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Exhaust Emissions from Two Euro 6d-Compliant Plug-In Hybrid Vehicles: Laboratory and On-Road Testing

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Abstract

This paper discusses the legislative situation regarding type approval of plug-in hybrid vehicles (also known as off-vehicle charging hybrid-electric vehicles, OVC-HEV) in the range of exhaust emissions and fuel consumption. A range of tests were conducted on two Euro 6d-complaint OVC-HEVs to quantify emissions. Procedures were based on EU legislative requirements. For laboratory (chassis dyno) testing, two different test cycles and three different ambient temperatures were used for testing. Furthermore, in some cases additional measurements were performed, including measurement of emissions of particulate matter and continuous analysis of regulated and unregulated pollutants in undiluted exhaust. Consumption of electrical energy was also monitored. On-road testing was conducted on the test vehicle tested on the chassis dyno in the tests mentioned above, as well as on a second OVC-HEV test vehicle. Both vehicles were tested using portable emissions measurement system (PEMS) in accordance with the EU's real driving emissions (RDE) requirements. Testing was performed over an RDE-compliant route, from cold start, commencing with a fully charged and fully depleted battery (in turn). The emissions behavior of the powertrain was analyzed based on results of the comprehensive emissions measurements described above. The battery's state of charge was found to have a noticeable impact on regulated emissions and especially fuel consumption, although the low battery charge start condition was not always associated with higher emissions than the fully charged condition. Overall, it can be stated that both vehicles easily met all EU emissions requirements, regardless of the battery charge condition at test start.

Introduction

Motivated by legal requirements to reduced carbon dioxide (CO_2) emissions, many manufacturers have developed passenger cars with hybrid powertrains. Further motivation for such developments relates to customer demands, as well as the limitation of pollutant emissions. Plug-in hybrid vehicles (also known as off-vehicle charging hybrid-electric vehicles, OVC-HEV) are gaining market share in the EU – in 2019 some 3% of new registrations were OVC-HEV or pure electric [1]. Registrations of OVC-HEVs continue to grow and the last few quarters have seen large surges in demand [2]; if current trends continue, then within a few years a sizeable portion of the in-use EU fleet will consist of such vehicles. Thus, the environmental performance of such vehicles has obvious implications for air quality and the distance-specific CO_2 emissions originating from road transport (setting aside the CO_2 originating from the production of electricity used for battery charging).

In terms of the legal requirements OVC-HEVs destined for the EU market must meet in the range of exhaust emissions, there are two complementary test types. In 2017 the EU introduced tighter requirements, requiring all new vehicles to pass both the new laboratory test and (the Worldwide harmonized light vehicles test procedure – WLTP) and the new on-road Road Driving Emissions (RDE) test [3]. RDE testing is carried out using portable emissions measurement systems (PEMS). It is important to distinguish WLTP testing from RDE testing – the former is carried out to determine whether levels of regulated pollutants are below the given limits, as well as to provide official CO_2/fuel consumption (FC) figures, while the latter focuses on a narrow range of pollutant emissions and does not produce CO_2/FC results of any legal relevance.

The aforementioned procedures (WLTP and RDE) share certain similarities (e.g. commencing from cold start urban driving), as well as multiple important differences [4, 5]. These differences are relatively well-known and have been commented upon in the literature. In the case of OVC-HEV, which are sensitive to many parameters, particularly battery state of charge (SOC), but also thermal start condition and be statistically significant. The root cause to which all of the above observations may be attributed is that motorway driving occurs at the end of the WLTC, by which time the powertrain has been operational for almost 25 minutes; cold start occurs well before this (except for charge depleting conditions) and so none of the test scenarios cause any difference in the thermal state of the powertrain that could influence CO_2 emissions. The fact that under conditions other than charge depleting CO_2 emissions were significant (of a similar order of magnitude to a non-hybrid vehicle with a similar combustion engine) is not unexpected, but such results are closely linked to trivial yet highly significant observations of the CO_2 emissions performance of OVC-HEVs under conditions differing from those specified for the WLTP type approval procedure (e.g. [10]). Deeper analysis of CO_2 emissions and fuel consumption behavior and comparisons of the two test vehicles based on empirical results of the type shown above are severely complicated by multiple factors, including the transmission type, engine combustion strategy, engine aspiration and the role played by EGR, where present [11]. Here further characterization is recommended, including investigation of the behavior resulting from intermediate SOC values (>>0%, but <<100%) for the various driving situations encountered in EU legislative procedures (the 4 phases of the WLTC and RDE urban/rural/motorway-compliant routes).

Summary/Conclusions

Two OVC-HEV passenger cars (plug-in hybrids) representing the latest market-available EU technology were subjected to RDE tests under two different SOC conditions (100%, nominal 0%). The ambient temperature was in the RDE "moderate" range and test conditions were comparable. Results were calculated, processed and analyzed in line with RDE methodology, which gives results for urban, rural and motorway driving, as well as a final weighted RDE test result. In all cases, both vehicles met the EU emissions limits when tested under RDE conditions. The single vehicle tested under laboratory conditions also met all relevant EU emissions requirements.

One vehicle was subjected to the laboratory test procedure performed at 23°C to examine emissions under charge depleting and charge sustaining conditions, as well as the transitional phase; an additional test with low-stabilized SOC was also conducted from fully stabilized cold start. The results were analyzed in terms of results from the entire tests, as well as results from the cycles' phases divided into categories broadly corresponding to RDE categories (urban/rural/motorway). The results of that analysis revealed variable relationships: as expected, urban emissions were dominated by the cold start low-stabilized SOC results. For rural driving, the transitional stage causes the highest regulated emissions (i.e. not for CO_2) simply because that is the speed range in which engine cold start takes place at the high SOC start condition; CO_2 emissions increase as powertrain temperature falls (i.e. cold start at low SOC causes the highest emissions, as is fully intuitive). For the motorway speed range, THC/NMHC and CO emissions were rather invariable, while CO_2 emissions from the conditions where the engine was running were numerically identical; THC, NMHC and CO emissions were similar for the conditions where the engine was running.

In many cases, emissions results were on the order of ~10% of the applicable legal limit, or even less, yet to a certain extent this is simply a result of emissions associated with cold start being divided by a rather high number of kilometers. Indeed, the raw results from low SOC cold start test's first phases (Low) caused distance specific emissions approaching 80% and 100% of the applicable Euro 6 limits for THC/NMHC (respectively) and exceeding 50% of the CO limit. The low emissions performance is strongly scale-dependent, as well as SOC-dependent; as is often noted, current EU test procedures cover very long distances and thus assign such emissions behavior a very low weighting [5]. Emissions of NO_x were however very low under all driving conditions, including for urban operation following cold start at low SOC. The excellent RDE NO_x emissions performance of test vehicle A was confirmed (and even surpassed) under laboratory conditions – some 93 km of mixed driving including 2 cold starts, urban stop-and-go traffic and several high speed motorway sections caused the emission of a total of 158 mg of NO_x, i.e. <2 mg/km.

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Definitions/Abbreviations

λ - lambda; the unitless ratio of the air:fuel ratio to the stoichiometric ratio for the fuel type

CO - carbon monoxide
CO2 - carbon dioxide
EU - European Union
FC - fuel consumption
GPF - gasoline particulate filter
NMHC - non-methane hydrocarbons
NOx - oxides of nitrogen
PEMS - portable emissions measurement system
PN - particle number
RDE - real driving emissions
SOC - state of charge
THC - total hydrocarbons
TWC - three-way catalyst
WLTC - World harmonized Light vehicles Test Cycle
WLTP - World harmonized Light vehicles Test Procedure