Final Report

Covering the project activities from 01/06/2014 to 30/05/2018

Reporting Date
05/03/2019

LIFE DI-CNG
Demonstration and validation of Direct Injection of CNG in vehicle engines and its environmental benefits

PROJECT DATA

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BENEFICIARY DATA

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</tr>
<tr>
<td>Contact person</td>
<td>Mr Camille Feyder</td>
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<td>Avenue de Luxembourg, L-4940 Bascharage, Luxembourg</td>
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<td>Visit address</td>
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<tr>
<td>Telephone</td>
<td>+352 50 18 43 70</td>
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<th>Description</th>
<th>Acronym</th>
<th>Description</th>
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<tr>
<td>BEV</td>
<td>Battery Electric Vehicle</td>
<td>LCI</td>
<td>Life Cycle Inventory</td>
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<tr>
<td>BMEP</td>
<td>Brake Mean Effective Pressure</td>
<td>LCIA</td>
<td>Life Cycle Impact Assessment</td>
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<tr>
<td>BoM</td>
<td>Bill of Material</td>
<td>LCM</td>
<td>Life Cycle Management</td>
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<td>CARB</td>
<td>California Air Resource Board</td>
<td>UST</td>
<td>Luxembourg Institute of Science &amp; Technology</td>
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<tr>
<td>CBG</td>
<td>Compressed Biogas</td>
<td>MPFI</td>
<td>Manifold Port Fuel Injection</td>
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<tr>
<td>CH4</td>
<td>Methane</td>
<td>NEDC</td>
<td>New European Driving cycle</td>
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<td>CHP</td>
<td>Combined Heat Power Plant</td>
<td>NGV</td>
<td>Natural Gas Vehicle</td>
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<td>CI</td>
<td>Carbon Intensity</td>
<td>NGVA</td>
<td>Natural Gas Vehicle Association</td>
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<td>CNG</td>
<td>Compressed Natural Gas</td>
<td>Nm3</td>
<td>Norm cubic meter</td>
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<td>CO</td>
<td>Carbon monoxide</td>
<td>NMHC</td>
<td>Non Methane hydrocarbons</td>
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<td>CO₂</td>
<td>Carbon Dioxide</td>
<td>NOx</td>
<td>Nitrogen Oxides</td>
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<tr>
<td>COV</td>
<td>Coefficient of Variation</td>
<td>PA</td>
<td>Polyamide</td>
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<td>DBFZ</td>
<td>Deutsches Biomasse Forschungszentrum</td>
<td>PFI</td>
<td>Port fuel injection</td>
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<tr>
<td>(German Research Centre for Biomass)</td>
<td>PHEV</td>
<td>Plug-in Hybrid Electric Vehicle</td>
<td></td>
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<td>Dena</td>
<td>Deutsche Energie Agentur (German Energy Agency)</td>
<td>PM</td>
<td>Particulate Mass</td>
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<tr>
<td>DI-CNG</td>
<td>Direct Injection of Compressed Natural Gas</td>
<td>PN</td>
<td>Particulate Number</td>
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<td>EBA</td>
<td>European Biogas Association</td>
<td>PSA</td>
<td>Pressure Swing Adsorption</td>
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<td>Fuel Quality Directive</td>
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<td>Real Driving Emission</td>
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<td>FRC</td>
<td>Fiat Research Center</td>
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<td>Renewable Natural Gas</td>
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<td>GasOn</td>
<td>Horizon2020 research program for demonstration of monovalent DI-CNG vehicles</td>
<td>SGC</td>
<td>Swedish Gas Centre (Svenskt Gastekniskt Center)</td>
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<tr>
<td>GDi</td>
<td>Gasoline Direct Injection</td>
<td>TFE</td>
<td>Tetrafluorethylene</td>
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<td>Green House Gas</td>
<td>TGI</td>
<td>Turbo Gas Injection</td>
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<td>GV</td>
<td>Geometric Variance</td>
<td>THC</td>
<td>Total Hydrocarbons</td>
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<td>GWh</td>
<td>Giga Watt hours</td>
<td>TSI</td>
<td>Turbo Stratified Injection</td>
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<td>HDPE</td>
<td>High Density PolyEthylene</td>
<td>TtW</td>
<td>Tank-to-Wheel</td>
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<tr>
<td>HEV</td>
<td>Hybrid Electric Vehicle</td>
<td>TWh</td>
<td>Terra Watt hours</td>
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<td>Variable Turbo Geometry</td>
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<td>IEA</td>
<td>International Energy Agency</td>
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<td>Waste Gate</td>
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<td>World harmonized Light duty vehicle Test</td>
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<td>&amp; Landscape Research</td>
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<td>Life Cycle Assessment</td>
<td>WtT</td>
<td>Well-to-Tank</td>
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<td>LCFS</td>
<td>Low Carbon Fuel Standard</td>
<td>WtW</td>
<td>Well-to-Wheel</td>
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2. Executive summary

The societal needs for cleaner air in cities and lower global Green House Gas emissions are impacting all industry sectors. The transport sector and, in particular, the surface mobility have objectives to reduce toxic emissions and CO₂ in order to reach sustainable mobility for people and goods. The automotive industry explores the use of different energy sources combined with adapted or optimized powertrains. In this context and with the support of the Life program of the European Commission, Delphi Technologies (former Delphi) as a partner of the automotive industry supply chain, ran the LIFE13 ENV/LU/00460 project with the title: “Demonstration and validation of Direct Injection of Compressed Natural Gas in vehicle engines and its environmental benefits”

The project consisted of a feasibility studio for the industrial manufacturability of a new injection technology, which allows Direct Injection (DI) of CNG into today’s modern car engines. The technology was developed and proven in a lab scale prior to the start of the project. The project demonstrated the possibility to manufacture injectors for DI-CNG that meet the industry standards.

Management system

Delphi Technologies as one of the leading automotive suppliers for injection systems is experienced in executing complex initiatives that include different interrelated actions and require the collaboration of various internal teams. The LIFE DI-CNG project was executed by defined, specialized teams for product and process engineering, project management, financial reporting, demonstrating/monitoring activities and dissemination actions.

Project execution was carried out through regular management meetings of those teams and the seamless application of the internal procedures applied to the LIFE project. Neemo and the European Commission remained supportive during the project and gave feedback in order to ensure that the LIFE Program Common Provisions were followed during the project implementation.

The Gantt Chart, as presented in the project proposal, was followed and kept updated during the project execution. It allowed to follow parallel activities and keep deadlines for milestones and deliverables as tight as possible. Delphi Technologies, as the only partner of LIFE DI-CNG, relied on external actors for project management support and life cycle assessment.

Implementation

All tests were performed using DI-CNG injectors from Delphi Technologies. Different design levels were used throughout the project. However, as the flow curves of the injectors and the critical performance parameters remained unchanged through all design iterations, all engine results were considered valid for all design levels. In the following, a brief description of each action is presented.

Injector development, prototyping and testing

Prior to the start of the Life project, early handmade prototype injectors were used to prove the concept of direct CNG injection into the combustion chamber of an internal combustion engine. During the project, the DI-CNG injector concept was transferred from the early prototype level to the so-called production intend design. The evolution progressed through several design iterations and was completed with fully validated production intend injectors, built with standard production processes and machines.

Several batches of the different prototype injector design levels were built for performance, durability and validation tests.
Pilot process optimization and testing

Existing lab space was refurbished at the Delphi Technologies Technical Centre Luxembourg to host the pilot line for DI-CNG injector manufacturing. The different manufacturing processes were developed in light of minimal energy & utilities usage.

System level implementation, testing, and demonstration of environmental impact

Several OEM manufacturers used the DI-CNG injectors on a number of test vehicles and engines. The common conclusions on different engine concepts and different vehicle applications were:

- Optimal engine efficiency with CNG is achieved with an engine compression ratio of around 13:1. This is significantly higher than for gasoline engines.
- The thermal efficiency of such modified and optimized engines is considerably better than on gasoline engines. This results in lower exhaust gas temperatures affecting the ability of standard catalytic converters to reduce emissions.

Monitoring of the environmental impact of the injector

The use of early development prototype injectors in prototype engines allowed to reach the CO\textsubscript{2} and particle matter targets as indicated in the grant agreement. It was of major importance to maintain the performance characteristics as seen on those early prototype injectors through all product development iterations. The key product characteristics that can influence the engine performance, the toxic emissions, the particles and the CO\textsubscript{2} are the flow rate and the leakage of a closed injector. Characteristics like lifetime durability and flow stability and leak rate over lifetime were added as criteria to be met during the industrialization process of the injector.

Monitoring of the industrial injector prototype performance

The monitoring of the injector performance during all design iterations and the full validation of the production intend design (last design iteration) confirmed that the design iterations generated the expected environmental impact when operated in engines. The initial environmental impact objectives for tank to wheel emissions were met.

Monitoring of the pilot process for injector manufacturing

This action was assessing the environmental impact and CO\textsubscript{2} footprint of the DI-CNG injector manufacturing process. The manufacturing of DI-CNG injectors was compared step-by-step to the manufacturing of DI-gasoline injectors. The objective to lower the carbon footprint was already taken into account in the design of the injector as well as the design of the pilot line. It is reflected in the selection of equipment and consumables. In total the energy consumption to manufacture a DI-CNG injector is around 7% lower than for a GD\textsubscript{i} injector.

Monitoring of the life cycle of the injector

The Life Cycle Assessment study was performed in close collaboration with the LIST (Luxembourg Institute of Science and Technology). It compared the CO\textsubscript{2} footprint for the manufacturing of a mono-valent DI-CNG car versus a GD\textsubscript{i} version. Converted into mg/km for a vehicle life time mileage of 210,000 km, the calculation revealed that the production of the concept specific components generates 291 mg CO\textsubscript{2eq}/km for GD\textsubscript{i} vehicles versus 389 mg CO\textsubscript{2eq}/km for DI-CNG vehicles. The difference of 100 mg/km appears negligible compared to Tank-to-Wheel and Well-to-Tank emissions.

The study concluded that monovalent DI-CNG vehicles can reduce the CO\textsubscript{2eq} emissions by around 30% compared to the DI- Gasoline technology when using CNG. Using bio-methane this value can be increased to more than 40%.
Monitoring of the socio-economic impact of the project

The positive impact that one single vehicle can generate for the environment, was described in the previous chapters. For the evaluation of the socio-economic impact, the assumption was made that a potential market uptake of the DI-CNG technology would be to the detriment of the classical gasoline or diesel technologies. The overall vehicle market was considered to be stable.

The impact on employment on the injector level was rated as negligible comparing DI-CNG to gasoline injectors as the production could take place in the same factories using manufacturing technologies comparable in complexity and number. On the vehicle level an impact on the employment was identified. The employment number might not change drastically, however a impact on products / manufacturing technologies / supplier competencies was identified: liquid fuels vs. CNG tanks; vehicle fuel pumps vs. gas pressure regulators; fuel vs. CNG gas lines.

The economic impacts over the value chain were rated to be minor comparing the build of a DI-CNG to a DI gasoline powered vehicle. The economic impact per driven km was best illustrated by the example here below:

A GDi vehicle that emits 130 g/CO\(_2\) per km consumes 5.45 l/100 km of fuel. A comparable DI-CNG vehicle might emit 104 g(CO\(_2\))/km, consuming 3.94 kg/100 km.

Dissemination

The dissemination activities as defined in the strategic dissemination plan were dedicated to reach several stakeholder groups across Europe. The activities that took place during the project execution are summarized in the table here below.

The project website with project information and including the Layman’s Report is embedded into the Delphi Technologies worldwide webpage under the following link:


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<th>Activity</th>
<th>Results</th>
<th>Targeted Audience</th>
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<td>Scientific Publications</td>
<td>9 publications</td>
<td>Automotive experts</td>
</tr>
<tr>
<td>Conference Presentations and Organizations</td>
<td>Automotive and gas vehicle community</td>
<td>5 conferences</td>
</tr>
<tr>
<td>Leaflets, Posters, Information Boards</td>
<td>500 leaflets 3 posters (1 linked to LCA) 7 information boards</td>
<td>General and specialized public</td>
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<td>International Fairs</td>
<td>Participation to 3 fairs, reaching approx. 500 participants</td>
<td>Specialized audience (automotive)</td>
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<tr>
<td>Guided Visits to Pilot Line</td>
<td>More than 50 guided visits</td>
<td>General public / stakeholders / clients / public authorities</td>
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Analysis on long-term benefits

DI-CNG vehicles offer the opportunity to meet future CO\(_2\) emission targets. The largest CO\(_2\) benefit can be achieved with a monovalent DI-CNG system. The TtW (tank to wheel) CO\(_2\) reduction of around 25-30% compared to GDi engines is a direct benefit while all toxic emissions can be managed to meet current and future Euro regulations. The cost to produce a monovalent DI-CNG vehicle is estimated to be close to diesel powered vehicles (around 2000
Euro above a same class GDi powered vehicle). Operating costs are substantially lower (45-
60% based on current energy prices).

Long term benefits for the environment:
A saving of 20g CO₂/km (vs. a GDi powered vehicle) for a mid-size vehicle results in 400 kg
CO₂ saving per year. The forecasted sales of CNG vehicles in Europe in the year 2025 is
267.854 units (source HIS Dec. 2018). The resulting CNG vehicle contribution in CO₂
reduction would be 107.14 t in that year.
3. Introduction: Project scope and objectives

The needs for cleaner air in cities and lower global Green House Gas emissions are impacting all industry sectors. The transport sector and, in particular the surface mobility have objectives to reduce toxic emissions and CO₂ in order to reach sustainable mobility for people and goods. The automotive industry explores the use of different energy sources combined with adapted or optimized powertrains. In this context and with the support of the Life programme of the European Commission, Delphi Technologies (former Delphi) as a partner of the automotive industry supply chain ran the LIFE13 ENV/LU/00460 project with the title: “Demonstration and validation of Direct Injection of CNG in vehicle engines and its environmental benefits”.

The project consisted in the pre-industrial demonstration of the direct CNG injection technology. The project demonstrated the possibility to manufacture injectors for DI-CNG that meet industry standards. They reach the same performance and thus the environmental impact as the R&D prototype and stay within the same production constraints as classical injectors.

The combustion of methane gas instead of fossil liquid fuels emits less pollutants and particulates. In addition, natural gas can be substituted by bio-methane making CNG injection an enabling technology for cleaner and more efficient vehicles in the future. Delphi Technologies initiated as of 2008 several international cooperation’s within the supply chain to evaluate the risks and opportunities of CNG DI injection. First test results indicated that the DI-CNG technology allows to increase the performance and the efficiency of natural gas powered engines.

The main objectives and achievements of the Life DI-CNG project were:

- Injector Development, Prototyping and Testing: The injector design progressed from early handmade prototypes to production intend. The product performances and durability requirements were met. The injector was fully validated.
- Pilot Process Optimization and Testing: A major task was the development of production processes and the installation of a pilot production line. This line allowed to build small batches of injectors under real production conditions, applying high volume production processes. All final design injectors were built on this pilot line and allowed to validate the production processes.
- System Level Implementation: The environmental impact of the DI-CNG technology was demonstrated on several prototype engines and vehicles. A Life Cycle Assessment (LCA) study allowed to assess the carbon footprint of the technology. The LCA study verified also the impact of bio-methane. Both testing and LCA confirmed the expected results and the environmental benefits as described in the grant agreement.

The achieved results on vehicle level are compliant to current Euro 6 regulations and to the CO₂ targets of the year 2021. Soot particles and Nitrogen oxides are largely reduced in the exhaust tailpipe which is an major benefit for the circulation in urban areas. More stringent requirements require additional development and fine tuning, paving the path to future post Euro 6d regulations. The success of this technology to achieve a major positive environmental impact is closely coupled to the fueling infrastructure in Europe and the wider acceptance of bio-methane as automotive fuel. The AFI (Alternative Fuels Infrastructure 2014/94/EU) directive might need to be revised to support the deployment of DI-CNG vehicles in all member states.
4. Administrative part

4.1. Description of the management system

The LIFE13 ENV/LU/000460 project was the first one from the Life program that was awarded to Delphi Technologies. Delphi Technologies made use of Life guidelines, templates and forms for reviews and reports while setting up a specific organization and applying internal project management tools for the execution of the project.

All activities took place in the Luxembourg Technical center with the exception of the engine and vehicle tests. The technical center is organized in a “matrix” type structure. In a matrix type structure the workers report to their functional management while actively working in one or more project teams. The project / program manager usually has no (or a few) direct reports. In order to capture the single efforts contributing to the Life project, the people that were assigned to the project filled in time sheets using the approved “Life” template.

Further support functions were involved such as marketing, communication, calibration, purchasing, finance, human resources, maintenance and facility management.

The Gantt Chart (Figure 4-1), as presented in the project proposal was kept in place during the project execution. It allowed to follow parallel activities and keep deadlines for milestones and deliverables. An updated GANTT chart, with the expected durations of actions and real durations, is depicted below:

Delphi Technologies was a single partner in the Life DI-CNG project. The initial timeline of the project was followed closely however slight deviations occurred in the installation of the pilot line. The installation of the pilot line was completed end of 2017. All activities to ensure the quality and the proper operation of the line were not impacted and were completed as scheduled.
External assistance
Delphi Technologies was supported in some management tasks by the consulting company Wavestone (former Kurt Salmon), that has gathered experience with LIFE projects in the past. No management activity was delegated to Wavestone, according to the art. 4 of the Common Provisions, and this external assistance was valuable in understanding the LIFE rules and in the preparation of meetings and reports. The diagram below illustrates the organization related to the project.

![Diagram showing consultancy and external assistance](image_url)

Figure 4-2 Consultancy and External assistance

The Luxembourg Institute of Science and Technology (LIST) was selected to execute the life cycle assessment study (LCA) and the calculation of the carbon footprint.

4.2. Evaluation of the management system
In order to ensure a flawless project execution, regular management meetings took place with functional leaders. More importantly the individual teams held weekly meetings to discuss activities and priorities. An intense exchange between different teams was possible as almost all relevant teams are located at same site.

The execution of the LIFE DI-CNG project followed the Delphi Technologies internal advanced development project procedures and the outcome of the project were documented according in technical reviews, gate reviews and quality criteria ratings.

During the annual meetings with the monitoring team, project challenges and deviations to the initial project proposal were discussed and agreed. The strategy to execute the LCA study was extended to include bio-methane in the monitoring section.
5. Technical part

5.1. Technical progress

5.1.1. Injector development, prototyping and testing

**Optimization of the injector design**

The Delphi Technologies DI-CNG initial injector concept was developed in 2012 and successfully demonstrated in several research and development projects, as for example the CULT project (page 22). In the frame of the LIFE DI-CNG project, the lessons learned of the early prototype injectors were transferred into a production ready DI-CNG injector design with optimized performance and fully in line with the automotive manufacturing and reliability standards. Figure 5-1 shows the initial take-apart design with several screwed interfaces, while in Figure 5-2 the latest generation GEN6 DI-CNG design is compared to the current production Multec 14 gasoline multi-hole injector.

![Diagram of injector design](Image)

**Figure 5-1** Early research injector for 1st. engine tests

![Comparison of injectors](Image)

**Figure 5-2** Delphi Technologies GEN6 Di-CNG injector vs. M14 gasoline injector
The GEN6 DI-CNG injector was designed to be adaptable to multiple customer applications. The injector opening and closing is controlled by the electrically driving solenoid actuator using a standard peak-hold drive waveform strategy. The valve lift dynamics is very sensitive to the internal gap settings and very precise process control and techniques were developed to achieve performance and part-to-part targets.

Prior to the start of the Life project Delphi Technologies demonstrated already with several single and multi-cylinder engine tests that the outwardly opening injector design is a valid concept for DI-CNG injection in today’s gasoline DI-engines. The outwardly opening design is the major difference of the Delphi Technologies DI-CNG injector compared to typical DI-gasoline injectors and most concepts of competitors working on the same topic.

The specific requirements for the DI-CNG injector like the main geometrical parameters, the static flow rate of ~7 g/s and the pressure range of 6 to 16 bar had been defined in 2012 in close collaboration with OEMs and remained unchanged during the Life plus project.

**DI-CNG injector design development**

The main focus for the design of the new DI-CNG injector was the reduction of complexity and the optimization in terms of manufacturing with focus on mass production capabilities. Even though the older injector generations performed well in terms of leak rate and met all performance criteria for successful engine testing, more mass production intend processes had to be developed. All GEN6 DI-CNG injectors were built after the complete installation of the pilot line.

A final customer specific design evolution will be the electrical connection where the solenoid assembly and the connector are made by one single over molding operation. At present a “pig tail” connection is used to ensure the proper electrical connection to the ECU while providing the necessary flexibility to deal with the different engine layouts and customer interfaces.

**Optimization of the injector control software and hardware**

Prior to the start of this project a basic injector driver was used with limited capacity and capabilities. During the project a new controller tailored for specific DI-CNG application and compatible with the power of modern Engine Control Units (ECUs) was developed. It includes the driver units for the injectors and capabilities to control as well components like the CNG pressure regulator which is not part of a standard gasoline engine structure and thus not necessarily part of the ECU capabilities. It can also read the output of a gas quality sensor. This makes the DI-CNG control unit compatible with current and future system architectures. A dedicated current waveform depending on the differential pressure between gas pressure at injector inlet and cylinder pressure is implemented. Closed-loop control monitoring and control of the velocity of the moving parts inside the injector is part of the capabilities as well and helps to ensure stable opening of the injectors, while reducing the impacted speed and forces to a minimum. The electronic control is crucial to control gas flow and injection timing.
In addition to the development of the software and hardware, a specific test setup has been put in place which allows to command and monitor the DI-CNG injectors while measuring the dedicated drive wave forms and the motion of the injector needle. This test bench enables the validation and optimization of the electronic control unit software/hardware as well as the optimization of the injector driving parameters in terms of stable operation and minimized wear. The DI-CNG controllers as shown on Figure 5-4 were successfully used within the GasOn project using different engine control systems.

Testing of the injector prototypes
The injector has to fulfill a series of specifications that are measured on each individual prototype and each injector design evolution. These characteristic properties are the leakage rate and the flow curve. The “performance test bench” which is needed to observe those injector characteristics was already installed for the proof of concept phase. Thus it was available already at the beginning of the project.
Some injectors were submitted to long-term durability testing to mimic the injector lifetime. In the frame of this project the durability test bench was modified and installed in a separate building at Technical Centre Luxembourg (Figure 5-5). This test bench allows to execute durability testing of DI-CNG injectors either with nitrogen up to 19bar. The data acquisition system, computer and control unit were upgraded to improve the monitoring of the flow performance during the test. The life cycle for an automotive fuel injector is typically defined by 400 million actuations. Due to the high gas consumption of nitrogen, a large container (around 5m height and 3 m in diameter) with liquid nitrogen was installed. The nitrogen is stored as liquid at very low temperature. The gas out of this liquid gas tank has very low lubricity since the liquefaction of nitrogen requires the complete removal of moisture and carbon dioxide. During first testing with previous injector version, it was found that such dry nitrogen gas did lead to significant wear on moving injector components. The complete absence of any lubrication is not realistic for injectors used in CNG cars. Filling stations typically use compressors to reach the typical filling pressure of 200 bar. Those compressors typically never completely oil free and an oil content of up to 50 ppm in the CNG is normal and not critical for the operation. In order to avoid preliminary failure when using dry nitrogen as a test gas, a lubrication unit was installed to simulate the typical gas quality from gas filling stations in terms of oil content.

The durability testing consists of opening and closing cycles without any combustion of gas, using the same parameters as applied during operation on a real engine with CNG. For the screening of different DI-CNG designs, nitrogen was used instead of compressed natural gas, mainly due to environmental and safety concerns. After successful screening of DI-CNG injector designs with lubricated nitrogen additional durability testing was performed with real CNG instead of nitrogen to fully validate the DI-CNG injector design and robustness.

Conclusions of DI-CNG injector development and testing
All requirements of action B1.3 were met:
- Flow delivery, sealing and leakage rate were measured for all injectors. The specifications including mean value and variation were met on all injectors.
- Durability testing was performed. 400 million cycles durability requirement was achieved on all tested parts.
5.1.2. Pilot process optimization and testing

The primary objective was to set up a pilot line in order to develop the production processes required to manufacture and provide DI-CNG injector prototypes in simulated regular production conditions. Data were collected on all manufacturing steps and intermediate injector subassembly dimensional checks, for manufacturing records and statistical analyses. The installed pilot line allowed the build of DI-CNG injectors in batches.

During the pilot line development all assembly process steps were reviewed and the injector design was adapted in parallel to fix all issues observed during testing and validation. During this optimization all specifications and requirements for production machine equipment were defined. This led to the selection and approval of suppliers for numerous equipment such as laser sources, presses, sensors etc. A separate laboratory area was refurbished to host the equipment.

The development of the pilot line also served to generate valuable information to define work instructions, process documentations, control plans etc. This set of quality control documentation is demanded to assure a smooth transition to large scale production such that all customer quality requirements will be met. All process data were stored in a database and statistical analysis were performed to control and monitor all manufacturing processes and key product characteristics.

The installation, setup and qualification of equipment was done by a Delphi Technologies manufacturing team, composed of technicians and engineers specialized in the manufacturing processes. They defined and followed written work instructions that were maintained up to date in the assembly area. The manufacturing team collaborated closely with design and product engineers to ensure that the injector design allowed a large scale manufacturing using state-of-the-art assembly equipment.

**Design of the pilot process**

The pilot production line followed the manufacturing sequence which resulted in subsequent build of different sub-assemblies. Each sequence contains multiple individual operations such as insertion by press fitting or laser welding of components.

To allow the best utilization of the installed equipment, the stations were designed for an easy changeover. In fact, a change of fixture and set up is required while changing from one operation to the other. This changeover allows sharing of equipment applying similar operations. Different operations and equipment were required for each sub-assembly. The assembly sequence and each individual process step was reviewed regularly with operators aiming to improve changeover time and to reduce cycle time which would result in an increase of capacity in production.

**Layout and installation of the pilot line**

The layout of the pilot line was designed aiming to optimize the handling of the components and to realize a smooth changeover. Several engineering workshops took place to exchange lessons learned and to review all process steps on the manufacturing equipment and the operation system. An operator balance study was conducted. The layout for the pilot assembly line was improved which resulted in an assigned increased floor space and dedicated areas.
Even though this layout did not provide one piece flow, it ensured that all process steps represent production conditions. A one piece flow typically allows for higher production capacity and which could be done by duplication of stations and re-arrangements. As the scope of a pilot line was not the production of high quantities of injectors the additional investment to reach one piece flow was not required.

Machine qualification
The equipment that was purchased for the pilot line, followed the assembly processes of the latest injector design. The focus was to replace manual by semi-automatic operations and eliminate bottlenecks. Key assembly operations are: laser welds, press fits, gaps checking and gaps setting. The requirements have been defined in the machine specifications and reviewed with selected machine builders during technical reviews. For each assembly operation all critical process control parameters were identified and monitored in detail. In addition, the sequence of operations and machine cycle times were optimized. A Helium leak testing device capable to detect external leaks at e.g. welding interfaces was available and used for the testing of the prototype injectors.

Similar to the product development, Delphi Technologies follows a standardized procedure for the qualification of manufacturing equipment. The machine requirements were defined and reviewed internally as well as with the suppliers. During the machine qualification the operation was executed on a batch of injector components. All key component dimensions were measured after the operation. Results were analyzed to verify if specifications were met. For each equipment a separate qualification report was generated. The machine qualification procedure also included several internal review meetings such as equipment concept review, equipment design review, equipment build review and a final machine qualification. This machine qualification procedure was mandatory for purchasing of any production equipment. The data on machine qualification were stored in a central database. The build and qualification of machines was executed at the suppliers location.

Generally, all machines were checked for safety, ergonomics, documentation availability, and operation modes functionality. Each machine was qualified for specific requirements. The main requirements were:

- Insertion forces repeatability & its measurement precision
- Laser welding parameters accuracy and repeatability
- Weld geometry repeatability
- Mechanical elongation accuracy & repeatability used for air gap settings
- Solenoid positioning repeatability
- Leak testing repeatability
- Electrical measurements repeatability for final tests

All machines were qualified and considered capable for manufacturing of DI-CNG injectors with the required accuracy and repeatability. All hardware equipment that has been installed on pilot line for DI-CNG manufacturing is labelled with a “Life” sticker.

Quality control for the operation of the pilot line
In addition to the machine qualification described above, the key product and key process characteristics were defined for each component and for each manufacturing process step. For each measured value a standard deviation value was determined. The measured values and data were stored in a separate database. Statistical analyses of these data was performed by the
engineering team. Based on these statistical data, deviations in production can be detected. Details of these activities were stored in pilot production gate charts, which are a standard tool for the monitoring of the production performance. The results were used for continuous improvement of the process and as well for the product design of the DI-CNG injector.

The pilot production of the DI-CNG injectors was done in batches aiming to simulate production conditions. This allows operators to act the same way as they would do in real mass production facilities. The pilot machines allowed quick changeover and workplace layout modifications, which made the system flexible also for late changes and continuous improvement. Prior to the build of each injector batch the entire list of components and part numbers, so called BOM (Bill of Materials), was revised and updated by the product engineer in charge and then reviewed together with the process engineer. It included latest changes in product design and manufacturing processes.

The components for those batches were collected from the storage area. All parts coming from this storage area were cleaned, inspected and released for production by the quality engineer with agreement of product and process engineers. The components are organized by part number in separate boxes, assuring flawless material flow through the production system.

Stations of the pilot production line are prepared to perform assembly operations following the manufacturing sequence, from sub-assemblies like armature assembly, gas inlet assembly etc. through cartridge / injector to final assembly.

A setup change, “changeover”, converts a station from one operation to another. It includes the dedicated tooling installation, the control program change and the workplace for material flow and operator movement change. After a batch of injectors or sub-assemblies went through the operation, the station can be setup for a next operation.

The quality control of the pilot production was performed as foreseen in production, but in more detail. In fact a 100% control strategy was implemented for the injectors built. That means all parts were measured and a full set of data was generated. The process control plan identified all critical process and product characteristics that were defined jointly by product, process and design engineers. They were measured using tailored gages/sensors either integrated directly into the machines or by external gages developed for DI-CNG production.

The fully qualified pilot line can reproduce regular production conditions and thus the scope as defined in the Life DI-CNG project was fully met.

Operation of the line after completion of equipment installation

The operation of the line was performed by producing several batches of identical DI-CNG injector designs in one shot. After completion of the equipment installation, a number of pilot batches of production intend injectors were produced. Engineering samples on a small scale with a maximum output of around 100 injectors per week can be manufactured on the pilot line. All change over processes in the pilot line are executed by operators without any support from robots.

Layout for the low volume and the high volume production line

Two production line layouts have been developed. The first scenario would allow an annual low volume production of 150.000 injectors. (Figure 5-6) It is composed of a series of U-shaped production cells and categorized by a relatively low level of automatization. When assuming a three or four cylinder DI-CNG engine, this capacity would be sufficient to build around 40.000 – 50.000 NGVs per year.
Figure 5-6 Design of a production line for low volume (150,000 injectors/year)

The planning for the layout of the production equipment and the production line considered the option for robotizing, the interfacing between humans and machine as well as digitalization. The production equipment contains fixtures for multiple injectors at the same assembly station. Thus it will become possible to increase throughput and production volume.

Summary of the pilot line installation and operation
All requirements of this deliverable were met:

- The installation of the pilot line was successful
- Several batches with latest design iterations were successfully built and validated
- It was demonstrated that the final DI-CNG injector design is producible and manufacturing processes are capable to represent production like conditions
- The specifications for all machines were defined in detail. Equipment suppliers and machines passed the qualification process successfully

During the operation of the pilot line and the build of various batches of injectors a full set of quality data was generated. These quality data include the control of all process parameters for each assembly operation, measurements of dimensions for each sub-assembly and end-of-line testing of the components to verify the design compliance. The key process control parameters and deviations were defined for each process. This enabled to monitor the quality of the manufacturing processes and the key product characteristics throughout the entire assembly process chain. The manufacturing process was proven to be very flexible to quickly react on potentially required injector design changes.

The installation and operation of the pilot line generated useful experiences and lessons learned that were applied to improve the manufacturing processes, the injector design and finally the product quality and robustness. This work of continuous improvement and close interaction between manufacturing, design and product engineers will be continued to reach high quality in large scale production.
5.1.3. System level implementation

Note: The results reported in this section were collected for completeness and to meet deliverable requirements. They were not necessarily done by Delphi Technologies nor within the scope of this Life DI-CNG project.

A short overview of engine projects is given in Table 5-1. Some of the available CO₂ emission results out of those projects are shown in Figure 5-7. The different projects are described more in detail on the following pages.

<table>
<thead>
<tr>
<th>Project partner</th>
<th>Configuration</th>
<th>Compared to</th>
<th>Test type</th>
<th>Test criteria</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>TU Vienna CULT project</td>
<td>ultra-light weight DI-CNG demonstration vehicle</td>
<td>ultra-light weight demonstration vehicle with GDi engine</td>
<td>vehicle test</td>
<td>CO₂</td>
<td>-31%</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>particles</td>
<td>Not tested</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>power/torque</td>
<td>comparable</td>
</tr>
<tr>
<td>Mahle</td>
<td>1.2L DI-CNG engine with variable turbo geometry</td>
<td>Gasoline 1.4L GDi</td>
<td>engine test</td>
<td>CO₂</td>
<td>-31%</td>
</tr>
<tr>
<td>Ford GasOn H2020</td>
<td>monovalent 1L DI-CNG engine in a mid-range vehicle</td>
<td></td>
<td>engine test</td>
<td>particles</td>
<td>Not available</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>engine test</td>
<td>power/torque</td>
<td>&gt;110kW</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>vehicle WLTP/RDE</td>
<td></td>
<td>Not available</td>
</tr>
<tr>
<td>Fiat GasOn H2020</td>
<td>monovalent 1L DI-CNG engine in a mid-range vehicle</td>
<td>0.9L CNG port fuel injection engine in the same mid-range vehicle</td>
<td>engine test</td>
<td>CO₂</td>
<td>-17.50%</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>vehicle WLTP/RDE</td>
<td>particles</td>
<td>90% below EU 6 limit</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>vehicle test</td>
<td>power/torque</td>
<td>Improved</td>
</tr>
</tbody>
</table>
Delphi Technologies cooperated as component supplier with IAV (Institute for Automotive Engineering) and TU Vienna for more fundamental investigations with the DI-CNG concept on single-cylinder, multi-cylinder and even vehicle level already in 2012.

A collaboration was started with Tier1 supplier Mahle. The company Mahle develops and produces a large variety of combustion engine components like pistons, valves, valve seats, bearings up to turbo chargers and other main engine components for internal combustion engines.

Application specific Delphi Technologies DI-CNG injectors were developed for the Horizon 2020 GasOn project with Ford and Fiat Research Centre (FRC).

The DI-CNG technology was demonstrated on different multi-cylinder engines and prototype vehicles. The main findings of all demonstration activities are highlighted in the following sections.

Collaboration with IAV: DI-CNG combustion development on single-cylinder engine

IAV had developed a single cylinder engine aiming to investigate the impact of direct injection of natural gas, downsizing and lean combustion. In a different project, IAV compared a 2.0L turbocharged engine powered by port fuel injection to a downsized 1.2L engine equipped with injectors from Delphi Technologies for direct injection of natural gas. IAV found a significant reduction of fuel consumption by around 15% due to the combination of direct injection and downsizing. IAV also concluded that NOx emissions can be reduced when lean combustion with stoichiometric ratio of 1<λ<1.5 is applied and catalytic converter with a light off temperature of 450°C is used. This study also demonstrated that the control of exhaust gas temperatures was crucial to reduce emissions. The toxic emission level at the tailpipe strongly depends on the exhaust after treatment system. Those challenges are not linked to the concept of direct injection of CNG, but driven by the fuel characteristics and the high thermal efficiency of the engines optimized for CNG. Due to the extremely high knock resistance of CNG compared to gasoline fuel, the full benefit of CNG can be achieved when the engine
compression ratio is be significantly increased. Using a higher compression ratio and being able to operate in almost all areas at the optimum in terms of spark advance without risk of engine knock, the thermal efficiency of the CNG operated engine is significantly better than for gasoline engines. On the other hand, this increased efficiency level leads to a reduction of the exhaust temperature compared to the gasoline engine while the required catalytic conversion temperatures of the HC emissions are higher for CNG than for gasoline fuel. In this context direct injection of CNG is beneficial to reach the required exhaust gas temperatures because of the increased flexibility in calibration strategies of DI compared to MPFI (Manifold Port Fuel Injection) injection systems.

Collaboration with TU Vienna: DI-CNG engine and light weight prototype vehicle
A very interesting DI-CNG vehicle demonstration project was the CULT program executed by the Technical University of Vienna. This project was awarded the Innovation Award of Austria in 2013. In the frame of the CULT program an ultra-light weight vehicle with only 600 kg was designed and a 0.66L, 3 cylinder DI-CNG engine was developed with aim to reach CO₂ emissions of only 50 g(CO₂)/km. First results have been presented during the 2013 Vienna Motor Symposium, prior to the start of Life DI-CNG project. TU Vienna continued the engine development and improved efficiency and performance of the system. The CULT project demonstrated that similar low end torque behavior like in GDi mode can be achieved by a DI-CNG engine with high compression ratio. While performing NEDC emissions testing on otherwise identical engine and vehicle, TU Vienna found 31% CO₂ reduction by DI-CNG operation compared to GDi gasoline mode.

Collaboration with Mahle: Development of a dedicated DI-CNG engine and prototype vehicle
The full benefit of CNG requires significant changes on the gasoline engine base hardware. The maximum combustion pressures that can be achieved on CNG engines without risk of knocking combustion or pre-ignition are similar to Diesel engines and significantly higher than on a standard gasoline engine. Therefore the engine needs to be redesigned to be able to resist the higher force levels. MAHLE carried out an extensive study, testing several hardware combinations and layouts in DI-CNG mode in comparison to an existing 1,2L gasoline direct injection (GDi) engine. The fully optimized monovalent version of the MAHLE engine equipped with Delphi Technologies DI-CNG injectors combined with a VTG (variable turbo geometry) turbo charger (yellow line in Figure 5-8) delivers almost the same performance as the GDi gasoline base version (black line in Figure 5-8), over the entire engine speed range. In CNG operation the benefit of direct injection (yellow curve) compared to port fuel injection (red curve) is clearly visible. The most significant improvement is in low end torque. With DI-CNG, the maximum engine torque was reached already at 1.500 rpm compared to around 2.500 rpm for port-fuel injection at identical compression ratio of 13.3.
The Mahle study allowed to perform a direct comparison of the CO₂ emissions in GDi and DI-CNG operation while mapping the complete engine speed / load (BMEP – Break Mean Effective Pressure) range (Figure 5-9). Interestingly the CO₂ savings are higher in areas of high specific engine load. Those high load areas are more important for the new emissions test cycles (World harmonized Light Duty Vehicle Test Procedure (WLTP) and real driving emissions (RDE) cycle) where the driving profile is significantly shifted to higher engine load (higher vehicle speed and stronger acceleration than in the old NEDC cycle). Depending on the engine load the CO₂ emissions reduction reaches from 23 up to 36%.

Figure 5-9 Relative CO₂ reduction by DI-CNG vs. GDi engine operation [Mahle Presentation – Ladungswechsel Konferenz Stuttgart - 2016]
Collaboration with Ford

Within the GasOn (Horizon 2020) project, Delphi Technologies DI-CNG injectors were used for more than 5,000 hours on multi cylinder engines at Ford in Cologne. The Ford GasOn engine is a 1,0L, 3 cylinder engine with a target peak power of > 110kW and BMEP limits of 30 bar over a wide operation range (Figure 5-10). This engine is equipped with 2 separate turbochargers (TC) to achieve a high power output combined with good drivability and low end torque.

The performance and power of the DI-CNG engine developed by Ford is shown in Figure 5-10. The maximum power is close to 120 kW/L. The target for maximum performance was exceeded by almost 10 kW and the BMEP target of 30bar was missed only in the small transition area when switching from single turbo charger to dual turbocharger mode. The engine performance in DI-CNG mode exceeds the performance of the Ford 1.0L Ecoboost (standard gasoline version of 1.0 l gasoline engine) GDi engine (blue dotted curve in Figure 5-10).

![Figure 5-10 Power and efficiency curves for Ford GasOn DI-CNG engine with 2 turbochargers (TC) compared to Ford 1.0 Liter Ecoboost GDi engine (blue line) [Final Workshop GAS ON – GAS ON Web page]](image_url)
Collaboration with Fiat Research Centre (FRC)

In order to demonstrate the potential of direct injection and natural gas combustion the aim was to achieve overall gasoline like performance, especially also in terms of low end torque and to substantially reduce CO₂ while being fully compliant with Euro6d emission regulations.

In order to take full advantage of the ultimate natural gas knock resistance and achieve optimal engine thermal efficiency, an increased compression ratio of more than 13:1 is required. Engine components are modified to maintain robustness and wear resistance. By retarding the injection event to after intake valves closing, it is possible to further increase the volumetric efficiency of the engine because more fresh air can enter the engine compared to an engine with MPFI CNG injection where a part of the air is replaced by the injected CNG. Thanks to direct injection, the use of a scavenging strategy and variable valve actuation the engine can deliver a maximum torque of 190 Nm already at 1.750 rpm. Engine development of FRC shows that the maximum torque remains almost constant over a broad range. This behavior is desirable to obtain a good drivability. Turbocharging enabled downsizing of the engine. Thus the DI-CNG engine developed by FRC yields a maximum power of around 88 kW (120 HP) @ 5.500 rpm. FRC performed a complete mapping of the engine performance and compared Break Specific Fuel Consumption (BSFC) directly to the bivalent production vehicle. In most areas they concluded that savings in fuel consumption range from 10-20%, depending on the engine load. At higher engine loads the high knock resistance of the CNG fuel is again most beneficial since the engine can be operated up to full load without knock limitation/spark. The total savings was attributed to the combined effect of different technologies: downsizing, direct injection, high compression ratio, turbo charging and de-throttling by advanced variable valve actuation. In addition, FRC lowered the weight of the CNG tank system and developed a novel gearbox that enables down-speeding, only possible with the good low end torque performance of the DI-CNG approach. The combination of all of the above mentioned technologies resulted in a CO₂ reduction of 17.5% when comparing the bivalent PFI-CNG production vehicle to the monovalent DI-CNG prototype vehicle. In constant operation conditions both the HC and NOx emissions are extremely low. Ultra-low levels of particulates both particulate mass and particulate matter were measured during all tests.

The main achievements of the GAS ON project WP 2 are summarized in Figure 5-11.
Summary on DI-CNG implementation and testing on engine and vehicle level

Engine testing demonstrates that the CO₂ reduction ranges from 23 up to 36% compared to GDi application. Vehicle testing gives a CO₂ reduction of 28% by WLTP testing and 31% by NEDC testing.

DI-CNG vehicle testing demonstrates that the particulate number (PN) is around 80% and the particulate mass (PM) is around 90% below threshold of the Euro6d regulation. As a consequence, no particulate filter is needed on DI-CNG engines.

The potential of the DI-CNG injection concept was demonstrated with several engine projects in different configurations. A very high potential in CO₂ and particulate emission savings was demonstrated in various engine layouts that were designed for the full benefit of the high knock resistance CNG fuel. DI-CNG is rated as a very interesting alternative to Diesel or gasoline direct injection (GDi) engines. It allows gasoline like performance with Diesel like efficiency without the penalty of high NOx and particulate emissions, nor the complex Diesel exhaust gas after treatment systems.

The DI-CNG injector concept works well in many different engine configurations and injector positions in the cylinder head. The Delphi Technologies DI-CNG injector can be easily implemented into almost all recent engine platforms using GDi injectors with a 7.5 mm tip diameter. DI-CNG engines with a power output of up to 120 kW per liter engine displacement were successfully built and tested. The low end engine torque can be significantly improved compared to a MPFI-CNG approach and is comparable to GDi engines.
5.1.4. Monitoring of the Environmental impact of the injector:

**Monitoring of the Pilot Process for injector manufacturing**

This action was assessing the environmental impact and CO₂ footprint of the DI-CNG injector manufacturing process. The manufacturing of DI-CNG injectors was compared step-by-step to the manufacturing of DI-gasoline injectors.

The objective to lower the carbon footprint was already taken into account in the design of the injector as well as in the concept of the pilot line. It is reflected in the selection of equipment and consumables.

The investigations determining the CO₂ footprint covered the following parameters:

- Materials used to build the injectors
- Transport of individual components from Tier2 suppliers to the Delphi Technologies production site
- Electricity used by the assembly equipment during injector built
- Use of chemicals such as lubricants, cleaning agents etc. during assembly and quality checks on the pilot line respectively the production line

The total energy consumption to manufacture a DI-CNG injector is around 7% lower than for a GDi injector. The analysis of carbon footprint, using the LCA (Life Cycle Assessment) methodology also allowed to assess the environmental impact for other categories like human health or toxicity and environmental impacts on water, soil etc. In a direct comparison it was assessed that the production of DI-CNG injectors generates lower negative impact in any of the environmental and health categories than the production of a GDi injector.

**Monitoring of the life cycle of the injector**

The LCA study by LIST was extended to the vehicle tests using the Delphi Technologies DI-CNG injectors and compared the CO₂ footprint for the manufacturing of a mono-valent DI-CNG vehicle versus a comparable GDi vehicle. The material information for this calculation was collected for the production of the essential engine and tank components of both vehicle technologies and concepts. The calculations were converted into mg/km values, based on a vehicle life time mileage of 210,000 km. The calculation revealed that the production of the vehicle and technology specific components generate 291 mg CO₂eq/km for GDi vehicles versus 389 mg CO₂eq/km for DI-CNG vehicles. Compared to orders of magnitude higher Tank-to-Wheel (TtW) and Well-to-Tank (WtT) emissions, the ~100 milligram/km higher DI-CNG production emissions are negligible.

WtT data respectively GHG (Green House Gas) intensities for natural gas from fossil sources can be accessed from literature/database [http://ngvemissionsstudy.eu]. Although not foreseen in the initial project scope, the impact of bio-methane and its potential for reduction of the carbon footprint was assessed. The organic feedstock can be manure, sewage sludge, straw, used organic fat and oils, energy crops, organic waste from households, wood waste or any other organic biomass. For the generation of bio-methane with high methane content, several technologies are already existing and in use today. The calculation of the GHG intensity of the bio-methane took the uptake of CO₂ during the generation of organic products into account. A mix of organic waste (food waste, gardening, agriculture, manure) was used and inventory data was extracted from a Swiss Federal Institute for Forest, Snow and Landscape research (WSL) report: [https://www.wsl.ch/de/publikationen/biomassepotenziale-der-schweiz-fuer-die-energetische-nutzung-ergebnisse-des-schweizerischen-energiek.html].
In the scenario presented, the utilization of energy crops, such as maize was excluded. For the calculations of GDi vehicles a baseline for consumption of 5.45L/100 km was used. This value corresponds to TtW emissions of 130 g(CO$_2$-eq)/km and reflects the average fleet target emissions for 2015. Using WtT emissions of 31 g(CO$_2$-eq)/km yield a total Tank-to-Wheel (WtW) emissions of 161 g(CO$_2$-eq)/km.

For the calculation of DI-CNG vehicles an average gas consumption of 3.94 kg/100 km equivalent to 104 g(CO$_2$)/km was used for the calculations. The estimated TtW emissions for a DI-CNG vehicle could be around 90 g (CO$_2$-eq)/km, corresponding to 3.35 kg/100 km. These data meet the 2020 target when tested per the WLTP cycle. The WtT emissions are 20 g(CO$_2$-eq)/km, WtW sum up to 110 g(CO$_2$-eq)/km. Based on these calculations, the CO$_2$ reduction potential of DI-CNG vehicles compared to GDi vehicles is 31%. This value was confirmed by the experimental results of TU Vienna and Mahle.

A further reduction of carbon footprint respectively CO$_2$-eq emissions is expected when using bio-methane. The procedure for the calculation of the carbon footprint was identical to the methodology that was applied in similar studies by JRC [JEC Well-To-Wheels Analysis - (Report EUR 26237 EN - 2014)] and NGVA Europe [Green House Gas Intensity of Natural Gas, Final report http://ngvemissionsstudy.eu/]. For the calculation of the carbon footprint (CO$_2$-eq emissions), it was assumed that the CO$_2$ balance is neutral. In addition the calculations did consider a methane slip during the purification process of bio-methane. Based on these calculations the TtW emissions were 80 g(CO$_2$-eq)/km and WtT emission are 9.5 g(CO$_2$-eq)/km.

Total WtW emissions of bio-methane summed up to 89.7 g(CO$_2$-eq)/km giving a reduction potential, according to this study, of up to 44% when using bio-methane compared to the GDi baseline. Carbon footprint results are summarized in Figure 5-12.

The CO$_2$-eq savings can be further reduced when methane slip during production of bio-methane can be avoided. As the calculation of the CO$_2$ footprint over the entire lifecycle is very complex and can lead to a large variation of results depending on assumptions and boundary conditions, the results presented here need to be compared to findings were therefore be compared to other WtW studies.

Figure 5-12 WtW emission results of carbon footprint calculations