Particle Reduced, Efficient Gasoline Engines

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Summary

The aim of Work Package (WP) 5 is the validation and assessment of the systems developed in the PaREGEn project (especially WP3 and WP4) through physical testing, with the final objective being to ensure the correct operation of the developed subsystems and their optimal integration to the demonstrator vehicles. A Jaguar XE and a Mercedes E180 were chosen as a baseline vehicles by Jaguar Land Rover and Daimler, respectively, for their demonstrators.

This deliverable describes the actitivies of tracking and monitoring the developments carried out throughout WP3 and WP4 in relation to the targets established at the beginning of the project. According to the improvements realised both in the engine and in the aftertreatment system of each vehicle, an extended assessment will be made to ensure the achievement of initial targets and to demonstrate that all modifications and improvements are reasonable.

Additionally, one visit to the OEM or OEM's partners' facilities of WP3 and WP4 has been made as a part of this task and these visits are reported in this deliverable. The visits were used to monitor the testing activities, the progress of the WP3 and WP4 and the results obtained in each WP.

With the visits mentioned, as well as an update of the current situation at the moment of the publication of this document, it has been feasible to make this deliverable, containing the status and the achievements of both demonstrator vehicles.

In terms of the level of progress observed at the time of both the visit to the Daimler facilities (WP3) as well as to the Ricardo and the University of Brighton facilties (WP4), it can be concluded that the developments carried out by both work packages are according to the expectations of IDIADA.

Summarizing, IDIADA can state that the tracking and monitoring of both WP3 and WP4 activities has been successfully completed and, whilst significant delays in WP4 have been experienced, the expectation is to receive the demonstrator vehicles from both work packages and to get the results expected, in terms of fuel consumption and emissions, especially with a threshold particle size of at least 10nm.

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1 Introduction

The aim of Work Package 5 is the validation and assessment of the systems developed in the PaREGEn project (especially in WP3 and WP4) through physical testing in the laboratory, the final objective being to ensure the correct operation of the developed subsystems and their optimal integration in the demonstration vehicles. A Jaguar XE and a Mercedes E180 have previously been chosen as baseline vehicles by Jaguar Land Rover and Daimler, respectively. Throughout the project, a tracking and monitoring of the developments will be performed in order to relate the project results against the targets.

This deliverable report describes the actitivies of tracking and monitoring of the developments carried out in WP3 and WP4. According to the improvements implemented in both the engine and the aftertreatment system in each vehicle, an extended assessment will be made of the achievement of the targets and to demonstrate all modifications and improvements are implemented as defined at the beginning of the project. Additionally, IDIADA will make sure that the methods and procedures developed in Task 5.1 have been taken into account, to facilitate the testing of the demonstrator vehicles and their measurement at IDIADA.

In that respect, one visit to the OEM or OEM's partners' facilities of WP3 and WP4 has been made, and it is reported in this deliverable. Each visit has been used to monitor the testing activities, the progress of the WP3 and WP4, and the results obtained in each WP.

Taking a deeper look into each WP separately, the main objectives of WP3 are the implementation of the new stoichiometric gasoline direct injection engine of the demonstrator vehicle developed by Daimler and its partners, and the optimal integration of other parts, such as the aftertreatment system delivered by Johnson Matthey, which is composed of a three-way catalyst (TWC) and a gasoline particle filter (GPF). To track these improvements, a visit to the R&D department in the Daimler facilities at Stuttgart has been made, where the engine test bench, the vehicle test cells and the test track have been visited by IDIADA.

Regarding WP4, led by Jaguar Land Rover and in conjunction with its partners, the aim is to deliver a Jaguar XE with an engine using dilute combustion (excess air, external EGR, internal exhaust residuals or a combination of all three) and with an aftertreatment system suitable for both stoichiometric and lean gasoline combustion. To achieve this, a revised combustion system (of increased compression ratio and higher air motion) and a new boosting system (Variable Nozzle Turbine (VNT) and electrical compressor) are being developed. In addition, a higher energy ignition system and optimized combustion system suitable for lean combustion are being implemented. In order to track and monitor this implementation, IDIADA has visited two of the WP4 partners to ensure the correct progression of the different tasks. Firstly, a visit to Ricardo facilities has been made to see the demonstator vehicle and, after that, a visit to the University of Brighton, where the multi-cylinder engine has been running on the engine test bench, has been made.

With the visits mentioned, as well as an update of the current situation at the moment of the publication of this document, this deliverable, containing the status and the achievements of both demonstrator vehicles, has been made.

2 Methods and Results: Tracking and Monitoring the Project Developments

2.1 Sub-task 5.2.1 Tracking and Monitoring of the Mercedes E180

The aim of this sub-task is to track and monitor the developments carried out in the PaREGEn project by WP3, by Daimler in conjunction with Bosch, FEV, RWTH Aachen University and UFI Filters. These developments include the new stoichiometric downsized gasoline direct injection engine and other parts, such as the aftertreatment system delivered by Johnson Matthey or the ECU of the demonstrator vehicle. With the information obtained, it will be feasible to make an assessment of the viability of achieving the final targets.

Table 1 Specifications of the WP3 Base and Demonstrator Vehicles

	Mercedes E-Class	
	Base vehicle	Demonstrator
Vehicle / Engine type	E-Class, 2016 model	
Vehicle mass (empty) [kg]	1575 → Demo. vehicle has additional weight due to measurement equipment and prototype status	
Drive axle	Rear wheel drive	
Transmission type	Automatic	
Power output [kW]	115	Target: 115
Torque [Nm]	250	Target: 250
CO_2 output (NEDC) [g/km]	Certified 137	Target: 123
Cylinders	4	
Orientation	Longitudinal	
Displacement [cm^3]	1595	1500
Compression ratio [:1]	10.5	Target >12.0
Bore [mm]	83	76
Stroke [mm]	73.7	83
Stroke:bore ratio	0.89	1.1
Combustion mode	Homogeneous	
Injection System Gasoline	GDI state of the art	Advanced injection system with increased injection pressure
Injector Gasoline	Piezo	Multi-hole solenoid
Injection Water	w/o	PWI (+ DWI)
Ignition	Multi-spark ignition	Multi-spark ignition
Valve control	Variable valve train with 2 lifts on intake side	Variable valve train with 2 lifts on intake & exhaust side
Valve timing	Conventional	Miller
Charge motion	w/o	Variable charge motion
EGR	Internal EGR	Extended internal EGR
Boosting	Monoscroll turbocharger	Advanced dual scroll turbocharger
Aftertreatment	TWC	Advanced TWC+GPF

In Table 1 the specifications of the Mercedes E-class base and the corresponding demonstrator vehicle are shown. On the one hand, the baseline vehicle specification is the most important characteristic of the Mercedes E-Class that was tested at IDIADA's facilities (in Task 5.1) to obtain the final targets of CO_2 emissions, fuel consumption and to determine the starting point in terms of pollutant emissions. On the other hand, the demonstrator vehicle specification shows the improvements, from the engine and aftertreatment system to achieve the target at the end of the PaREGEn project.

The main activity in this sub-task was the visit to Daimler facilities in Stuttgart, Germany, in order to monitor the developments carried out by the WP3 partners and to verify that everything is on time. This last part is very important due to the fact that any delay on the WP3 and, as a consequence, in the MS04 (Availability of the demonstrator vehicles) would be a critical risk for the Tasks 5.3 and 5.4, which are the independent testing of the demonstrator vehicles and the impact assessment.

Regarding the engine, the demonstrator vehicle will have an engine based on the Mercedes-Benz M270/M274 family. It will be a 4 cylinder engine with a swept volume about 1.5 litres. The engine will be arranged for longitudinal mounting in the vehicle. The bore will decrease to about 76 mm, yet there will be a larger stroke resulting in a higher charge motion level. The engine crank housing had to be changed in order to realize the smaller bore and a low friction cylinder liner. The intake port will generate a high level of charge motion (tumble). A variable tumble device is also implemented in the system for evaluation. The cylinder head design and packaging need to allow, next to the direct injector for the fuel, an additional injector for direct high pressure water injection into the combustion chamber. In addition, the intake manifold needs to be prepared for the optional installation of port water injection.

In the next section, a detailed explanation of the most important achievements witnessed during the visit to the Daimler facilities on 4th July, 2018 will be given.

2.1.1 Mercedes E180: Visit to the Daimler R&D Department in Stuttgart, Germany

The main developments to check were those related to the new engine and the Johnson Matthey aftertreatment system, which was to be delivered to Daimler for the demonstrator vehicle.

At the beginning of the visit, the current scenario of the WP3 was explained: the most important things to take into account were the fuel consumption of the new engine and the water supply system for the water injection. Daimler mentioned that the improvement in the combustion efficiency of the engine is due to the Miller Cycle that had been implemented, and that the results were excellent. Based on engine test bench measurements, the fuel consumption had been reduced by about 2% to 6% across a wide range of engine operation and by up to 12% near peak power.

Another point to take into account, as explained by Daimler, was the supply system used for the water injection. The water injection system will be supplied by a tank with a capacity of 23 litres. Parallel to the development of this water supply system, the study into a new exhaust condensed water filtering system was on-going (see Deliverable 3.3).

In the second part of the visit, the modifications to the engine to achieve the final targets, in terms of CO_2 reduction, particulate matter and pollutant emissions control, were shown. A "non-final version" engine was set on the engine test bench and a verification of the different improvements of the engine was made. The following paragraphs explain whether these improvements are implemented or not and why, the gains made with the modifcations, and other considerations to take into account.

The following figures show the engine test bench from different perspectives, where some of the improvements made could be seen.

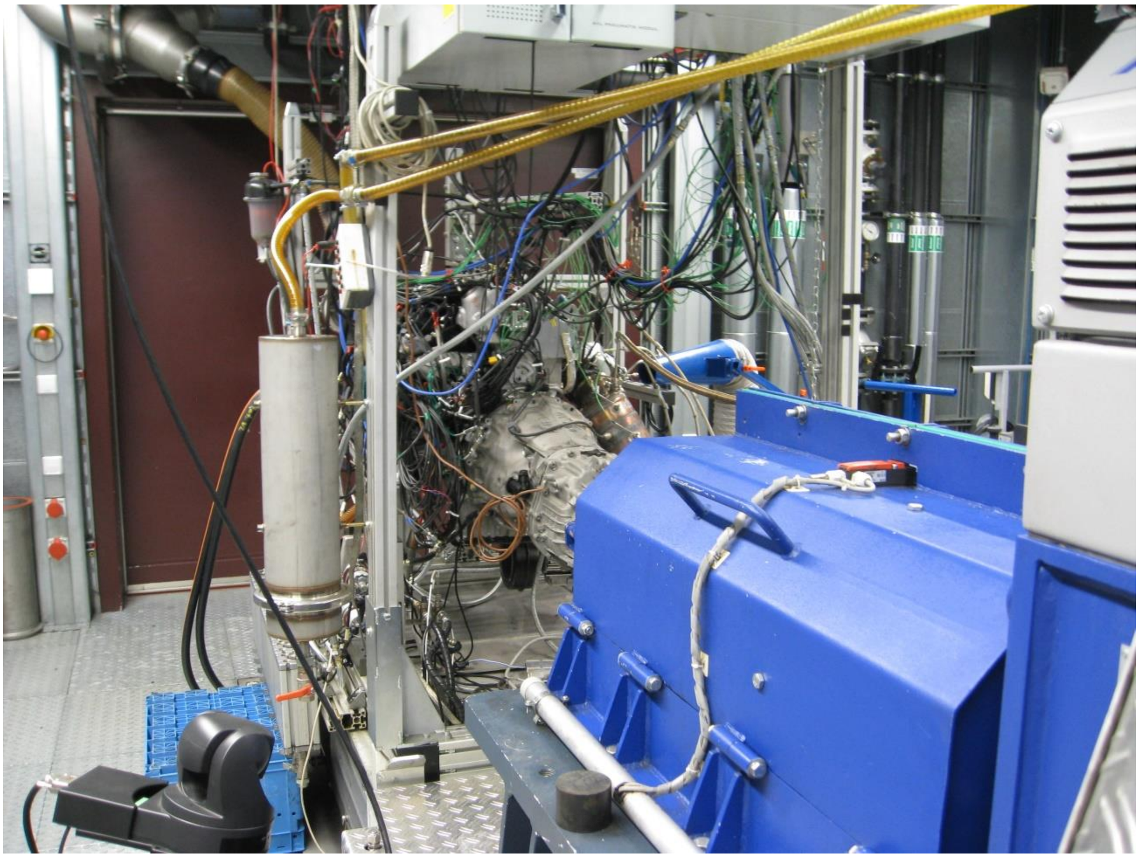


Figure 1 Rear view of the engine on the test bench

Before starting with the explanation of the modifications to the engine, it is worth looking at the vehicle that has been chosen for the project, its engine type and some of the engine properties. The vehicle is an E-Class, 2016 model with a mass (empty) of 1575 kg (the demonstrator vehicle has additional weight due to measurement equipment and prototype status).

Regarding the engine type, as mentioned, it is based on a Mercedes-Benz M270/M274, some of the most important characteristics are:

- Power output [kW]: 115
- Torque [Nm]: 250
- 4 cylinders with a longitudinal orientation.

Those parameters are not modified in the demonstrator vehicle, as was checked during the visit. Specifically, the engine power is between 115 and 130 kW, so the target has been achieved. Regarding the torque, the maximum torque of the engine is 250 Nm and is equal to the target torque according to the simulation done on the engine test bench. In addition, the baseline vehicle had a RWD (rear wheel drive) and the transmission was automatic, the same as the demonstrator vehicle.

After this explanation of the main parameters of the engine that are not modified in the final demonstrator vehicle, a detailed explanation of all the changes included in the engine at the time of the visit by IDIADA will be made.

The first focus has been the main features of each cylinder of the 4-cylinder engine. According to Daimler and at the time of the visit, the downsizing from 1.6 to 1.5 litres had already been made. This reduction is a result of the reduction of the bore (from 83 to 76 mm) and an increase of the stroke (from 73.7 to 83 mm). This corresponds to a change in the stroke:bore ratio from 0.89 to 1.1:1. The compression ratio (CR) has been increased in the vehicle engine to up to 12.0:1.

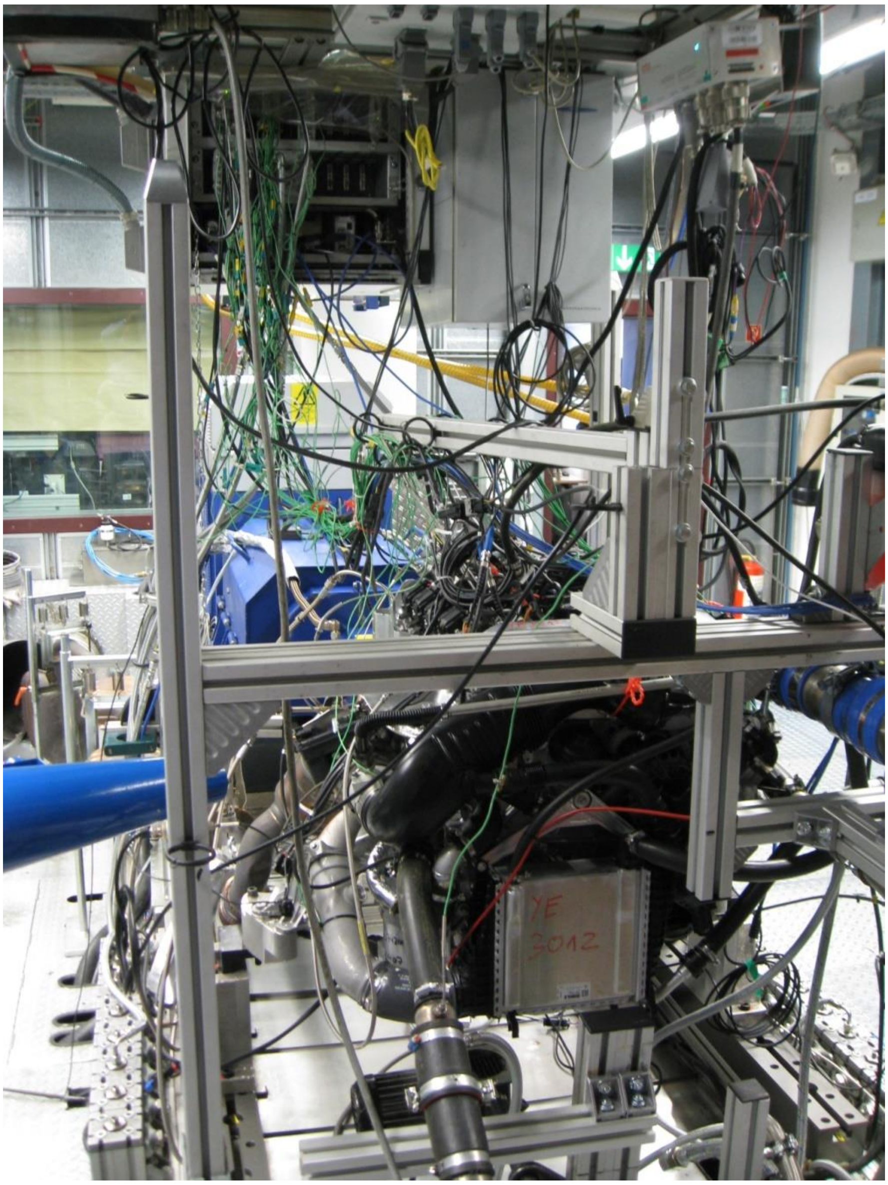


Figure 2 Front view of the engine on the test bench

The second focus has been the combustion process and all the systems involved. Firstly, the combustion mode is the same for both the base and the demonstrator vehicle: homogeneous. Secondly, the gasoline injection system has been changed. The GDI (Gasoline Direct Injection) system of the baseline vehicle has been improved with a more advanced injection system that works with an elevated system pressure of 350 bar. After this modification, several hardware and calibration parameters needed to be adapted to achieve a good mixture homogenization. All these changes of the injection system and mixture formation will have impact on the engine out PN emissions.

Another part that has been improved is the fuel injector (gasoline injector, in this case). Instead of a piezo injector, a multi-hole solenoid injector provided by the PaREGEn Partner Bosch, has been chosen. The ignition system has had no change compared to the baseline vehicle, a multi-spark ignition system has been chosen for this engine.

Concerning the valve system of the engine, the baseline vehicle had a variable valve train (VVT) with one lift on the intake side: the possibility to enhance the VVT with two lifts on both intake and exhaust side has been investigated. According to the results of the development simulations, there is not a significant improvement on either the intake or exhaust side. Hence, it was decided that the final engine will not have the variable valve system with two lifts, but retain the variable valve train with only one lift. Therefore, the biggest enhancement of the engine, in terms of CO_2 emissions reduction, has been made through the implementation of the Miller Cycle instead of the conventional cycle. This has already been tested into the engine test bench and as a result, in comparison to the base engine, the PaREGEn demonstrator vehicle engine shows substantial improvement in fuel economy over a wide range in the engine map.

An important component, that is related with the valve control and valve system, is the EGR (Exhaust Gas Recirculation). EGR systems on gasoline engines are employed primarily to reduce throttling losses at part load, in order to reduce fuel consumption, and, secondarily, to reduce NO_x emissions. In addition, EGR can replace fuel enrichment in gasoline engines to inhibit knock. The baseline vehicle had an internal EGR implementation. Internal EGR is achieved by increasing NVO (negative valve overlap), for example during the exhaust stroke, which requires an improved camshaft that can rapidly switch cam profiles to achieve any variable valve timing. A comparison of the effectivity of water injection compared to internal EGR was being made.

Concerning the charge motion, at the beginning of the project, a variable charge motion was defined as a possibility for the final demonstrator vehicle engine. This device would allow a variable admission into the engine chamber, such that turbulence could be generated. However, due to the limited benefit of the variable charge motion system in the target engine and the limited period for the vehicle calibration, it was decided not to include this variable charge motion in the demonstrator vehicle. The influence and improvement of this device will be investigated by the WP3 partner FEV on the test bench.

Another focus of the visit was the Boosting System. This has been implemented with a new advanced dual scroll turbocharger that enhances the engine performance. This turbocharger is required by the Miller Cycle valve system timings and it also has the characteristic to increase the boost pressure. Although a VNT (variable nozzle turbine) has also been tested, a segmented turbine has been chosen for the turbocharger.

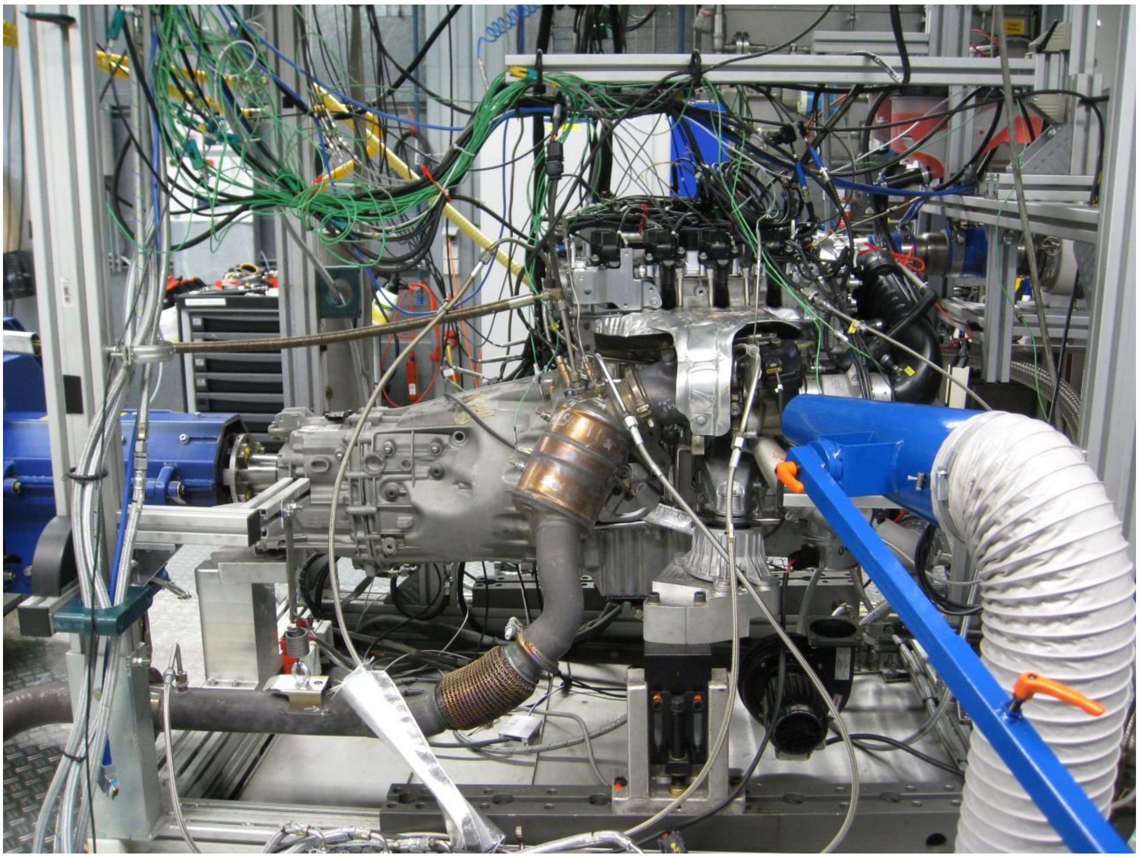


Figure 3 Right side view of the engine on the test bench

Although these many systems had already been implemented at Daimler, there were two system which had not yet been installed. These were the water injection system and the aftertreatment supplied by Johnson Matthey.

Concerning the water injection, a fundamental understanding of the water injection process has been gained. In addition, Daimler has made an assessment of potential of direct and of port water injection, so as to decide which system is better to implement in the engine. The system implemented in the demonstrator vehicle will only use the port water injection (PWI). This system, basically, will help to avoid wall film formation on the engine's cylinders in the demonstrator vehicle, among other enhancements. The direct water injection (DWI) will be investigated and simulated by the WP3 partner FEV so as to acquire a know-how related this technique. As mentioned before, the water needed for the water injection system will be supplied by a tank (similar to the urea tank) with a capacity of 23 litres. This tank must be filled with water and alcohol (ethanol) in a proportion of 2:1 (2 litres of water for each litre of ethanol). It is worth mentioning that, although the water injection system control has been successfully implemented within the ECU on the engine test bench, the integration of the PWI in the vehicle ECU was still pending at the time of the visit.

In addition, a study of a new exhaust condensed water filtering system, which includes neutralisation of the water from the exhaust, is being performed with the contribution of UFI Filters.

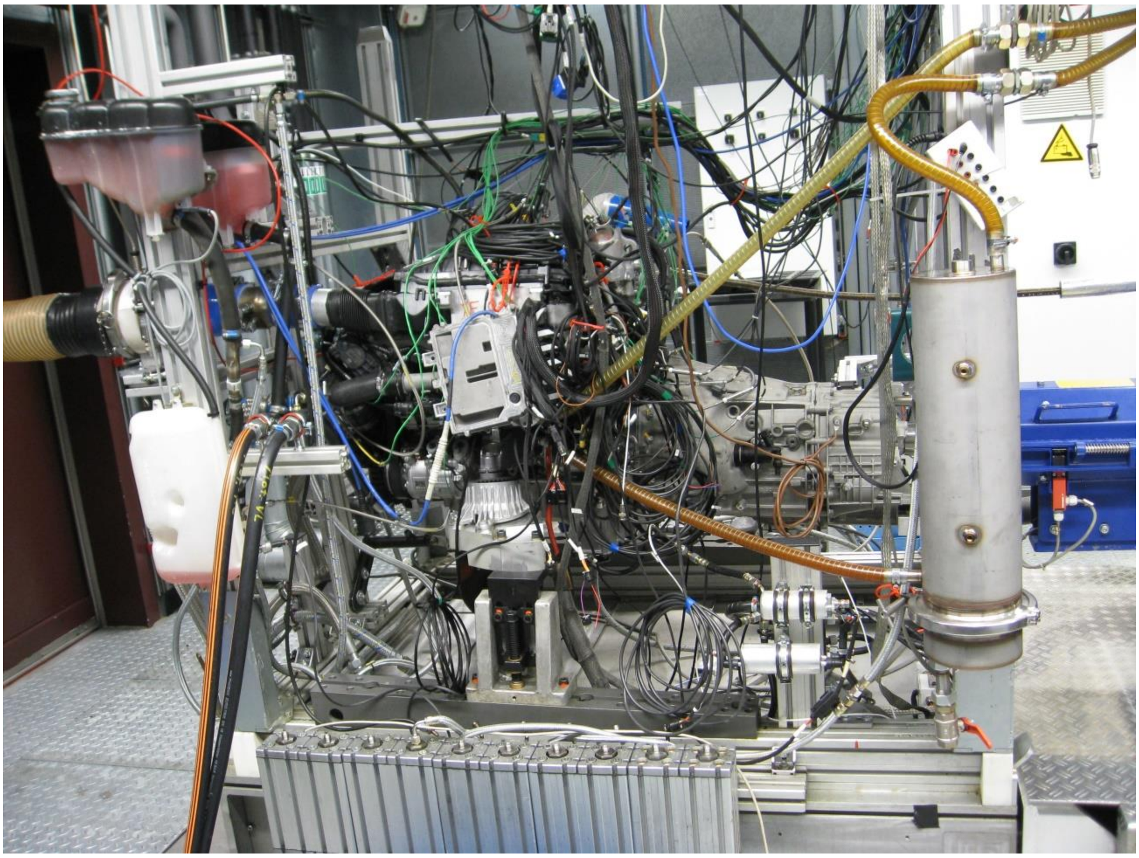


Figure 4 Left side view of the engine on the test bench

At the time of the visit, the aftertreatment system was still to be supplied by Johnson Matthey. A back-up system, using Daimler sourced parts, had been made ready for the demonstrator vehicle. Hence, depending upon the system performance and packaging, the Johnson Matthey system will be tested on the engine test bench and, if showing sufficient further benefit, be fitted to the demonstrator vehicle.

Finally, another point to take into account is the final delivery of the demonstrator vehicle to IDIADA. It is planned to transport the demonstrator vehicle from Daimler Stuttgart to IDIADA, in order to make some developments and conduct the validation. This delivery of the demonstrator vehicle it is scheduled to be on time according to MS04.

2.1.2 Current State of the WP3 Activities

The objective of this sub-section is to give an update on the current state of the WP3 activities. Since the time of IDIADA's visit, the following activities have occurred within WP3:

- **Condensed water filtering system.** The filtering system has been delivered to Daimler. First runs on the test bench have been made with water condensation system and the quality of unfiltered exhaust gas condensate is better than expected (see Deliverable report D3.3)

- **Development and evaluation of engine combustion strategies.** FEV has completed the engine measurements and the engine has been sent to BOSCH. Daimler has successfully finalized the preparation for the PWI system (hardware and functions). In addition, the internal EGR strategy has been finalized on test bench.

- **Vehicle build-up, transient operation, software development and calibration.** The main achievements are:
    - The ECU calibration on the engine testbed with the PWI system has been finalized.
    - The integration of the target engine with PWI into the demonstrator vehicle has been completed.
    - First test in the chassis dynamometer with the demonstrator vehicle have been done and WP3 were able to work with the vehicle properly.

2.2 Sub-task 5.2.2 Tracking and Monitoring of the Jaguar XE

The aim of this sub-task, as it also has been for the previous sub-task, is to track and monitor the developments carried out in the PaREGEn project by WP4 (the new dry dilute combustion demonstrator with all the systems into the powertrain and aftertreatment adapted for a lean gasoline combustion), which is led by Jaguar Land Rover and in conjunction with Bosch, Ricardo, the University of Brighton, Johnson Matthey and Garrett. All the information gathered during this sub-task will be used to assess the achievement of the final targets, as defined in the Deliverable D5.1, and validate the results.

Table 2 Specifications of the WP4 baseline vehicle and the demonstrator vehicle concept

	Base Vehicle and Engine	PaREGEn Engine and Vehicle
	XE Auto, 2015MY, GTDi	XE Auto, 2017MY, Ingenium
Cylinders	4	
Orientation	Longitudinal	
Stroke/Bore Ratio [ratio]	1.11	
Displacement [cc]	1996	
Compression Ratio [Ratio]	10.5:1	11:1
Max Power [PS]	200	
Max Torque [Nm]	320	
Combustion Mode	Stoichiometric	Dilute
CO_2 Output NEDC [g/km]	179	N/A
CO_2 Output WLTC Low/High [g/km]	171/181	145/154
Drive Axle	RWD	
Gear Shift	8-speed automatic	
Vehicle Mass (empty) [kg]	1515	

In Table 2 above, the most important specifications of the Jaguar XE baseline and the concept for the demonstrator vehicle are shown. The two biggest changes in the demonstrator vehicle, that will help to achieve the final targets, are the Compression Ratio (CR) increase and the combustion mode, which will change from stoichiometric to a combination of stoichiometric and dilute (lean) combustion. Initially, a higher compression ratio was targeted for the PaREGEn vehicle, but mechanical considerations uncovered during development have led to a more conservative value for the demonstrator vehicle, although this is still an increase relative to the baseline engine. Additional engine test bed work and simulation are to be made to fully evaluate the potential of the full compression ratio increase.

The WP4 demonstrator vehicle seeks to advance the state-of-art on lean burn engine technology by combining advancements in fuel injection, boosting and Continuously Variable Valve Lift (CVVL) technologies in a high compression ratio engine operating over the Miller Cycle.

According to the WP4 targets, in order to achieve the CO_2 values shown in the table above and to be compatible with the emissions requirements, the dilute combustion of the demonstrator vehicle can take the form of excess air (lean), external Exhaust Gas Recirculation (EGR), trapped residuals or a combination of all three.

Utilising lean combustion for maximum efficiency typically brings additional challenges for the aftertreatment system, in particular maintaining suitably low tailpipe NO_x emissions. Therefore, to obtain maximum benefit, a more complex aftertreatment system has been specified, compatible with the requirements of both stoichiometric and lean combustion.

One of the main actions in this sub-task was to visit facilities at Ricardo and the University of Brighton, where the demonstrator vehicle and engine test benches are, respectively. In addition, tracking of the developments was made and the monitoring of the testing activities and the results obtained done. The timing of the developments is one of the key factors that WP4 has to be specially careful about due to the direct impact on the final timing of the project. If the vehicles are not received by IDIADA in a suitable timeframe, completion of WP5 and thus completion of the project could be delayed.

The next section will show extracts from the IDIADA's visit report to the Ricardo facilities and the University of Brighton (September 19th, 2018), and the main conclusions therefrom.

2.2.1 Jaguar XE: Visit to the Ricardo facilities and the University of Brighton, United Kingdom

The aim of the visit was to observe progress and verify that the tasks are progressing at an appropriate rate.

IDIADA saw the progress with the combustion system, the boosting system from Garrett and the aftertreatment system developed by Johnson Matthey. In addition, the demonstrator vehicle was checked at the Ricardo facilities, with the different parts of the new engine and aftertreatment implementation, as well as the engine test bench with the MCE (Multi-Cylinder Engine) at the University of Brighton.

The visit was made to review work package progress and understand the hardware development actions, viewing the vehicle at Ricardo and the engine test bed at University of Brighton. Specifically, these are the points reviewed at each location:

- **Ricardo facilities:** Overview of the whole WP4, where the different tasks of the work package were reviewed. After that, the demonstrator vehicle was shown with almost all the parts of the new engine and the aftertreatment implemented.
- **University of Brighton:** Combustion system overview, engine test bench viewing: WP4 & WP5 timing and targets are shown and discussed.

In the following paragraphs, the status of the modified systems for the demonstrator vehicle will be explained.

<u>Engine, Combustion and Variable Nozzle Turbine (VNT) Design</u>

A non-IEM (Integrated Exhaust Manifold) cylinder head was procured as back-up hardware. As the baseline engine had an IEM, removal of the IEM necessitated design and procurement of both a new cylinder head and a new exhaust manifold. This work had been completed and prototype parts procured, but the scheduling did not permit the installation of the non-IEM hardware to the vehicle. Hence, calibration activities in WP4 will try to mitigate the risk of catalyst light-out with the IEM engine in the vehicle.

Regarding the combustion mode of the new engine, WP4 is working on the stoichiometric/lean transitions. The control system is under development, some control issues are being worked on and, after that, the calibration will be done. However, the calibration was expected to be verified on the engine test bench only in the weeks after IDIADA's visit to Ricardo.

Another important system to monitor was the Boost System, which is composed of a Garrett Variable Nozzle Turbocharger (VNT) and a Honeywell 48 V e-Charger. The main parts of the system are:

- The VNT matched to deliver boost at low exhaust gas flow and temperature conditions;
- The 48V e-Charger enables fast transition from stoichiometric to lean operation and it reaches torque target at 1200 rpm;
- Custom pipework and adapters have been designed and procured;
- Silicone hose and custom moulded intake air pipework have been designed to match the packaging constraints.

<u>Aftertreatment System Design and Build</u>

The aftertreatment system has been adapted for both stoichiometric and lean gasoline combustion; it consists of:

- Electrically-heated 3-way Lean NOx Trap (EHC-TWLNT);
- 3-way Gasoline Particle Filter (TWGPF);
- Active Selective Catalytic Reduction (SCR) – integration of an SCR system with a lean gasoline-specific brick into the gasoline demonstrator vehicle.

AdBlue injection for the SCR is done with a dosing unit coming from a diesel engine. Due to the fact that the exhaust temperatures are higher in a gasoline engine, this dosing unit must be cooled by water. The cooling circuit was modified in order to make use of existing electrical pumps and radiators.

The aftertreatment has been designed to provide robust emissions control when operating under both lean and stoichiometric conditions.

Control System Design and Build

Concerning the control system, there are the following comments:

- All major sections of the software have been delivered and verified;
- Initial lean switching has been achieved, but there are some issues still to be resolved.

Combustion System Design and Build

The combustion system was originally developed by Jaguar Land Rover for very lean operation at a nominal compression ratio of 12.5:1. Single Cylinder engine testing with this combustion system, conducted by Jaguar Land Rover, demonstrated that the intended combustion system could achieve the intended performance level, however, there were challenges implementing the original piston design into the Multi- Cylinder PaREGEn engine. In the interests of timeliness, it was decided to modify the piston for the multi-cylinder engines. This change resulted in a reduction in the nominal compression ratio, which is expected to compromise the thermal efficiency of the engine at some speeds and loads. Consequently, some of the targeted CO_2 saving may require demonstration through analytical methods rather than being physically demonstrated on the vehicle.

Combustion System Development

Single Cylinder Engine (SCE)

The development of the combustion system was done firstly in the Single Cylinder Research Engine (SCRE) in the Jaguar Land Rover facilities. Those activities were finished successfully, including the selection of the most beneficial injection system. In conclusion: Jaguar Land Rover demonstrated the results from SCE testing to IDIADA's satisfaction.

Multi-Cylinder Engine (MCE)

Ricardo, with the help of University of Brighton (UoB), has continued with the support to Jaguar Land Rover in terms of the Multi-Cylinder Engine. The UoB has a new engine test cell with the engine and aftertreatment fully installed in it.

At the visit to the UoB facilities, UoB showed the prototype engine installed in the engine test cell. The engine installation was almost done and ready to start the testing. There are more information and pictures of the engine in the *Vienna Motor Simposium paper* [1] made by WP4. But it is worth noting that:

- The engine installation and instrumentation was correct. Tthe complete exhaust line has been installed on the test bench to replicate as closely as possible the vehicle installation;
- The engine installation was done in a way as close as possible to the in-vehicle configuration (engine's air path and exhaust system are installed to match the in-vehicle configuration);
- The engine is equipped with in-cylinder pressure and exhaust pressure measurement (cooled Kistler sensors).

Demonstrator Vehicle

The demonstrator vehicle of WP4 was built with the PaREGEn hardware and was located at Ricardo facilities. The vehicle was already wrapped with the PaREGEn logo, the same way it will be delivered to IDIADA.

Figure 5 WP4 demonstrator vehicle

The main tasks concerning the demonstrator vehicle were already implemented according to planned expectations. In the following, the actual situation of the vehicle will be explained:

- The level of instrumentation is quite high and packaging issues have been solved;
- The vehicle has been fitted with a prototype ECU integrated with the rest of the vehicle;
- The vehicle is equipped with different emission sample lines.

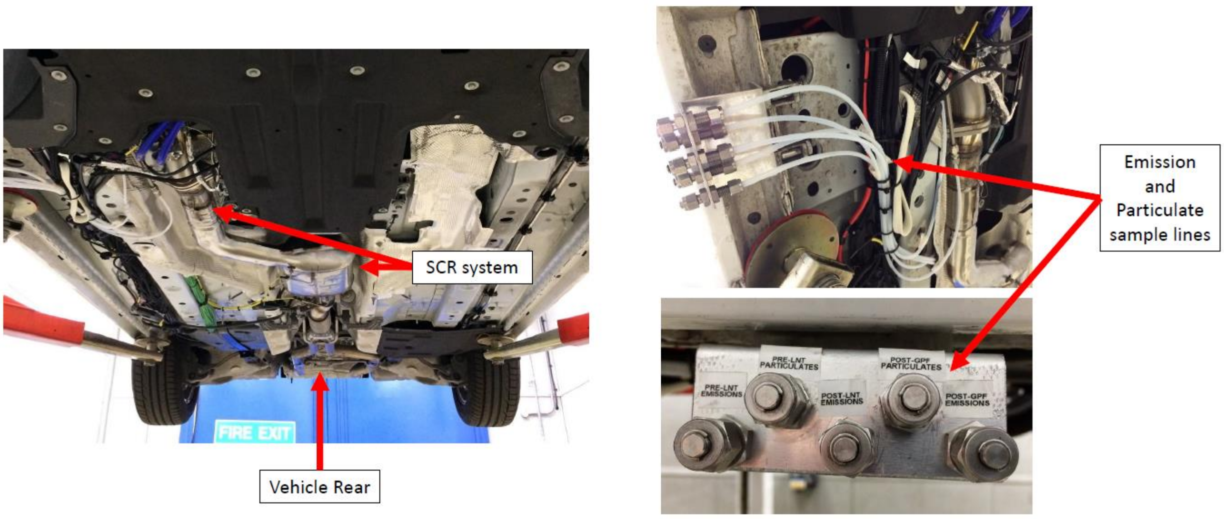
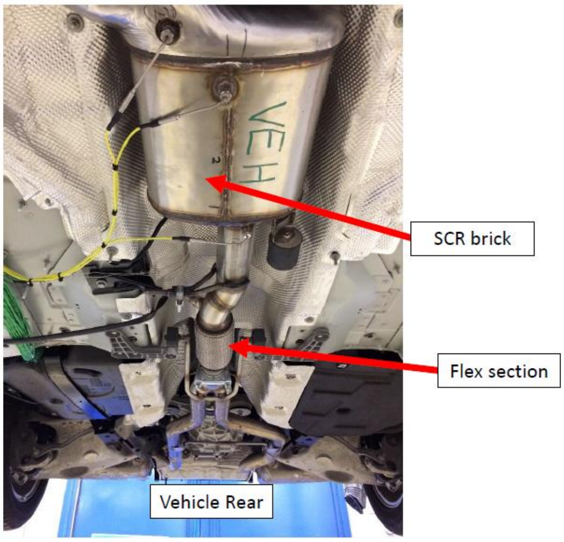


Figure 6 Aftertreatment and instrumentation of the WP4 demonstrator vehicle

In the following images, the engine, aftertreatment and the exhaust line into the demonstrator vehicle, with the final packaging to those systems, are shown.



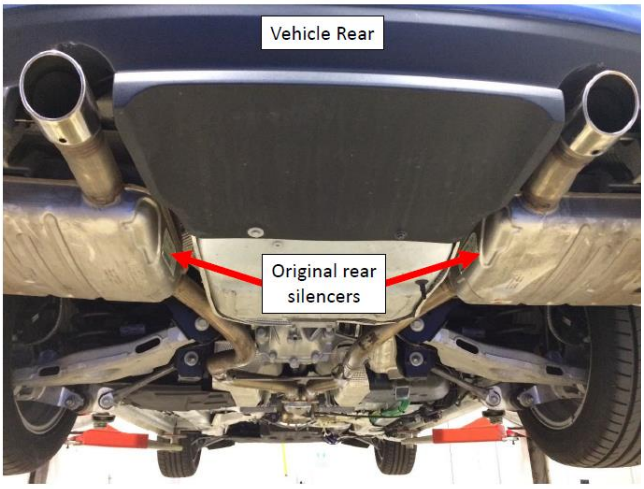


Figure 7 Aftertreatment and exhaust line of the WP4 demonstrator vehicle

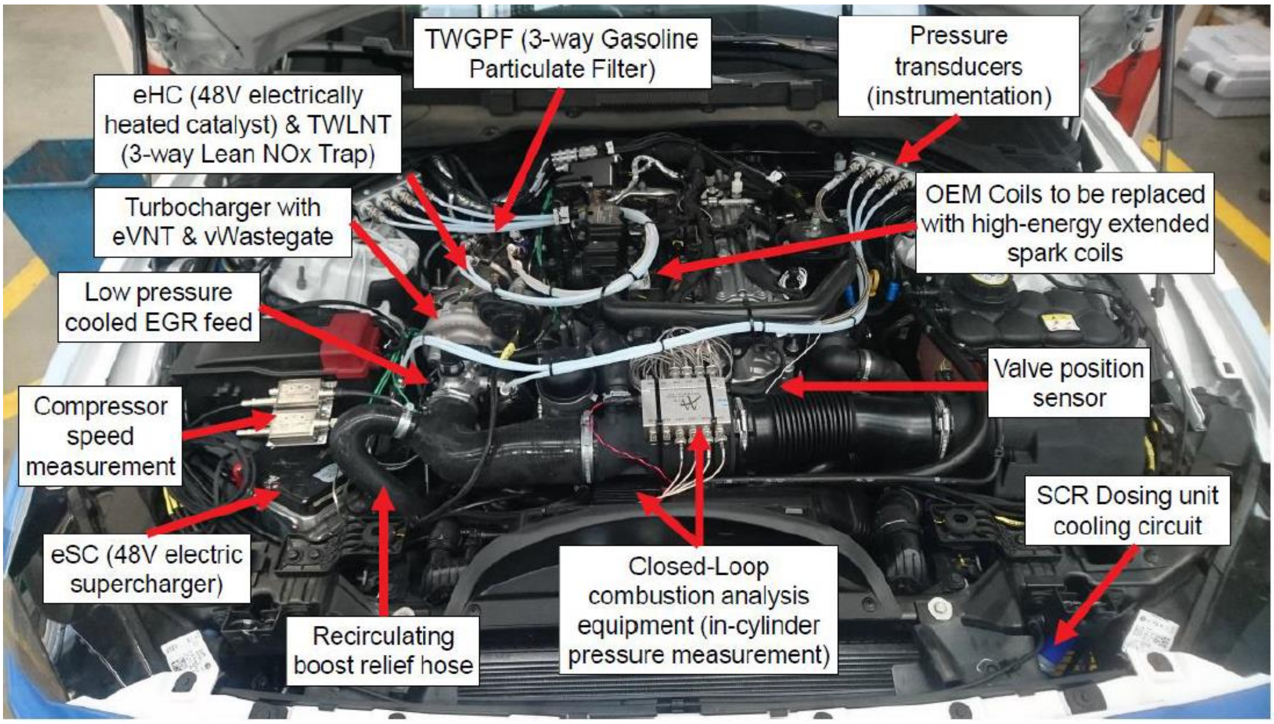


Figure 8 Engine of WP4 inside the demonstrator vehicle

Once the current state of the engine, the aftertreatment and the demonstrator vehicle, in terms of implementation of the new technology, equipment, instrumentation and so on, the next part of the tracking was to check the targets in terms of CO_2 saving and the schedule remaining for WP4 from the moment of the visit.

With the objective to create the WP4 demonstrator vehicle, some tests were carried out at Ricardo to provide a starting point for calibration. The Jaguar XE was progressing successfully to achieve the targets in CO_2

saving. The demonstrator vehicle was likely to achieve a CO_2 improvement and, through a combination of physical testing (SCE and MCE) and analytical techniques, WP4 still aimed to achieve the project targets.

Concerning the timing schedule for WP4, the summary was:

- Currently, the Multi-Cylinder Engine development activities are proving more challenging than originally expected and delay has been incurred. However, remedial actions have been put in place and it is expected the vehicle will still be available for WP5 to complete its activities.
- The vehicle demonstrator is prepared to start the in-vehicle activities.
- At the time of the visit, on September 19th 2018, the vehicle was expected to be ready in time for IDIADA to complete their work within the project timelines.

2.2.2 Current State of the WP 4 Activities

This sub-section is to update the status of the WP4 activities at the moment of this deliverable submission. Since the time of IDIADA's visit, the following activities have occurred within WP4:

- **Development of the Control System.** Many of the outstanding issues observed by IDIADA in September 2018 have since been resolved sufficiently to enable calibration of the engine and vehicle for completion of the drive cycles relevant for this project.

- **Development of stoichiometric and lean calibrations.** The initial stoichiometric calibration supplied with the control system has been markedly improved and the first lean calibrations have been developed.

- **Revision of aftertreatment system.** Initial aftertreatment performance testing identified scope to improve the NOx reduction capability of the system, primarily related to the quantity of NO_2 reaching the SCR catalyst. A revised GPF catalyst was formulated to improve the conversion efficiency of the SCR, which has now been implemented.

- **Undertaking of initial drive cycle testing.** The calibration activity is now sufficiently advanced that the first drive cycle tests have been undertaken with the vehicle. While the results are not yet representative of the expected final performance, the tests have been completed successfully and have identified the operating conditions where further calibration development should be focused.

In terms of timing, there has been an important update. The milestone MS04 (Demonstrator vehicles available) will be delayed from May 2019 (M32) to August 2019 (M35). The main reason is related to some issues with testing and prototype hardware to date in WP4. Despite efforts to mitigate these issues, a significant delay in the project completion is expected.

3 Discussion and Conclusions

The main activity in this task was to track and monitor developments carried out in the project, specially within WP3 and WP4, in order to relate them to the targets. After completing the task, IDIADA can report state that both work packages are progressing successfully in general terms but with significant delays. In the following lines, some conclusions will be presented.

In terms of the level of progress observed at the time of both the visit to the Daimler facilities (WP3) as well as to the Ricardo and the University of Brighton facilties (WP4), it can be concluded that the developments carried out by both work packages are according to the expectations of IDIADA.

It has to take into account that, at the moment of the visits, the two work packages were at different levels of development. On the one hand, the main focus was to track in the work done by Daimler and the rest of the WP3 partners in relation to the new engine (fuel consumption focus), the water storage system for the water injection and the aftertreatment of the vehicle (although this latter part was still not provided by Johnson Matthey at that time). On the other hand, the monitoring of the WP4 activities led by Jaguar Land Rover had its focus, at the time of the visit, on the combustion, boosting and aftertreatment systems as well as the demonstrator vehicle itself (which was already built up at that time). In addition, the MCE activities in the UoB were also tracked.

From IDIADA’s point of view, the major risk with each demonstrator vehicle was:

- WP3: Possibility of delay in the demonstrator vehicle delivery due to further testing on the chassis dynamometer for detailed optimisation and calibration.
- WP4: Some technical risk around the hardware of the combustion system remaining to be validated and both technical as well as timing risks of the demonstrator vehicle still being present.

These risks had already been detected and an action plan to reduce the possibility of their occurrance had been made. The risk posed to get the vehicles for testing on time (according to the actual plan) was well-controlled for both work packages together with IDIADA by reviewing the current state of the activities on each work package, at least monthly. However, a significant delay within WP4 could not be fully mitigated.

Concerning the risk posed to get the level of benefit expected to be observed from testing, IDIADA is optimistic for the results of the upcoming tests in both demonstrator vehicles. According to the information provided by WP3 and WP4 and the testing already done by them in their facilities, the fuel consumption reduction targets are likely to be achieved in the independent testing at IDIADA’s facilities. In both cases, there will be some extra fuel economy potential that will be assessed through alternative validation strategies (simulation, SCE or MCE testing).

Summarizing, IDIADA can state that the tracking and monitoring of both WP3 and WP4 activities has been successfully completed and, whilst significant delays in WP4 have been experienced, the expectation is to receive the demonstrator vehicles from both work packages and to get the results expected, in terms of fuel consumption and emissions, especially with a threshold particle size of at least 10nm.

4 Recommendations

IDIADA recommend WP3 and WP4 to give as much feedback as possible to prevent any delay in the WP5 final independent testing and to have time enough in case the timing scheduled for testing had to be changed.

5 Deviations

A deviation from the original plan of the project has to be mentioned. The milestone MS04 (Demonstrator vehicles available) will be delayed from May 2019 (M32) to August 2019 (M35). The main reason is related to some issues with testing and prototype hardware to date in WP4. The progress and effort done by the WP4 to mitigate these issues has to be remarked upon. This fact, together with a long-planned improvement of the IDIADA chassis dynamometer test facilities, during July and the beginning of August 2019, will require an extension of the project, as is currently being discussed with the Project Officer.

6 References

[1] Dr. Richard Osborne and Andrew Lane - Ricardo, Shoreham-by-Sea; Niall Turner, Dr. Lyn McWilliam, Dr. Nathan Hinton, John Geddes - Jaguar Land Rover, Coventry; Dr. Jeremy Gidney, Dr. Jason Cleeton - Johnson Matthey, Royston; Dr. Penny Atkins, Prof. Rob Morgan - University of Brighton; **"A New-Generation Lean Gasoline Engine for Reduced CO_2 in an Electrified World"**, Vienna Motor Symposium 2019.

Appendix A – Acknowledgement

The author(s) would like to thank the partners in the project for their valuable comments on previous drafts and for performing the review.

Table 3 Project partners

#	Partner	Partner Full Name
1	RIC	RICARDO UK LIMITED
2	DAI	DAIMLER AG
3	JLR	JAGUAR LAND ROVER LIMITED
4	BOSCH	ROBERT BOSCH GMBH
5	FEV	FEV EUROPE GMBH
6	JM	JOHNSON MATTHEY PLC
7	HON	HONEYWELL, SPOL. S.R.O
8	JRC	JOINT RESEARCH CENTRE – EUROPEAN COMMISSION
9	UNR	UNIRESEARCH BV
10	IDIADA	IDIADA AUTOMOTIVE TECHNOLOGY SA
11	SIEMENS	SIEMENS INDUSTRY SOFTWARE SAS
12	LOGE	LUND COMBUSTION ENGINEERING LOGE AB
13	ETH	EIDGENOESSISCHE TECHNISCHE HOCHSCHULE ZUERICH
14	UDE	UNIVERSITAET DUISBURG-ESSEN
15	RWTH	RWTH AACHEN UNIVERSITY
16	UFI	UFI FILTERS SPA
17	UOB	UNIVERSITY OF BRIGHTON

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Appendix B – Abbreviations / Nomenclature

Table 4 List of Abbreviations / Nomenclature.

Symbol / Shortname	
CH4	Methane
CO	Carbon Monoxide
CO2	Carbon dioxide
CR	Compression Ratio
CVVL	Continuously Variable Valve Lift
DWI	Direct Water Injection
ECU	Engine Control Unit
EGR	Exhaust Gas Recirculation
EHC-TWLNT	Electrically-heated 3-way Lean NOx Trap
GDI	Gasoline Direct Injection
GPF	Gasoline Particle Filter
MCE	Multi-Cylinder Engine
MS	Milestone
NOx	Oxides of Nitrogen
NVO	Negative Valve Overlap
OEM	Original Equipment Manufacturer
PM	Particulate Matter
PN	Particle Number
PWI	Port Water Injection
RWD	Rear Wheel Drive
SCE	Single Cylinder Engine
SCR	Selective Catalytic Reduction
SCRE	Single Cylinder Research Engine
THC	Total hydrocarbons
TWC	Three-Way Catalyst
TWGPF	Three-Way Gasoline Particle Filter
UoB	University of Brighton
VNT	Variable Nozzle Turbine
VVT	Variable Valve Train
WP	Work Package