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Engine-out emissions from a modern high speed diesel engine – The importance of Nozzle Tip Protrusion

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HIGHLIGHTS

- The effect of injector Nozzle Tip Protrusion (NTP) is compared in a high speed diesel engine.
- An excellent experimental-CFD match is observed and used to understand the results.
- A minor variation (0.5 mm) in NTP is shown to have a statistically significant effect on soot emissions.
- The effect of in cylinder mixing revealed by the CFD explains this variation.

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ABSTRACT

Engine out emissions from a diesel engine are highly dependent on the nature of the fuel/air interactions in cylinder, which in turn depend on the detail of the fuel injection process. High temperatures, which promote soot oxidation, also promote NO_x formation. Carefully controlling these interactions can lead to cleaner combustion resulting in lower engine-out emissions, thus reducing the burden on the aftertreatment system. In this work a minor (0.5 mm) variation in injector Nozzle Tip Protrusion (NTP) is tested, both experimentally and numerically, at two part-load and four full-load test points. The results indicate that a 0.5 mm variation in NTP can have a significant benefit in reducing soot emissions, across the engine operating map, whilst not having an impact on other emissions or fuel consumption. This paper demonstrates the practical importance of NTP, and demonstrates the sensitivity of engine-out emissions to relatively minor variations of this key element of the combustion system geometry which might occur naturally either in production or in service.

1. Introduction

Diesel engines are seen as a key pathway towards reducing CO_2 emissions from hydrocarbon fuelled powertrains – diesel powered light-duty vehicles emit up to 20% less CO_2 than gasoline equivalents [1]. In 2017, 42% of all light duty vehicles (including those with hybrid and electric powertrains) sold in the UK were powered by diesel powertrains [2] while light duty vehicles with diesel engines made up 49% of all registrations in the EU [3]. The modern diesel engine, coupled with a matched aftertreatment system, emits very low levels of pollutants at the tailpipe; however, the required aftertreatment devices add significant complexity and cost (around $1500 [4]) to a vehicle. Additionally, there are costs, in terms of engine efficiency, fuel economy, and maintenance associated with the operation of the aftertreatment systems through the lifetime of the vehicle.

The aftertreatment system on a modern diesel vehicle typically includes a Diesel Particulate Filter (DPF) for soot and Particulate Matter (PM) control, a Diesel Oxidation Catalyst (DOC) for hydrocarbon removal and some form of NO_x catalyst. Usually DPFs have a filtration efficiency of > 99% after a few minutes of soot loading. However, soot loading increases the flow resistance in the DPF by a few kPa, which, in turn, increases the pumping work of the engine and reduces engine efficiency [5]. As a result, DPFs require periodic regeneration to clean (via oxidation) the trapped soot/PM from the substrate. Typically, DPF regeneration is achieved by operating the engine with increased exhaust temperature – thus incurring a fuel economy penalty of 1–3% [6].

NO_x emissions may be controlled using either a Lean NO_x Trap (LNT) catalyst, Selective Catalytic Reduction (SCR), or a combination of

Abbreviations: CA b(a)TDC, Crank Angle before (after) Top Dead Centre; CAD, Crank Angle Degrees; CFD, Computational Fluid Dynamics; DOC, Diesel Oxidation Catalyst; DPF, Diesel Particulate Filter; EGR, Exhaust Gas Recirculation; HSDI, High Speed Direct Injection; IMEP, Indicated Mean Effective Pressure; ISFC, Indicated Specific Fuel Consumption; NO_x, Indicated Specific Nitrogen Oxides; LNT, Lean NO_x Trap; nIMEP, Net Indicated Mean Effective Pressure; NO_x, Nitrogen Oxides; NTP, Nozzle Tip Protrusion; PM, Particulate Matter; SCR, Selective Catalytic Reduction; TDC, Top Dead Centre; TKI, Tabulated Kinetic Ignition; TP, Test Point

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Table 1
Specifications of the single-cylinder engine.

Bore × Stroke	83 × 92.4 mm
Displacement	500 cm^3
Valves per Cylinder	2 intake, 2 exhaust
Compression Ratio	15.4:1
Fuel Pressure	400–1800 bar
Injector	DI common rail

the two [7]. LNTs are typically 70–90% efficient, and work by trapping NO_x on the catalyst which is then catalytically reduced by hydrocarbons during engine rich operation. This periodic rich operation to regenerate the LNT typically incurs a fuel consumption penalty of 5% [8]. SCR reduces NO_x to nitrogen and water in the presence of ammonia. SCRs require a supply of Diesel Exhaust Fluid (DEF) – an aqueous solution of urea – meaning an extra tank and injection equipment is required on vehicle as well as additional monitoring. Efforts to reduce the capital and operating cost of diesel aftertreatment systems, through reducing engine out emissions, are therefore of importance if diesel engines are to continue to contribute reducing CO_2 from the light-duty fleet.

It is well understood that engine-out emissions (i.e. before any aftertreatment) from diesel engines are highly dependent on the detail of the interaction between the fuel being injected and the air in-cylinder at injection. Combustion initiates in zones that are locally fuel rich (overall the mixture in-cylinder is typically lean) and at relatively low temperatures (as combustion is just beginning) causing large quantities of soot to be generated. Much of this soot is subsequently oxidized in the diffusion phase of combustion, which occurs at higher temperatures. These higher combustion temperatures lead to the formation of NO_x.

It is also well established that greater air entrainment into the diesel spray at injection will lead to a reduction in soot emissions and an improvement in efficiency, as there will be more oxygen available to oxidise the fuel completely [9], but that this greater air entrainment typically leads to an increase in NO_x as combustion temperatures are higher and there is more oxygen available to react with nitrogen [10]. Commonly, such air/fuel mixing is improved by using high fuel injection pressures (promoting spray atomization) and the use of multiple injections (entraining air into the fuel jet). In addition, it has been shown that the interaction of the fuel spray with motion of the charge in-cylinder and combustion chamber geometry will have a significant impact on the fuel/air mixing due to air entrainment [11,12]. This occurs regardless of the method of changing the fuel/air mixing whether injector technology [13] or in conventional or low temperature combustion [14].

In any modern diesel engine the final design must ensure that the fuel/air interactions on injection lead to low emissions without compromising performance. In production, designers must also consider robustness against deviations from the ideal, for example due to manufacturing tolerances. Fuel spray targeting is often controlled by

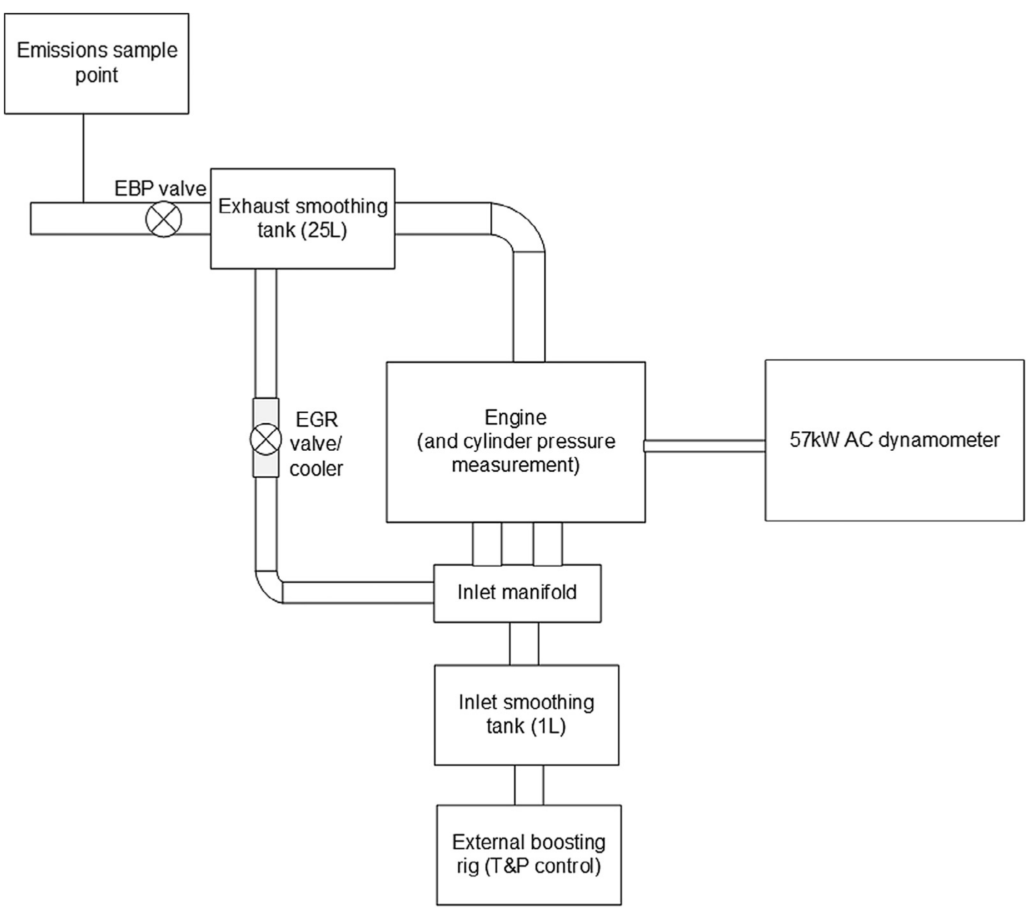

Fig. 1. Test cell schematic. Adapted from [22].