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PROJECT FINAL REPORT

Grant Agreement number: SCP8-GA-2009-233541

Project acronym: ECOQUEST

Project title: Efficient Cooling Systems for Quieter Surface Transport

Funding Scheme: Collaborative project

Period covered: from 2009/12 (PM1) to 2013/05 (PM42)

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4.1 Final publishable summary report

4.1.1 Executive summary

An indispensable subsystem in surface transportation vehicles (rails bound, automotive) is the engine cooling module with its demand of external energy and its sound emission. Under specific operational conditions the cooling system is the major noise source and the component with the second largest consumption of energy (after the engine). The overall objectives of ECOQUEST were novel contributions towards reduced noise radiation and decreased CO_2 emissions by (i) revision of the general system layout, (ii) optimization of components from the thermal, acoustic and fluid dynamics viewpoint, and (iii) modification of the control strategy. For that, innovative complex multiphysics computational methods had to be developed - either by combination or by extension of known methods - and validated.

In a first step, ECOQUEST focused on fundamental acoustic modeling and sound prediction methods. A distinction was made between tonal and broadband noise, and broadband noise scattering. In all of these fields the theoretical background was enhanced. Aero-acoustic sources were computed by means of Computational Fluid Dynamics (CFD), a simulation code for acoustic prediction was implemented and applied, and results were validated against measurements. Moreover, the three mechanisms were integrated into a single sound prediction tool.

In a second step, we revisited the state-of-the-art thermal layout of automotive and locomotive cooling systems. Optimization methods were applied targeting on cooling capacity, energy consumption, and noise emission. Optimization included the thermo- and fluid dynamics of the circuits and the implementation of advanced control strategies. Given the thermally optimized systems, innovative components such as optimized fan units designed for maximum efficiency and very low noise emission and novel sound attenuators based on micro-perforated plates (MPPs) were developed. In contrast with earlier design procedures, the components were tailor-made for their applications, which was achieved by considering installation effects at an early stage of component optimization. The effectiveness of the new components was proven by (i) model tests, (ii) full scale mock-up tests, and (iii) full-scale vehicle tests. In order to assess the effect of the individual measures, driving cycles of the vehicles were simulated. For the automotive vehicle a standardized driving cycle was used, for the Diesel locomotive a new generic cycle was defined.

The new automotive cooling unit showed a reduction of total sound power by 1.5 to 4.5 dB(A). A reduction of CO_2 production by 7% compared to the baseline design is anticipated which corresponds to 0.2 grams of CO_2 per kilometer. The cooling capacity of the new loco unit was enhanced by 10% while the external energy consumption dropped by 20%. The overall sound power level decreased up to 7 dB, the tonal noise by more than 10 dB. CO_2 production could be decreased by 51 g/km which reduces the annual expenses for fuel by around 1000 € assuming a typical driving cycle. Side benefits of ECOQUEST are (i) a new simulation method for broadband fan noise radiation and scattering that will be commercialized in one of the partners existing acoustic software packages and (ii) a performance prediction model for Diesel locomotives

Results of ECOQUEST were disseminated in numerous ways, among others by three applications for a patent, exhibiting at the International Trade Fair for Transport Technology InnoTrans in Berlin 2012, some 30 publications at scientific conferences and in archival journals, and four PhD theses. Additionally, a lecture series at Von Karman Institute for Fluid Dynamics in which scientific findings were taught to engineers from industrial companies was held.

4.1.2 Summary description of the project context and objectives

Background

An important subsystem in surface transportation vehicles (rails bound, automotive and heavy duty) is the cooling unit. Present European standards for interoperability of rail bound traffic require low noise levels while manufactures need to meet the vehicle performance and energy efficiency requested by the operators. The stringent EU6 emission limits expected to come into effect will increase dramatically the demand for cooling power in road vehicles without accepting a noise penalty. Manufactures need innovative methods for reducing costs of development and testing and thus further improving their competitiveness in the global market.

The objectives are innovative contributions towards novel cooling units with reduced noise radiation and decreased CO_2 emissions. We aim at new compact layouts, innovative heat management strategies and low energy/noise components. Intermediate objectives concern (i) implementation of an integrated simulation platform for noise mechanisms, scattering and propagation; (ii) development of design procedures for thermally and acoustically optimal cooling units; (iii) research on innovative fan designs and new passive noise control measures and their integration into novel cooling units. Mass produced automotive units and large locomotive systems produced at small numbers are considered simultaneously - strong synergies and cross-fertilization are expected.

The project is structured in five work packages. WP1 deals with the project co-ordination, WP2 focuses on the acoustical models and their integration, WP3 takes into account realistic train and automotive environments, WP4 deals with full scale vehicle tests and WP5 concludes the project with an assessment and an exploitation plan and dissemination. Being an upstream-research oriented project, a majority of the person-month and budget, especially within WP2 and WP3, are committed to three universities and a research establishment. WP4 and 5 are performed primarily by industrial partners to enable immediate exploitation of the results. A more detailed discussion of each work package (except the management part in WP1) is given in the following.

WP2: Extension, validation, and integration of acoustic prediction methods

WP2 is concerned with the combination of different modeling strategies involved in the prediction of the noise emitted by generic cooling units. Regarding source modeling, we address individually the tonal and broadband noise and the broadband noise scattering. Combining the methods yields a simulation platform addressing all noise features. This integration/interfacing is performed with the aim of obtaining a seamless, yet non-proprietary simulation strategy.

Regarding tonal noise, modeling approaches have been developed for the tonal noise emitted by fans at low rotational Mach numbers. A first family of modeling approaches is based on the replacement of the moving surfaces by point forces. A common underlying assumption of these approaches is to consider a listener placed in the acoustical and geometrical far field of the radiating fan. This allows simplifying the mathematical derivation, but restricts the applicability to propellers in free field or at most placed in duct systems with simplistic geometries, i.e. not representative of the problem at stake in this project. We address this issue by evaluating more accurate tonal noise modeling approaches that are also valid in the near-field of the fan. The numerical performance and accuracy of two alternatives is assessed and validated by comparison with an analytical approach in the case of a fan-wedge noise interaction problem. A second family of modeling approaches, popular for ducted fan configurations, is based on the evaluation of the acoustic near field over permeable surfaces that are delocalized from the moving surfaces. The fan component is then represented as an acoustical multi-port. This method is attractive for it does not necessarily require a thorough knowledge of the pressure field in the rotating framework and is more generally applicable in duct systems. Its robustness, however, has to be proven, especially with regard to the required quality of the CFD data.

For better modeling of broadband noise, we develop a methodology based on Amiet’s theory, which assumes some a priori knowledge of the turbulence statistical quantities (spectral shape, turbulent kinetic energy and spatial correlation length of the unsteady blade surface pressure). We apply a novel hybrid method based on RANS and/or coarse LES calculations to obtain the required scaling data, and achieving a trade-off between accuracy and computational effort. Besides our strong focus on incoming turbulence noise, we shall also assess the relative importance of self-noise using established theories and considering degrees of inflow turbulence for automotive/truck and locomotive applications.

Addressing scattering effects, we explore a new numerical simulation approach for broadband noise throughout the cluttered path towards the listener position, and asses the performance of the method. The assessment is based on experimental data: a small fan is placed in an anechoic room and the scattered sound filed is measured.

The performance of the new simulation tool is gauged by a so called validation. In simulation technologies validation is the process of comparing predicted with experimental results and assessing the validity of the physical/mathematical models chosen for simulation. Since the tool to be validated in this WP is focusing on flow induced acoustics, a cooling unit without thermal function, hence referred “isothermal”, is sufficient. A laboratory scale generic cooling unit consisting of stator-rotor axial fan with radiator and inlet mock-ups is chosen. Tonal and broad band noise are measured and compared with prediction. The relatively simple generic cooling unit allows analyzing detailed parameters such as the flow velocity and their distribution which are essential parameters in the aeroacoustic models. In addition the variation of critical geometry parameters such as the fan inflow region can be studied easily.

WP3: Integrated design and mock-up tests

In WP3 realistic train and automotive environments are considered. The design of mobile cooling systems is revisited in a more integrated manner as compared to the state-of-the-art. Within a multidisciplinary study we optimize the thermal layout of cooling systems and the overall flow employing advanced numerical simulation tools. For the automotive application, a typical car platform is selected. For the specified heat dissipations, various module configurations are modeled and analyzed with system tools such as the multiphysics simulation software Kuli® and Flowmaster®. The cooling module has three baseline heat exchangers: a radiator for the cooling loop, a condenser for the climate control loop and a charge air cooler (CAC) for the turbocharged air loop. The consequent module configurations can then range from multi-layers layouts to side-by-side layouts and mixed versions. The initial single fan system configuration which restrains the design space to heater core that have an aspect ratio close to 1 (square configuration) is also relaxed to account for dual fan systems and heater cores that have aspect ratios closer to 2. Attempts are also made to have various fan system axial depths to allow for various design options such as axial, mixedflow or radial fans and fans with stators of different kinds. On the locomotive side, addressing all aspects of engine cooling requires a detailed view on the coolant efficiency ratio, noise emission and energy consumption, space required and weight, integratebility into a powertrain and packaging. Therefore in a first step a one-dimensional system analysis with respect to the thermal management of the cooling systems is performed. In a following step a parametric study by varying the cooling unit lay out is done. This includes number/size of radiators, number/size of fans, radiator at intake ore pressure side, variation of rotational speed, etc. Furthermore various options of controlling strategies for the cooling unit (e.g. slow acceleration of ventilator speed, predictive cooling, use of vehicle speed for cooling (bypass, flaps etc.)) are investigated. Eventually this simulation is combined with a holistic simulation of the vehicle on a track.

Given the thermally optimized layouts, innovative components are developed including energy efficient and low-noise fans as well as sound attenuators. The fans are optimized under the constraints of spatial and temporal distortions usually encountered in cooling modules. A successful axial fan design strategy with respect to spatial inflow disturbances is blade sweep. However, as a matter of fact, blade sweep also increases the flow losses and thus decreases the efficiency due to increased secondary flow effects in the rotor. In this work package the optimization of fan blade geometry is extended towards minimization of unsteady blade forces (i.e. the acoustic sources) due to generic spatial inflow distortions and turbulent inflow. For that we design a series of fan rotors with moderately to highly swept blades. The most promising fan designs are further analyzed and improved by USI employing the 3-D, steady and unsteady, RANS- and SAS-flow simulation method as implemented in ANSYS CFX®. In order to assess the typical behavior in the actual environment, we carry out under hood CFD simulations on a full automotive configuration. The passive attenuation of noise can be arranged by adding acoustic liners. This is however impractical as it typically yields considerable additional weight and volume, which goes against energy efficiency and neutral CO_2-impact. We propose two innovative approaches for passive noise control, susceptible to bring huge acoustic benefit at neutral CO_2-impact. The first approach consists in the integration of specifically designed microperforated liners, in place of existing elements such as guide vanes, housing surfaces and walls inside heat exchangers. A second approach is optimizing a natural acoustic barrier and absorber: the heat exchangers themselves. By performing the acoustic characterization of the heat exchangers, we provide guidelines to include acoustical constraints to the design of these elements, which are usually only considered for their heat extraction capabilities.

Eventually a variety of new cooling system designs is evaluated which allows the final selection for full scale manufacturing. Then, experimental mock-up test serve validating the impact of the new design strategies on the goals. The intensive involvement of the industrial partners ensures a strong industrial relevance. The outcomes of these tasks directly point to WP4 where a full scale test in a car/truck and a locomotive is carried out.

WP4: Full-scale tests

WP4 uses the outcomes from WP2 and WP3. The impact of the new design strategies is validated by full scale tests. Two full scale modules, one for car/truck and another one for locomotive are implemented in vehicles and experimentally investigated under realistic test conditions. The technologies developed are assessed with respect to thermal efficiency, energy consumption (CO_2-emission), noise benefits, packaging and costs. The results are used in the technology implementation plan. In addition, a high-performance numerical acoustics simulation method is adapted, validated by a separate series of small scale model tests at the acoustic laboratory and eventually used to predict the far field noise by the vehicles under the existing test environment. This is rated as an important tool for future component development e.g. with respect to the envisaged certification of the vehicle. WP4 is performed primarily by industrial partners to enable immediate exploitation of the results.

The work performed in the full-scale tests regard mostly near-field propagation. However, for the purpose of certifying vehicles, the acoustic field must be evaluated at a precise far-field position prescribed in standards (standstill test for locomotive, pass-by test for automotive). The prediction of the far field is also essential for assessing the effect of noise producing components during vehicle development and the effect of reflecting surfaces in the vicinity of the vehicle. Subtasks are:

- Development of a method for the sound propagation from vehicles at large distances in the far acoustic field, involving sophisticated numerical technologies such as a fast Multipole Boundary Element Method.

- Manufacture of a 1:20 model of a vehicle and implements a model source (small fan or loudspeaker). The source frequency content is selected such that acoustic similarity between model and full scale (i.e. the equality of the Helmholtz number) is ensured. The acoustic far field of the model is measured a anechoic room.
- Validation of the far field noise prediction method utilizing the model test results.
- Assessment of relevant acoustic installation factors such as non-ideal test environments (partially reflecting ground, reflecting walls etc.).
- Validation of the far field noise prediction method utilizing full scale vehicle tests results.

WP5: Exploitation plan and dissemination

WP5 deals with the overall assessment of the outcomes of the whole project, guidelines, exploitation plan and dissemination of the knowledge generated during the project beyond the Consortium.

The outcomes of the project are assessed in terms of technological break through and costs vs. benefits. With the assistance of the industrial partners USI compiles guidelines on new validated methodologies as well as new design rules.

Two exploitation managers (VAL and VTA) overview the evolving market situation and communicates this to Consortium members; they inform the Consortium on how the product requirements are affected by the evolution of international or local noise standards; they co-ordinate issues related to Intellectual Property Rights; they issue an Exploitation Plan aimed at technology implementation.

VKI plans to make its world-wide recognized Lecture Series program available to disseminate the results of the project in dedicated short courses. In addition KTH is the leader of the ECO2 centre (www.eco2vehicledesign.kth.se) where a number of leading European industry partners is members. Via this centre all open results from the project work can be disseminated.

4.1.3 Description of the main S&T results/foregrounds

Major progress was achieved in the fields of

- acoustic modeling and prediction
- cooling circuit simulation of mobile cooling units on realistic tracks
- energy efficient and low-noise axial fans
- modeling and application of acoustic absorbers
- advanced testing methodology

Some highlights of the technical improvements are:

- automotive cooling system: CO_2 reduction of 0.5 g/km, 4.5 dB sound reduction
- locomotive cooling system: CO_2 reduction of 51 g/km, 7 dB sound reduction

Subsequently, a set of achievements is described individually.

Near-field effects in tonal interaction noise from fans

In this Task, we focused on the role played by near-field terms in the acoustic scattering. Existing formulations, such as presented by Goldstein, discard explicitly the near-field terms to derive an elegant formulation for tonal fan noise, involving Bessel functions that represent the phase modulation related to Doppler effects. However, Roger showed recently that the near-field terms can account for important phase-shifting effects, which can play a significant role, even in the amplitude of the acoustic far field, if for example the edge of a semi-infinite plane is present in the near field of the fan. The work performed in this task pursued this analysis for several cases of interest to the present project. Firstly, the importance of near-field terms was assessed in free-field, in order to quantify the distance from the fan beyond which the far-field approximation can be retrieved. Secondly, the implementation of the fan as a source in the context of Boundary Element and Finite Element Methods was validated by placing it within a cylindrical straight duct with anechoic boundary conditions at both ends. This permits validation of the approach by comparison with the analytical solution based on the duct modes. The near-field solution was applied to the case of a Valeo fan, for which the BLHs were obtained through CFD simulations.

The accurate prediction of the tonal noise emitted by a low-subsonic fan relies on two main ingredients: the modeling of the force field exerted by the blades during their revolution, and the proper accounting of the scattering by the duct walls in general and by the duct inlet mouth in particular. Synthetic blade forces and Computational Fluid Dynamics have been adopted regarding the first aspect. A numerical approach was also proposed and validated for the acoustic part, which accounts for near-field effects in the calculation of the scattering. The results demonstrate that while the near-field terms can be regarded as negligible for source-listener distances exceeding one wavelength in free field, these near-field effects can be significant when a scattering entity is located in the acoustic near- field of the fan. The general formulation including near-field effects has been applied to a generic automotive fan provided by Valeo. URANS simulations performed by Valeo have been used to provide unsteady blade forces to the acoustic solver Virtual.Lab, and the preliminary results show that the rotor dominates the sound field for the first BPFH, while the second and third harmonics seem to be dominated by the stator, emitting predominantly in the fan rotation plane. Significant discrepancies are however observed between the Virtual.Lab predictions and the measured acoustic field, which deserve further investigations to be fully understood and eventually improved.

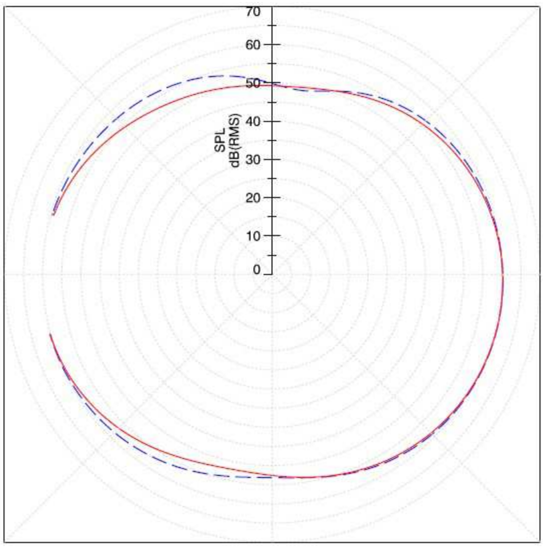

Figure 1: Role of near-filed effects in the prediction of the tonal noise of an axial fan from Valeo. Red line: far field approximation. Blue line: enhanced general solution.

Analytical modeling of tonal Interaction noise from fans including installation effects

Facing the large variety of fan system configurations, generic test cases that can be treated analytically are useful for a better understanding of both the aerodynamic sound generating mechanisms and the main installation effects. The work was devoted to simple prediction models addressing two main mechanisms, namely rotor-stator or stator-rotor wake-interaction noise, and the potential-interaction noise of a rotor operating in the close vicinity of a downstream or upstream strut or obstacle. Only the tonal noise at the harmonics of the blade passing frequency was considered, and the broadband noise is addressed in another task.

When the fan noise sources radiate in a space bounded by solid surfaces, the scattering by the surfaces must be accounted for. This again was achievable analytically for very simple geometries. Two examples were considered, namely the half-plane and the corner.

The source models were assessed on a test configuration involving a small-size, rotor-stator fan used in electronic bay cooling and a cylindrical radial obstacle installed closely upstream of the rotor. In the experiment, the sound was measured with and without a scattering screen of large dimensions mimicking a rigid half-plane. The measured data both in the free-field and with-screen conditions were compared with the analytical predictions.

A first series of acoustic measurements has been performed in the baseline configuration of the fan in free-field for which a priori only the wake-interaction noise makes sense. In parallel analytical predictions have been performed, based on a strip-theory approach with two segments. A very good agreement obtained at the blade passing frequency despite crude assumptions made in the predictions states that the wake interaction is clearly the dominant mechanism, as expected, and that the analytical approach is relevant. In contrast the predictions depart from the measurements for the second tone, with an unexpected main lobe around the axis. This suggests that wake-interaction noise is hidden by a secondary mechanism at higher harmonics. On-axis radiation corresponds to the symmetric mode and could originate from a residual simple distortion associated with the mounting of the fan on its support. This distortion has not been further investigated because it contributes at a very low level, typically 20 dB below the dominant BPF tone.

In a second series of experiments a radial, cylindrical obstacle of 7 mm diameter has been mounted 8 mm upstream of the rotor leading edge in order to generate a strong azimuthal distortion. Therefore two main sources of tonal noise are expected now, namely the aforementioned rotor-stator wake interaction and the interaction of the rotor with the obstacle. Free-field measurements in a plane containing the fan axis and normal to the rod have been made and compared to the baseline configuration. The level of the first tone is just moderately increased with a slight angular shift of the directivity pattern. This suggests that both the wake-interaction noise and the rod-interaction noise contribute and interfere at this frequency. In contrast the second tone is increased by up to 10 dB with two inclined main lobes. this part of the acoustic signature is essentially attributed to the installation of the rod. Finally, the harmonic 3 BPF also experiences a weak sound level increase, whereas the harmonic 4 BPF is nearly unchanged.

In a last step the support plate has been installed vertically in the anechoic room for convenience, and the measurements are made over an arc in the horizontal plane containing the fan axis. The rod was kept installed.

For negative angles from which the fan is directly visible and away from the axis, the sound is globally reinforced in the presence of the screen due to the rigid reflection. But the non-compactness interference fringes of the set of sources made of the fan and its acoustic images causes either reinforcement or attenuation at higher frequencies. The sound measured in the presence of the screen starts to be lower than the free field around 0, thus in the continuation of the plate, unlike what would be expected for a plate extending to infinity. For significantly positive angles such that the fan is not visible anymore, the masking by the screen becomes effective and makes the sound level drop increasingly with increasing frequency.

It must be noted that the similarity of the spectra with and without the screen installed, in 20 directions roughly normal to the screen, is in favour of the assumption that adding the screen does not significantly changes the source mechanisms of the fan. A closer inspection of the results shows that edge scattering causes a different amount of masking on the tonal noise and on the broadband noise in the shadow zone and over an extended frequency range.

RANS/LES based methods for broadband turbulence noise

In this task, the acoustic prediction methods described based on Amiet's theory for leading and trailing edge noise have been implemented and tested. We also pointed out the relative importance of both noise phenomena in rotating machine applications and the necessity to account for both of them in order to have a correct noise prediction in the whole frequency range. In addition we focused on the development of interfacing techniques between those acoustic prediction methods and LES/RANS incompressible computations. Innovative methods to take into account spanwise flow variations along the airfoil span were developed. This was required for rotating machine applications. Based on the necessary inputs for the acoustic methods and their respective extraction position, we developed a methodology to provide the required input data. The computational cost and accuracy of the new proposed methods compared to classical methods based on Curle's analogy have been evaluated. We measured the self noise and turbulence generated by locomotive heat exchangers. This data is also required for reliable sound prediction.

A study about competing sources of fan broadband noise revealed that all statistical models indicate that broadband-noise intensity or power is fundamentally proportional to the product of the wetted span length and of the spanwise correlation length of the sources, as far as the latter is much smaller than the former. This holds generally for turbulence-impingement noise, trailing-edge noise and vortex-shedding noise. For highly correlated phenomena such as stall noise generation, this scaling could be with the squared span length. In a rough estimate of the broadband noise contributions of the leading edge and the trailing edge of an airfoil embedded in turbulence, significant error or misunderstanding could arise if in the same time turbulence-impingement noise is overestimated because thickness effect is ignored, on the one hand, and trailing-edge noise underestimated because the enhancement by the pressure gradient or flow separation is ignored, on the other hand.

Another study was the assessment of the respective merits of deterministic and statistical models for predicting the sound emitted by turbulence around airfoil-like bodies. Two main simulation strategies were considered. In the context of the aeroacoustic analogy, the most straightforward approach consists in a numerical implementation of the Lighthill/Curle analogy, where the acoustic solver is given as input a source field processed from unsteady Computational Fluid Dynamics (CFD) simulations such as Large Eddy Simulation (LES) or Detached Eddy Simulation (DES). This method has proven its value for cases when the source field is essentially dominated by dipolar contribution, synthesized from the unsteady pressure field at the surface of the body. In cases where the quadrupolar sources contributes significantly to the sound field as well, this approach can still be applied, however at the expense of a much larger dataset to process. In parallel with this deterministic approach, a statistical approach based on Amiet's theory was investigated. In this procedure, the turbulence is described in terms of its Power Spectral Density (PSD), decomposed into Fourier modes (gusts) and used as input to a linearized airfoil theory for the calculation of the perturbation lift. The sound field emitted by all the gusts is then recombined to yield a far-field sound PSD. This approach can be considerably less CPU-intensive than the deterministic way described above, since a statistical description of the turbulence can be obtained by scaling canonical spectra using integral parameters. These can be obtained from rough estimations of quantities like the turbulence intensities and integral length scales, or by processing Reynolds-Averaged Navier-Stokes (RANS) calculations that are orders of magnitude cheaper to obtain compared to LES or even DES. However more insight is required from the user in order to apply the proper scaling and provide meaningful input turbulence spectra. In this task, we described the respective ranges of application, advantages and drawbacks of both strategies as implemented by LMS, assessed from the viewpoints of the CPU cost, ease of use and required user know-how. It will be seen how both methods can be eventually combined to cover the significant sound spectrum in the ECOQUEST applications. The accuracy of both methods proved very satisfactory as long as the correct flow behavior was captured by the CFD and/or obtained from statistical parameters. The results indicate that a combination of both methods – deterministic at low frequencies, statistical at the high frequencies – offers the best compromise between the cost/generality of the deterministic method and the speed of the statistical approach. It can be therefore concluded that the objectives have been achieved, resulting in a simulation methodology based on both the deterministic and statistical theories for leading and trailing edge noise.

Further research was done to improve Amiet’s theory to take into account the spanwise variation of the flow along the span of the blade are first presented. Two different applications related to leading-edge noise (jet-airfoil interaction case) and trailing-edge noise (Valeo CD airfoil) were proposed. For both cases, strategies to extract data from RANS or LES computations were analysed. An uncertainty quantification study was then presented on the reconstruction methods developed for RANS strategies for trailing-edge noise.

Self noise and turbulence generation by heat exchangers

The investigation of the heat exchangers is important to add their self-noise into the sound prediction tools and to estimate the turbulence generation which is an input to the fan noise modeling. Two heat exchangers were investigated which proved to have similar turbulence inducing characteristics. It could be revealed that the thin cooling fins have almost no impact on turbulence. In contrast, the ten times thicker water bearing ducts create an enormous turbulent intensity in the vicinity of the heat exchanger. Further downstream, the turbulence decays rapidly and reaches its minimum after around 250 mm. The maximum was found directly behind the test object (water bearing ducts) or at some 35 mm (cooling fins). Peak values amount to 35 %. Close to the minimum of turbulence, there is only little influence of the heat exchanger type and the impact of ducts is not measurable at all. The turbulent intensity then amounts to some 4 % with an exponential decay between the extremes. The decay roughly follows the empirical formula by Roach. A moderate influence of inflow velocity was revealed. Close to the heat exchangers, turbulence decreases through higher flow velocities. This effect is reversed further downstream. The inflow velocity furthermore effects the distance where the influence of the different obstructions vanishes. The integral length scale of turbulence shows a strong dependence on distance to the test object. In the first 150 mm it follows the empirical law by Roach, further downstream higher values are obtained.

Broadband noise scattering - theoretical modeling and simulation

The prediction of the broadband noise scattered by the fan environment involves several aspects: the prediction of the noise emitted by the fan towards the listener as if it were placed in free field (incident field), and the calculation of the scattered field in a second step. When the fan source is described in deterministic terms, i.e. when the wave fronts emitted by the fan are known in both phase and amplitude, the calculation of the scattered field by numerical means (Boundary Element Method or Finite Element Method) is relatively straightforward. However, in the present case the fan source is known in statistical terms, and the free field Power Spectral Density that is predicted by standard methods is not a suitable input to the numerical approaches cited above. The approach that has been pursued here consists in expressing the source field within a formalism compatible with the numerical software developed by LMS, following the Acoustic Transfer Vectors approach in particular. Another important point is the proximity of the fan blades with the acoustic environment. As a result, the classical formulations of Amiet are not applicable since they assume that the listener (or scattering surface in the present case) is located in the acoustic and geometrical far-field of the fan blade. Besides, the fan blades have to be segmented in order to account for the spanwise variation of the flow properties, and the long-span assumption cannot be used anymore.

The results demonstrate that in order to obtain numerically consistent results where the far field assumption is not valid, spanwise near-field effects must be included in a generalized derivation of Amiet's theory for incoming turbulence noise. The solution is compared with a direct numerical integration and an important improvement is observed. Finally, the presence of solid surfaces in the neighbourhood of the radiating airfoil, as for airframe flap or slat noise for example, imposes to compute the scattering of the incident sound field obtained by the generalized Amiet model presented herein. A method based on Acoustic Transfer Vectors, obtained by means of a Boundary Element solver, was proposed and validated against experiments for two different configurations. The results showed that the analytical model combined with Acoustic Transfer Vector approach is a useful tool to predict the scattered acoustic field of a stationary airfoil due to its installation effects. The acoustic production of the axial fan was then investigated in both free and scattered-field. A method based on Acoustic Transfer Vectors, obtained by means of a commercial Boundary Element solver, is proposed and validated against the ideal case model. A fair agreement was observed in comparison with experimental data gathered in the anechoic room using an industrial low-speed axial cooling fan.

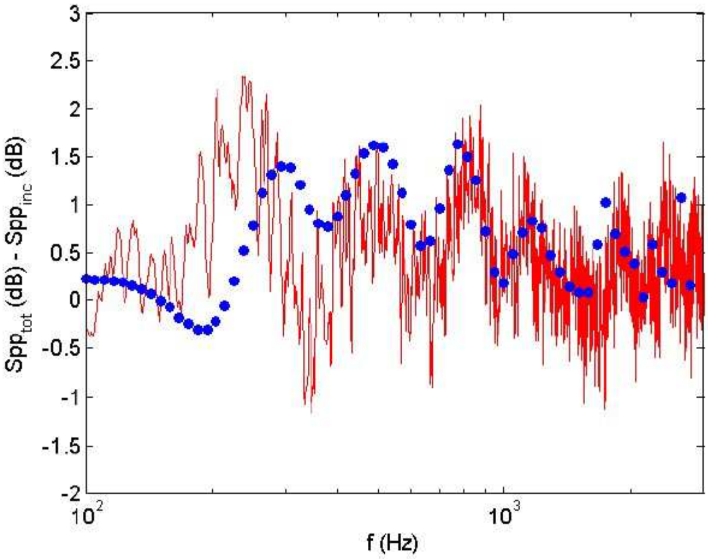

Figure 2: Comparison of the scattered component of the acoustic field determined by measurements (red) and numerical prediction (blue). The trend matches satisfactory, especially towards higher frequencies.

Model test of a generic isothermal cooling unit

The objective of this task was the application of the aeroacoustic simulation tools developed in before to a cooling unit, specifically designed to permit the detailed validation of the flow and acoustic fields. The model is largely made of Plexiglas to allow PIV measurements, and is designed to be representative of a scaled-down locomotive cooling unit. The model was fitted upside down in an anechoic room of the von Karman Institute, permitting to measure the noise emitted outside of the module through the heat exchangers and inlet grid. The noise that would be radiated through the roof in the real configuration is here propagating through a duct equipped with azimuthal microphone arrays, for the investigation of the spinning acoustic modes. The flow field has been simulated using the OpenFOAM software from which the necessary inputs for sound predictions models were extracted. The incident broadband acoustic field is scattered on the mock-up geometry using a specific numerical methodology based on a Boundary Element Method validated in previous tasks. The heat exchanger is there represented by a lumped model characterized through transfer admittance matrix.

Before validating the full configuration, tests with an artificial noise source were conducted. The fan module was replaced by a flat plate, drilled in its center with a 1 cm-diameter hole, below which a loudspeaker was placed and fed with various signals. Several measurement campaigns were conducted in order to validate the acoustic simulations with increasing complexities. The first tests were conducted without the plexiglas box (below referred to as monopole-nozzle configuration), to validate the monopole source model and identify the range of frequencies for which the residual vibrations of the steel plate, output of the loudspeaker-nozzleplate system and anechoic properties of the room give a large enough signal-to-noise ration and reproducibility for the next tests. The next step consists in placing the plexiglas box, without the inlet grid and without the heat exchanger (monopole-box configuration). The last tests were conducted with the grid only (monopole-box-grid configuration), the heat exchanger only (monopole-box-HE configuration), and both grid and heat exchanger (monopole-box-grid-HE configuration). Figure 3 compares the results. It can be seen that the accuracy between measurement and prediction decreases with increasing complexity.

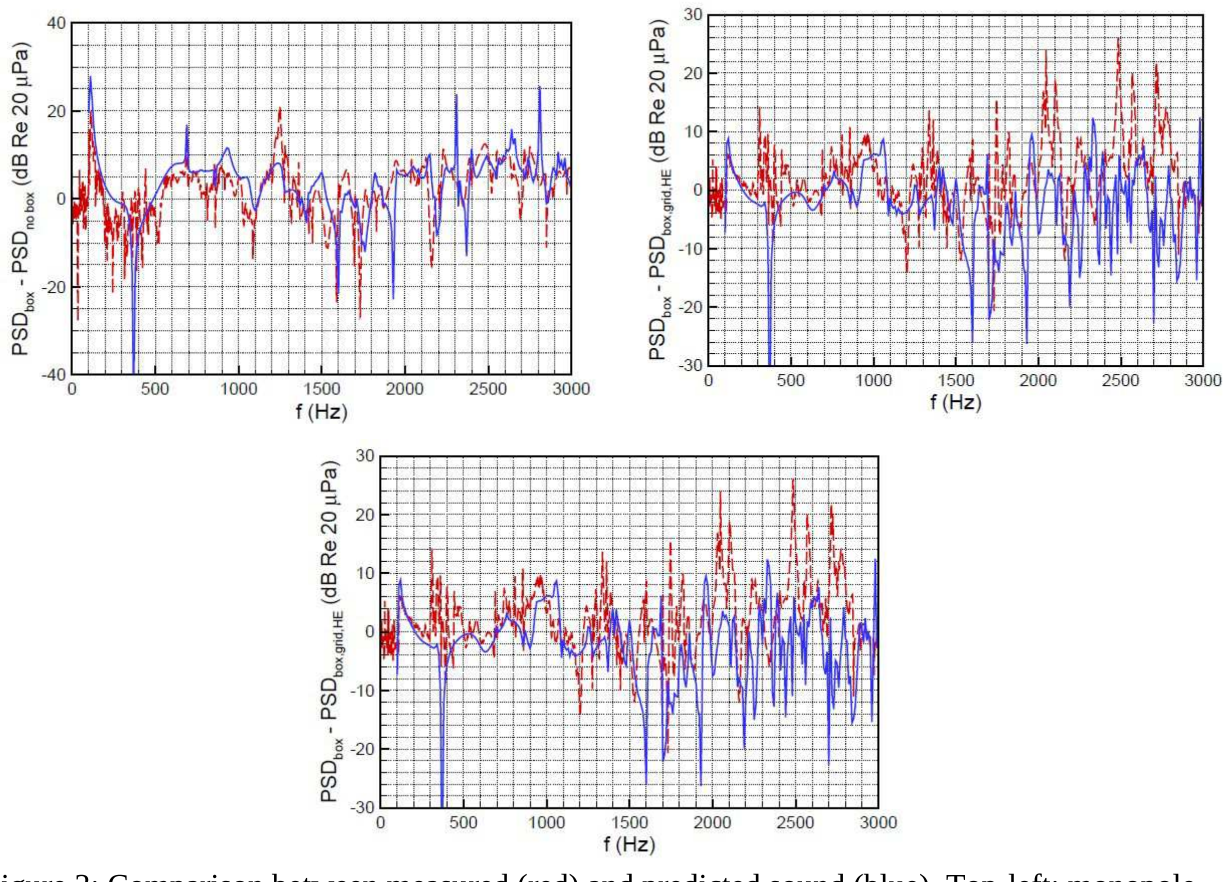

Figure 3: Comparison between measured (red) and predicted sound (blue). Top-left: monopole-box configuration. Top-right: monopole-box-grid configuration. Bottom: monopole-box-grid-HE configuration.

After using the artificial monopole sound source, the real cooling system with fan was investigated. The broadband fan noise model detailed above was employed for 2 spanwise strips. In order to model the heat-exchanger, the transfer relation admittance through the heat-exchanger surface was. Combining all the models and employing the flow properties extracted from the RANS simulation and hot-wire measurements, the acoustic field emitted by the axial fan was computed.

Figure 4 shows the measured and predicted acoustic spectra at the observer points. The red line stands for the measurements. The black solid line and circles represent the free-field and scattered-field predictions using the data extracted from RANS simulation. No agreement has been observed between the measurements and predictions. Both amplitude and trend of the predictions are different than measurements. However, using the data extracted from hot-wire measurements, the free-field propagation (blue solid line) shows agreement in the trend. This is due to the larger turbulence length scales exported. The free-field spectrum is smoother than the one of measured, simply introducing the scattered-field contribution from the RANS results, it can be seen that the pattern due to the interference fringes is captured accurately. However, there is still a 20 dB difference between predictions and measurements. This may be due to the effect of the other sound source mechanisms applying on the blade and vanes. One possible explanation can be that the heat-exchanger is lowering the turbulence intensity in the flow and the flow becomes close to laminar. Hence, the dominant source of the sound is not turbulence-interaction anymore. However, even though the source term is not captured accurately, it can be seen that the contribution of the scattering obstacles is captured. The difference between the free-field and scattered-field results can reach up to 10 dB, such that the free-field propagation assumption is not accurate anymore.

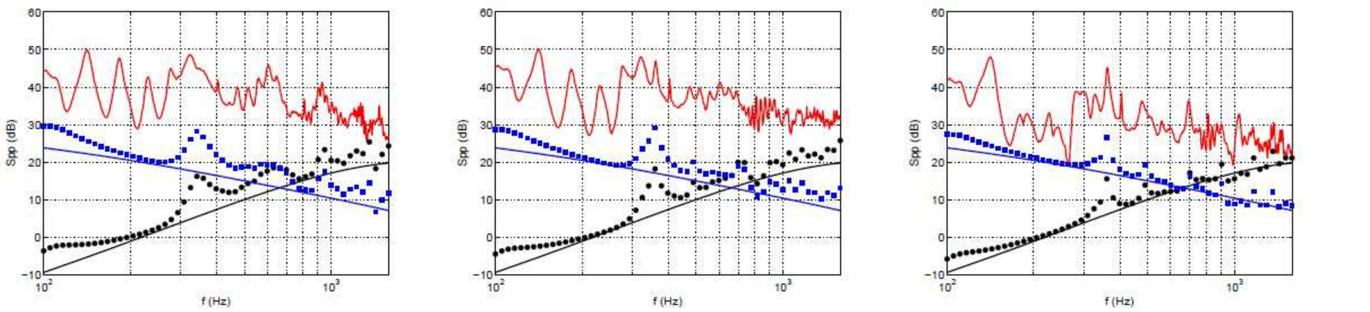

Figure 4: Acoustic spectrum at the observer positions; measurements (red solid), free (black solid) and scattered-field (circles) predictions using RANS data and free (blue solid) and scattered-field (blue square) predictions based on hot-wire data.

As a final conclusion it must be stated that - even though the different aspects involved in the full simulation have been validated separately on simple configurations - their combination to our combined mock-up yields a significant under-prediction of the measured spectrum. A likely explanation for the discrepancies stands in the fact that potentially important sources of noise have been neglected such as the rotor trailing-edge noise, stator noise or the noise associated to the complex vortical motion that develops between the shrouded rotor ring and the casing. More investigations are required as well about the structure of the turbulence ingested by the rotor, which appears to poorly represent the turbulence physics across the heat exchanger, while properties such as the turbulence intensity and correlation length play a crucial role in the level and spectral decay of the acoustic field generated by the fan rotor.

System auto/truck - thermal optimization

A system-level thermal optimization of automotive/truck cooling modules has been conducted using two different approaches. The first method consists in studying different configurations via a Kuli model and was applied to a Renault Laguna. The Kuli model was calibrated to account for the car's geometry by post-processing wind tunnel tests results. The second method is more general, and consists in running a numerical Design Of Experiment using Computational Fluid Dynamics in order to construct a neural network that is capable of computing a velocity map on the heat exchanger instantaneously. The velocity map takes into account upstream mean flow distortions due to the dissymmetry of the front-end air intake or to the cross-beam as well as the effect of the downstream blockage that is due to the combustion engine. The neural network covers 22 geometric and physical parameters and requires 129 simulations to be run in order to be initialized. The first approach was much more straightforward, and resulted in the selection of one (or more) optimal solution(s) for the selected platform.

The initialization of the neural network was still ongoing when the task report was written due to the considerable computational time resulting from the numerous simulations, but it is completed now. The neural network was constructed, and was coupled with a Kuli model similar to the one that was previously constructed.

After studying several single and dual fan systems, the optimal solution for CO_2 and cost reduction was found to be a single-440-mm- diameter fan. The fan has a major influence on the system's thermal efficiency, thus, there is still room for improvement by improving the fan's efficiency. This was subject to T3.3.

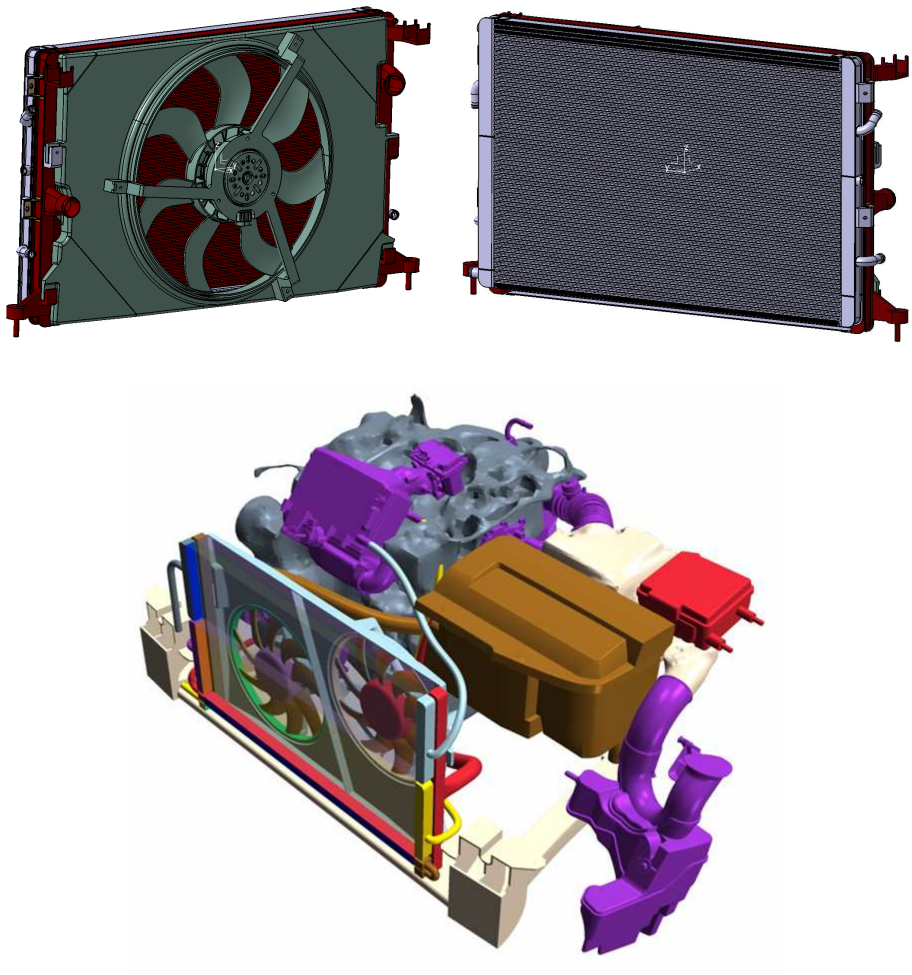

Figure 5: Final design of the newly developed automotive cooling unit (top) and assembly with the engine and other vehicle components (bottom).

Sytem loco - thermal optimization

In this task, we focussed on the general layout and design of locomotive cooling unit including the complete system. First, the cooling system with respect to the thermal management, the noise emission, the energy consumption and the system layout was performed in a 1D simulation suite. In following steps this system was optimized with respect to the objectives of the ECOQUEST project. This parameter study includes controlling, strategy and layout variations of the total cooling system.

As a result, the energetic and acoustically optimal cooling system can be determined. Different variants of the complete cooling system were analysed with the 1D system simulation. Very good acoustic results can be achieved by an optimized control strategy. The Fuzzy controller (PD based controller) has been found to be suitable. The technical implementation of the optimized controller could be realised without additional work and expense. The energy consumption of the fan can be significantly reduced by using a balancing strategy between the both water circuits. The simulated balancing system with a connectable heat exchanger or an additional variable water heat exchanger shows a great prediction for energy consumption. Therefore the connectable water heat exchanger obtains the best energetic performance but it is difficult to realise. The system with the variable water heat exchanger is a good compromise in terms of functionality and cost/benefits. By combining the controller management with the Fuzzy controller and the balancing system an acoustic and energetic optimum can be achieved. These results are based on a total system simulation. The simulation result does not allow reducing the initial cooling system size.

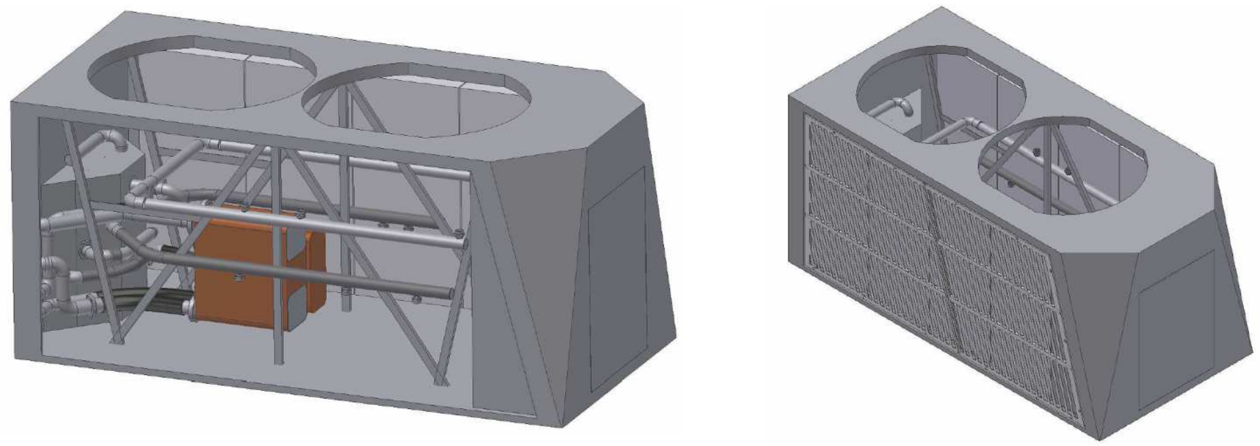

Figure 6: Final design of the newly developed locomotive cooling unit.

Innovative axial fan blades

New fans for the automotive and locomotive cooling systems were developed. The main objectives were increased energy efficiency and reduced sound emission.

First attempts to design the automotive fan used the analytical 2D fan design tool "dAX" developed by USI. The designs were then simulated by VAL. However, it was found that the extraordinary design point prohibits this procedure for several reasons such that a decision was made to do without analytical methods and to optimize the fan blades by CFD simulations embedded in an evolutionary optimization algorithm. Evolutionary algorithms are powerful optimization tools which are able to satisfy several target functions simultaneously. The incorporation of constraints can easily be implemented and the algorithm is less prone to converge to local optima than other optimization tools. The biggest disadvantage is the huge computational effort which was, however, accepted for this project.

In the present application, the target function was maximization of total-to-static efficiency and was evaluated by RANS simulations. Since the main dimensions as well as the rotational speed are fixed, the optimization parameters only comprise the blade design. The resulting optimal parameters are discussed in detail in Deliverable D3.3. In the final report, only the very surprising result of the stagger angle distribution is considered. The optimal stagger angle decreases from hub to mid-span and increases again towards the shroud. This is in contrast to common design assumptions in which the stagger angle always decreases from hub to shroud due to the difference in circumferential velocity. The finding of the unexpected optimal distribution is the main reason for the massive increase of efficiency from 50 to 70%.

The locomotive cooling system was analyzed by a CFD simulation of the benchmark system. Losses were allocated to the individual components of which the heat exchanger were found to be most significant. However, several CFD studies showed that these losses can hardly be influence. This also applies to the second biggest loss mechanism, i.e. the meridional component of the exit velocity. Hence, the biggest potential for energetic improvements lies in the implementation of guide vanes reducing the circumferential exit losses. A further possibility is the enhancement of fan efficiency by adapting the design to the inflow velocity profile. Both components were optimized with modern optimization algorithms. The target functions (efficiency, loss reduction) were always evaluated by CFD analysis.

Since a CFD based optimization loop with respect to aeroacoustic target functions has an immense computational cost, the measures for acoustic improvement are based on analytical considerations without the help of optimization algorithms. The major changes are reduction of rotational speed, reduction of fan diameter, higher axial length, and constant chord length.

These measures were fixed and not changed in the optimization loops. A comparison of the optimized system with the benchmark system revealed a 13% energy saving, mainly due the reduction of swirl energy at the exit.

The acoustic comparison is based on experiments with a 1:4 model of the cooling module. The measured sound power levels are depicted in Figure 7. In was shown that the specific sound power level decreased by approximately 2.5 dB. The (generally most annoying) tone at the blade passing frequency decreased by even 5 dB. The experiments furthermore confirmed an increase of flow rate by 10% at equal rotational speed, and hence an increased cooling capacity.

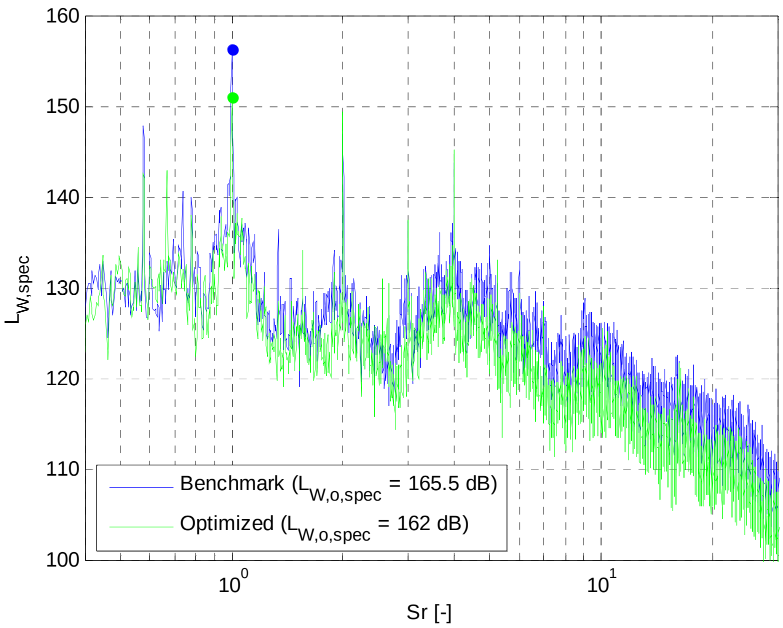

Figure 7: Acoustic comparison of the benchmark and optimized locomotive cooling system model.

Innovative passive noise control

Within this project two different main objects for fan passive noise control have been examined both experimentally and theoretically; the heat exchanger and inlet parallel baffle silencers. For the first object seven heat exchangers were experimentally assessed, using a modified version of ISO 15186-1:2000, to test the acoustic transmission for a diffuse field. In addition a sample from each heat exchanger type was cut out and tested by measuring the acoustic two-port in a duct, i.e., the transmission and reflection at normal incidence were determined. Theoretically, the basic configuration is assumed to be a matrix of parallel and rectangular narrow channels. The developed model is based on a so called equivalent fluid for an anisotropic medium. It is mainly dependent on the heat exchanger geometry combined with the Kirchhoff model for thermo-viscous wave propagation in narrow tubes. This model is a continuation of earlier work by Yan and Åbom. In order to reduce the transmission through heat-exchangers they can be fitted with parallel baffle silencers. In ECOQUEST a new type of such silencers using Micro Perforated Panels (MPP:s) have been designed and tested.

Results from this work are presented showing that such MPP baffle silencers can provide up 10-20 dB added damping in the frequency range of interest. A model for sound transmission through plate type heat exchangers was developed. This type of model is valid as long as the characteristic length scale of the heat exchanger inner structure is much smaller than the wavelength. The data needed for the model can be estimated from the geometry of a given heat exchanger. The propagation losses are then modeled by applying the Kirchhoff model for visco-thermal sound waves in narrow tubes. The flow related losses can be estimated via pressure drop data. The model gives a good agreement with the measured results but can require some tuning in order to account for details in the inner structure, e.g., louvers. Here this was done by adjusting one parameter (the effective hydraulic) radius based on measurements of a heat exchanger piece in a two-port test rig. A new type of (MPP) micro-perforated parallel splitter (baffle) type of silencer has also been proposed and examined both experimentally and theoretically. The transmission loss and pressure drop have been investigated for seven prototypes of this new silencer. It is found that the transmission loss can be enlarged by increasing the number of baffles, i.e., reducing the ratio free air space to baffle thickness (h/H), adding inner rigid walls inside the baffle and using inclined baffles. The inclined MPP baffles with inner rigid walls have the largest transmission loss. The inclination increases the high frequency performance while the inner rigid walls give an increase for the mid frequency range. The flow effect

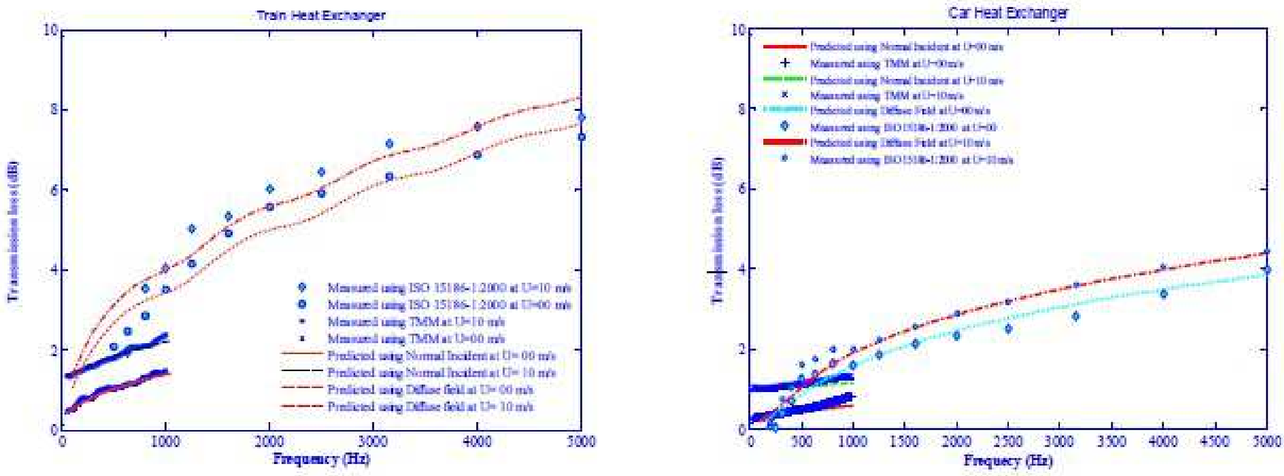

Figure 8: Transmission loss versus frequency at different flow speeds. The measurements and calculations are in one third octave band for the upper four curves in each figure while it is measured and calculated in narrow band for the lower 4 curves in each figures (i.e. up to 1 kHz).

for flow speeds up to 10 m/s is small and can be neglected. Theoretically, the basic configuration is assumed to be a matrix of parallel and rectangular channels with an acoustic lining boundary. The acoustic lining is a MPP sheet mounted on a locally reacting core without impervious backing. The model shows good general agreement with the measured data.

Prediction of noise emitted by full-size cooling systems

The prediction of the noise scattered by the fan environment involves several aspects: the prediction of the noise emitted by the fan towards the listener as if it were placed in free field (incident field), and the calculation of the scattered field in a second step. When the fan source is described in deterministic terms, i.e. when the wave fronts emitted by the fan are known in both phase and amplitude, the calculation of the scattered field by numerical means (Boundary Element Method or Finite Element Method) is relatively straightforward. The difficulty lies in the source representation. An additional difficulty is the presence of the scatterer in the near field which significantly makes the computation of the incident more complex. This step is extensively presented in deliverable D2.1 for tonal fan noise scattering. When the fan source is known in statistical terms (broadband fan noise), and the free field Power Spectral Density that is predicted by the methods explored in Task 2.2 is not a suitable input to the numerical approaches cited above. The approach that has been pursued in the project has consisted in expressing the source field within a formalism compatible with the numerical software developed by LMS, following the Acoustic Transfer Vectors approach in particular. Another important point is the proximity of the fan blades with the acoustic environment. As a result, the classical formulations of Amiet are not applicable since they assume that the listener (or scattering surface in the present case) is located in the acoustic and geometrical farfield of the fan blade. Besides, the fan blades have to be segmented in order to account for the spanwise variation of the flow properties, and the long-span assumption cannot be used anymore. Those steps are extensively presented in deliverable D2.2 for the incident broadband fan noise and in D2.3 for broadband fan scattering. In task 3.1 and 3.2, system level Auto and Loco cooling units have studied and CFD analyses have been performed by Valeo and University of Siegen respectively. The CFD analyses were used to perform acoustic analyses and convergence studies based on the approaches mentioned above. The acoustic analyses and studies are presented and compared to experimental results obtained in task 3.6 for the auto and 3.7 for the loco.

The comparison between the simulation results and experiments shows severe underestimation by the simulations concerning the tonal automotive noise. At this stage the root cause of this not fully understood but it is highly expected by the partners that this is due to the noise generated by the ring around the blade which proved to be quite noisy. This would explain why the noise seems to be globally under estimated, as the broadband noise is underpredicted by around 20 dB, too. It is also found that taking the contribution of the scattered-field can reach up to ±13 dB, hence free-field propagation is not a valid assumption anymore and the effect of the scattering obstacles should be taken into account. The under-prediction compared to experiments can be due to under-prediction of the turbulent length scales. A preliminary test is performed by simply assuming larger turbulence length scales (5 times) in free-field propagation and adding the scattered-field contribution. The comparison between experiments and new predictions then shows a good agreement at the most of the frequency range of interest. Especially at frequencies lower than 400 Hz, the effect of the scattering geometry around the axial fan is well captured.

Better results are obtained for the locomotive cooling system, see Figure 9. While the first tone is still under predicted by 6.5 dB the results for the 2^{nd} and especially the 3^{rd} tone are much better, which are under predicted by 1.5 dB and over predicted by 2.1 dB, respectively. The discrepancy is attributed to the fact that the 11 stators were not taken into account in the simulation. After close checks, it turned out that the stators should play an important role and should be taken into account in subsequent computations.

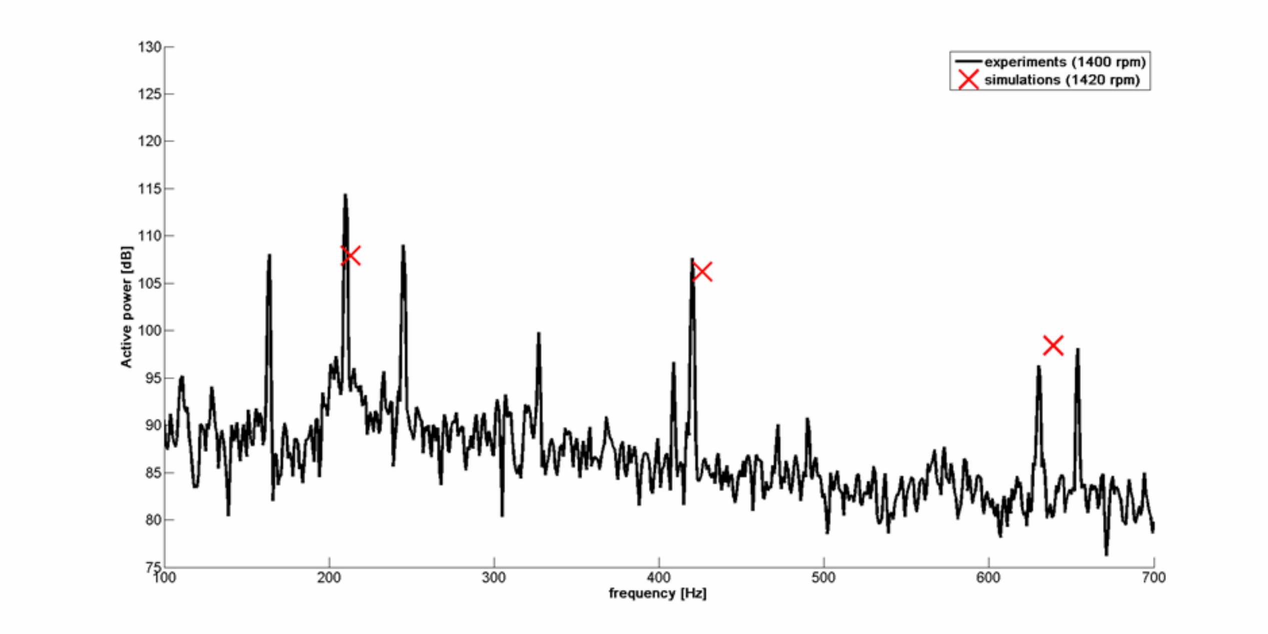

Figure 9: Comparison between simulation results and experiments for the optimized fan.

Automotive mock-up tests

In this work the interest is the sound power generated by automotive cooling units. The units were mounted in a wall between two rooms, one room being the ISO qualified reverberant test room at the Marcus Wallenberg Laboratory (MWL), KTH. By rotating the units this room could be used to determine both the up- and down-stream sound powers using the ISO 3747 method and a reference source. The back ground noise has been canceled out from the final results. All measured results in this report have been performed using Spectra PLUS - FFT Spectrum Analyzer and the results are presented as 1/3 octave-bands.

Based on the project plan and meetings and discussions between the task partners it was decided to change the fan shroud to a micro-perforated plate (MPP), in order to study its effect on Fan Cooling Unit radiated sound power. Both of the units were then fixed in the wall between the reverberant and anechoic rooms at MWL and tested at different fan operating conditions.

Based on the measured results presented in this section, summarized in Figure 10, it can been concluded that the MPP shroud reduce the radiated sound power up to 4 dB(A) on the downstream (fan) side. The reduction on the upstream side (heat exchanger side) is less than 1 dB(A). The MPP plates used for this and all the tests in T3.6 was of the same type as described in the report for T3.4, see Figure 27, i.e., normalized resistance around 1.5 and 1 mm thickness. This is the standard MPP plate provided by the partner SNT.

A detailed experimental investigation combining two different types of fans (a five bladed semi radial fan and an eight bladed axial fan) was carried out. The effect of shroud, back plate material and a dummy engine block on the acoustic source strength (radiated sound power) was measured under different controlled conditions using the ISO 3747 method. The dummy engine was positioned at 110 mm from the fan units (back-plate or shroud) for all tests. For the back plate two MPP arrangements were used. A single (standard) MPP plate and a double wall MPP with two standard plates separated ~10 mm by a space filled with melamine foam. The cooling unit was mounted between two acoustic test chambers with the receiving (downstream) side in reverberant chamber where a rotating boom was used to measure the source strength for different fan RPM´s.

The radiated sound power could be reduced with 1.5 dB(A) by using a MPP shroud compared with the original metal shroud. This is smaller than the first tested case in section 2 mainly because of the smaller area covered with MPP, around 22% of the total area of the shroud, but it can be increased to 4 dB(A) by also making the back plate of MPP. However, it can be noted that this reduction goes down as the RPM goes up. The reason is that a MPP has a frequency limit where the imaginary part of its impedance starts to dominate. For the MPP used this is around 1-2 kHz and for frequencies higher than this the damping is poor. This limit can be controlled by using a MPP with smaller holes, which will push the frequency limit up in frequency. Another alternative to handle this problem discussed in section 4 is to use a resonant volume on the back side of the MPP. The use of a double wall MPP has a small effect and gives no significant improvement.

In summary it is concluded that based on the results presented, a MPP shroud can reduce the total sound power radiated from the cooling fan in the range of 1.5 to 4.5 dB(A) depending on covered area and fan speed. Also the absorption on the engine side is increased which can reduce the installed noise further. The concept of using quarter-wave resonators to tune the damping maximum of a MPP to a desired range is tested with promising results. At the optimum working condition and for the same volume flow the new Axial Fan prototype is quieter than the new Semi – Radial Fan prototype.

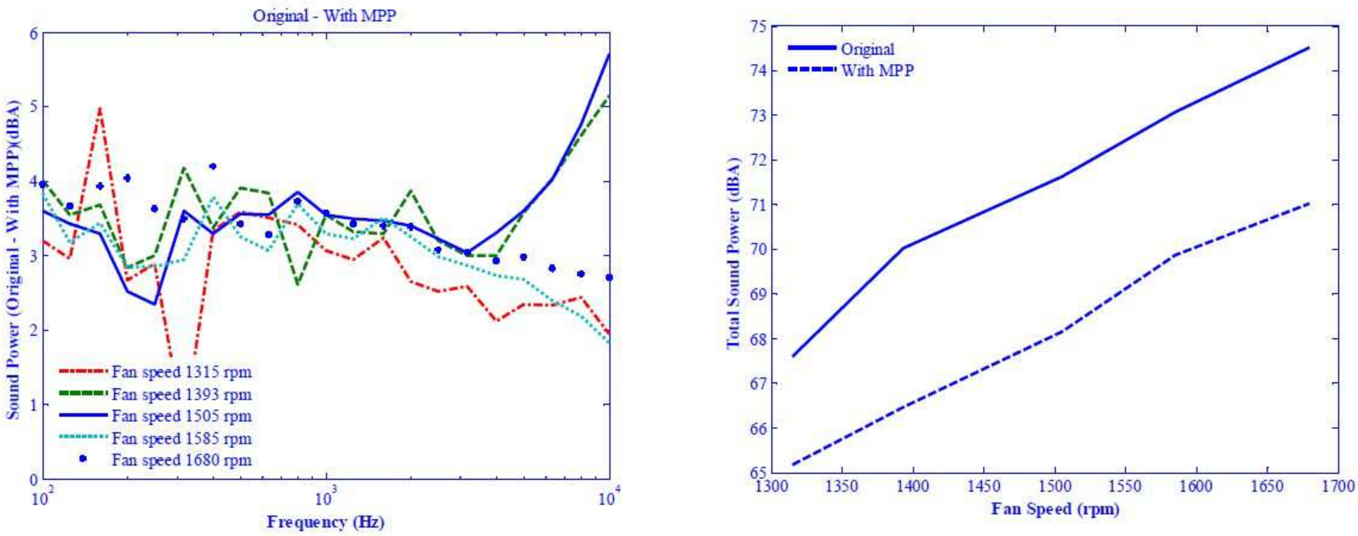

Figure 10: (a) Reduction in sound power when adding a MPP shroud. (b) Total sound versus fan speed for original and modified shroud.

Locomotive mock-up tests

All experiments were conducted at the test field of VTA in Heidenheim-Mergelstetten. The cooling unit was operated without thermal load, i.e. no coolant was pumped through the heat exchangers. Moreover, only the rear part of the cooling module is considered, wherefore the front fan remained in standstill and the module was divided by a wooden separating plate. The fan was driven by a hydraulic motor in the fan hub which is also used in the full-scale tests and in everyday operation. Hydraulic pressure was provided by a pump driven by an electric motor. The drive was operated in emergency mode meaning that there is no throttling of in the hydraulic cycle and the rotational speed of the fan is directly controlled by the speed of the electric motor (= pump speed). Potential throttling of the air flow due to contamination of the heat exchangers was simulated by covering 10 % of the heat exchanger area with strips.

A total of six microphones by Bruel & Kjaer (Type 4190) were placed around the cooling module. All of the microphones used were set at a height of h = 1750 mm from the floor which is approximately the height of the module roof. The acoustic pressure was captured via two NEXUS Conditioning Amplifiers. The sound power was determined according to ISO 3741 via a reference sound source which was placed above the hydraulic motor in the fan hub, thus at a position close to the fan center. Pressure transducers and revolution counters were installed in the same manner as in serial tests by VTA to measure the hydraulic pressure downstream of the pump and the rotational speed of the pump and the fan, respectively. Velocities were measured manually by vane anemometers. Four test cases were distinguished: (i) benchmark fan without attenuator, (ii) benchmark fan with attenuator, (iii) optimized fan without attenuator, and (iv) optimized fan with attenuator. Each configuration was operated at distinct fan speeds between n_{min} = 600 min^{-1} and n_{max} = 1540 min^{-1}.

It was found that the optimized fan leads to a 10% higher flow rate when operated at equal rotational speed as the benchmark fan. This corresponds to a higher cooling capacity which was not the primary target of the research in ECOQUEST, but is nevertheless an important improvement from a practical point of view.

The power consumption could be reduced significantly due to the optimized fan. The ratio between Configuration II and IV (benchmark vs. optimized fan both with attenuator) is remarkably constant over the flow rate and amounts to $P_{II}(\dot{V})/P_{IV}(\dot{V}) \approx 1.21$ meaning a total energy saving of 21 %. The differences between the configurations with and without attenuators originate from the fact, that the sound attenuator is an additional flow resistance. However, in a practical application there always needs to be a protection grid which would have the same effect. Thus, the increased power consumption due to the sound attenuator is not discussed any further.

From an acoustic point of view, both, the sound attenuator and the optimized fan were successful. This is shown by the spectra depicted Figure 11. While there is only a moderate sound reduction due to the attenuator the optimized fan reduces sound significantly. The most important effect occurs at the blade passing frequency and amounts to around 15 dB.

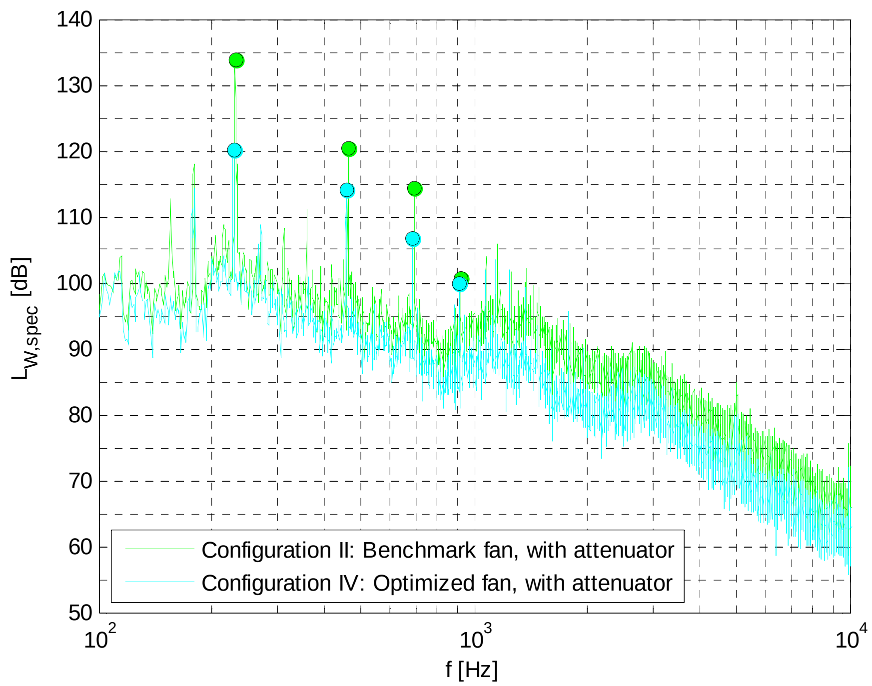

Figure 11: Acoustic spectra of the benchmark and optimized fan in the locomotive mock-up tests.

Full-scale tests of automotive cooling unit

Tests on vehicle tests were conducted in the climatic wind tunnel located at La Verrière (France). The selected car was equipped with Valeo components, designed and prototyped during the Ecoquest project. Various configuration of the cooling module have been used and have lead to the recording of several sets of results. Two types of cooling were tested, i.e. the direct cooling with the baseline, and the indirect cooling with the "Ultimate CoolingTM" module. On this latter, several adaptations of fan system were tested: a solution with a dual fan system, a solution with an optimized single fan system, and an innovative solution with a concept of semi-radial fan.

Results of heat rejection, electrical power and mechanical consumption were used to calibrate different Kuli models. These methods are applicable to systems with direct or indirect cooling as the one promoted by Valeo with Ultimate CoolingTM. The models allow testing and comparing "virtually" vehicles on driving cycles by predicting the effects on consumption and CO2 production. The analysis includes the complete system with engine cooling and climate control.

The indirect cooling module takes advantage of aerodynamics gains and of a better thermal control which prevents temperature peaks. Gains on CO2 production for the two indirect cooling modules tested are about 4 to 7% compared to baseline, which represent about 0,1 to 0,2 g. of CO_2 per km. It is possible that in the future additional gains could be obtained when full advantage of optimization tools will be taken, and when design rules favoring aerodynamics will be applied.

Some results showed the importance of aerodynamics which is prominent on consumption compared to fan system power. This gives as an indication that it is preferable whenever possible to promote heat exchangers rejecting more thermal power even if they are more resistant. The limitation lies in the operating points at low speeds, where the fan must overcome a higher resistance and will have to consume more. However, since the time of use at full power is limited, its use will not be detrimental to the overall energy balance. For instance, studies on the radiator resistance showed that 0.5 g. of C02 can be saved if the cooling at low speed is successfully managed. These aerodynamics need can be fulfilled without additional cost if the fan operating point fit perfectly to the characteristic of the cooling module. Optimization techniques developed during the project are intended to promote a perfect matching of all components, working together at their higher level of efficiency. This conclusion validates also the new trend observed with the spreading of new functionalities: fan speed control and active air shutters to close the front end whenever possible.

NEDC driving cycle	Baseline	UC Dual Fan System		UC Optimized fan	
Effect of Fan systems	g CO2/km and reduction %				
Tamb = 24°C / No AC	3,15	3,00	-5%	3,03	-4%
Tamb = 24°C / With AC	3,32	3,13	-6%	3,18	-4%
Tamb = 33°C / No AC	3,27	3,06	-7%	3,10	-6%
Tamb = 33°C / With AC	3,42	3,19	-7%	3,24	-6%

Figure 12: Comparison of CO2 production with different fan systems.

Full-scale test of loco cooling unit

The locomotive full-scale tests were conducted in June 2012 in Lüneburg, Germany. It was distinguished between three states of the locomotive:

1. Locomotive in standstill with fixed fan speed and twelve microphones placed around it (see Figure 13, top).
2. Six fixed microphone positions passed by the locomotive at constant speed (40 km/h)

3. Onboard measurements with three microphones attached to the locomotive which drove a 23 km test track with 500 t of load and realistic driving conditions with respect to velocity, acceleration, breaking, and terrain slopes

This short summary of the experiments is structured according to the three states. The experiments with standing locomotive were used to compare the benchmark fan with the optimized fan and the benefit due to replacement of the usual protection grid upstream of the heat exchangers by micro-perforated acoustic absorbers (MPPs). It was found that both, the optimized fan and the sound attenuators, reduce noise. While the reduction due to the damper is limited to directions perpendicular to the heat exchanger, the optimized fan reduces noise in all directions. The benefits in overall sound pressure level are up to 4.5 dB (fan) or 2.7 dB (attenuator). In case of the optimized fan, an additional immense reduction of the tone at the blade passing frequency (up to 15 dB) is observed.

The tests with passing locomotive only compared the effect of the optimized fan. The locomotive was accelerated to 40 km/h and passed the microphones with fixed fan speed. The example with maximum fan speed (n_{max} = 1540 min^{-1}) is depicted in Figure 13. In can be seen how the sound pressure level increases as the locomotive approaches and decrease after it has passed. The difference originating from the fan configuration is almost constant over time and amounts to 5 dB or 7 dB when flow rate correction is taken into account. The flow rate correction considers the difference in cooling performance and assumes that the optimized fan could be operated at 10% lower speed to obtain the same cooling capacity.

The onboard measurements were used to compare again the fan configurations but also to assess the new cooling strategy with fuzzy controller and balancing heat exchanger. The balancing heat exchanger can transfer heat from the high temperature to the low temperature cooling cycle which leads to a more similar cooling demand of the two cycles. This is valuable as the fan speed is always driven by the cycle with the instantaneously higher load.

The test track was split into five parts of which two (#3 and #5) are most suitable for comparison due to the very successful reproducibility in terms of driven conditions (speed, acceleration, breaking). The maximum sound radiation decreased due to new cooling strategy. This effect is strongest in cycle 3 and reaches almost 7 dB(A). Regarding energy efficiency, there is only a very little improvement at cycle 5, but a remarkable improvement at cycle 3 (24%). The optimized fan has a similar acoustic benefit. However, the accumulated acoustic effect of both measures together is not much higher (still around 7 dB(A)). In contrast, the energetic efficiency increases dramatically due to the two innovations. Now, significant improvements can also be observed in cycle 5. The improvement in cycle 3 increases to 39%.

Altogether, the full-scale tests were very satisfactory. All measures (cooling strategy, optimized fan, attenuator) lead to considerable sound reduction. Moreover, there are also remarkable energy savings originating from the new fan and balancing heat exchanger.

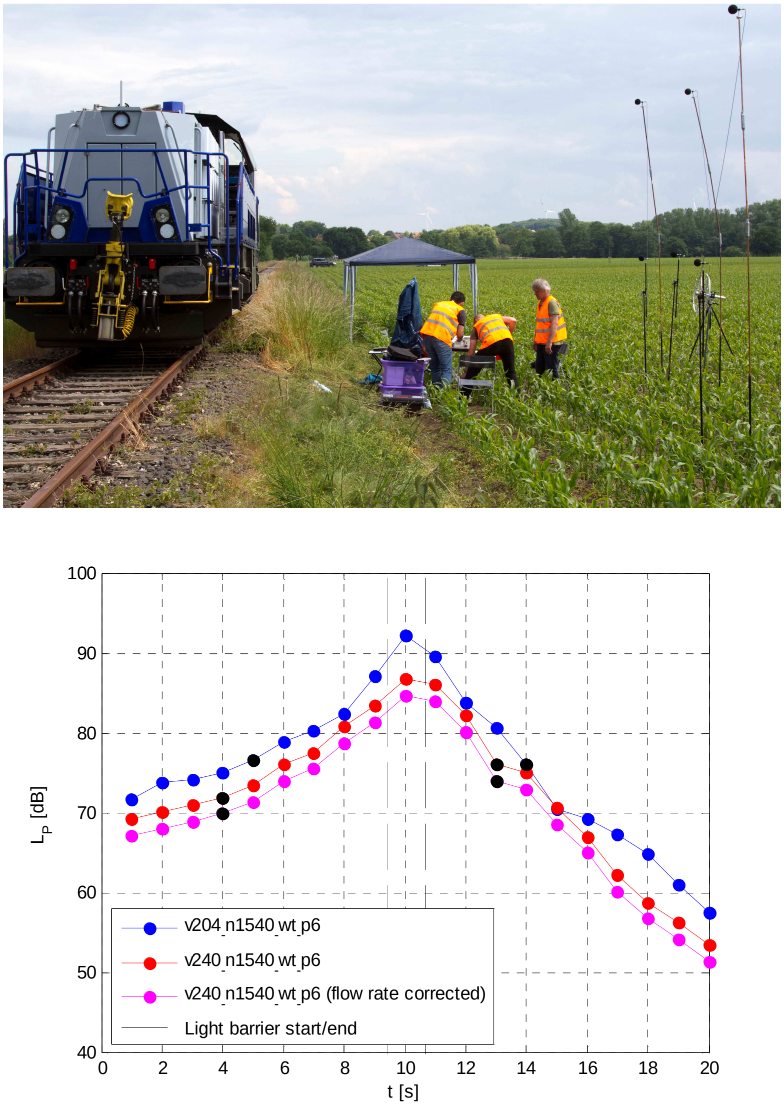

Figure 13: Top: Locomotive and measuring set-up for standstill measurements. Bottom: Benchmark fan (v204) vs. optimized fan (v240) at n = 1540 min^{-1} for passing locomotive measurements.

Acoustic environment effects

This task is about the experimental characterization of the sound field around a simplified locomotive at 1/16 scale in semi-anechoic room, and the comparison with BEM simulations. Sources mimicking the fans or the air-inlet grids are located either on the top or on the sides of the mockup. A reflecting ground and an optional vertical rigid wall at different distances are considered. Sound is measured for broadband excitation in a horizontal plane between the locomotive and the wall (the so-called platform area), at equivalent height of human head. Sample post-processed data are discussed and interpretations of major observed effects are provided. Characterizing fan noise in absence of any surrounding surfaces provides key information on the sound generating mechanisms and is relevant for strategies of noise reduction at source. However exposure of passengers in the environment of a railway station involves other aspects related to the scattering of fan noise by the locomotive itself, on the one hand, and to multiple reflections and diffraction by architectural elements of the station, on the other hand. Typically people on a platform can be quite close to the locomotive or close to a vertical building wall at some limited distance. The effect of that wall on the annoyance can be as important as the sound generation itself. This is why an academic experiment has been decided in the ECOQUEST program to address such a situation of practical interest. The main objective is to identify key effects that are expected for a locomotive in the presence of two perpendicular half-planes. Typically it is focused on the difference between sound fields with and without side-wall, for the sake of assessing the ability of some prediction models to reproduce it. However many configurations can be encountered in real stations and a complete modeling of the environmental effect would not be tractable if all geometrical details were included. It is guessed that major effects only involve design details that remain of the same order of magnitude as the acoustic wavelengths of interest. This led to the following criteria for the definition of the experiment.

- The true shape of the locomotive can be strongly simplified. It can be manufactured ignoring geometrical details. Geometrical simplification is also the condition for the problem to remain tractable numerically using a boundary-element method (computational effort provided by partner LMS). Furthermore diffraction is more pronounced at relatively low and middle-range frequencies, whereas high frequencies could be described using simplified approaches based on ray-tracing theory.
- The ground-only (full ground plane) configuration is considered as a reference case, corresponding to the absence of building around the machine. Two configurations with distances 2L and 3L of the vertical half-plane (wall) to the side of the locomotive are investigated, L being the width of the locomotive. The measurements make sense in horizontal planes that are believed representative of human hearing, typically 1.6m at full scale.
- The scale of the mockup must be compatible with the instrumentation and the size of the anechoic room. The value 1/16 has been selected. This is why the measuring plane has been fixed 10 cm above the ground.

The results of the impact of the scattering plane for sources on the roof show that with respect to the reference pattern in absence of wall, the presence of the wall at 3L causes horizontal wiggles in the map. The wiggles are interference fringes produced by interfering direct and reflected sounds, as confirmed later. They are also observed at different locations for a wall at distance 2L. Wall-reflection fringes are more easily quantified by plotting SPL profiles along lines of constant x value, in other words vertical cuts in the color maps. The same analysis for BPF1 is repeated for sources on the platform side. Such sources directly radiate towards passengers or technical staff with a minimal diffraction by the locomotive itself. The reference radiation map is characterized by three lobes featuring a playing-card club symbol, one lobe pointing normal to the side and the other two aligned with the side, in forward and backward directions. The backward lobe is modulated by additional vertical fringes that are attributed to sound reflection of the front wall of the cabin; the cabin itself is indicated by the red segment on the x-axis. Relative sound extinction areas appear in blue. One is pointing obliquely from $x/d = 20$; it results from masking by the corner of the cabin. The wider other one is near the top of the map for $x/d > 20$. Adding a vertical wall has a strong effect. The low-noise areas now receive much more sound. The three-lobed pattern is strongly distorted and clear horizontal interference fringes smoothly bending towards the x-axis are observed. The fringes are much more pronounced than for aforementioned roof sources.

Tests with the loudspeakers positioned on the platform side have been repeated with the full locomotive mock-up and without the baluster of the same side. Indeed in this configuration the baluster acts as a screen between the sources and observers standing on the platform. Optimizing its shape could be an efficient way of reducing sound exposure. The effect of adding the baluster is to partially deactivate the cancellation of direct and ground-reflected sound fields, and consequently to regenerate sound in the extinction area. In this area the presence of the baluster is not a benefit. Nevertheless, the baluster will still globally reduce the sound level and has the tendency to spread the noise emission (i.e. maxima of sound drop but minima increase), getting closer to homogeneous exposure. This might be of benefit for people operating around the locomotive. The typical radiation at 1BPF in absence of the baluster features three main lobes one of which points normal to the locomotive wall. In this direction sound first attenuates with increasing distance (along y axis), then has a minimum and grows up. The same lobed pattern is found with the baluster except that now there is less evidence of a minimum; it is also guessed that the minimum could be displaced beyond the limit of the measurement area.

By its simplicity and the anechoic quality of the setup, the experimental protocol developed in the task could be reused in future studies to address additional topics, such as balustrade optimization, synchronizing of tonal sources, geometrical modifications and so on.

Figure 14: Acoustic measurements of the model locomotive.

Novel auto/truck cooling units: Guidelines on methodology, design and cost/benefits

Valeo has conducted during this project investigations on automotive engine cooling systems. The work included important considerations on energy efficiency, helping to reduce fuel consumption and CO_2 emission, and aiming also to reduced noise pollution. Even beyond the mere cooling module, the studies have considered the effects on the vehicle drag and on the climate control loop (air conditioning compressor and heat exchangers).

The work was conducted with the goal of building a platform for cooling module design that includes numerical methods and analytical models. All future studies on cooling systems will take advantage of these improved methodologies, and it is expected that new technologies and scientific progress could also be added progressively in this set of tools.

Many lessons have been made for thermal systems, ventilation systems, for integration into the vehicle. It must be added those acquired in the areas of modeling, simulation and optimization (thermal and acoustic). Several procedures have been developed and are used. Enhanced methodologies due the ECOQUEST project comprise: global performance prediction due to fan simulation, fan design by optimization methods, CAD of the shroud for fan system simulation with “PCC” geometry, simplified module simulation, post-processing of global performances and flow distribution, unsteady simulation with various flow rates, tonal noise minimization with rotor stator interaction, unsteady simulation for tonal noise prediction, fan system selection according to customer specifications, KULI calculation with EXCEL control, dynamic modeling of an engine cooling system, aeraulic calibration of an engine cooling system - according to wind tunnel test results, air conditioning system modeling with KULI - AC system and cooling system interaction, and direct and indirect cooling system modeling with KULI.

A new best practice guidelines was created in the field of cooling module aerodynamic resistance and the effect on CO2 balance considering drag and thermal management. This work presented earlier in the project has involved two different techniques that have been coupled. Another best practice guideline deals with fan performances on the cooling efficiency during MVEG cycle and the effects on the CO2 balance of the vehicle.

Thermal performances have been predicted using a dual flow-stream technique that computes precisely heat exchanges between air flow and cooling fluid. Mechanical power needed for the cooling at different vehicle speed has been assessed and compared to thermal exchanges for different conditions. Final results are presented for NEDC driving cycle and different conditions, i.e. 24 or 33 °C and with or without climate control. Gains on CO2 production are about 4 to 7% compared to base line, which represent about 0,1 to 0,2 g per km.

These gains are only due to the fan system and they represent a significant advance in terms of impact on the automotive fleet and regarding the additional cost which is null. It is even found that the single fan-system solution is almost at the dual fan system level, despite this latter is deemed more expensive, heavier and noisier. This is especially remarkable since the surface coverage of single fan system on the heat exchanger was lower than the dual one (Figure 27).. A better area ratio, which would appeal to less elongated exchangers (typically square section) could probably further improve the performance.

The project has promoted the development of techniques for analyzing the efficiency of vehicle thermal management. The numerical simulation has been widely used and it has provided predictions of aerodynamic and aerothermal performances. These tools have been implemented in some optimization processes based on a design of experiment, the construction of response surface using neural networks and research algorithms. All the methods investigated are incorporated in a virtual platform for development of cooling systems.

Significant progress has been made for complete simulation of the cooling system, either for cooling modules or for underhood conditions. Results were coupled with thermal modeling tools that provided assessment on CO_2 production during driving cycles. The analysis includes the complete system with engine cooling and climate control. These methods are applicable to systems with direct or indirect cooling as the one promoted by Valeo with Ultimate Cooling^{TM}. This latter significantly improves the aerodynamics of the vehicle and the thermal management, which results in reduced production of CO_2.

Comparisons were made between different types of fan system, either with a single fan, or with 2 fans, or with innovative geometries such as the semi-radial fan. In terms of conception, it has been further demonstrated that the perfect adaptation of fan nominal operating point to the cooling module yields improvements and reduces the fan system power consumption.

Aeroacoustics has been considered during the development of analytical methods for predicting the tonal noise and its directivity, and through experiences dealing with effect of fan integration in the shroud on the acoustic power. In addition to the advances in the analysis and the modeling, micro-perforated plates for acoustic damping were tested and innovative stator geometries were produced.

These methodologies are gradually incorporated into customer projects and should lead to a constant improvement of cooling modules delivered to our customers. They also confirm and substantiate the current technological trends, i.e.:

- An increasing use of indirect cooling
- A willing to improving vehicle aerodynamics with controlled flaps at air entrance
- A strong necessity to adapt perfectly fan system efficiency to their operating points.

Novel loco cooling units: Guidelines on methodology, design and cost/benefits

We here cover three main issues: guidelines for future fan optimization, guidelines for future system optimization and cost/benefit analysis. It will be shown, that the ECOQUEST project considerably improved the methodologies and ECOQUEST results will be used extensively in future projects.

In the ECOQUEST project, we conducted system analysis, simulations of the benchmark system at full-scale and model scale, optimization of fan, guide vanes and diffuser, simulation of the optimized system at full-scale and model-scale, and instationary flow simulations. In future designs, some items might be spared. Especially the unsteady flow simulations have extremely high computational cost which is by no means reasonable from an economic point of view. Owing to increased trust in our methods, the full-scale simulations can potentially be spared as well because the differences between a simplified downscaled system and the non-simplified full-scale system turned out to be very small. This would in particular decrease the time for meshing and the computational cost. The remaining tasks to be performed would then be: development and simulation of a simplified and downscaled cooling module, assessment of the results, fan optimization taking installation effects into account, guide/vane diffuser optimization, integration of the new fan unit into the module and renewed system simulations, and construction of prototype cooling systems at model scale and aerodynamic/acoustic experiments.

The optimization conducted within the ECOQUEST project required much higher effort. Future optimization work will benefit from the following points:

- development of the general method is no longer required as it can be applied to arbitrary systems
- theoretical system analysis is existent in case the same cooling module type will be reused
- the optimization algorithms are fully developed and implemented such that they can be applied in arbitrary optimization work
- automated CFD loops are existent and just need to be modified for new tasks
- the relevant geometrical parameters for fan and guide vane optimization are now known such that from now on the first optimization loop should already lead to a good design
- the parameterized generation of geometry (required for CFD and CAD work) is existent and just needs to be scaled for other sizes
- drawings for the test rig are parameterized and can easily be adapted to other dimensions of the components
- the measuring equipment as well as scripts for evaluation of measuring data have been purchased/programmed and are suitable for any future designs

- there is an immense gain of experience of the people involved in the project

The cooling module in a locomotive interacts mutually with other components in a locomotive where as the system ‘locomotive’ is part of the large system ‘track - train - environment’. Most components of the locomotive’s powertrain produce heat - according to their efficiency - that has to be transferred into the environment at a huge range of ambient conditions. With the focus on diesel-hydraulic locomotives the diesel engine in traction mode and the hydrodynamics transmission in braking mode are the major heat sources and require the most cooling. Modern cooling systems are based on complex coolant networks with different temperature levels in different hydraulic systems. State-of-the-art systems consist of two water circuits. The first circuit handles, at a high temperature level, the heat management of the diesel engine and the powertrain. The second low temperature level circuit indirectly handles the heat regulation of the charged air for the diesel engine. Due to the design of a locomotive, the ram pressure created by the vehicle can not be used so that cooling system needs fans to create an active forced cooling airflow. These fan drives consume considerable energy and the fans are, as already described, a main noise source of the locomotive. Therefore, the research and development of components and systems for cooling has been an ongoing activity for many years as a large number of publications indicate. However, the overall energy consumption and noise emission does not necessarily depend only on details of the fan design, but, in general, on the interaction of all components in the complete system. The cooling unit as taken into account in this study includes the hydraulic network, the aerodynamic fan, the hydrostatic drive and associated network and the controlling system with their representative geometrical and physical parameters. Because of the complexity, the complete system is modeled by means of a multi-domain simulation tool, here LMS Imagine.Lab AMESim. This tool allows a dynamic analysis of all components and its interaction as function of locomotive loading, drive cycle and environmental conditions and a subsequent optimization of the complete system and isolated components. In more detail, the cooling unit is split into different subsystems:

- The hydraulic network is parameterized for the pipe design and additional components. For instance the water pump, the bypass system and heat exchanger were adapted to the pipe-work. These models compute the transient pressure drop and flow rates within the network, depending on thermal, mechanical and aerodynamic boundary conditions.
- Analogue to the hardware design, the control unit is implemented with the temperature sensor, control logics and signal processing. The temperature of the coolant is monitored and controlled by the controller.
- The control variable is the input for the hydrostatic subsystem which powers the fan. With the input of ambient conditions (e.q. track topology, curved track, ambient temperature) and a chosen control strategy the driving performance of the vehicle can be analyzed in the complete vehicle-track system. For brevity the sub-models are not given here in detail but the modeling level is similar to the fan model described earlier. Finally the vehicle-track model is coupled with the cooling unit model.

With the model described a system optimization is carried out. We select the two target functions “energy consumption” and “emitted sound power”. In general they are functions of

- Principal system layout (Thermal coupling/decoupling of the water/oil circuits, coupling/decoupling of water pump from drive train etc.),
- Control strategies (type of controller, integration of ambient temperature sensor etc.)
- Size and number of heat exchangers / fans and further geometrical details of the ooling unit
- Operating cycle
- Ambient conditions

4.1.4 Potential impact

Reduction of external and interior noise, also in view of compliance with legislation

In the past, technical progress made in noise reduction of vehicles was over-compensated by the growth of ground transportation. Given the predicted rate of traffic growth acceptable noise levels can be partly achieved through noise abatement measures (tunnels, barriers), but a substantial part of the reduction has to be achieved through reduction of the noise at source. For this reason the automotive and rail industry (worldwide as well as the European) has initiated a sustained research effort. The European Road Transport Research Advisory Council (ERTRAC) sets “noise reduction” as one of the major goals for future surface transport research: “Noise levels (must be) appropriate to individual locations including quiet zones. ... The research challenge is to deliver low emissions while also meeting ... vehicle performance,....”

The European Rail Research Advisory Council (ERRRAC) identifies very similar future efforts: “Simulation tools for noise assessment, the effectiveness of noise reduction measures .... are all areas for further study.... Deliverables include reduction in noise .... in addition to what will have been achieved through the FP6 projects SILENCE and QCITY.”

Thermodynamic principles require cooling systems for all present and future vehicle power trains. The stringent EU6 emission limits expected to come into effect in 2014 may require up to twice as high cooling power in road vehicles as compared to present technologies. Cooling systems are a major noise source, especially at standstill or stop and go traffic.

According to the latest European standards for interoperability of rail bound traffic within Europe the averaged sound pressure level $L_{pAeq,T}$ must not exceed 75 dB for both, electric power units and power units with internal combustion engines (EU 2005); ISO 3095 (CEN 2005). The research on noise prediction from mobile cooling units is widespread. Several groups in Europe are working on specific items to overcome the existing shortcomings and to extend the predictive methods to this complex application.

The ECOQUEST project overcomes the fragmentation of research in this particular field. Since all major players in Europe are participating, the project brings the critical mass together which guarantees major achievements in the development and industrial utilization of noise prediction tools for mobile cooling units. In terms of noise levels, the consortium partners agreed prior to the project that for the locomotive applications, gains of the order of 6-8 dB(A) could be achieved through the thermal management and acoustic optimization procedures, including passive noise control at the source, that are developed in the project. This target was fully achieved. In fact, even the fan optimization alone lead to an overall sound reduction of more than 7 dB. The sound attenuators showed an additional benefit by 1-2 dB. The assessment of the benefit due to the optimized thermal management is more difficult as it heavily depends on the operating conditions. Tests on a 23 km test track with a realistic driving profile revealed an average reduction by 4 dB with special benefits concerning maximum noise levels.

As for the automotive applications, which have been the subject of optimization for some time already, the consortium estimated a further reduction of 3-4 dB(A) prior to the project. Again, the target was fully achieved. In contrast to the locomotive, the sound attenuator played a more important role while the fan only contributed moderately.

Contribution to CO_2 emissions reduction (or at least neutral impact to climate change)

Predicted traffic growth poses a significant hazard to achieving CO_2 emission targets. Furthermore, the EU6 emission limits require up to twice as high cooling power in road vehicles as compared to present technologies. In the past, technical progress made in emission by the vehicles was over-compensated by the growth of ground transportation. Again, the European Road Transport Research Advisory Council (ERTRAC) sets "low emission" as one of the major goals for future surface transport research: "...The research challenge is to deliver low emissions while also meeting ... vehicle performance, reduction in green house gas emissions and improvements in energy efficiency." (ERTRAC, Strategic Research Agenda 2020). The European Rail Research Advisory Council (ERRAC) identifies very similar future research needs.

In ECOQUEST no technology was accepted which achieves noise reduction by adding weight or increasing energy consumption of the vehicle. Thus, the technologies aimed at are CO_2 neutral or CO2 reducing. This was provided by introducing new simulation tools for optimization, novel noise reduction measures such as innovative fan designs with increased or neutral efficiency and micro-perforated components rather additional damping material.

Typically the combustion of 1 litre gasoline produces 2.38 kg of CO_2, of diesel fuel 2.66 kg. For cars the latest EU-wide goal of CO_2-emission of 120 g/km corresponds to 5.0 litre gasoline or 4.5 litre Diesel consumption per 100 km. As a rule of thumb 100 kg less vehicle weight reduces the fuel consumption by 1 litre per 100 km. Thus, decreasing the weight of an automotive cooling module by 2 kg yields an improvement in fuel consumption by 1%, i.e. a reduction of CO_2 by 1.2 g/km. Although this does not seem a lot the automotive industry is putting tremendous effort on reducing weight of each component - even by the gram - which eventually sums up to a substantial weight reduction of the complete vehicle. In addition, an increase of efficiency of the electric or hydraulic fan (typical power consumption: 100 W to 1 kW), say by 5%, reduces the CO_2-emission in the same order of magnitude. The actual result of the project is exactly in this range, see reports (especially D3.3, D3.6, D4.1).

The Diesel engine in a large locomotive is rated 3,600 kW, the maximum power required by the cooling fans is 270 kW. Typically the specific fuel consumption of the locomotive at full load is 191 - 195 g/kWh. The power required for operation depends very much on the load (weight of the train), the track and the climate. VTLT estimates that a reduction of the cooling fan power in a Voith loco by 10% may lead to an overall fuel saving of 1,300 kg, i.e. 3 tons less CO_2-emissions per year. This target was considerably outperformed. The fan alone reduced the energy consumption by 20%. Together with the optimized cooling control strategy, the reduction amounts to almost 40%. According to the assumption above, the annual saving per locomotive will be 12 tons of CO_2 per year instead of only 3 tons.

European competitiveness and economic impact

ECOQUEST provides the European automotive and train industry with demonstrated methods to reduce noise at source while increasing energy efficiency and reducing CO_2 emissions. In doing so, it contributes to achieve European industries' objectives for greener vehicles to meet society's needs for more environmentally friendly ground transport of people and goods, and to enhance European global competitiveness. The economic impact of the ECOQUEST programme on the European ground transport sector will derive not only from increasing European competitiveness but also from contributing to the removal of a potential limit on the natural growth of the sector worldwide.

Recent research in the USA and Japan has established a lead in some of the technology areas being considered. The work proposed in ECOQUEST will at least re-establish parity in those areas whilst moving ahead across energy saving and CO_2 emission reduction concepts.

ECOQUEST is an essential element in ensuring that ground traffic can grow in harmony with other modes of transport. It has to be assumed that any restriction of this growth due to inability to meet noise and CO_2 emission targets will have a detrimental effect on European businesses which would otherwise be using air transport for freight or passengers. Moreover, the development of innovative modeling approaches and their implementation in sophisticated software tools is meant to enhance system assessment and facilitate decision-making in ground transportation, but also in other applications of economical relevance such as

- heating, ventilating and air-conditioning systems for any transportation (including aerospace), residences and factories;
- cooling systems for electronic devices, that present strong similarities with the ECOQUEST applications regarding cluttered environments: laptops for example;
- energy processes, being not necessarily confined but that show very similar broadband noise issues such as wind turbines.

Finally, it must be anticipated that the future of ground transportation will involve a growing fraction of electrically-powered trains and hybrid automotive propulsion as well. It is nowadays acknowledged that whichever hybrid technology becomes predominant in the future (fuel cells, etc.), the controlling electronics and power transformation will require sophisticated cooling management, with two very strong challenges to be faced. Firstly, in the absence of an internal combustion engine running, the cooling system will become the dominant sound source for low-to-medium rolling speeds. Secondly, energy intensity and storage being key factors in these hybrid technologies, the energy efficiency of the cooling system will become determinant for the overall viability of the system. ECOQUEST anticipates on these needs by addressing altogether thermal efficiency and acoustic performance of the cooling system.

Education

The consortium includes 4 renowned European Universities and Research Centres, i.e. nearly one half of the total partnership, a situation which is highly beneficial to training and education. For undergraduate, post-graduate and PhD students, the participation to such programs is a unique opportunity: the research performed is of high quality due to the expertise accumulated in the consortium, the concentration of financial resources and the innovative scientific route which ECOQUEST develops i.e. new flow control concepts. It also provides exposure to a multicultural environment and to establish international relationships that are useful to build and strengthen the European Research Area.

As users, developers and suppliers of advanced innovative technologies, automotive and locomotive/train manufacturer know the value and importance of continuously developing human skills, contributing to the European objective of moving toward a knowledge-based society. The partnership brings students and scientists an excellent opportunity to gain experience in the European scientific community in the field of engineering. Giving education a high priority ensures the long-term supply of first-class, well-trained and suitably qualified engineers and scientists.

The integration of PhD students into the project team lead to the successful completion of at least two PhD thesis's, two being still in progress. In addition, numerous students were involved as research assistants in the project who gained exceptional experience in international research.

Dissemination

Dissemination was one of the major concerns throughout the project which can in particular be observed in the Tables A1 and A2. There was a strong focus on publication in journals 5 contributions) and on conferences/workshops (39 contributions), all listed in Table A1 and A2. Among the publications there are also two PhD thesis's which are based on work within ECOQUEST. Two further PhD thesis's shall be finished soon. Besides, there have been some other events where we presented our project and its outcomes. The two most important events were a three days lecture series and a contribution to the InnoTrans Exposition 2012.

The three days lecture series was held at von Karman Institute for Fluid Dynamics April 22nd-24th entitled "Modeling, measurement and control of ventilation and cooling fan noise". The first two days were used for general lectures about acoustics which partly covered novel ECOQUEST outcomes. The last day was an ECOQUEST workshop in which we exclusively reported about project results. All lecturers belong to the consortium. Lecture notes were created for each contribution and distributed among the participants. They were also disseminated. The individual contributions are listed in Table 1.

Table 1: Contributions to the lecture series at VKI.

Main lecture series		
Title	**Lecturer**	**Affiliation**
Fundamentals of aeroacoustic analogies	C. Schram	VKI
Linearized methods for broadband fan noise	M. Roger	ECL
Multiport education for ducted components	M. Abom	KTH
Noise control in ducts	M. Abom	KTH
Boundary Element Methods for fan noise scattering	M. Tournour	LMS
Innovative passive control of cooling fan noise	M. Abom	KTH
Innovative blade design	K. Bamberger	USI
Heat exchanger modeling	M. Abom	KTH
ECOQUEST workshop		
Title	**Lecturer**	**Affiliation**
Efficient prediction of acoustic installation effects	M. Roger	ECL
Aeroacoustic modeling and validation of generic locomotive cooling unit	C. Schram	VKI
Aeroacoustic and thermal optimization of automotive cooling system	M. Henner	VAL
Advanced passive noise control using micro-perforates	M. Abom	KTH

The contribution to the InnoTrans 2012 was mainly organized by VTA with support from USI. The exposition took place in Berlin, Germany, from September 18th until 21st. InnoTrans is the most important world-wide exposition for the railway industry. In 2012, around 126,000 professional visitors and 20,000 public visitors came to see the stands of more than 2,500 exhibitors from 49 countries. One booklet at the VTA stand was exclusively dedicated to our ECOQUEST project and presents our major achievements concerning locomotive cooling. The EC funding was acknowledged. The booklet was explained and handed out to interested visitors and is also publicly available in the internet:

http://www.voithturbo.com/applications/vt-publications/downloads/1962_e_2012-07-31-g2283-ecoquest_e_screen.pdf

Commercial exploitation in automotive industry

This summary describes benefits of the mains innovations that have been considered during the ECOQUEST project. A brief technical presentation highlights main advances offered by the systems studied. Potential gains in terms of reducing CO_2 emissions are presented for the new technologies. Assessments on the market penetration and on the automotive growth are presented to figure out future impacts of the innovations proposed for the thermal management.

Traditional systems for thermal management are constituted by two loops, dedicated respectively to engine cooling and climate control (heating, cooling, defrosting, demisting). Thermal exchanges with the exterior are made on the front end, which is equipped with a cooling module. Among the various heat exchangers, one can find the radiator (engine cooling), the Charge Air

Cooler (engine air entrance), the condenser (refrigerant loop) and sometimes an oil cooler (transmission, driving assistance and/or gear box).

The concept that equips the ECOQUEST test vehicle has been designed to minimize the total thermal power, previously distributed on three separate loops, and now shared on two simplified loops. This concept named Ultimate Cooling^{TM} and developed by Valeo is presented in figure 16. It proposes different thermal exchangers for each function that are indirectly cooled by only two loops. High and low temperature loops are used for the Water Condenser (WCDS), the Water Charge Air Cooler (WCAC), eventually by the Water Oil Cooler (WOC), the Water cooling for Exaust Gaz Recirculation and of course for the engine cooling.

Cooling components are no longer designed for the maximum use of each function, and the architecture optimizes the overall performance to the just needed. The main benefit comes from the sizing of heat exchangers to the just needed thermal performance. All components are not used at their peak level at the same time.

The cooling module architecture that has been redesigned with the Ultimate Cooling^{TM} architecture yields to some aerodynamic effects that have been investigated during the ECOQUEST project. In particular it is found that the cooling module has a lower porosity, which leads to the benefit of a reduced vehicle drag. This is explained by the decrease in airflow under the hood, causing less friction and losses. This favorable effect is counter-balanced by the higher load which is imposed on the fan system: at low vehicle speed, the natural flow is insufficient and must be forced by ventilation. It appears that the design of the module and its coverage by one or two fans becomes an important criterion for the effectiveness of the concept. The combination of the two effects (less drag, more fan power) is however favorable to the concept UC showing gains on the fan system power of around half a gram of CO_2 per kilometer.

This concept brings also some modularity in its architecture since additional functions can be easily added (or removed) on the water circuit. Additional cooling is organized for battery, electronics and electrical motor. The heat exchangers are furthermore optimized to perform the cooling at the closest location of the component to be cooled. It allows standardization and a simplification in the management of the different versions across of powertrain across platform. For hybrid vehicles, the battery, electronics and electrical motor are cooled by the same coolant liquid, via the low temperature loop.

In terms of fan system sales, Valeo has the ambition to increase its market penetration from 8 to 11 %, and following the global market growth worldwide it is expected to increase sales by 50% between 2010 and 2023 (see figure 15). This aim could be achieved if Valeo maintains its expertise on this product by applying methodologies for aerodynamic optimization and acoustic level minimization. The growth produced by this increase in market share represents a global amount of 500 millions of Euros.

The total Charge Air Cooler market for Valeo is expected to increase from 18 to 48 millions of units between 2010 and 2023. The sharing between direct technology (CAC) and indirect technology (WCAC) will evolve in the same time, the WCAC rising from 3% to 33% of penetration (see figure 16).

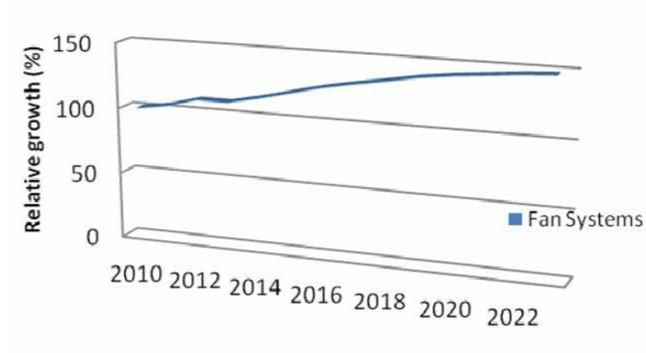

Figure 15: Forecasted sales of fan systems (present = 100%).

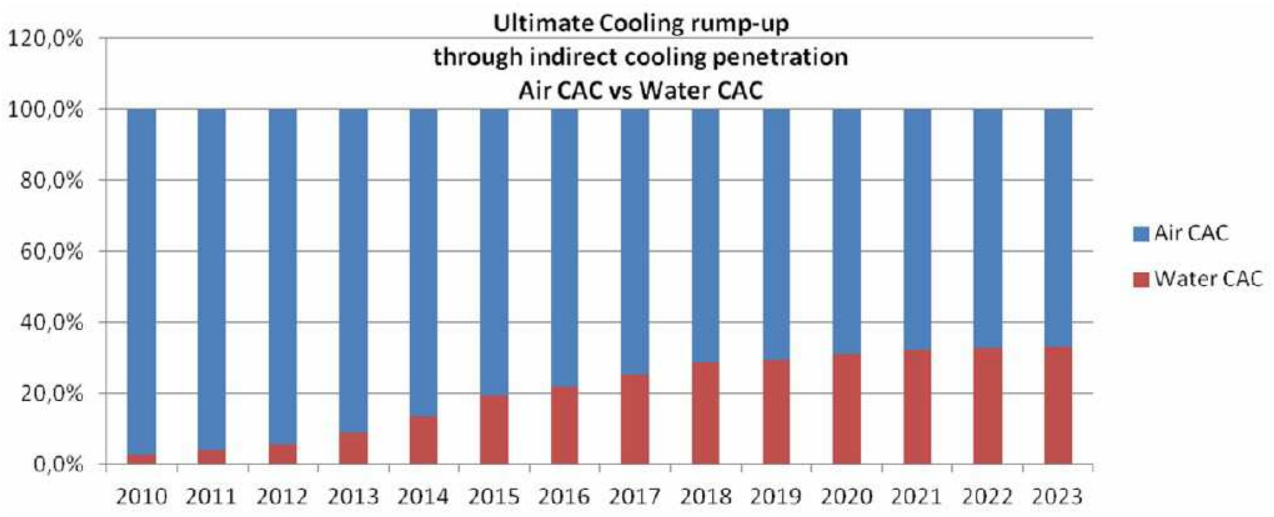

Figure 16: Market sharing between Air CAC and Water CAC.

Commercial exploitation in locomotive industry (1): Technical and methodical achievements

The exploitation plan is discussed with respect to three major fields which will be described separately.

Fan optimization

The team carried out fundamental systems analyses as well as CFD simulations and acoustic experiments with mock-up units. The following insights were gained:

- Reduction of the fan diameter smoothes the speed profile at the fan inlet and thus decreases leading edge noise.
- Further noise reduction is achieved by optimized blade profile and improved blade sections (“sickles”), which also increases efficiency.
- The highest energetic saving potential lies in the reduction of the exit losses through guide vanes and diffusers. The solution combines both components in one compact unit. Optimum aerodynamic design was achieved through CFD simulations and an optimization algorithm. The geometry thus achieved differs from conventional designs and excels by higher efficiency.

- Homogenization of the exit flow decreases losses and compensates anticipated drawbacks due to the smaller fan diameter.

Improvements achieved:

- Cooling capacity increased by approx. 10 %
- Energy consumption decreased by approx. 20 %
- Broadband noise levels decrease by approx. 6 dB
- Specific level at blade-passing frequency reduced by more than 10 dB

System optimization

The energy consumption and the noise emissions of cooling systems not only depend on the fan design but also on the interaction of all systems components such as cooling unit, vehicle and environment. Apart from the aerodynamic fan, the cooling system used for this study also includes the hydraulic systems, the hydrostatic drive with associated peripherals, as well as the control systems with relevant geometric and physical parameters. The model for the complete vehicle-rail system is divided into various sub-models (e.g. diesel engine, hydrodynamic transmission, vehicle, driver, track profile), which characterize the system's behavior and the interaction with the entire vehicle. By coupling the vehicle model with the cooling system, the entire system can be examined. The following variations were applied:

- Fundamental design studies and detailed component optimization
- Control strategy e.g. of fan regulation
- Operating circuit and ambient conditions

Depending on the ambient temperature, significant energy saving and noise reductions can be achieved. Minimum noise emissions can be realized by modified control strategies for the reduction of the dynamic fan speed. Minimum noise emissions can be achieved by modified control strategies for the reduction of the dynamic fan speed. In combination with a load balancing mechanism between the various water circuits and the cooling system, the operating load of both circuits can be adapted to the same level, which allows significant energy savings.

- Energy savings of up to 50 %
- Noise reduction of up to 3 dB(A) just by system optimization

Sound attenuator design

Sound absorption systems have proven themselves in cooling systems as acoustically effective, passive sound dampers. “Passive” in this context means that no additional energy is required for sound absorption. The aim is to reduce noise effectively by simple and space saving measures without modifying the aerodynamic operating point of the fan. For this purpose, the cooling grid of the prototype locomotive was temporarily installed with sound damping elements to allow measurements. With new locomotives, the two functions “protection” and “sound absorption” have to be constructively combined in the vehicle.

VTA achieved the aim of reducing the energy consumption and noise emissions with the outcomes of the ECOQUEST project. Depending on the requirements of the customer, the energy saving and noise reduction outcomes can be integrated in future cooling system designs.

Commercial exploitation in locomotive industry (2): Cost-benefit analysis

A TecRec is a UIC/UNIFE standard designed to be used within the European region. This document provides a voluntary standard on the "Specification and verification of energy consumption for railway rolling stock" for use by companies in the rail sector if they so choose. The document is set out in the same format than EN standards including, where appropriate, normative and informative annexes. This is so as to facilitate the interface with the ENs.

The freight mainline profile over 300 km includes three planned stops plus two stops in front of red signals. Two third of the line is horizontal track whereas the middle part includes a mountain passage. This reflects the fact that long distance freight train operation includes railway lines with significant gradients in many countries, not only through the Alps. The gradients of the profile are selected in such a way that a four-axle locomotive can haul the same train as the reference train with average mass as specified below. Although locomotives and wagons of many freight trains may be capable to run faster than 100 km/h, the profile is limited to 100 km/h, which is the maximum speed for most loaded freight trains according to lines and wagons of Class D (22.5 t axle load). Timetable requirements have to be interpreted in the same way as for intercity passenger traffic. Train and timetable are applicable for electric trains or fast freight DMUs only. Trains hauled by diesel locomotives can not hold the timetable for the mountain section, unless they have an uneconomically high number of locomotives.

The system performance with the validated system simulation model of the complete locomotive is investigated for the freight mainline profile. The following figures show the huge benefit of all systems (“new fan”, “balancing heat exchanger”, “ECOQUEST”):

- fuel saving: 0,5%
- CO_2 saving: 3,6kg/h or 51 g/km
- hydrostatic power saving: 24%
- sound pressure reduction: 3,9dB or 5,0 dB(A)

The results are input for the live cycle cost investigation. The main quantifiable LCC argument is the achieved fuel consumption saving within the ECOQUEST developments. With the cooling system cost (Funding cost and maintenance cost excluded) the amortization time can be investigate. Therefore standard values for operation hour, fuel price and fuel price escalation is assumed. The costs are based on manufacturing costs (standard parts and additional components) and development cost (Based on a batch size of 20 cooling units).

Altogether, VTA achieved the aim of reducing the energy consumption and noise emissions with the outcomes of the ECOQUEST project. Therefore the consortium develops new methods and components for rail applications. A huge emission reduction 51 g/km and noise reduction up to 7 dB(A) can be achieved. The most designs can be implemented in future cooling modules with attractive cost/benefit ratio. The current international or local noise standard does not necessitate the immediate realization of all ECOQUEST outcomes. Major standard specified no usual operation point of the cooling module. Therefore the fan isn’t running during certification measurement. Moreover, the real operation cycle doesn’t consider in the certification process. On the other hand the fuel consumption saving can become to a commercial issue to implement the ECOQUEST outcomes.

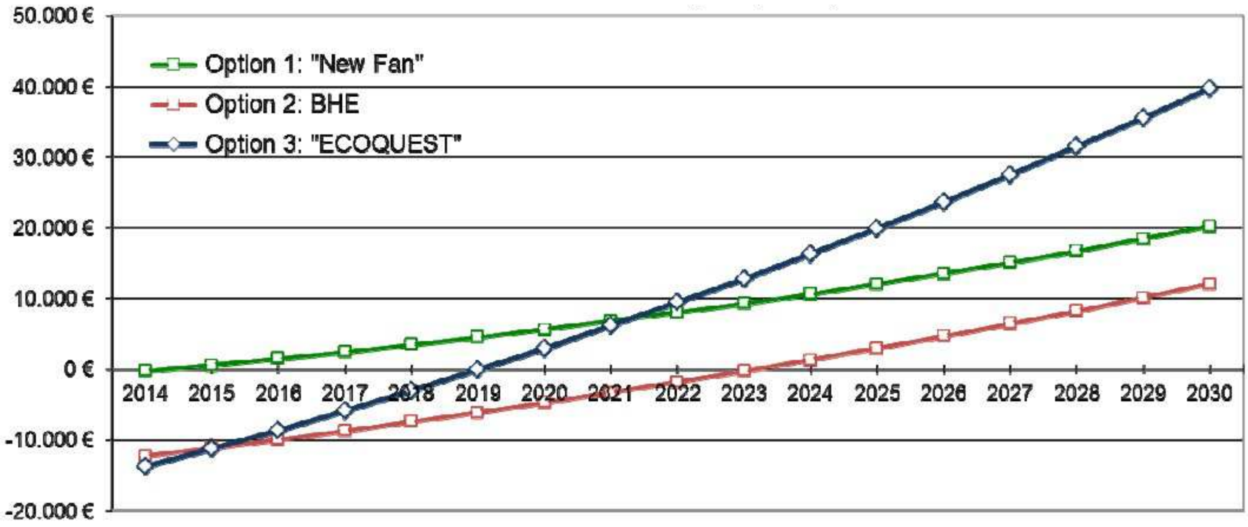

Figure 17: Amortization curves for ECOQUEST cooling module options compared with benchmark cooling unit (0 € curve).

Commercial exploitation in simulation industry

During ECOQUEST, LMS with other partners has investigated a new technique for broadband fan noise radiation and scattering. The approach proved to be quite accurate for a number of well-defined and control test cases.

The scattering part is based on the computation of transfer vectors (or transfer function) which can be computed using any PDE methods such as Boundary Elements and Finite Elements. Not only this allows to apply the methods to FEM (combined to Perfectly Matched Layer for open domains) but also makes it easier to apply to BEM techniques such as Fast Multipole BEM or H-Matrix.

It is therefore expected that the approach will be commercialized in the LMS Virtual.Lab aero-acoustic solution. Nevertheless, the approach did not prove to be convincing on the VALEO test case and some further investigation and tuning are unfortunately needed. It is expected that the new approach will open doors to new applications and will allow to better iterate on the design refinement.

4.1.5 Address of the public website

The address of the public website is: http://www.uni-siegen.de/ecoquest/

4.2 Use and dissemination of foreground

Section A (public)

TEMPLATE A1: LIST OF SCIENTIFIC (PEER REVIEWED) PUBLICATIONS, STARTING WITH THE MOST IMPORTANT ONES										
NO.	Title	Main author	Title of the periodical or the series	Number, date or frequency	Publisher	Place of publication	Year of publication	Relevant pages	Permanent identifiers[2] (if available)	Is/Will open access[3] provided to this publication?
1	*Optimization of axial fans with highly swept blades with respect to losses and noise reduction*	*Bamberger, K.*	*Noise Control Engineering Journal*	*Vol. 60 (6)*	*Institute of Noise Control Engineering*	*Washington, D.C., USA*	*2012*	*pp. 716-725*	*http://ince.publisher.ingentaconnect.com/content/ince/ncej/2012/00000060/00000006/art00007*	*no*
2	*Noise control for cooling fans on heavy vehicles*	*Allam, S.*	*Noise Control Engineering Journal*	*Vol. 60 (6)*	*Institute of Noise Control Engineering*	*Washington, D.C., USA*	*2012*	*pp. 707-715*	*http://ince.publisher.ingentaconnect.com/content/ince/ncej/2012/00000060/00000006/art00006*	*no*
3	*Influence of blade compactness and segmentation strategy on tonal noise prediction of an automotive engine cooling fan*	*Tannoury, E.*	*Applied Acoustics*	*75 (5)*	*Elsevier Limited*	*Munich, Germany*	*2013*	*pp. 782-787*	*http://www.sciencedirect.com/science/article/pii/S0003682X12003374*	*no*
4	*Tonal noise prediction of an automotive engine cooling fan: comparison between analytical models and acoustic analogy results*	*Tannoury, E.*	*Journal of Mechanical Engineering and Automation*	*Vol. 2 (7)*	*David Publishing Company*	*El Monte, CA, USA*	*2012*	*pp. 455-463*	*http://www.davidpublishing.com/davidpublishing/Upfile/9/7/2012/2012090702452474.pdf*	*yes*

[2] A permanent identifier should be a persistent link to the published version full text if open access or abstract if article is pay per view) or to the final manuscript accepted for publication (link to article in repository).

[3] Open Access is defined as free of charge access for anyone via Internet. Please answer "yes" if the open access to the publication is already established and also if the embargo period for open access is not yet over but you intend to establish open access afterwards.

5	Broadband scattering of the turbulence interaction noise of a stationary airfoil: experimental validation of a semi-analytical model	Kucukcoskun, J.	International Journal of Aeroacoustics	Vol. 12	Multi-Science Publishing Co. Ltd	Chicago, IL, USA	2013	pp. 83-102	http://multi-science.metapress.com/content/f300571127201867/?p=7656d7bb7da54a1780ec449352d70af0&pi=4	no

TEMPLATE A2: LIST OF DISSEMINATION ACTIVITIES

NO.	Type of activities[4]	Main leader	Title	Date/Period	Place	Type of audience[5]	Countries addressed
1	Conference: Fan 2012	USI	Optimization of axial fans with highly swept blades with respect to losses and noise emission	18/04/2012	Senlis, France	Scientific community, industry, policy makers	Worldwide, mainly Europe
2	Conference: European Turbomachinery Conference 2013	USI	Performance prediction and optimization of low pressure axial fans by artificial neural networks	15/04/2013	Lappenranta, Finland	Scientific community, industry, policy makers	Worldwide, mainly Europe
3	Conference: 19th AIAA/CEAS Aeroacoustics Conference	USI	Impact of different aerodynamic optimization strategies on the sound emitted by axial fans	27/05/2013	Berlin, Germany	Scientific community, industry, policy makers	Worldwide, mainly Europe and USA
4	Conference: ASME Turbo Expo 2013	USI	Aerodynamic and acoustic optimization of axial fans for locomotive cooling units	03/06/2013	San Antonio, TX, USA	Scientific community, industry, policy makers	Worldwide, mainly Europe and USA
5	Conference: Fan 2012	ECL	Free and scattered acoustic field predictions of the broadband noise generated by a low-speed axial fan	18/04/2012	Senlis, France	Scientific community, industry, policy makers	Worldwide, mainly Europe
6	Conference: AIAA Aeroacoustics 2012	ECL	On the scattering of aerodynamic noise by a rigid corner	04/06/2012	Colorado Springs, USA	Scientific community, industry, policy makers	Worldwide, mainly Europe

[4] A drop down list allows choosing the dissemination activity: publications, conferences, workshops, web, press releases, flyers, articles published in the popular press, videos, media briefings, presentations, exhibitions, thesis, interviews, films, TV clips, posters, Other.

[5] A drop down list allows choosing the type of public: Scientific Community (higher education, Research), Industry, Civil Society, Policy makers, Medias, Other ('multiple choices' is possible).

							and USA
7	*Conference:* *Fan 2012*	*KTH*	*Noise control for cooling fans on heavy vehicles*	*18/04/2012*	*Senlis, France*	*Scientific community, industry, policy makers*	*Worldwide, mainly Europe*
8	*Conference:* *European Automotive Noise Conference*	*KTH*	*Acoustic modelling and characterization of plate heat exchangers*	*13/06/2012*	*Graz, Austria*	*Scientific community, industry, policy makers*	*Europe*
9	*Conference:* *41st International Congress an Exposition on Noise Control Engineering*	*KTH*	*Cooling Fan Noise Control using Micro-Perforates*	*19/08/2012*	*New York, USA*	*Scientific community, industry, policy makers*	*Worldwide, mainly Europe*
10	*Conference:* *19th AIAA/CEAS Aeroacoustics Conference*	*KTH*	*Investigation of installation effects for an axial fan*	*27/05/2013*	*Berlin, Germany*	*Scientific community, industry, policy makers*	*Worldwide, mainly Europe and USA*
11	*Conference:* *European Automotive Noise Conference*	*KTH*	*Whistling Potential for Duct Components*	*13/06/2012*	*Graz, Austria*	*Scientific community, industry, policy makers*	*Worldwide, mainly Europe*
12	*Conference:* *IWAVE 2011*	*KTH*	*Acoustic Assessment of Plate Heat Exchangers*	*22/10/2011*	*Cairo, Egypt*	*Scientific community, industry, policy makers*	*Worldwide, mainly Sweden and Egypt*
13	*Conference:* *IWAVE 2011*	*KTH*	*Acoustics of parallel baffles muffler with Micro-perforated panels*	*22/10/2011*	*Cairo, Egypt*	*Scientific community, industry, policy makers*	*Worldwide, mainly Sweden and Egypt*
14	*Conference:* *IWAVE 2012*	*KTH*	*Cooling Fan Noise Control using Micro-Perforates*	*13/10/2012*	*Cairo, Egypt*	*Scientific community, industry, policy makers*	*Worldwide, mainly Sweden and Egypt*
15	*Conference:* *ASA Fall 2012*	*KTH*	*On the use of micro-perforates for machinery and vehicle noise control*	*22/10/2012*	*Kansas City, MO, USA*	*Scientific community, industry, policy makers*	*Worldwide, mainly Europe*
16	*Conference:* *European Turbomachinery Conference 2011*	*VAL*	*Tonal noise prediction of an automotive engine cooling fan: comparison between analytical models and acoustic analogy results*	*21/03/2011*	*Istanbul, Turkey*	*Scientific community, industry, policy makers*	*Worldwide, mainly Europe*
17	*Conference:* *ISROMAC-14*	*VAL*	*Blade segmentation strategy for tonal noise computation of low Mach number axial fans*	*27/02/2012*	*Honolulu, HI, USA*	*Scientific community, industry, policy makers*	*Worldwide, mainly Europe and USA*
18	*Conference:* *Fan 2012*	*VAL*	*A design of experiment for evaluating installation effects and the influence of blade loading on the aeroacoustics of automotive engine cooling fan*	*18/04/2012*	*Senlis, France*	*Scientific community, industry, policy makers*	*Worldwide, mainly Europe*

19	Conference: 7th International Styrian Noise, Vibration and Harshness Congress	KTH	Efficient cooling systems for quieter surface transport	13/06/2012	Graz, Austria	Scientific community, industry, policy makers	Worldwide, mainly Europe
20	Conference: ASIM Konferenz	VTA	Modellbasierte Simulation einer Kühlanlage für Schienenfahrzeuge	24/02/2011	Krefeld, Germany	Scientific community, industry, policy makers	Germany
21	Conference: LMS European Vehicle Conference	VTA	Enhancement of product development of rail vehicle components by holistic multi-physics systems simulation	11/05/2011	Munich, Germany	Scientific community, industry, policy makers	Worldwide, mainly Europe
22	Conference: Transport Research Arena 2012	VTA	Locomotive cooling system: A multi-domain system strategy for efficient and quieter cooling units	23/04/2012	Athens, Greece	Scientific community, industry, policy makers	Worldwide, mainly Europe
23	Conference: Bahnakustik 2012	VTA	Entwicklungsmethodik für leise und engergieeffiziente Kühlanlagen und Fahrzeuge	12/11/2012	Munich, Germany	Scientific community, industry, policy makers	Germany
24	Conference: 13th International Symposium, Automotive and Engine Technology	VTA	Holistic considerations of the drive trains of rail vehicles	26/02/2013	Stuttgart, Germany	Scientific community, industry, policy makers	Worldwide, mainly Europe
25	Conference: ASME Turbo Expo 2013	VTA	Forced-air Diesel locomotive cooling: Prediction of noise and energy consumption under realistic operational conditions	03/06/2013	San Antonio, TX, USA	Scientific community, industry, policy makers	Worldwide, mainly Europe and USA
26	Conference: 19th AIAA/CEAS Aeroacoustics Conference	VKI	Tonal and Broadband sound prediction of a locomotive cooling unit	27/05/2013	Berlin, Germany	Scientific community, industry, policy makers	Worldwide, mainly Europe and USA
27	Conference: VKI Lecture Series: Modeling, Measurement and Control of Ventilation and Cooling Fan Noise	VKI	Fundamentals of aeroacoustic analogies	22/04/2013	Brussels, Belgium	Scientific community, industry	Europe
28	Conference: VKI Lecture Series: Modeling, Measurement and Control of Ventilation and Cooling Fan Noise	ECL	Linearized methods for broadband fan noise	22/04/2013	Brussels, Belgium	Scientific community, industry	Europe
29	Conference: VKI Lecture Series: Modeling,	KTH	Multiport Education for Ducted Components	22/04/2013	Brussels, Belgium	Scientific community, industry	Europe

	Measurement and Control of Ventilation and Cooling Fan Noise						
30	*Conference: VKI Lecture Series: Modeling, Measurement and Control of Ventilation and Cooling Fan Noise*	*KTH*	*Noise Control in Ducts*	*22/04/2013*	*Brussels, Belgium*	*Scientific community, industry*	*Europe*
31	*Conference: VKI Lecture Series: Modeling, Measurement and Control of Ventilation and Cooling Fan Noise*	*LMS*	*Boundary Elements Methods for Fan Noise Scattering*	*22/04/2013*	*Brussels, Belgium*	*Scientific community, industry*	*Europe*
32	*Conference: VKI Lecture Series: Modeling, Measurement and Control of Ventilation and Cooling Fan Noise*	*KTH*	*Innovative Passive Control of Cooling Fan Noise*	*22/04/2013*	*Brussels, Belgium*	*Scientific community, industry*	*Europe*
33	*Conference: VKI Lecture Series: Modeling, Measurement and Control of Ventilation and Cooling Fan Noise*	*USI*	*Innovative Blade Design*	*22/04/2013*	*Brussels, Belgium*	*Scientific community, industry*	*Europe*
34	*Conference: VKI Lecture Series: Modeling, Measurement and Control of Ventilation and Cooling Fan Noise*	*KTH*	*Heat Exchanger Modelilng*	*22/04/2013*	*Brussels, Belgium*	*Scientific community, industry*	*Europe*
35	*Conference: ECOQUEST Workshop*	*ECL*	*Efficient Prediction of Acoustic Installation Effects*	*22/04/2013*	*Brussels, Belgium*	*Scientific community, industry*	*Europe*
36	*Conference: ECOQUEST Workshop*	*VKI.*	*Aeroacoustic Modeling and Validation of Gerneric Locomotive Cooling Units*	*22/04/2013*	*Brussels, Belgium*	*Scientific community, industry*	*Europe*
37	*Conference: ECOQUEST Workshop*	*KTH*	*Advanced Passive Noise Control Using Micro-Perforates*	*22/04/2013*	*Brussels, Belgium*	*Scientific community, industry*	*Europe*
38	*Conference: 17th AIAA/CEAS Aeroacoustics*	*ECL*	*A Semi-Analytical Approach on the Turbulence Interaction Noise of a Low Speed Axial Fan Including Broadband*	*06/06/2011*	*Portland, OR, USA*	*Scientific community, industry, policy makers*	*Worldwide, mainly Europe*

	Conference		*Scattering*				*and USA*
39	*Conference: Symposium of VKI PhD Research 2012*	*VKI*	*Prediction of Free and Scattered Acoustic Fields of Low-Speed Fans: Scattering of Tonal Fan Noise by a Rigid Corner*	*05/03/2012*	*Brussels, Belgium*	*Scientific community, industry, policy makers*	*Belgium*
40	*PhD Thesis*	*VAL*	*Contribution à la prévision du bruit tonal des machines tournantes subsoniques: couplage des simulations numériques et des modèles analytiques avec les analogies acoustiques*	*05/07/2013*	*Paris, France*	*Scientific community*	*France (or other French speaking countries)*
41	*PhD Thesis*	*ECL, LMS, VKI*	*Prediction of Free and Scattered Acoustic Fields of Low-Speed Fans*	*22/03/2012*	*Lyon, France*	*Scientific community*	*Worldwide*
42	*Organisation of Workshops*	*VKI*	*Lecture Series: Modeling, Measurement and Control of Ventilation and Cooling Fan Noise (Part 1)*	*22/04/2013*	*Brussels, Belgium*	*Scientific community (higher education, Research) - Industry*	*Europe*
43	*Organisation of Workshops*	*VKI*	*ECOQUEST Workshop*	*24/04/2013*	*Brussels, Belgium*	*Scientific community (higher education, Research) - Industry*	*Europe*
44	*Organisation of Workshops*	*VKI*	*Lecture Series: Modeling, Measurement and Control of Ventilation and Cooling Fan Noise (Part 2)*	*23/04/2012*	*Brussels, Belgium*	*Scientific community (higher education, Research) - Industry*	*Europe*
45	*Exhibitions*	*VTA*	*InnoTrans 2012 (Day 1)*	*18/09/2012*	*Berlin, Germany*	*Scientific community (higher education, Research) - Industry - Civil society - Policy makers - Medias*	*Worldwide*
46	*Exhibitions*	*VTA*	*InnoTrans 2012 (Day 2)*	*19/09/2013*	*Berlin, Germany*	*Scientific community (higher education, Research) - Industry - 47Civil society - Policy makers - Medias*	*Worldwide*
47	*Exhibitions*	*VTA*	*Innotrans 2012 (Day 3)*	*20/09/2012*	*Berlin, Germany*	*Scientific community (higher education, Research) - Industry - Civil society - Policy makers - Medias*	*Worldwide*
48	*Exhibitions*	*VTA*	*InnoTrans 2012 (Day 4)*	*21/09/2012*	*Berlin,*	*Scientific community*	*Worldwide*

					Germany	(higher education, Research) - Industry - Civil society - Policy makers - Medias	
49	Flyers	VTA, USI	Advantage Through Research - The ECOQUEST Project	18/09/2012	First published in Berlin, Germany. Now available in internet.	Scientific community (higher education, Research) - Industry - Civil society - Policy makers - Medias	Worldwide
50	Press releases	USI	Damit Autos und Loks leiser unterwegs sind - Erfolgreicher Abschluss des EU-Projekts ECOQUEST	01/07/2013	Siegen, Germany	Scientific community (higher education, Research) - Industry - Civil society - Policy makers - Medias	Germany
51	Oral presentation to a scientific event	USI	Locomotive Cooling Systems: A New Design Strategy for the Fan Unit	21/03/2012	Karlsruhe, Germany	Scientific community (higher education, Research)	Germany
52	Oral presentation to a scientific event	USI	Locomotive Cooling Systems: Researach for High Efficiency and Low Noise	04/10/2012	Tirana, Albania	Scientific community (higher education, Research)	Albania, Germany
53	Oral presentation to a wider public	USI	Steigerung der Energieeffizienz von Axialventilatoren durch optimierungsgestützte Auslegung	27/07/2013	Siegen, Germany	Scientific community (higher education, Research) - Industry - Civil society	Germany
54	Posters	USI	Aerodynamic, Thermodynamic and Acoustic Optimization of Cooling Units for Diesel Locomotives	03/09/2012	Siegen, Germany	Scientific community (higher education, Research)	Germany

Section B (Confidential[6] or public: confidential information to be marked clearly)
Part B1

The consortium did yet succeed to obtain a patent. An attempt of Voith to patent the connectable heat exchanger and thus the balancing between the high and low temperature cooling circuit was not successful. Three further patents are aspired by Valeo (see Table B2). Furthermore, LMS plans to integrate project results into a commercial software that is licensed for customers.

TEMPLATE B1: LIST OF APPLICATIONS FOR PATENTS, TRADEMARKS, REGISTERED DESIGNS, ETC.

Type of IP Rights[7]:	Confidential Click on YES/NO	Foreseen embargo date dd/mm/yyyy	Application reference(s) (e.g. EP123456)	Subject or title of application	Applicant (s) (as on the application)

[6] Note to be confused with the "EU CONFIDENTIAL" classification for some security research projects.

[7] A drop down list allows choosing the type of IP rights: Patents, Trademarks, Registered designs, Utility models, Others.

Part B2

Please complete the table hereafter:

Type of Exploitable Foreground[8]	Description of exploitable foreground	Confidential Click on YES/NO	Exploitable product(s) or measure(s)	Sector(s) of application[9]	Timetable, commercial or any other use	Patents or other IPR exploitation (licences)	Owner & Other Beneficiary(s) involved
Commercial exploitation of R&D results	*Fan system support with optimized struts for aerodynamics and aeroacoustics*	*Yes*	*Automotive fans*	*Automotive industry*	*During the next 10 years*	*Patenting process ongoing*	*Valeo (VAL)*
Commercial exploitation of R&D results	*Acoustic damping in automotive blowers by use of micro perforated plate on the housing*	*Yes*	*Automotive cooling systems*	*Automotive industry*	*During the next 10 years*	*Patenting process ongoing*	*Valeo (VAL)*
Commercial exploitation of R&D results	*Acoustic damping in an engine cooling module*	*Yes*	*Automotive cooling systems*	*Automotive industry*	*During the next 10 years*	*Patenting process ongoing*	*Valeo (VAL)*
Commercial exploitation of R&D results	*New techniques for modeling and prediction of broadband fan noise radiation and scattering*	*Yes*	*Noise simulation software*	*Any application in which fan noise is a concern*	*During the next 20 years*	*To be integrated into and licensed within the software "LMS Virtual.Lab aero-acoustic solution"*	*LMS (supplier), VAL&VTA (users)*

[19] A drop down list allows choosing the type of foreground: General advancement of knowledge, Commercial exploitation of R&D results, Exploitation of R&D results via standards, exploitation of results through EU policies, exploitation of results through (social) innovation.

[9] A drop down list allows choosing the type sector (NACE nomenclature) : http://ec.europa.eu/competition/mergers/cases/index/nace_all.html

Explanation of exploitable foreground of patents aspired by Valeo

Traditional systems for thermal management are constituted by two loops, dedicated respectively to engine cooling and climate control (heating, cooling, defrosting, demisting). Thermal exchanges with the exterior are made on the front end, which is equipped with a cooling module. Among the various heat exchangers, one can find the radiator (engine cooling), the Charge Air Cooler (engine air entrance), the condenser (refrigerant loop) and sometimes an oil cooler (transmission, driving assistance and/or gear box).

The concept that equips the ECOQUEST test vehicle has been designed to minimize the total thermal power, previously distributed on three separate loops, and now shared on two simplified loops. This concept named Ultimate Cooling^{TM} and developed by Valeo is presented in figure 16. It proposes different thermal exchangers for each function that are indirectly cooled by only two loops. High and low temperature loops are used for the Water Condenser (WCDS), the Water Charge Air Cooler (WCAC), eventually by the Water Oil Cooler (WOC), the Water cooling for Exaust Gaz Recirculation and of course for the engine cooling.

Cooling components are no longer designed for the maximum use of each function, and the architecture optimizes the overall performance to the just needed. The main benefit comes from the sizing of heat exchangers to the just needed thermal performance. All components are not used at their peak level at the same time.

The cooling module architecture that has been redesigned with the Ultimate Cooling^{TM} architecture yields to some aerodynamic effects that have been investigated during the ECOQUEST project. In particular it is found that the cooling module has a lower porosity, which leads to the benefit of a reduced vehicle drag. This is explained by the decrease in airflow under the hood, causing less friction and losses. This favorable effect is counter-balanced by the higher load which is imposed on the fan system: at low vehicle speed, the natural flow is insufficient and must be forced by ventilation. It appears that the design of the module and its coverage by one or two fans becomes an important criterion for the effectiveness of the concept. The combination of the two effects (less drag, more fan power) is however favorable to the concept UC showing gains on the fan system power of around half a gram of CO_2 per kilometer.

This concept brings also some modularity in its architecture since additional functions can be easily added (or removed) on the water circuit. Additional cooling is organized for battery, electronics and electrical motor. The heat exchangers are furthermore optimized to perform the cooling at the closest location of the component to be cooled. It allows standardization and a simplification in the management of the different versions across of powertrain across platform. For hybrid vehicles, the battery, electronics and electrical motor are cooled by the same coolant liquid, via the low temperature loop.

In terms of fan system sales, Valeo has the ambition to increase its market penetration from 8 to 11 %, and following the global market growth worldwide it is expected to increase sales by 50% between 2010 and 2023. This aim could be achieved if Valeo maintains its expertise on this product by applying methodologies for aerodynamic optimization and acoustic level minimization. The growth produced by this increase in market share represents a global amount of 500 millions of Euros.

The total Charge Air Cooler market for Valeo is expected to increase from 18 to 48 millions of units between 2010 and 2023. The sharing between direct technology (CAC) and indirect technology (WCAC) will evolve in the same time, the WCAC rising from 3% to 33% of penetration.

Explanation of exploitable foreground of software aspired by LMS

During ECOQUEST, LMS with other partners has investigated a new technique for broadband fan noise radiation and scattering. The approach proved to be quite accurate for a number of well-defined and control test cases.

The scattering part is based on the computation of transfer vectors (or transfer function) which can be computed using any PDE methods such as Boundary Elements and Finite Elements. Not only this allows to apply the methods to FEM (combined to Perfectly Matched Layer for open domains) but also makes it easier to apply to BEM techniques such as Fast Multipole BEM or H-Matrix.

It is therefore expected that the approach will be commercialized in the LMS Virtual.Lab aero-acoustic solution. Nevertheless, the approach did not prove to be convincing on the VALEO test case and some further investigation and tuning are unfortunately needed. It is expected that the new approach will open doors to new applications and will allow to better iterate on the design refinement.

4.3 Report on societal implications

Replies to the following questions will assist the Commission to obtain statistics and indicators on societal and socio-economic issues addressed by projects. The questions are arranged in a number of key themes. As well as producing certain statistics, the replies will also help identify those projects that have shown a real engagement with wider societal issues, and thereby identify interesting approaches to these issues and best practices. The replies for individual projects will not be made public.

A General Information *(completed automatically when* ***Grant Agreement number*** *is entered.*	
Grant Agreement Number:	SCP8-GA-2009-233541
Title of Project:	Efficient Cooling Systems for Quieter Surface Transport (ECOQUEST)
Name and Title of Coordinator:	Prof. Dr.-Ing. Thomas Carolus

B Ethics	
1. Did your project undergo an Ethics Review (and/or Screening)? • If Yes: have you described the progress of compliance with the relevant Ethics Review/Screening Requirements in the frame of the periodic/final project reports? Special Reminder: the progress of compliance with the Ethics Review/Screening Requirements should be described in the Period/Final Project Reports under the Section 3.2.2 *'Work Progress and Achievements'*	***NO***
2. Please indicate whether your project involved any of the following issues (tick box) :	
RESEARCH ON HUMANS	
• Did the project involve children?	NO
• Did the project involve patients?	NO
• Did the project involve persons not able to give consent?	NO
• Did the project involve adult healthy volunteers?	NO
• Did the project involve Human genetic material?	NO
• Did the project involve Human biological samples?	NO
• Did the project involve Human data collection?	NO
RESEARCH ON HUMAN EMBRYO/FOETUS	
• Did the project involve Human Embryos?	NO
• Did the project involve Human Foetal Tissue / Cells?	NO
• Did the project involve Human Embryonic Stem Cells (hESCs)?	NO
• Did the project on human Embryonic Stem Cells involve cells in culture?	NO
• Did the project on human Embryonic Stem Cells involve the derivation of cells from Embryos?	NO
PRIVACY	
• Did the project involve processing of genetic information or personal data (eg. health, sexual lifestyle, ethnicity, political opinion, religious or philosophical conviction)?	NO
• Did the project involve tracking the location or observation of people?	NO
RESEARCH ON ANIMALS	
• Did the project involve research on animals?	NO
• Were those animals transgenic small laboratory animals?	-
• Were those animals transgenic farm animals?	-

• Were those animals cloned farm animals?	-
• Were those animals non-human primates?	-
RESEARCH INVOLVING DEVELOPING COUNTRIES	
• Did the project involve the use of local resources (genetic, animal, plant etc)?	-
• Was the project of benefit to local community (capacity building, access to healthcare, education etc)?	-
DUAL USE	
• Research having direct military use	NO
• Research having the potential for terrorist abuse	NO

C Workforce Statistics

3. Workforce statistics for the project: Please indicate in the table below the number of people who worked on the project (on a headcount basis).

Type of Position	Number of Women	Number of Men
Scientific Coordinator	0	1
Work package leaders	0	4
Experienced researchers (i.e. PhD holders)	0	9
PhD Students	0	4
Other	0	6

4. How many additional researchers (in companies and universities) were recruited specifically for this project?	**4**
Of which, indicate the number of men:	4

D Gender Aspects

5. Did you carry out specific Gender Equality Actions under the project?

○ Yes
x No

6. Which of the following actions did you carry out and how effective were they?

		Not at all effective				Very effective
❑	Design and implement an equal opportunity policy	○	○	○	○	○
❑	Set targets to achieve a gender balance in the workforce	○	○	○	○	○
❑	Organise conferences and workshops on gender	○	○	○	○	○
❑	Actions to improve work-life balance	○	○	○	○	○
○	Other:					

7. Was there a gender dimension associated with the research content – i.e. wherever people were the focus of the research as, for example, consumers, users, patients or in trials, was the issue of gender considered and addressed?

○ Yes- please specify

x No

E Synergies with Science Education

8. Did your project involve working with students and/or school pupils (e.g. open days, participation in science festivals and events, prizes/competitions or joint projects)?

x Yes- please specify
Presentations and open days at the University of Siegen.
○ No

9. Did the project generate any science education material (e.g. kits, websites, explanatory booklets, DVDs)?

x Yes- please specify
Lecture notes of the VKI lecture series on ECOQUEST results are available online.
○ No

F Interdisciplinarity

10. Which disciplines (see list below) are involved in your project?

x Main discipline[10]: 2.3
x Associated discipline[10]: 2.2
○ Associated discipline[10]:

G Engaging with Civil society and policy makers

11a Did your project engage with societal actors beyond the research community? *(if 'No', go to Question 14)*

○ Yes
x No

11b If yes, did you engage with citizens (citizens' panels / juries) or organised civil society (NGOs, patients' groups etc.)?

○ No
○ Yes- in determining what research should be performed
○ Yes - in implementing the research
○ Yes, in communicating /disseminating / using the results of the project

11c In doing so, did your project involve actors whose role is mainly to organise the dialogue with citizens and organised civil society (e.g. professional mediator; communication company, science museums)?

○ Yes
○ No

12. Did you engage with government / public bodies or policy makers (including international organisations)

○ No

[10] Insert number from list below (Frascati Manual).

- ○ Yes- in framing the research agenda
- ○ Yes - in implementing the research agenda
- ○ Yes, in communicating /disseminating / using the results of the project

13a Will the project generate outputs (expertise or scientific advice) which could be used by policy makers?

- ○ Yes – as a **primary** objective (please indicate areas below- multiple answers possible)
- ○ Yes – as a **secondary** objective (please indicate areas below - multiple answer possible)
- ○ No

13b If Yes, in which fields?

Agriculture Audiovisual and Media Budget Competition Consumers Culture Customs Development Economic and Monetary Affairs Education, Training, Youth Employment and Social Affairs		Energy Enlargement Enterprise Environment External Relations External Trade Fisheries and Maritime Affairs Food Safety Foreign and Security Policy Fraud Humanitarian aid		Human rights Information Society Institutional affairs Internal Market Justice, freedom and security Public Health Regional Policy Research and Innovation Space Taxation Transport	

13c If Yes, at which level? ○ Local / regional levels ○ National level ○ European level ○ International level	

H Use and dissemination

14. How many Articles were published/accepted for publication in peer-reviewed journals?	**4**
To how many of these is open access[11] provided?	**1**
How many of these are published in open access journals?	**1**
How many of these are published in open repositories?	**1**
To how many of these is open access not provided?	**3**
Please check all applicable reasons for not providing open access:	
x publisher's licensing agreement would not permit publishing in a repository ❑ no suitable repository available ❑ no suitable open access journal available ❑ no funds available to publish in an open access journal ❑ lack of time and resources ❑ lack of information on open access ❑ other[12]: ……………	

15. How many new patent applications ('priority filings') have been made? *("Technologically unique": multiple applications for the same invention in different jurisdictions should be counted as just one application of grant).*	**3**

16. Indicate how many of the following Intellectual Property Rights were applied for (give number in each box).	Trademark	**0**
	Registered design	**0**
	Other	**0**

17. How many spin-off companies were created / are planned as a direct result of the project?	**0**
Indicate the approximate number of additional jobs in these companies:	**0**

18. Please indicate whether your project has a potential impact on employment, in comparison with the situation before your project:

❑	Increase in employment, or	x	In small & medium-sized enterprises
x	Safeguard employment, or	❑	In large companies
❑	Decrease in employment,	❑	None of the above / not relevant to the project
❑	Difficult to estimate / not possible to quantify		

19. For your project partnership please estimate the employment effect resulting directly from your participation in Full Time Equivalent (*FTE = one person working fulltime for a year*) jobs:	*Indicate figure:* *0*
Difficult to estimate / not possible to quantify	❑

[11] Open Access is defined as free of charge access for anyone via Internet.
[12] For instance: classification for security project.

I	Media and Communication to the general public		
20.	**As part of the project, were any of the beneficiaries professionals in communication or media relations?** ○ Yes x No		
21.	**As part of the project, have any beneficiaries received professional media / communication training / advice to improve communication with the general public?** ○ Yes x No		
22	**Which of the following have been used to communicate information about your project to the general public, or have resulted from your project?**		
x	Press Release	❑	Coverage in specialist press
❑	Media briefing	❑	Coverage in general (non-specialist) press
❑	TV coverage / report	❑	Coverage in national press
❑	Radio coverage / report	❑	Coverage in international press
x	Brochures /posters / flyers	x	Website for the general public / internet
❑	DVD /Film /Multimedia	x	Event targeting general public (festival, conference, exhibition, science café)
23	**In which languages are the information products for the general public produced?**		
❑	Language of the coordinator	x	English
❑	Other language(s)		

***Question F-10*:** Classification of Scientific Disciplines according to the Frascati Manual 2002 (Proposed Standard Practice for Surveys on Research and Experimental Development, OECD 2002):

FIELDS OF SCIENCE AND TECHNOLOGY

1. NATURAL SCIENCES

1.1 Mathematics and computer sciences [mathematics and other allied fields: computer sciences and other allied subjects (software development only; hardware development should be classified in the engineering fields)]

1.2 Physical sciences (astronomy and space sciences, physics and other allied subjects)

1.3 Chemical sciences (chemistry, other allied subjects)

1.4 Earth and related environmental sciences (geology, geophysics, mineralogy, physical geography and other geosciences, meteorology and other atmospheric sciences including climatic research, oceanography, vulcanology, palaeoecology, other allied sciences)

1.5 Biological sciences (biology, botany, bacteriology, microbiology, zoology, entomology, genetics, biochemistry, biophysics, other allied sciences, excluding clinical and veterinary sciences)

2 ENGINEERING AND TECHNOLOGY

2.1 Civil engineering (architecture engineering, building science and engineering, construction engineering, municipal and structural engineering and other allied subjects)

2.2 Electrical engineering, electronics [electrical engineering, electronics, communication engineering and systems, computer engineering (hardware only) and other allied subjects]

2.3. Other engineering sciences (such as chemical, aeronautical and space, mechanical, metallurgical and materials engineering, and their specialised subdivisions; forest products; applied sciences such as geodesy, industrial chemistry, etc.; the science and technology of food production; specialised technologies of interdisciplinary fields, e.g. systems analysis, metallurgy, mining, textile technology and other applied subjects)

3. MEDICAL SCIENCES

3.1 Basic medicine (anatomy, cytology, physiology, genetics, pharmacy, pharmacology, toxicology, immunology and immunohaematology, clinical chemistry, clinical microbiology, pathology)

3.2 Clinical medicine (anaesthesiology, paediatrics, obstetrics and gynaecology, internal medicine, surgery, dentistry, neurology, psychiatry, radiology, therapeutics, otorhinolaryngology, ophthalmology)
3.3 Health sciences (public health services, social medicine, hygiene, nursing, epidemiology)

4. AGRICULTURAL SCIENCES
4.1 Agriculture, forestry, fisheries and allied sciences (agronomy, animal husbandry, fisheries, forestry, horticulture, other allied subjects)
4.2 Veterinary medicine

5. SOCIAL SCIENCES
5.1 Psychology
5.2 Economics
5.3 Educational sciences (education and training and other allied subjects)
5.4 Other social sciences [anthropology (social and cultural) and ethnology, demography, geography (human, economic and social), town and country planning, management, law, linguistics, political sciences, sociology, organisation and methods, miscellaneous social sciences and interdisciplinary , methodological and historical S1T activities relating to subjects in this group. Physical anthropology, physical geography and psychophysiology should normally be classified with the natural sciences].

6. HUMANITIES
6.1 History (history, prehistory and history, together with auxiliary historical disciplines such as archaeology, numismatics, palaeography, genealogy, etc.)
6.2 Languages and literature (ancient and modern)
6.3 Other humanities [philosophy (including the history of science and technology) arts, history of art, art criticism, painting, sculpture, musicology, dramatic art excluding artistic "research" of any kind, religion, theology, other fields and subjects pertaining to the humanities, methodological, historical and other S1T activities relating to the subjects in this group]

2. FINAL REPORT ON THE DISTRIBUTION OF THE EUROPEAN UNION FINANCIAL CONTRIBUTION

Report on the distribution of the European Union financial contribution between beneficiaries

The figures in the subsequent table are based on the Form Cs submitted to the EC in August, 2013. At this time, there has not been any check by the EC. Hence, figures can change according to the results of the official check. An amendment of this report might be necessary!

Name of beneficiary	**Final amount of EU contribution per beneficiary in Euros**
University of Siegen (USI)	546,306.78
Ecole Centrale de Lyon (ECL)	277,200.88
Kungliga Tekniska Högskolan (KTH)	354,424.93
LMS International (LMS)	279,019.27
Sontech Noise Control (SNT)	61,465.20
Valeo Sytèmes Thermiques (VAL)	334,786.74
Von Karman Institute for Fluid Dynamics (VKI)	404,258.05
Voith Turbo Antriebstechnik (VTA)	131,854.37
Voith Turbo Lokomtivtechnik (VTLT)	36,367.66
Total	**2,425,683.88**