Improving Air Quality and Climate Through Modern Diesel Vehicles

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In various technical projects, the Association for Emissions Control by Catalyst (AECC), Robert Bosch, Vitesco Technologies, IAV and FEV are working intensively on the future of diesel vehicles. This paper summarizes the results of various aspects and shows how modern diesel vehicles contribute to the improvement of local air quality and CO_2 emissions.

BACKGROUND

European Union legislation has recently undergone major changes to improve air quality and mitigate climate change. Further restrictions are expected with the announced legislative measures under the EU Green Deal.

To improve air quality and to address the gap between on-road emissions and laboratory tests, Euro 6 RDE was introduced in the pollutant emissions legislation toward Euro 6d. Data from type approval and independent third party testing confirms Euro 6d Temp diesel vehicles have low on-road NO_x and PN emissions.

WLTP was introduced to determine fuel consumption and CO_2 emissions that are more representative of normal vehicle use. To mitigate climate change, fleet-wide average CO_2 targets for new passenger cars were set for 2025 and 2030. Modern diesel vehicles are part of the strategy to meet these targets because of the inherent efficiency advantage of diesel combustion in combination with powertrain electrification.

This paper will analyze results of recent developments on demonstrator vehicles to show that a combined reduction in pollutant and CO_2 emissions is possible with the latest diesel technology through an integrated system approach of engine, hybrid and emission control technologies. It will furthermore show that the existing technologies for achieving low pollutant emissions are compatible with renewable fuels for further reducing GHG emissions. An example will be shown for HVO (Hydrogenated Vegetable Oil), reducing CO_2 up to 66 % on a well-to-wheel basis.

NO$_x$ EMISSIONS

Diesel powered vehicles are regarded as the main cause of high NO$_x$ concentrations in urban areas [1]. The introduction of Euro 6 RDE requirements is starting to improve the situation. This paper assesses the factors affecting NO$_x$ emissions under on-road driving conditions for several demonstrator vehicles with state-of-the-art diesel technology. It is highlighted that good results are now achieved in the key areas linked to the observed impact on air quality.

A single consideration of the total test result alone is not sufficient to describe the interaction between the technology used and the conditions impacting the emissions, since overlapping effects are often averaged in the test result. Several efforts have been made to simplify the visualization of the NO$_x$ emissions fluctuation over the full Euro 6 RDE operational range, either by plotting versus the mean vehicle velocity [2 and 3], the rate of positive acceleration [4] or via some combined form of cycle parameterization [5].

When tailpipe NO$_x$ emissions of cold start tests (when the vehicle has not been operated for several hours at the current ambient temperature) are plotted as a function of average velocity and vehicle mass for four-cylinder engines with a displacement of 2 l (for Euro 6d and beyond), **FIGURE 1** (bottom left), it can be seen that there are increased emissions below 25 km/h in all vehicle weight classes. For lighter vehicles this is caused by low exhaust gas temperatures and mass flows, resulting in overall lower conversion rates, **FIGURE 1** (bottom right). This typically has to be compensated via catalyst heating after engine cold start and, if necessary, by temperature-hold measures at the expense of an increase in CO$_2$ emission which is typically inversely proportional to the total NO$_x$ emission observed under these conditions. For heavier vehicles higher NO$_x$ raw emissions can be found, caused by high acceleration peaks, **FIGURE 1** (top left).

However, it can also be seen that heavier vehicles also produce higher tailpipe emissions when operating at high speeds. Despite the high exhaust gas enthalpy flows under such conditions, the increased concentrations of raw NO$_x$, combined with high space velocities, cause shorter exhaust gas residence times in the emission control system. This leads to an increase in observed tailpipe emissions, **FIGURE 1** (bottom left). As a result, there is a general increase in tailpipe NO$_x$ emissions as a function of vehicle weight. Nevertheless, low emission results are still possible for all diesel passenger cars with state-of-the-art calibration or hardware measures, **FIGURE 1** (top right).

When tailpipe emissions of different emission tests are plotted as a function of the mean vehicle speed of the test, **FIGURE 2**, it can be observed that the factors discussed above result in what is called a “NO$_x$ tailpipe bathtub curve.” This graph shows data from four different demonstrator vehicles [2–5] with diesel technology for Euro 6d and beyond. Results measured over different emission tests including cold-start are shown, covering a wide range of driving conditions. The figure also contains a scatter band illustrating the impact of driver, driving pattern and road traffic on the NO$_x$ tailpipe emissions in addition to the mean vehicle speed. The left part of this diagram with slightly higher tailpipe emissions is mainly caused by cold starts in combination with stop and go driving. The major reason here is the low exhaust temperature, leading to lower catalytic converter efficiency. Although most of the real driven duty cycles include cold start phases, the graph also shows two examples of low speed driving with warmed up exhaust lines for the car being tested [5]. When continuously driving with a warm exhaust system at low average vehicle speeds, NO$_x$ conversion rates of up to 99 % and thus near-zero tailpipe NO$_x$ emission levels can be achieved. This condition can also be kept if the vehicle is restarted after a short stopping phase of a couple of minutes, as the exhaust systems are designed to retain the heat for as long as possible.

The right part of the curve in **FIGURE 2** is caused by the increasing engine-out NO$_x$ emissions during high speed driving. This shows the need to focus future developments on both low temperature and high temperature emissions, by implementing heating measures or increasing catalyst performance or high load EGR for the high speed and high load area of the engine map.

AUTHORS

Dr.-Ing. Joachim Demuynck
is Technical Manager of the Association for Emission Control by Catalyst (AECC aisbl) in Brussels (Belgium).

Dr.-Ing. Andreas Kufferath
is Vice President of the Powertrain Solutions Division at Robert Bosch GmbH in Stuttgart (Germany).

Dr.-Ing. Oliver Kastner
ist Senior Technical Expert Diesel Combustion, Engine and Drivetrain Systems of Vitesco Technologies in Regensburg (Germany).

Dr.-Ing. Maximilian Brauer
is Head of Advanced Powertrain Development in the Powertrain Mechatronics Diesel business unit of the IAV GmbH in Berlin (Germany).

Dr. Michael Fiebig
is Project Engineer in the field of Diesel Powertrains of the FEV Europe GmbH in Aachen (Germany).

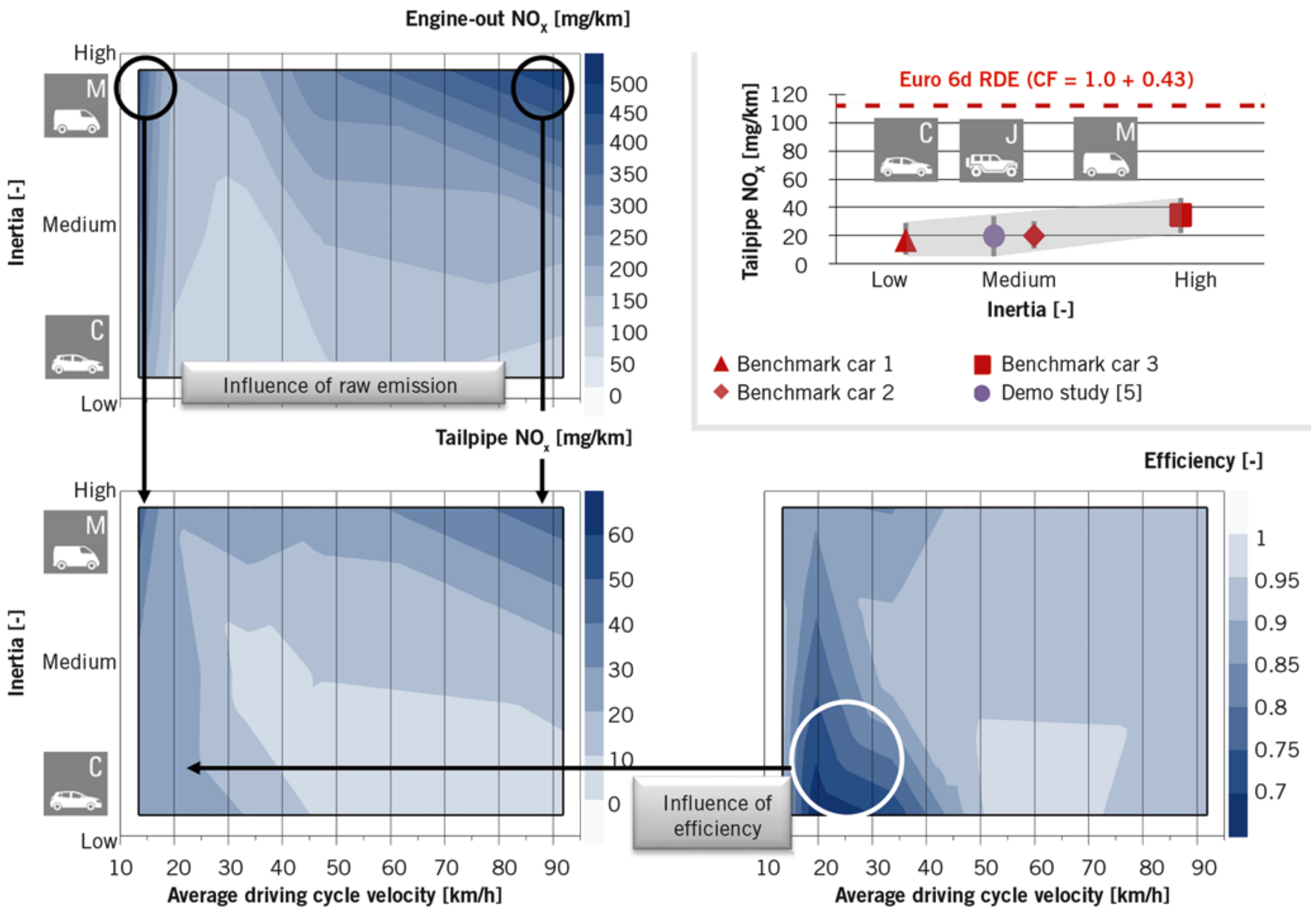

FIGURE 1 NO$_x$ emissions of Euro 6d and beyond with 2-l four-cylinder engines as function of weight and average cycle velocity under cold start conditions (© FEV)

The other constraint considered when conducting Euro 6 RDE tests is the rate of positive acceleration. Highly dynamic driving is known to create high NO$_x$ peaks which, combined with the highly transient conditions within the exhaust system results in increased tailpipe emissions. This can however be mitigated by robust engine and emission control calibration strategies [4].

PN EMISSIONS

The introduction of the DPF on diesel vehicles has ensured that, since the introduction of Euro 5 standards, tailpipe PN emissions are well below the limit of 6 × 10^{11} #/km under real driving conditions on the road. **FIGURE 4** confirms the low level of PN emissions for the demonstrator vehicles which have an SCR integrated on the DPF (Note: data at higher vehicle speeds was not separately measured). Results fluctuate between 10^8 and 10^{10} #/km depending on the filter design and soot load present in the filter. Reference emissions factors from [1] for Euro 6 diesel vehicles are also shown, up to high vehicle speed. These emissions factors already include a K$_i$ factor to account for the contribution of the DPF regeneration. PN emissions slightly increase toward the end of the regeneration as the filtration efficiency drops due to the temporary reduction of the soot layer. A K$_i$ factor of 2 to 3 is reported in [1], but emissions still stay well below the limit of 6 × 10^{11} #/km when taking this factor into account. [1] furthermore shows a positive trend toward Euro 6d.

Regulated tailpipe PN measurements do not take into account the particles smaller than 23 nm. However, the DPF captures these smallest particles well because of the diffusion mechanism, confirmed by low sub-23 nm measurements on the demonstrator vehicle being studied [3]. Non-exhaust PN emissions, for example from brakes and tires, are expected to be addressed as well to further reduce the impact of vehicles on air quality.

URBAN AIR QUALITY IMPACT

Air quality in Europe is a local challenge. Exceedances of the given air quality standards mainly occur in some inner-city hotspots and areas with high industrial activity in combination with insufficient air exchange. Transport's contribution to these hotspot measuring stations is significant in the case of high traffic density. The relevant species with defined European air quality limits are particulate matter (measured as PM$_{10}$) and nitrogen oxides (measured as NO$_2$), both with a yearly average limit of 40 µg/m³.

The introduction of the wall-flow particulate filter for diesel passenger cars and commercial vehicles allowed tailpipe particulate emissions to be reduced to a level that is no longer considered a relevant contributor to direct particulate pollution. Local authorities banning diesel vehicles without a particulate filter observed the success of this measure; Stuttgart for example no longer has a particulate matter alarm as of

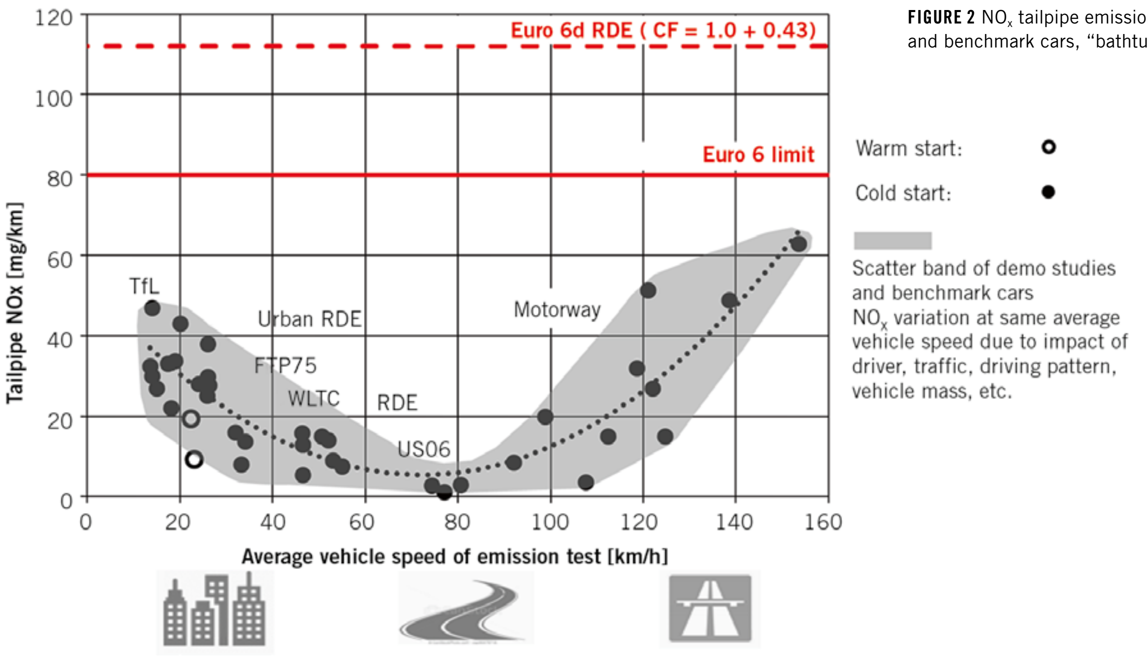

FIGURE 2 NO$_x$ tailpipe emission of various studies and benchmark cars, "bathtub-curve" (© FEV)

this year for the well-known hotspot "Am Neckartor" [4].

A similar trend exists for NO$_2$, but there are still some stations with exceedances of the annual mean value of 40 µg/m³. Fleet renewal toward Euro 6d vehicles is expected to further drastically improve this situation based on EU-wide air quality modeling [6]. NO$_2$ exceedances are predicted to drop from 20 in 2015 to below 2 % in 2030. The model assumptions on Euro 6d emissions factors (120 mg/km) were even far too conservative compared to the latest values (46 mg/km) published in [1]. With the emission results presented in this publication, an assumption of the entire diesel fleet below 10 mg/km (Close to Zero scenario) in an air quality simulation for an urban hotspot seems to be justified for the possible driving conditions at these hotspots linked to high traffic density (driving with warmed exhaust). Applying this for the hotspot "Am Neckartor" in Stuttgart results in a calculated overall contribution of the whole diesel fleet in the range of about 1 µg/m³, **FIGURE 4**. The figure also shows that the air quality in 2019 has already significantly improved compared to the reference simulation case of 2015. The results for the abovementioned Stuttgart hotspot can be transferred to other cities with similarly high traffic density. The idea that the diesel engine's contribution to total NO$_2$ emissions can be considered insignificant can become reality under urban driving conditions.

INHERENT EFFICIENCY ADVANTAGE OF DIESEL COMBUSTION

Diesel engines have an inherent efficiency advantage compared to their gasoline counterparts. Firstly, the higher compression ratio of diesel engines combined with a higher excess air ratio and secondly, the lower throttle losses at low torque are the reasons for the overall higher efficiency. This results in an lower average fuel consumption of up to about 20 % in real driving situations assuming equal vehicles and similar engine power, **FIGURE 5**. The effect is even greater for pure city driving situations, where mostly low load is required, and for elevated engine loads as required by D- and E-segment vehicles, including SUVs and light commercial

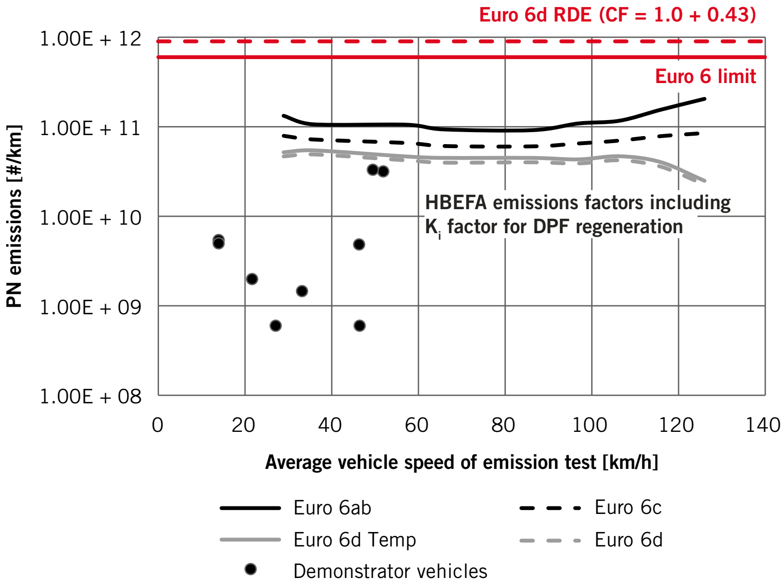

FIGURE 3 Low PN emissions over a range of driving conditions (© AECC)

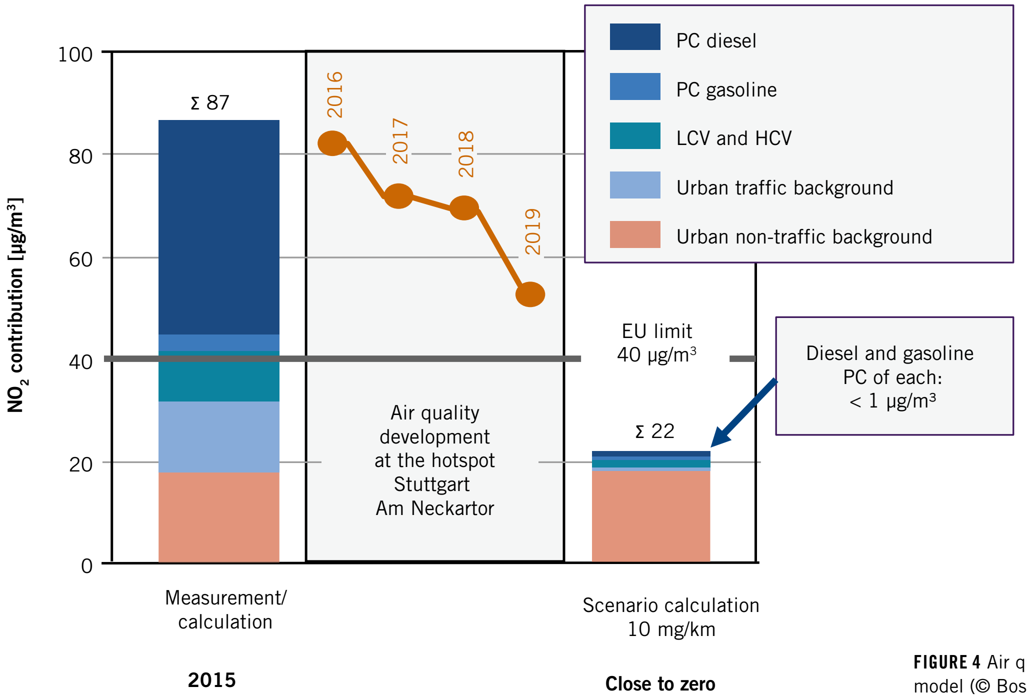

FIGURE 4 Air quality impact in a street canyon model (© Bosch)

vehicles, due to their high vehicle weight.

Development strives toward a combined CO_2 and NO_x reduction through an integrated design of the entire propulsion system, consisting of the combustion engine, the emissions control system and, more frequently, 48-V electrified components, as illustrated in **FIGURE 6**. The sophisticated design and well balanced interaction between these components lead to improved propulsion efficiencies and lowest CO_2 and NO_x emissions on the road. As an example, thermal management technologies ensure a fast heat-up of the emission control technologies so that the ICE can run more quickly at the operation with lowest CO_2, as resulting higher engine-out emissions can be converted. 48-V torque assist also helps the ICE operate at highest brake thermal efficiency.

RENEWABLE FUELS

Beyond achieving low pollutant emission levels under a wide range of driving conditions, future ICE powertrains also need to contribute to a significant CO_2 reduction in the transportation sector. In addition to the remaining potentials in ICE development, the introduction of renewable fuels brings enormous potential to

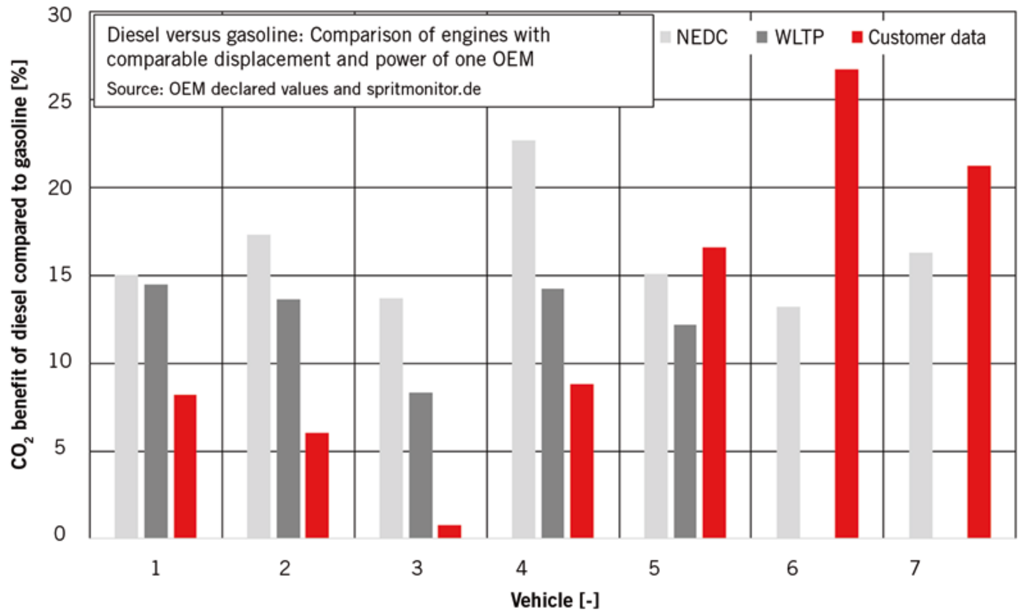

FIGURE 5 Inherent CO_2 advantage of diesel engines versus their gasoline counterpart for a specific vehicle model (© FEV)

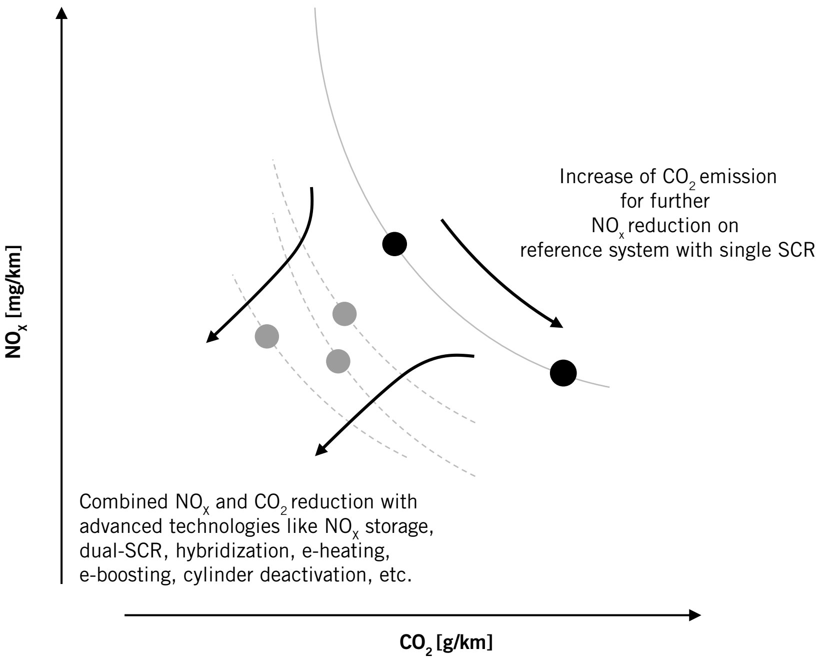

FIGURE 6 Schematic illustration of a possible combined NO_x and CO_2 reduction (© AECC)

lower CO_2 in case of a well-to-wheel or lifecycle consideration.

HVO is one of the promising renewable fuel candidates for diesel engines made from different types of feedstock including for example industrial waste and plant residues (so-called second generation biofuel). HVO fuel is already available at large scale nowadays and it is generally of superior quality in comparison to fossil diesel fuel due to its purely paraffinic composition. The properties of HVO in comparison to diesel fuel are shown in **TABLE 1**.

HVO is slightly outside the fuel specification of EN590. A large number of tests have been carried out on the diesel demonstrator vehicle in [3] with both diesel and HVO fuel in order to validate the technical compatibility and low emission capability of this renewable fuel. **FIGURE 7** gives an overview of the obtained tailpipe NO_x results for different chassis dynamometer and on-road PEMS tests. It can be concluded that a very comparable NO_x emission level can be obtained when HVO is used instead of fossil diesel fuel. Furthermore, benefits in HC and CO directly after cold start and under low load conditions were observed for HVO due to its higher cetane rating.

FURTHER STEPS

Modern diesel engines can deliver high fuel efficiency and low CO_2 emissions. **FIGURE 8** shows the relative WLTC CO_2 emission of the demonstrator cars from [2 and 3] in tank-to-wheel and well-to-wheel consideration. In addition to the figures displayed for representative diesel fuel, **FIGURE 8** also shows results for HVO and R33 Blue Diesel (a blend of HVO, FAME and fossil diesel). In line with the inherent tank-to-wheel CO_2 advantage of HVO fuel stated in **TABLE 1**, a CO_2 emission reduction of approximately 4 % was validated by the tests.

However, the real CO_2 reduction that can be achieved by using a regenerative fuel like HVO is much greater. The right side of **FIGURE 8** shows the potential of HVO fuel to reduce well-to-wheel CO_2 emissions. Based on typical feedstocks and production processes for HVO, additional CO_2 savings of 65 % [7] occur leading to a total well-to-wheel CO_2 reduction of approximately 66 % in comparison to fossil diesel fuel.

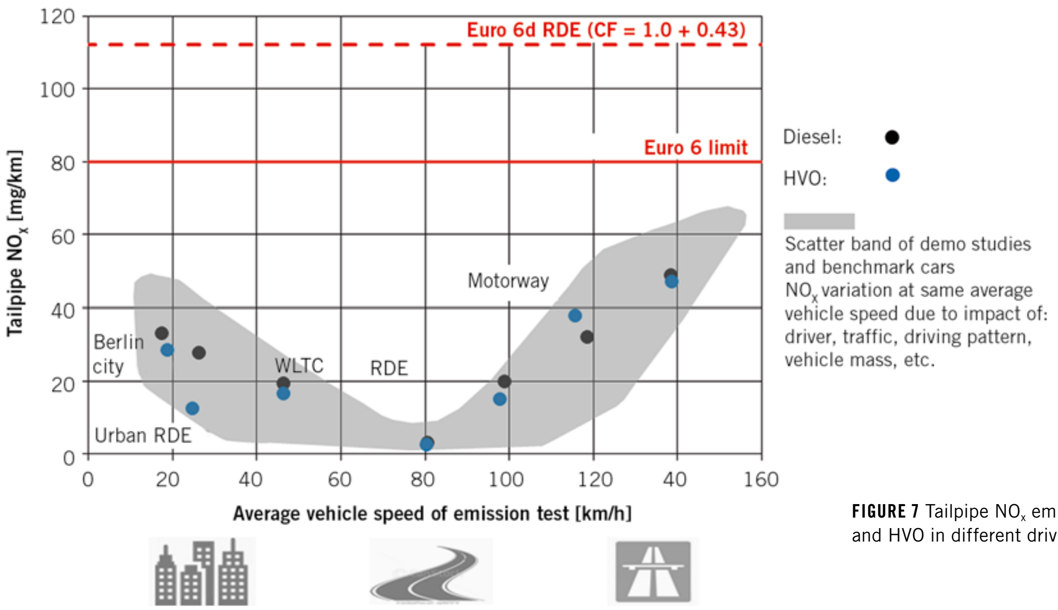

FIGURE 7 Tailpipe NO_x emission for diesel and HVO in different driving cycles (© IAV)

		Diesel	**HVO**
Substitute chemical formula	-	C14.3$H_2$6.8	C14.2$H_2$9.1
Lower heating value	MJ/kg	42.7	43.6
Density	kg/m³	842	780
Cetane number (BASF)	-	53	>70
Total aromatics (wt-%)	%	30	0
CO_2 emission/energy content	kg/kWh	0.267	0.258
Tank-to-wheel CO_2 potential compared to fossil diesel	%	0	-3.25
Well-to-wheel CO_2 potential compared to fossil diesel (depending on feedstock and fuel production process)	%	0	-65

TABLE 1 Fuel properties of Hydrogenated Vegetable Oil (HVO) in comparison to diesel fuel (© IAV)

In the context of climate change mitigation and short-term regulation changes, it is very important to consider that regenerative fuel capacities are available now and should be used to bring down CO_2 emissions quickly by using them in the existing vehicle fleet. Different fuel blends are already developed and proven to be compatible with the existing car fleet. Examples for regenerative diesel fuel blends are R33 Blue Diesel and C.A.R.E. Diesel.

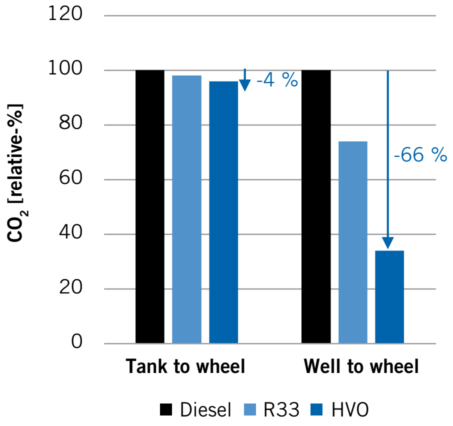

FIGURE 8 CO_2 emission for diesel and HVO in tank-to-wheel versus well-to-wheel consideration (© IAV)

CONCLUSIONS AND OUTLOOK

Diesel vehicles are part of the future mobility. They are a medium-term solution to meet CO_2 reduction targets, while having low pollutant emissions on the road, even under urban driving conditions. The vision of a diesel powertrain with negligible impact on air quality is becoming a reality. In the long term, technologies are compatible with renewable fuels to maintain the low pollutant emissions while further reducing the carbon footprint on a well-to-wheel or lifecycle basis.

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