa 150 data points.

Note 2: Industry trend line aligns with ACEA specification, Ricardo trend line meets or exceeds ACEA specification. The industry standard test is now supplemented by those of individual OEMs that use their own tests to enable more bespoke lubricant formulations to be used to further enhance the benefits for their vehicles.

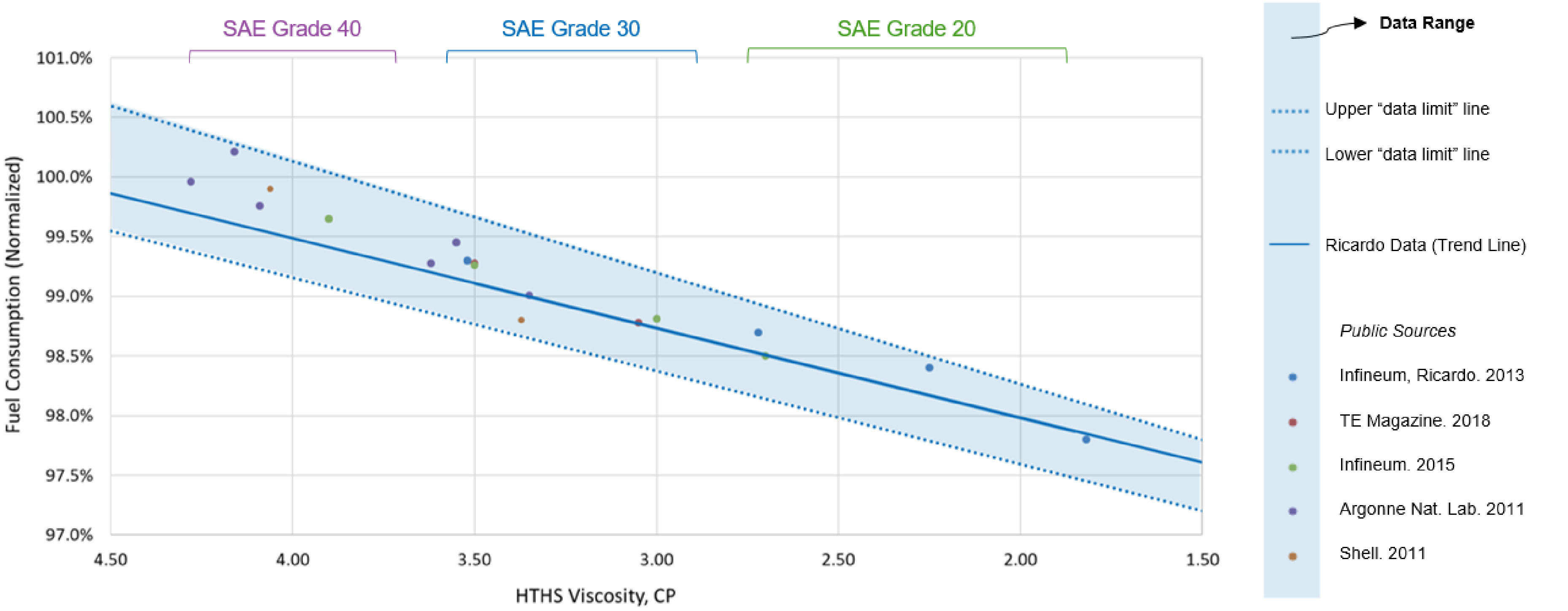
Figure 3.11: Light-duty diesel engine normalised fuel consumption variation with lubricant viscosity



Source: Ricardo analysis from the following data sources: literature available in the public domain, data supplied by the lubricant industry / ATIEL and Ricardo data.

Note: Industry trend line meets or exceeds ACEA specification. The industry standard test is now supplemented by those of individual OEMs that use their own tests to enable more bespoke lubricant formulations to be used to further enhance the benefits for their vehicles.

Figure 3.12: Heavy-duty diesel engine normalised fuel consumption variation with lubricant viscosity



Source: Ricardo analysis from the following data sources: literature available in the public domain and Ricardo data.

3.2.2 Indirect benefits

Considerable engine technology changes have occurred for mainstream vehicles, both light and heavy-duty, between 2000 and 2018, and more are expected towards 2030. A high level overview of the engine technology changes both historically and Ricardo's expectations for the future are shown in the roadmaps, these are Figure 3.2 and Figure 3.3 for light-duty vehicles and Figure 3.4 for heavy-duty vehicles.

The technologies through which the lubricant has indirect fuel consumption benefits are considered as those technologies which:

- A standard lubricant from the year 2000 would prevent the new technology from effectively working.
- A standard lubricant from the year 2000 would not provide the required engine durability with the new technology.

The technologies providing an indirect CO2 emissions benefits are shown in green and the technologies providing an engine tail pipe emissions benefit are shown in orange. Table 3.2 shows the technologies for light-duty engines which are included in the quantitative assessment of the indirect benefits. Table 3.3 shows the equivalent for heavy-duty engines.

For each technology, a high-level estimate of the CO_2 benefit was made. This varied by both year and vehicle category for many of the technologies. The estimates are based on published industry data and Ricardo technical research. Table A1 and Table A2 in Appendix A1.2 show the CO_2 benefit ranges and uptake rates used. The CO_2 benefit was combined with the new vehicle technology uptake rate in each vehicle category at each year. The technology uptake rate was based on a combination of industry market databases, combined with Ricardo's expectation. For future technologies Ricardo's expectation was guided by several factors including legislative requirements, technology cost and technology readiness level (TRL).

Real world CO_2 benefits are achieved using biofuels throughout Europe. Up to 7% by volume of regular grade pump diesel can be Fatty Acid Methyl Ester (FAME), and up to 10% by volume of regular grade gasoline can be ethanol (Ricardo, 2019). The introduction of biofuel blends, particularly the use of FAME blended in diesel when combined with DPF regeneration, caused significant challenges for the lubricant. Consequently, the ACEA sequences were specifically adjusted. However, biofuels are excluded from the quantitative assessment of indirect benefits as they are not an engine technology. The effects of biofuel usage across Europe are already accounted for in the SULTAN model used in Section 3.4.

The lubricant changes which have enabled these technologies include changes to the base stock and additives. The key base stock change was the mainstream engine move from predominately refined mineral oil (Group I) base stocks in 2000 to predominately synthetic (Group III and Group IV) base stocks by 2018. Synthetic base stocks have permitted increased engine temperatures, allowing technology such as downsizing, steel pistons and operating the engine hotter to reduce lubricant viscosity. The additive changes since 2000 have included low SAPS permitting the aftertreatment systems (DPF and GPF) required for reduced particulate matter (PM) mass and particle number (PN). Further base stock and additive changes have been made to accommodate the use of Exhaust Gas Recirculation (EGR) to reduce nitrogen oxide emissions (NO_x).

3.2.2.1 Light-duty

The significant light-duty CO_2 reducing technologies are listed in Table 3.2. These include hybridisation, ranging from stop-start which is expected to transition to mild hybridisation as well as full hybridisation, and downsizing. Historically, downsizing in gasoline engines has caused an increased uptake of turbocharging, enabled by lubricants capable of tolerating high temperatures. Low Speed Pre-Ignition (LSPI) control may enable further downsizing and is achieved by altering the lubricant additives, in particular the amount, type and ratio of calcium and magnesium detergents. Downsizing for light-duty diesel and the associated increased turbocharger boost pressures and higher temperatures have required changes to the lubricant formulation.

Future gasoline engine technology expected for CO_2 reduction which impact the lubricant include water injection and cooled EGR which enable real driving emissions (RDE) compliance with continued downsizing as well as a CO_2 reduction.

Lubricant formulations have also changed to enable the introduction of emission control technology without poisoning of the catalysts. This included low SAPS lubricant formulations for close coupled catalysts for faster catalyst warm up, and for diesel engines, DPF and Selective Catalytic Reduction (SCR) systems.

Table 3.2: Light-duty engine indirect impacts 2000 to 2030 (Vehicle categories 1, 2 and 4)

Technology	Fuel type affected	CO_2 impact	Comments
Hybridisation	G D	■■■	Increased engine stop-start and cold starts can lead to increased water in oil, which has required lubricant changes.
Start-stop	G D	■■□	Optimised oil to reduce low temperature viscosity to account for increased cooler engine operation caused by longer engine off periods.
Downsizing	G D	■■□	Downsizing caused higher oil temperatures (especially compressor outlet temperatures) which were enabled by fully synthetic oil, and increased lubricant acidity, managed by anti-oxidants.
Turbocharging	G D	■■□	Higher oil temperatures occurred with gasoline turbocharging (links to gasoline downsizing).
LSPI prevention	G	■■□	Switching to a balanced detergent formulation (not Ca or Mg) or different dispersants prevents LSPI for highly turbocharged engines.
Water injection	G	■■□	Water injection is expected to increase the water in oil content, which is anticipated to require oil development to mitigate. There is some uncertainty over the projected future uptake.
Cooled EGR	G D	■□□ □□□	EGR causes an increase of abrasive soot particles entering the lubricant, causing wear, and increased acidity. Both require lubricant base stock and additive changes to mitigate. Cooled EGR for gasoline has a fuel consumption benefit, and therefore CO_2 reducing impact, while for diesel cooled EGR reduces NOx emissions.
Close coupled catalysts	G D	■□□	Predominately adopted by diesel vehicles during this period. An already high adoption on gasoline vehicles increased further. Lower SAPS limited the formation of sulphated ash for filters and reduced poisoning for flow through catalysts. This enabled optimised catalyst volume for the desired emissions legislation, with a lower impact of poisoning on the catalyst durability, lowering exhaust back pressure and reducing fuel consumption.
DPF	D	□□□	Change in lubricant ash limits and switch to low SAPS enabled DPF compatibility with oil.
GPF	G	□□□	Similarly to DPF, lubricant ash limit changes are expected to enable GPF compatibility.
Biofuels	G D	■■□	The introduction of ethanol blends of up to 10% in regular grade gasoline across Europe, and biodiesel blends of up to 7% FAME in regular grade diesel across Europe required significant changes to lubricant formulation to prevent oxidation. As a result the ACEA sequences were specifically adjusted. Impacts of biofuel are not included in the analysis.

Notes: Fuel type: green G denotes gasoline, red D denotes diesel;
CO_2 impact: higher number of blue squares represents higher lubricant indirect impact from the technology.

3.2.2.2 Heavy-duty

The lubricant for heavy-duty engines has been required by OEMs to be more robust, primarily due to the high lifetime durability requirements of heavy-duty engines. The focus has been on engine protection rather than providing maximum fuel economy benefits. As a result, there has been more margin to change engine technology without significant lubricant viscosity changes than for light-duty. Consequently, heavy-duty (Table 3.3) indicates fewer engine system technologies than light-duty (Table 3.2).

The key impacts for heavy-duty engine CO_2 reduction are focused around increased power density (as engine power has historically increased in Europe) and downsizing (as future engine power remains constant). Downsizing is only applicable for a modest part of the heavy-duty vehicle market, which is limited by the volume of goods rather than their mass. The switch to fully synthetic lubricants combined with additives to reduce compressor deposits, has enabled an increase in compressor outlet temperatures required for increased power density and downsizing.

Similarly, the adoption of steel pistons requires synthetic oil due to higher lubricant temperatures on the underside of the piston. By 2025 the adoption of steel pistons is expected across the majority of the heavy-duty engine market. Variable displacement oil pumps require good lubricant contaminant control and are expected across approximately half the heavy-duty engine market by 2030.

Lubricant changes since 2000 have also enabled the fitment of DPF emissions control equipment on heavy-duty vehicles (typically for Euro VI). Low SAPS lubricants reduce DPF ash levels leading to increased intervals between filter cleaning resulting in reduced backpressure and reduced real world fuel consumption over the vehicle life. While these technologies do not provide a direct quantifiable CO_2 reduction they have enabled significant emissions reduction. It is the first catalyst in the exhaust system which is typically impacted by sulphur or other poisons from the lubricant. SCR systems are typically post Diesel Oxidation Catalyst (DOC), therefore, the lubricant component of SCR sulphur poisoning is limited and is not considered in this analysis

Table 3.3: Heavy-duty engine indirect impacts 2000 to 2030 (Vehicle category 3)

Technology	CO_2 impact	Comments
Downsizing	■■□	As demand for increased power falls, downsizing is possible, which will increase engine stress and compressor outlet temperatures further, which is enabled by lubricant changes.
Power density	■□□	Increased compressor outlet temperatures as power density increases have been enabled by fully synthetic lubricant and formulation changes (such as new anti-oxidant and detergent additives) to reduce compressor deposits.
Steel pistons	■■□	Steel pistons increase the temperatures which the lubricant is exposed to, which has required synthetic oil.
Variable displacement oil pump	■■□	Good lubricant contaminant control is required due to the sliding surface contacts within the pump.
Cooled EGR	□□□	When introduced, cooled EGR did not reduce fuel consumption, but relative to the alternative methods (available at the time to meet the legislative emissions requirements), EGR prevented an increase in fuel consumption. EGR causes an increase of abrasive soot particles entering the lubricant, causing wear, and increased acidity. EGR required fundamental changes in lubricant formulation to mitigate engine issues.
DPF	□□□	Change in lubricant ash limits enabled DPF compatibility with lubricant. DPF required fundamental lubricant additive changes to mitigate engine issues.
Biofuels	■■□	The introduction of biodiesel blends up to 7% FAME in regular grade diesel across Europe required significant changes to lubricant formulation to prevent oxidation. As a result the ACEA sequences were specifically adjusted. Impacts of biofuel are not included in the analysis.

Notes: CO_2 impact: higher number of blue squares represents higher lubricant indirect impact from the technology.

3.3 Future lubricants challenges

The roadmaps (Section 3.1) and the indirect benefits (Section 3.2.2) show, respectively, the direction of future engine technology and discuss some of the lubricant challenges. This section also considers more technologies not included in the quantitative analysis as they are either not CO_2-related or they are forecast to be technologies with low uptake. Both will challenge future lubricant development.

Light-duty gasoline

Significant powertrain electrification is expected for mainstream light-duty gasoline engines towards 2030: both mild hybridisation and full hybridisation. Under some driving cycles, both systems have increased cold engine operation which can allow increased levels of contaminants to enter the lubricant. For full hybrids, especially plug-in hybrids, significant time between engine use can also occur. These could cause a significant challenge for the lubricant.

Electric turbochargers and superchargers are expected to increase modestly in market share towards 2030, particularly for premium vehicles. These may challenge the lubricant by increasing engine boost pressures and therefore lubricant temperatures.

Technologies required for RDE compliance of highly downsized engines at Euro 6d and beyond are expected to cause some level of future lubricant challenge. These include water injection and cooled EGR. Water injection could result in an increase of water entering the lubricant, while cooled EGR is expected to increase the lubricant exposure to combustion contaminants. Gasoline EGR combustion contaminants differ to those of diesel EGR, which the lubricant industry has already responded to.

Light-duty diesel

Due to the higher cost of diesel vehicles, full hybridisation is not expected to be as mainstream as for gasoline, but mild hybridisation is expected. Therefore, the same mild hybrid lubricant challenges will occur as for gasoline.

Market share corrections following "diesel-gate" are expected to reduce the European diesel powertrain share further, reducing European diesel technology development. Therefore, significant future on-engine lubricant challenges are not expected.

However, future emissions limits are expected to cause lubricant challenges. The European Commission is expected to reduce limits further and include new emissions species in "Euro 7" or equivalent legislation. These are expected to require changes to the aftertreatment, which may require further changes to the lubricant to prevent catalyst poisoning.

Heavy-duty diesel

Engine technology development for HDD is relatively conservative compared to light-duty, and combined with a greater margin to change engine technology without impacting the lubricant, means fewer lubricant challenges are expected.

For example, some hybridisation is expected for long-haul HDD towards 2030, although it is only likely to give a cost-effective benefit on some routes and so the market uptake is uncertain. However, it is unlikely that any long-haul truck would operate as described for light-duty gasoline, so few lubricant challenges are expected.

As with light-duty diesel, future lubricant challenges are expected to ensure lubricant compatibility with future aftertreatment requirements; these are related to new emissions species and further emissions limit reductions.

Reducing viscosity

Perhaps the biggest future challenge for the lubricant industry is the development of lower viscosity lubricants such as 0W-16, 0W-12 and possibly 0W-8 (as discussed in the analysis of direct benefits, Section 3.2.1). To ensure that these lubricants provide fuel consumption benefits while simultaneously meeting all the various engine and aftertreatment durability requirements will be a significant challenge.

Future opportunities

The lubricant industry expects that there are greater opportunities to optimise the lubricant for lower CO_2 through greater collaboration between OEMs and the lubricant industry. Through improved collaboration between all parties, the lubricant could have a greater role to play in the whole engine optimisation process. The resulting greater CO_2 reduction of this approach could benefit the whole automotive industry, reducing European vehicle CO_2 emissions further.

3.4 Contribution of lubricants to CO_2 emissions reductions

3.4.1 Fleet modelling

To assess the overall benefits of lubricants on the EU road vehicle parc, Ricardo conducted a fleet scenario modelling analysis using the SULTAN model.

The SULTAN model has developed into a well-known policy analysis tool for transport in the EU. It uses a simplified stock-modelling approach and information on transport activity, emission factors, and fuel efficiency to develop estimates for net energy consumption and emissions from different transport modes. The impact of various policy decisions can be analysed in both a forward- and backward-looking way, in order to develop understandings of industry changes associated with policy decisions.

An overview of the SULTAN model and the modelling process is provided in Box 1 and Figure 3.13 below, respectively.

The outputs from the analysis of lubricants' direct and indirect impacts on the fuel efficiency of different vehicle types, outlined in sections 3.2.1 and 3.2.2, were fed directly into the SULTAN scenario modelling analysis. For this, the baseline scenario values for fuel efficiency of each powertrain type (car, LCV, heavy truck, etc.) were adjusted in line with outputs from the data collection and consultation with ATIEL. The amended fuel efficiency values were then used within the stock modelling process aligned to the relevant year, consequently feeding through into the derived evolution in the overall fuel consumption of the entire EU vehicle parc.

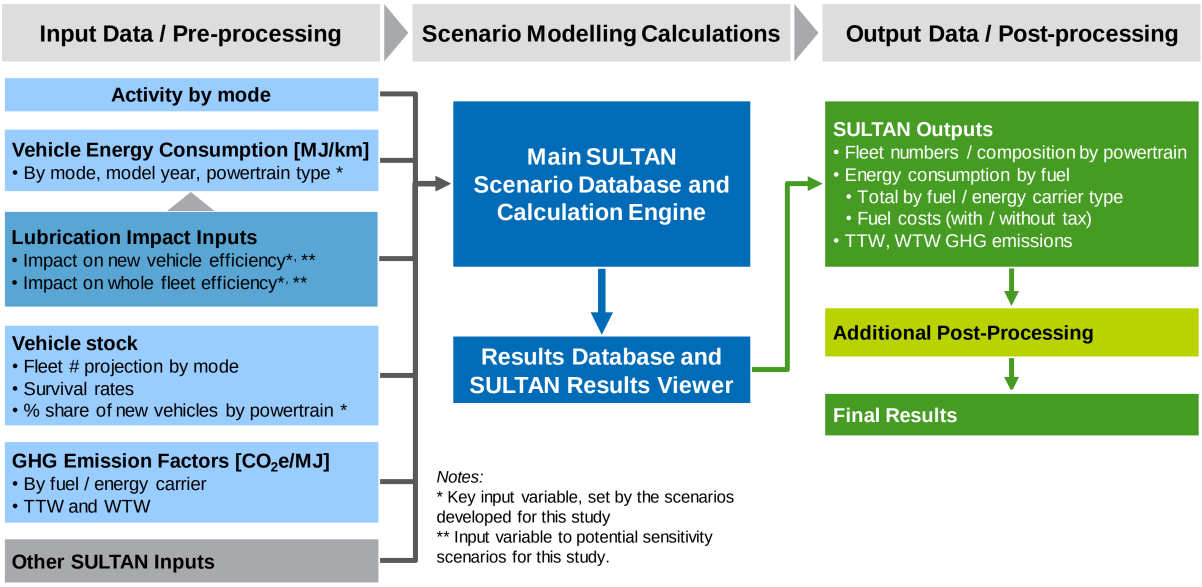
Box 1: Overview of the SULTAN model

In previous work for the European Commission's Directorate General on Climate Action (DG CLIMA) (the EU Transport GHG: Routes to 2050 projects[2]), Ricardo Energy & Environment developed the sustainable transport illustrative scenarios tool called SULTAN (SUstainabLe TrANsport). The model has most recently been enhanced and updated to the European Commission's 2016 Reference scenario (REF2016), as part of work for DG CLIMA considering transport's potential contribution to the EU's 2030 decarbonisation objectives. It has also been further utilised in a number of other UK and European projects, e.g.:

- Analysing the potential impacts of different ultra-low emission vehicle (ULEV) measures/incentives on emissions from European passenger cars (for Greenpeace and T&E).
- Evaluating the potential energy, GHG, NOx and PM emissions impacts of different low emission vehicle uptake scenarios in London (for Transport for London).
- Evaluating the potential fuel consumption and GHG impacts of uptake of cost-effective lightweighting by heavy-duty vehicles (for DG Climate Action).
- Evaluating the wider impacts of scenarios for High EV uptake in Europe to 2050, in comparison to alternatives with more significant use of low carbon fuels (CONCAWE).
- Analysis of the potential contribution of low carbon fuels in decarbonising light-duty vehicles (LDVs, i.e. passenger cars and vans) from 2020-2050 in the context of the European Commission's 2nd Clean Mobility Package (CMP), and the EU's medium- and long-term GHG reduction targets (for ePURE).

[2] http://www.eutransportghg2050.eu/

Figure 3.13 SULTAN modelling process



For the fleet-level analysis, this study considers both forward- and backward-looking scenarios to estimate both the historic benefits and the future potential. These scenarios are set up in different ways: (i) The backward-looking scenarios adjust baseline fuel efficiency figures in the period 2005-2020 to calculate the increase in emissions if the direct and indirect lubricant impacts were removed. (ii) The forward-looking scenarios were developed from Ricardo analysis and estimates of future lubricant improvements in the period 2020-2030, also in comparison with the anticipated trends in emissions to meet post-2020 CO_2 targets for light-duty and heavy-duty vehicles. The developed scenarios used to develop this picture are discussed in more detail in Table 3.4.

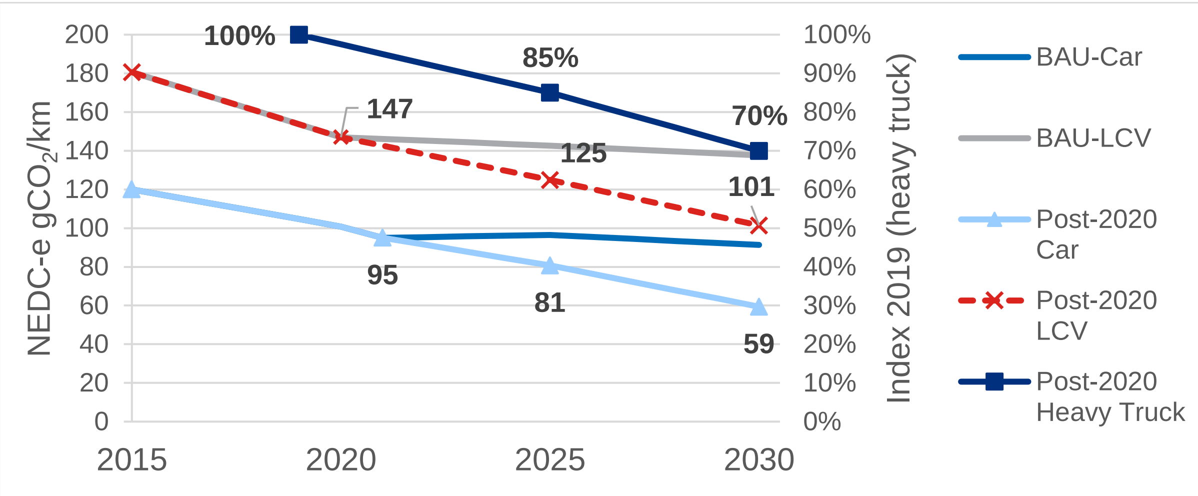
Table 3.4: Overview of the modelled scenarios

#	Scenario name	Summary of scenario definition
0	Baseline	This scenario represents the business as usual (BAU) case for road transport in the EU, consistent with the EC's 2016 Reference scenario (REF2016). (This excludes the post-2020 CO_2 reduction targets for cars, vans and heavy trucks). This scenario is based on the assumption that no new policy is introduced to change the current fleet share or vehicle efficiency figures. REF2016 has been used as a basis for the modelling analysis for a wide range of EC impact assessments.
	Historic/backward-looking scenarios	
1	Minus Direct Lube[3] (MinusDL)	This scenario has been developed to calculate the direct impact on CO_2 emissions of advanced lubricant technology on the European vehicle fleet from 2005 to the current day. Removal of the improvements in lubricant technology over this time lead to lower modelled vehicle efficiencies as the scenario answers the question: *If lubricants had not improved since 2005, what would the emissions be?*
2	Minus Lube Enabled (MinusLE)	This scenario has been developed to calculate the historic impact on CO_2 emissions of lubricant enabled technologies since 2005. It does this in the same way as the Minus-DL scenario i.e. calculating the avoided emissions from lubricant enabled technologies over the period.

[3] The estimated minimum (Min) and maximum (Max) benefits are assessed in two scenario variants.

#	Scenario name	Summary of scenario definition
	Future/forward-looking scenarios	
3	Post-2020 targets (Post2020T)	A projection for improvements to CO_2 emissions consistent with the now finalised post-2020 CO_2 reduction targets for LDVs (European Commission, 2019) and near finalised targets for heavy-duty vehicles (as context for the lubricant contribution), i.e. by 2030: 37.5% for cars, 31% for vans versus 2021; 30% for heavy trucks versus 2019. [Note: there are no specific targets are yet for smaller trucks and for buses, so it is assumed that post-2020 targets are set similarly to heavy trucks].
4	Shift to xEVs (ShiftxEV)	This scenario has been developed to follow a trajectory consistent with the shift to xEV deployment to 2030 that is required/included in the Post-2020 targets scenario. Vehicle powertrain efficiency has been set unchanged from the baseline scenario. This scenario therefore provides an estimate of the CO_2 emission impacts directly resulting from the shift to xEVs only.
5	Direct Lube[3] (DirectL)	This scenario models the potential changes in fuel efficiency arising from current and future improvements in lubricant technology by changing fuel efficiency values of new vehicles entering the fleet from the baseline scenario in the period from 2020 onwards.
6	Lube Enabled (Lube-EN)	This scenario calculates the potential future reductions in emissions through the technologies enabled by advances in engine lubrication, factoring in a Ricardo estimate of their potential deployment in future new vehicles as part of efforts to meet future CO_2 reduction targets. This is based on the baseline scenario and adjusts fuel efficiency figures for new vehicles from 2020 onwards based on estimations of the future changes.
(7)	Remaining CO_2 reduction	Scenario is defined as the difference between scenarios 3 ,4 and 5 and the Post2020T scenario, i.e. the additional CO_2 emissions required to reach the EU post-2020 targets for road vehicles (i.e. through the application of additional technical measures).

Figure 3.14: Illustration of context / challenge of future CO_2 targets for cars, LCVs and heavy trucks



Source: SULTAN for BAU scenario; Ricardo analysis of legislative targets for post-2020 trajectory.

Notes: 2021/2020 targets for cars/vans, respectively, are set on a NEDC-basis. Post-2020 CO_2 targets for passenger cars and vans (LCVs) are set as % reductions on the final WLTP values for 2021. Ricardo has converted these reduction levels into NEDC equivalent values for ease of presentation here.

3.4.2 Results and discussion

The scenario modelling carried out in SULTAN has calculated the impact lubricants have had on EU emissions and fuel costs for the entire European vehicle fleet in the period in the period 2005-2030. This is shown in Sections 3.4.2.1 and 3.4.2.2.

From a historic perspective, lubricants have avoided 17.8–33.4 $MtCO_2e$ since 2005 and will continue to result in a further 6.0–9.0 $MtCO_2e$ reduction in road transport emissions by 2030. This has contributed to a 2.2–4.1% decarbonisation of the road transport sector (2005-2020) and will continue to provide further future GHG savings in the road transport sector, contributing to the 2030 CMP target.

This is matched with significant financial savings for consumers due to the improved fuel efficiency of their vehicles. These cost savings have been enabled through a relatively low intervention approach when compared to other fuel efficiency improvement technologies.

3.4.2.1 Contribution of lubricants to historic GHG and fuel costs savings from EU road vehicles

The potential avoided emissions from advanced lubricant technologies is shown in Figure 3.15. This shows the range of impacts (Min-Max) from the lubricant's direct impact on fuel economy (from lower viscosity). The range of indirect impact is also shown (Min-Max), i.e. from the role lubricants play in enabling other technologies which then play a role in improving fuel efficiency.

The results in the charts show the in-year impact for the entire vehicle fleet since 2005, and this results in a relatively wide range between the minimum and maximum impacts, with a direct contribution of 1.2–3.9 $MtCO_2$ in emissions reductions by 2020, and 16.6–29.5 $MtCO_2$ emissions by lubricant enabled technologies.

EU 2020 climate & energy package, agreed in 2009, set the target of a 20% reduction in GHG emissions by 2020 (versus 1990); the analysis shows that lubricants have played a significant role in contributing to this objective. Based on the fleet analysis a reduction of 2.2–4.1% in road transport emissions by 2020 has been enabled by the advances in lubricants in this timeframe. Additionally, as road transport accounted for 27% of all EU emissions in 2016, this would represent a contribution of almost 1% of the decarbonisation of the entire EU economy in that year.

In addition to the contribution to CO_2 reduction, a further substantial impact that lubricants have had is on reducing fuel costs to drivers. The improvement in fuel efficiency lubricants enables, leads to a direct reduction in fuel costs. The estimated results of this impact for EU road transport end-users is shown in Figure 3.16, with engine lubricants contributing €1.1–€3.0 billion in end-user fuel savings per year by 2020, and contributing to even greater savings by lube-enabled technologies.

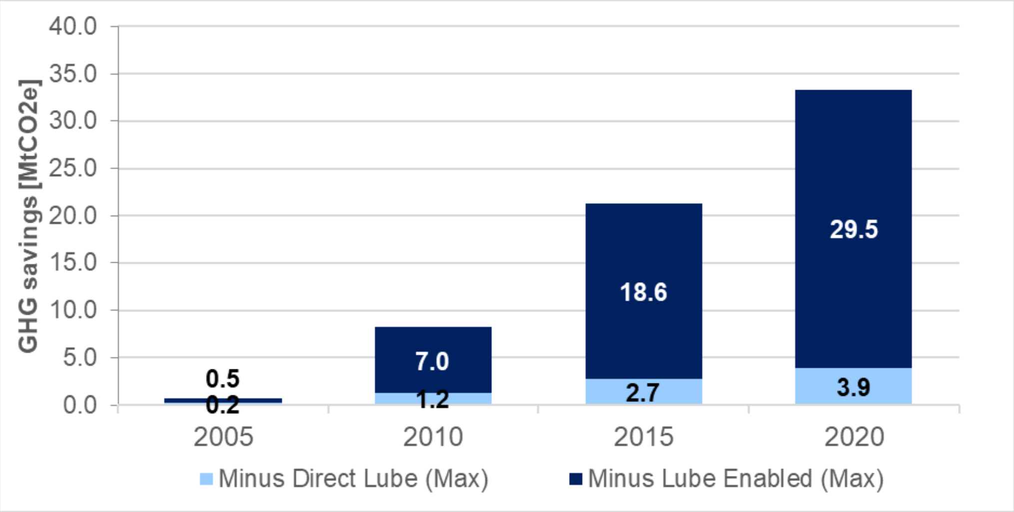
A 2.8–4.7% reduction in the overall fuel bill has potentially been enabled from lubricant improvements over the modelled timeframe.

Overall, the above range of fuel savings equate to the average annual saving per vehicle (for combined direct lubricant and lube-enabled savings) by 2020 reaching between €37–€67/year for cars and €720–€1282/year for heavy trucks.

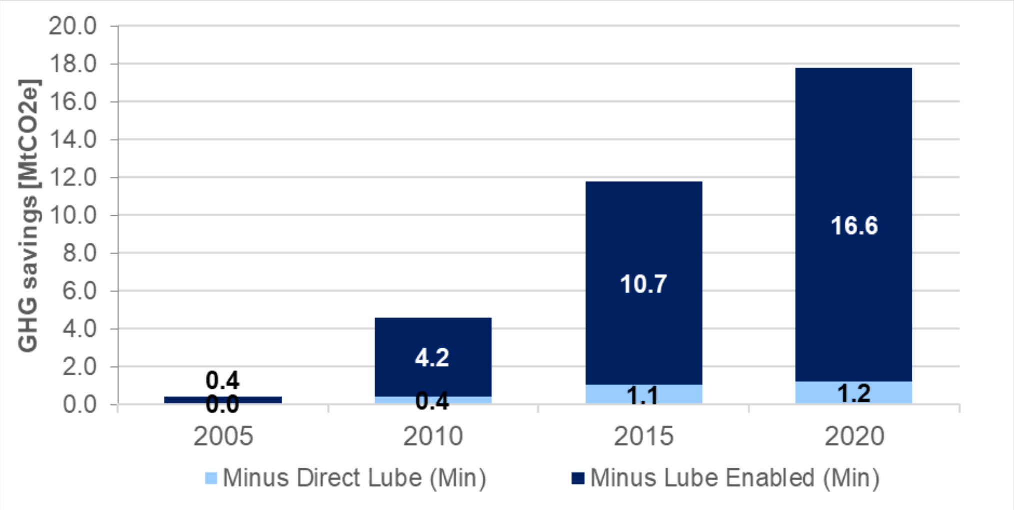
Whilst the cost of implementing the lubricant enabled technologies can be high, the incremental cost for improved lubricants is small (especially when compared to other fuel efficiency interventions or vehicle replacement), this represents a significant saving for both commercial and private road users.

Figure 3.15: Historical estimates for direct tailpipe (tank-to-wheel, TTW) GHG emissions from EU road vehicles and the contribution of engine lubricants to emissions savings

GHG savings (Max)



GHG savings (Min)

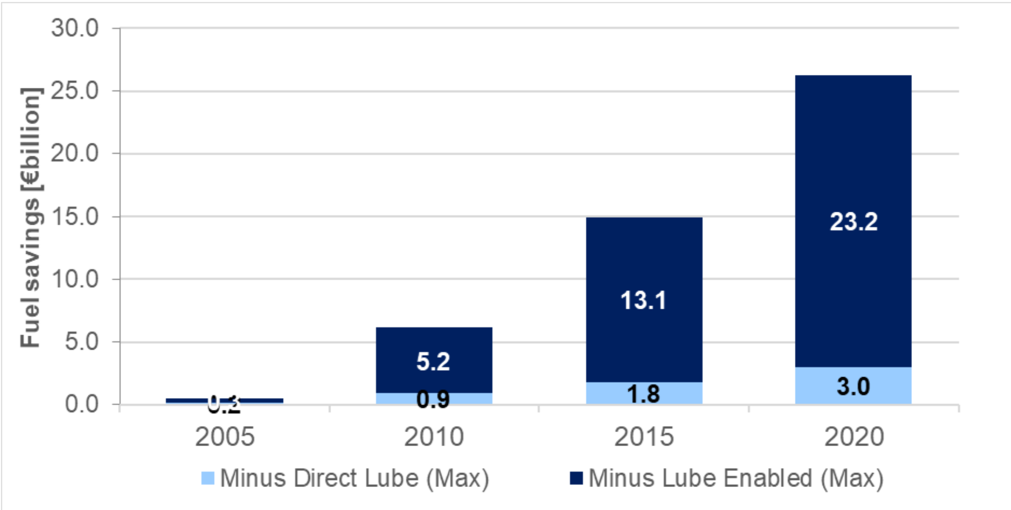


Source: Ricardo scenario modelling using SULTAN.

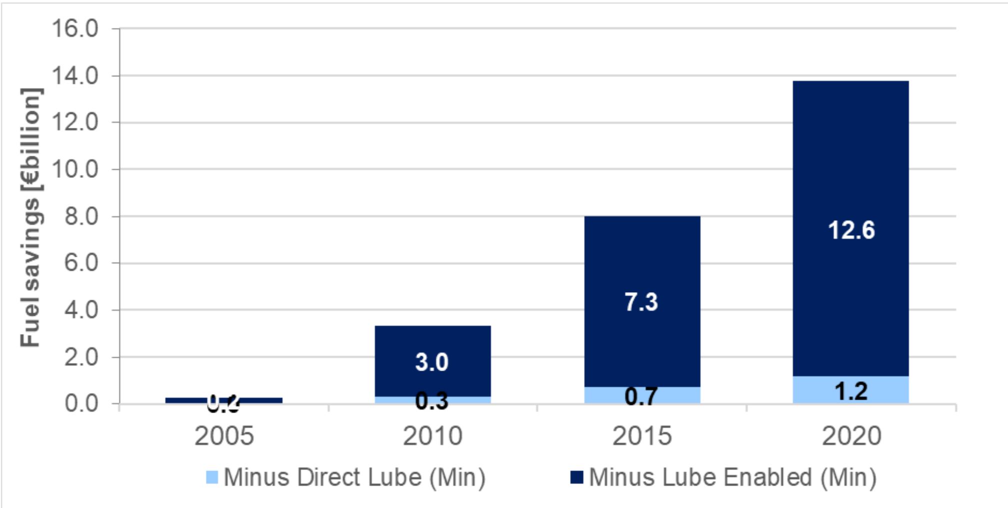
Note: The 'Lube Enabled' impacts include only estimates due to technologies applied to vehicles, and do not include estimates for other impacts resulting from biofuel uptake.

Figure 3.16: Historical estimates for fuel costs from EU road vehicles and the contribution of engine lubricants to fuel savings

Fuel savings (Max)



Fuel savings (Min)



Source: Ricardo scenario modelling using SULTAN.

3.4.2.2 Potential contribution of lubricants to future GHG and fuel cost savings from EU road vehicles

The forward-looking scenarios estimate the future reductions in GHG emissions which will be enabled by further improvements in lubrication technology from the present day. It should be noted that these GHG and fuel savings are in addition to the improvements already implemented in previous years. Figure 3.17 shows this estimated reduction from 2020-2030. This is an important time period for EU GHG emissions as it will see a rapid change in the targeted emissions reduction due to the EU 2030 climate & energy framework. This sets targets for a 40% reduction in EU GHG emissions (from 1990 levels) by the end of the decade, and an objective for 2030 to reduce EU non-ETS sector GHG emissions by 30%, relative to 2005. The difference between the 'Post2020T' scenario and the other modelled scenarios shows that current measures are unlikely to be enough for the road transport sector to meet the EU targets.

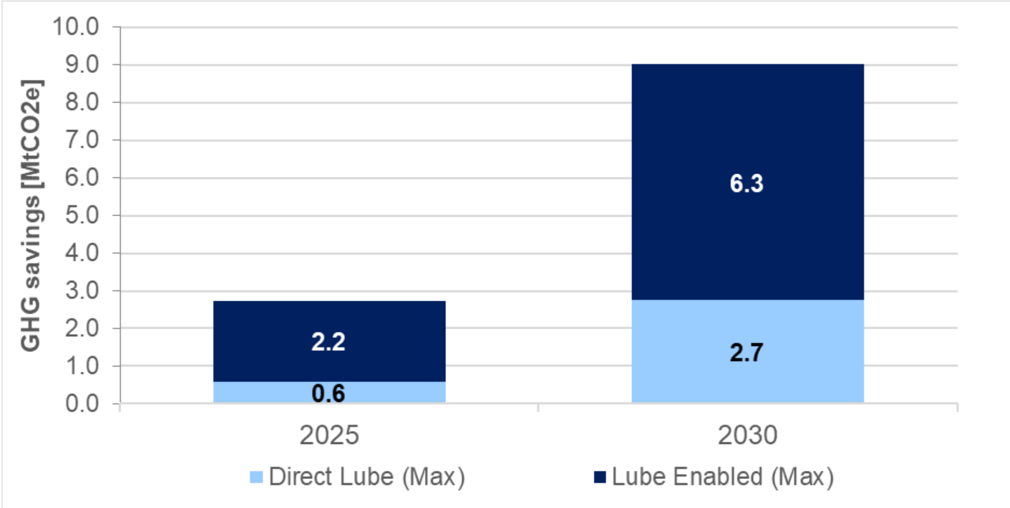
In this work, it is estimated that between 6.0–9.0 $MtCO_2e$ can be avoided through expected improvements in lubricants and their enabling effect on other vehicle technologies in the year 2030. The forward-looking lubricant impacts shown here represent a 0.8–1.3% reduction in emission from the transport sector over this time. This reduction can be set against wider system reductions in GHG emissions, and as this trend continues, further emissions reductions may become more difficult (and expensive), therefore those arising from lubricant technologies may become relatively more valuable.

Further fuel cost reductions are expected for vehicle end-users to 2030, due to the positive impact that lubricants have on road vehicle efficiency. The potential fuel costs savings are shown in Figure 3.18. In the maximum improvement scenario, a saving of €8.25 billion/year is estimated to be possible for EU road transport in 2030.

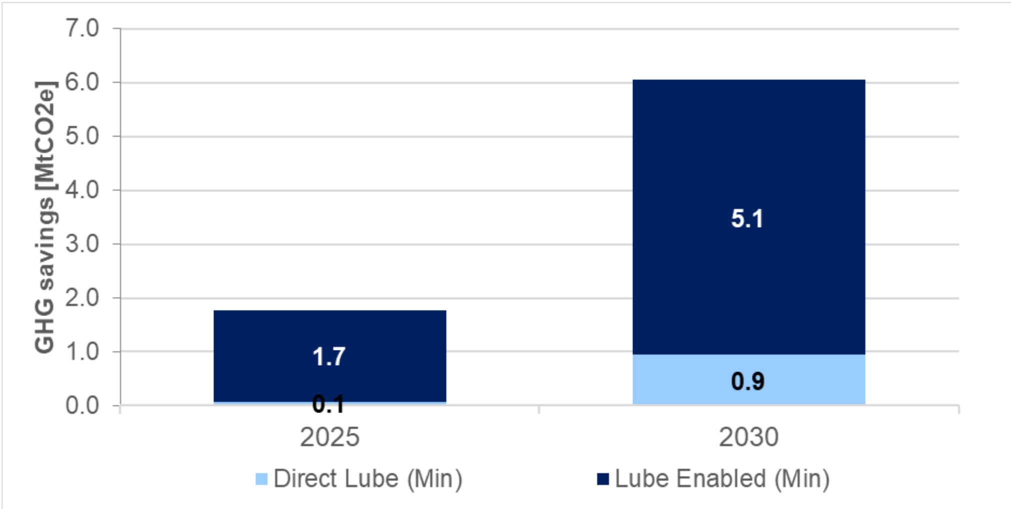
This will mean an *additional* average annual saving per vehicle by 2030 of between €16–€25/year for cars and €164–€207/year for heavy trucks (for combined direct lubricant and lube-enabled savings).

Figure 3.17: Potential contribution of lubricants to future GHG savings from EU road vehicles

GHG savings (Max)



GHG savings (Min)

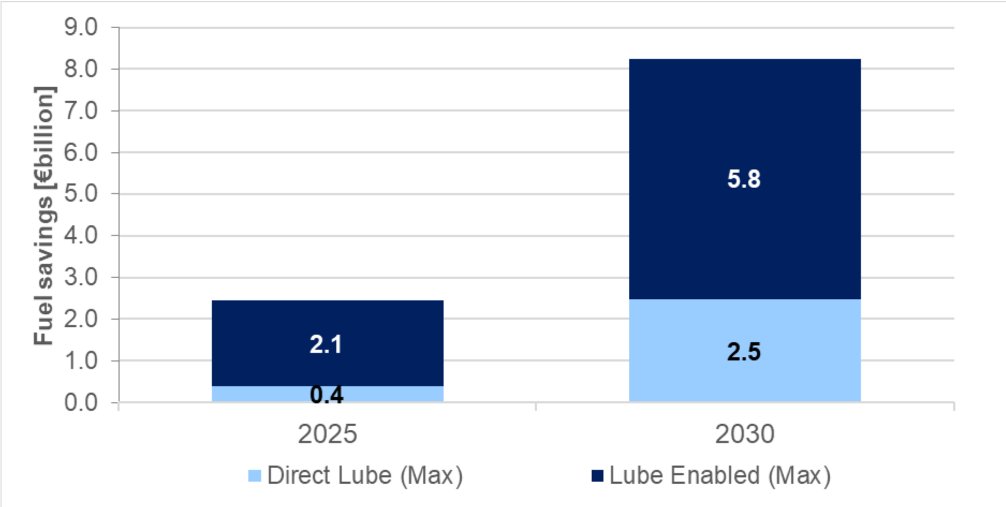


Source: Ricardo scenario modelling using SULTAN.

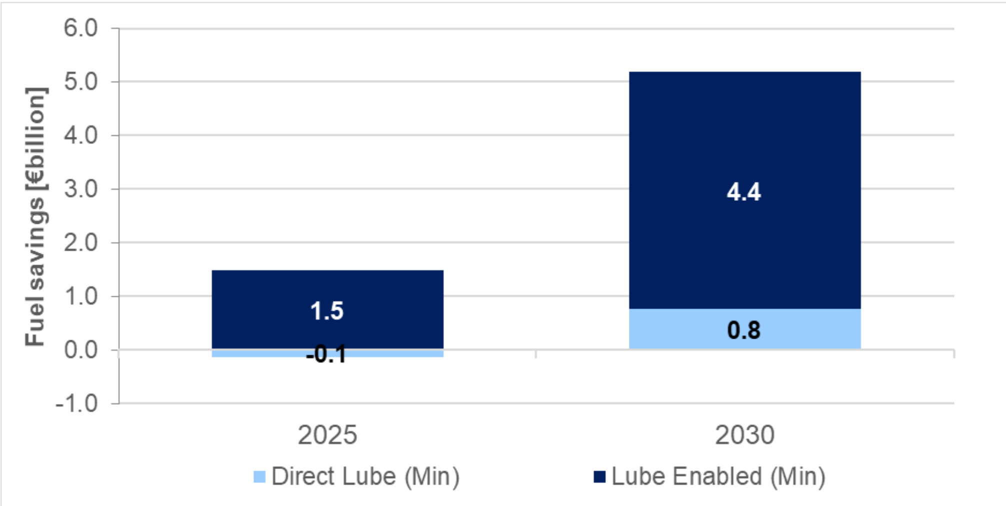
Note: The 'Lube Enabled' impacts include only estimates due to technologies applied to vehicles, and do not include estimates for other impacts resulting from biofuel uptake.

Figure 3.18: Potential contribution of lubricants to future fuel cost savings from EU road vehicles

Fuel savings (Max)



Fuel savings (Min)



Source: Ricardo scenario modelling using SULTAN.

4 Conclusions

This report shows the key role the lubricant industry has played and will continue to play in decarbonising the road transport sector. This decarbonisation has been evaluated through two main mechanisms – direct and indirect benefits.

The direct benefits refer to the engine fuel efficiency improvement from using a more advanced engine lubricants, in particular lower viscosity lubricants, enabled by advances in lubricant formulation, including both additive and base oil technology. The analysis of the direct benefits shows a clear historical shift to lower viscosity lubricant specification since 2000 across passenger car and commercial vehicle engines. This shift is expected to continue towards 2030. Testing evidence (public domain, lubricant industry and Ricardo) shows a clear trend of CO_2 reductions attributable to the use of lower viscosity lubricant specification. The true real-world magnitude of this reduction in Europe falls within a range depending on a number of factors.

The indirect benefits refer to engine technologies which have been enabled by a shift to more advanced lubricants. Of these, eleven technologies were found to have benefited by advances in lubricants for light-duty vehicles and seven for heavy-duty vehicles.

From the road vehicle fleet scenario analysis using the SULTAN model, it has been estimated that the direct benefit from engine lubricant technologies has increased to up to 3.9 $MtCO_2e$/year of avoided emissions in 2020 (compared to 2005 lubricant technology) and future improvements to lubricants have the potential to continue to reduce emissions by up to a further 2.7 $MtCO_2e$/year in 2030.

To understand the wider benefit from engine lubricant technology improvements, consideration of the indirect benefits is also important – i.e. due to the enabling/optimisation of other vehicle technical fuel efficiency improvements. When this is also considered, total avoided emissions have been estimated to increase by 16.6–29.5 $MtCO_2e$/year in 2020 and further direct and indirect emissions reductions beyond 2020 could reach 6.0–9.0 $MtCO_2e$/year by 2030. This backward-looking aspect of this modelling suggests that lubricants have constituted a significant portion of the decarbonisation of the EU. The avoided emissions indicated above account for a 2.2–4.1% reduction in GHG emissions in the year 2020. This figure equates to almost 1% of the decarbonisation of the entire EU economy (for 2016 EU emission figures from road transport).

Further emissions reductions are possible also as a result of future advances in the industry to 2030, potentially leading to both direct and indirect benefits. These could lead to an *additional* 0.8–1.3% reduction in road transport sector emissions per year by 2030 (based on 2020 levels).

As the use of advanced lubricants will lead to an increase in vehicle fuel efficiency, there is also a cost saving from reduced fuel usage. The estimated value of this is €13.8–€26.2bn when compared to 2005 and a further reduction of €5.2–€8.3bn for EU road transport as a whole could be enabled to 2030.

This equates to a historical annual cost saving per vehicle (for combined direct lubricant and lube-enabled savings) of €37–€67/year for passenger cars and €720–€1282/year for heavy trucks by 2020. Future potential *additional* annual cost savings per vehicle are estimated between €16–€25/year for cars, and €164–€207/year for heavy trucks by 2030.

The internal combustion engine is unlikely to be completely phased out soon and continues to see widespread use. In this context, it is important to see that the advancement of lubricant design has enabled a material emission reduction for a major part of the transport sector, seen since 2005, and will continue to have an impact on the wider EU emissions reduction targets through 2030 and potentially beyond.

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Appendices

A1 Appendix 1: Technical Assumptions

A1.1 Direct benefit quantitative assumptions

New vehicle production volumes

- Light-duty vehicle production in Europe:
    - To simplify the analysis, only engine families with over 100,000 units annual production were considered. This results in circa 50 engines variants being considered at each year, and represents circa 80% of the total new engine installations (83% in 2018). This ensures that the majority of the market is represented in the viscosity grades selected.
- Heavy-duty vehicle production in Europe:
    - The heavy-duty category considers only circa 40 tonne haul tractor units, which typically have engines capacities between 9.0 and 16.0 litres; these constraints were applied when processing the data
    - Again, so simplify the analysis, only engine families with over 5,000 units annual production were considered. This results in nearly all engines variants being considered. This ensures that the majority of the market is represented in the viscosity grades selected.

Viscosity grades

- Light-duty viscosity grades:
    - Historical viscosity grades for each engine type for 2000, 2005 and 2010 were based on lubricant retailer recommendations for applicable vehicles.
    - Current viscosity grades (2018) were based on vehicle manufacturer and lubricant retailer recommendations.
    - Future viscosity grades for 2025 and 2030 are Ricardo's expectations based on individual manufacturer trends and market conservativism, fuel type, level of engine rating (such as Brake Mean Effective Pressure (BMEP) level and whether it is a naturally aspirated or turbocharged engine). Ricardo have categorised future lubricants with viscosities lower than 0W-20 into two categories:
        - Low viscosity 1 (LV1) is 0W-16.
        - Low viscosity 2 (LV2) is 0W-12 or 0W-8, as there is uncertainty which viscosity grade will become mainstream. For simplicity the CO_2 benefit is assumed to be the same for both.
- Heavy-duty engine viscosity grades:
    - Historical viscosity grades for each engine type for 2000 and 2005 were based on a Ricardo database.
    - Current viscosity grades (2018) were based on vehicle manufacturer and lubricant retailer recommendations.
    - Future viscosity grades for 2025 and 2030 are Ricardo's expectations based on individual manufacturer trends and market trends.

A1.2 Indirect benefit assumptions

Table A1: Light-duty indirect technology: High-level estimate of the CO_2 benefit (relative to 2000 baseline) and uptake rate for new light duty vehicle sales

LD Vehicles

Title	FE% Min	FE% Max	Years	Uptake					
				2000	2005	2010	2018	2025	2030
Hybridization	Various	Various	All years	Calculated using market data					
Start-Stop	3.8 %	6.0 %	All years	Calculated using market data					
Downsizing	2.7 % per 15% of ds	5.5 % per 15% of ds	'05 - '30	Calculated using market data					
LSPI prevention	-	-	-	-	-	-	-	-	-
Cooled EGR	2.5 %	3.6 %	'20 - '30	-	-	-	-	12%	20%
	-	-	-	-	-	-	-	-	-
Close coupled cats	0.0 %	0.5 %	All years	-	40%	80%	99%	99%	99%
Water Injection	2.5 %	8.0 %	'25 – '30	-	-	-	-	8%	20%
Fast warm-up	-	-	'25 – '30	-	-	-	-	-	-
Turbocharging	3.0 %	7.0 %	All years	Calculated using market data					

Above given values are only applied to applicable engine/fuel categories
Sources: Ricardo Data and Analysis, ICCT

Table A2: Heavy-duty indirect technology: High-level estimate of the CO_2 benefit (relative to 2000 baseline) and uptake rate for new heavy-duty vehicle sales

HD Vehicles

Title	FE% Min	FE% Max	Years	Comments
Downsizing	2.7 % per 15% of ds	5.5 % per 15% of ds	All years	Average engine size is calculated for each year and decrease in size is multiplied by the FE% metric
Power Density	-	-	-	Power density is removed from the model, as it causes double counting when combined with downsizing.
Steel pistons	1.0 %	1.5 %	'10 – '30	Ricardo estimation on uptake is combined with fuel economy benefit expectation
Variable displacement oil pump	1.0 %	2.0 %	'25 - '30	Ricardo estimation on uptake is combined with fuel economy benefit expectation
EGR rate	-	-	-	No fuel economy benefit from EGR Rate

DPF is not included in this list, as the technology does not present fuel economy benefit against baseline
Sources: Ricardo Data and Analysis, ICCT

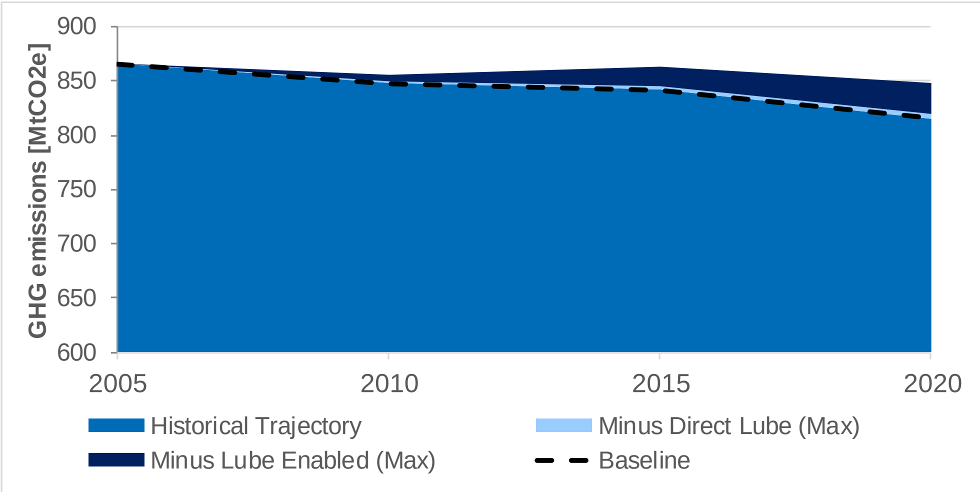
A2 Appendix 2: Additional Scenario Analysis Results

Presented below in Figure A1 and Figure A2 are the tailpipe GHG emissions and end-user fuel cost savings in context with overall GHG emissions and fuel costs from EU road transport.

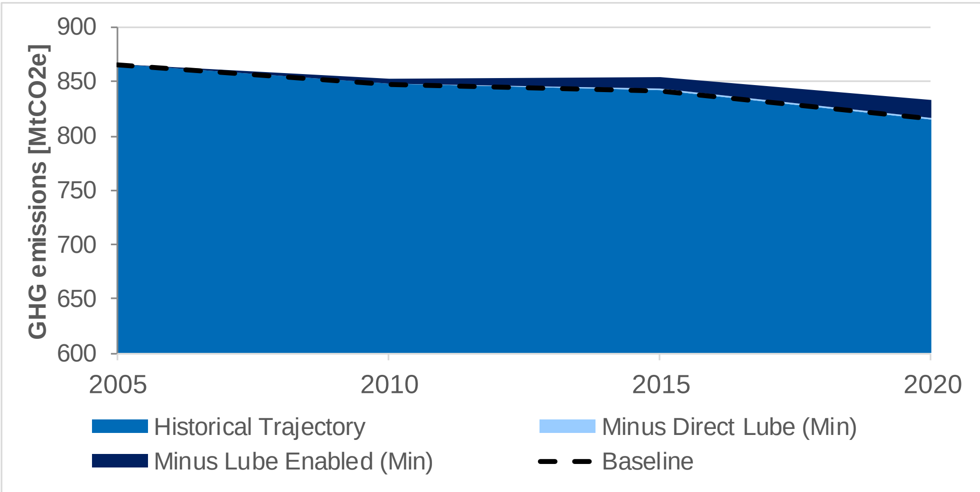
Figure A1: Historical estimates for direct tailpipe (tank-to-wheel, TTW) GHG emissions and end-user fuel costs from EU road vehicles and the contribution of engine lubricants to savings

Field | **Chart**

GHG emissions (Max benefit)



GHG emissions (Min benefit)



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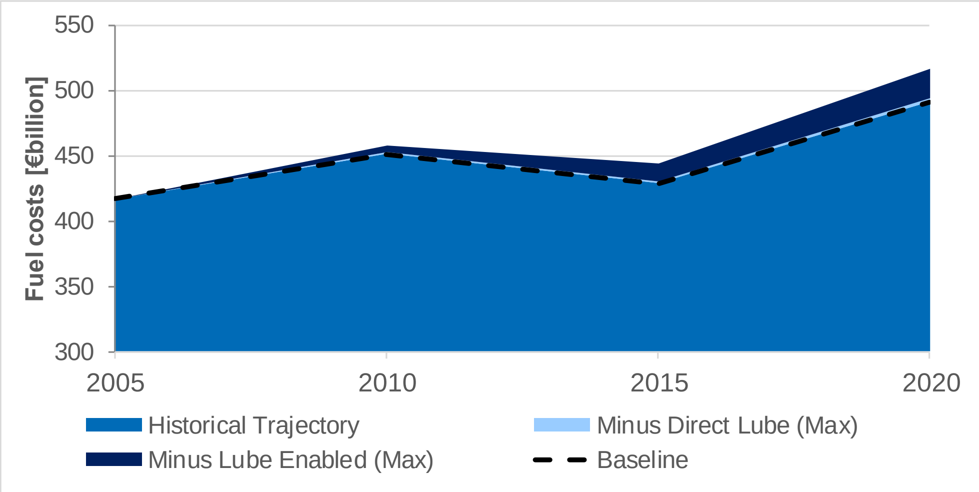
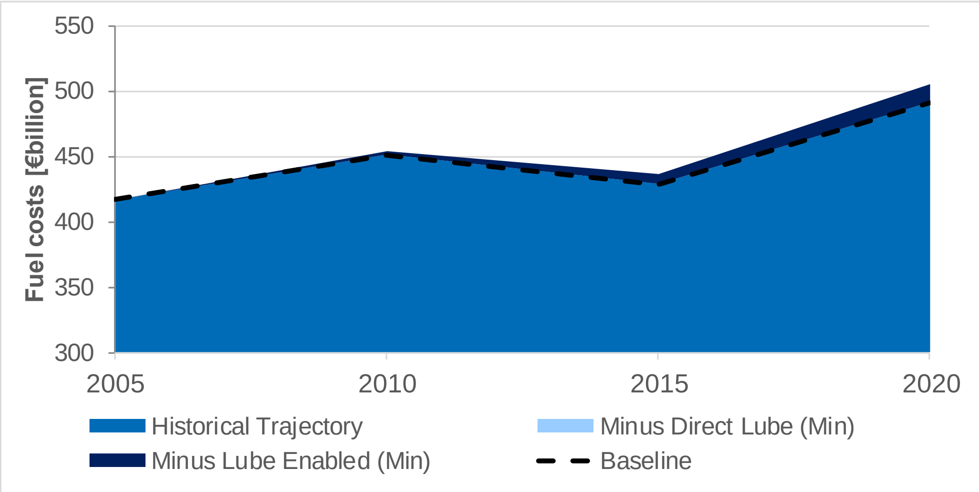
Fuel costs (Max benefit)	
Fuel costs (Min benefit)	

Source: Ricardo scenario modelling using SULTAN.

Notes: The 'Lube Enabled' impacts include only estimates due to technologies applied to vehicles, and do not include estimates for other impacts resulting from biofuel uptake.

Figure A2: Potential contribution of lubricants to future GHG and end-user fuel cost savings from EU road vehicles

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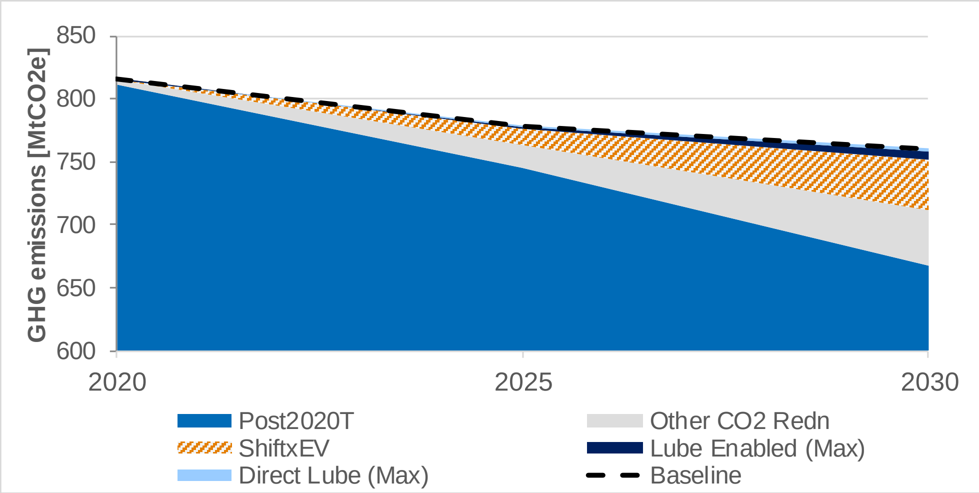
<tr><td>GHG emissions (Max benefit)</td><td>
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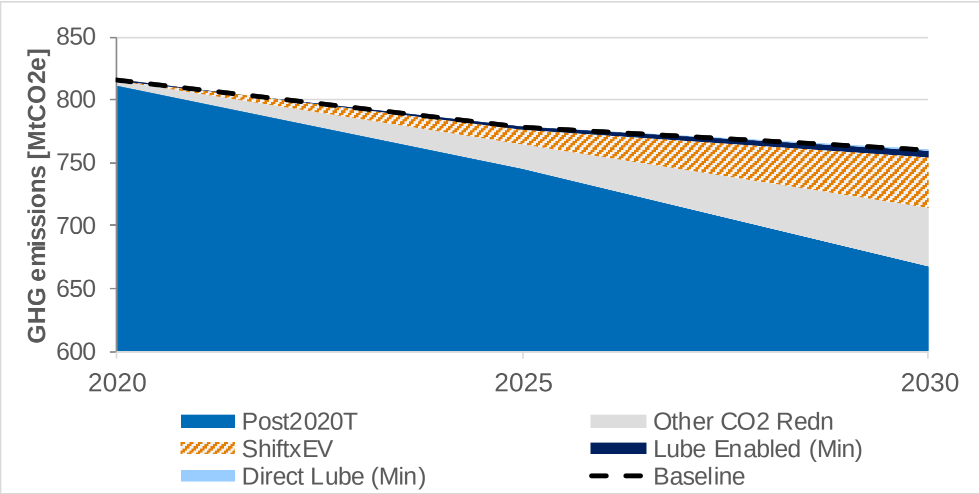
<tr><td>GHG emissions (Min benefit)</td><td>
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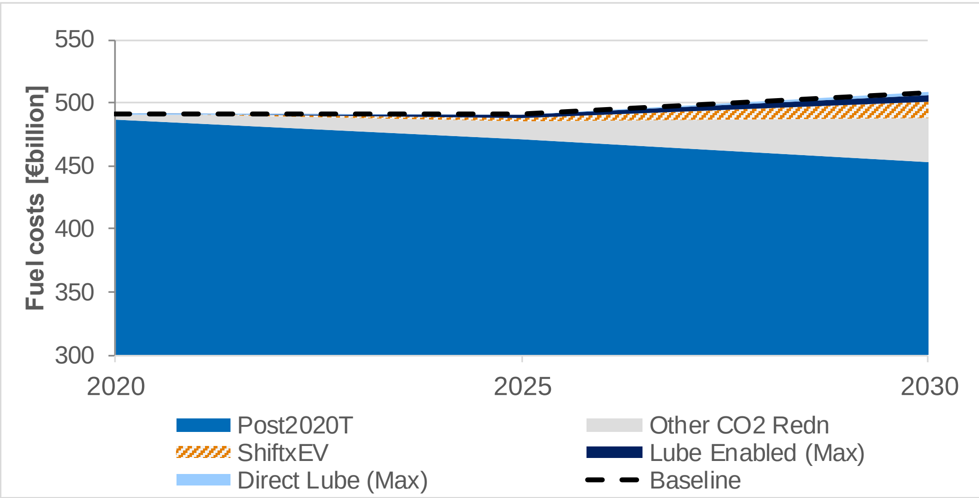
<tr><td>Fuel costs (Max benefit)</td><td>
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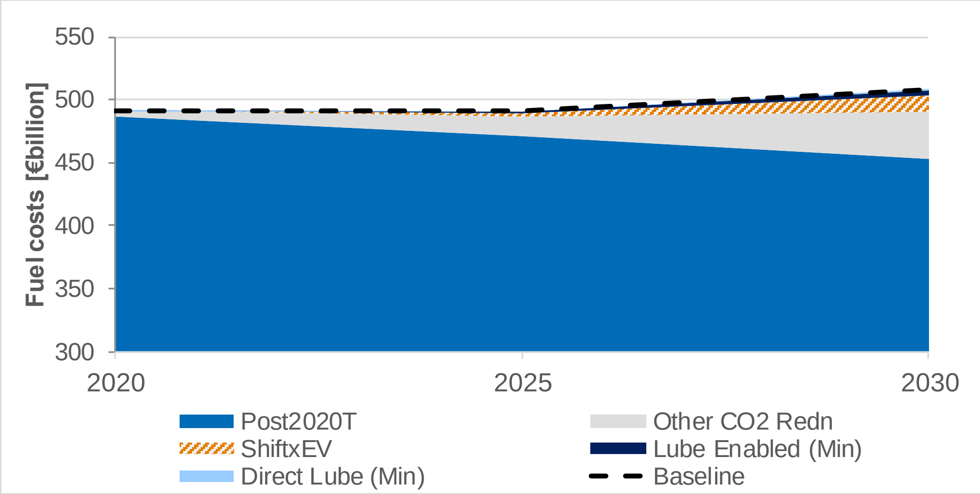
Field	Chart
Fuel costs (Min benefit)	

Source: Ricardo scenario modelling using SULTAN.

Notes: The ‘Lube Enabled’ impacts include only estimates due to technologies applied to vehicles, and do not include estimates for other impacts resulting from biofuel uptake.

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