

The Necessity of Optimizing the Interactions of Advanced Post-Treatment Components in Order to Obtain Compliance with SULEV-Legislation

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ABSTRACT

Fleet tests conducted on electrical vehicles around the world have very clearly shown that battery-powered cars may be regarded as zero-emission vehicles with respect to their local environments only. Emission measurements on vehicles powered by internal-combustion engines equipped with optimized exhaust-post-treatment systems have indicated the prospects the latter offer for cleaning up the environment, i.e., for yielding negative emissions, when run at their normal operating temperatures. Replacing electric cars with SULEV's is thus a matter currently under discussion. This paper will cover the functions of the various individual components of such post-treatment systems, and will show that optimizing the interactions among those components will improve their catalytic efficiencies.

1. INTRODUCTION

The tendency for further lowering of exhaust emission levels continues worldwide. Legislators in industrial countries call for the use of *Best available technology*® (BAT). This requires major development work by automobile manufacturers and suppliers and thus encourages innovation. Environmental problems caused by traffic are more pressing in rapidly developing countries, as the two stroke engine is still the commonest source of power there. Countries such as Taiwan or India have thus become models of environmental protection in the limits which they have set for two- and three-wheelers.

As mobility and division of labour are the prerequisites for obtaining or maintaining prosperity, a further increase in vehicle production can be expected worldwide, and there will necessarily be a worldwide demand for cars to be environmentally friendly. Some environmental politicians assumed for a long time that the electric vehicles would have no emissions, and called for the *Zero emission vehicle* (ZEV). But a battery-driven ZEV included in a fleet test has shown clearly that it could only satisfy this

requirement on a local basis [1].

The first scientific papers [2] contain impressive proof that the electric vehicle cannot possibly be an alternative to a vehicle with an improved conventional Otto (spark ignition) drive, owing the losses of efficiency in the energy chain. It is only locally, e. g. in towns, that electric vehicles play no part in increasing the concentration of pollutants, and this is at the expense of the regions where the power is generated and where the vehicles are produced and recycled. It has been shown in the above literature that a low-emission vehicle of this type, even with an emission level typical of the „Münchener Stachus“, will be able to clean the hydrocarbon pollution in the ambient air (negative emissions).

Consideration of the total emission balances in California has similarly led to reassessment and introduction of the super ultra-low emission vehicle (SULEV) legislation (still under discussion). This will allow automobile manufacturers replace so-called “zero-emission vehicles” with SULEV's under a point system [3]. If the proposed legislation came into force, up to 30% of the new registrations in model year 2003 would have to be produced and sold as SULEV vehicles, with the limits given in Table 1 (approx. 300.000 vehicles p.a.).

	HC	NOx	CO
120,000-mile tolerated emissions	0.01 g/mile	0.02 g/mile	1.0 g/mile

Table 1: Exhaust Gas Limits for SULEV - Legislation (Proposal for MY 2004, revised on Sept. 1998).

A wide variety of different drives are being developed at the present time, e. g. hybrid technology [4], the direct injection Otto [5] and fuel cells. But we can already predict that only a technology which is almost at the

production stage already will have to be available by then. If the existing development potential is critically assessed, the most promising solution found will be further development of the existing Otto engine drive with very low engine out emissions. Even in the past, test engineers have measured negative emissions under Bag 2 of the FTP-test for optimally configured and tuned vehicles operated at their normal operating temperatures, i.e., that vehicles operated under such conditions emit less pollution than they induct, and thus actively help clean up the environment. But until a few years ago there were neither suitable components nor the application know-how for effective reduction of cold-start emission. Cold-start emission were so high that the total balance in the test was negative. So if SULEV limits are to be reached with a present-day drive such as the Otto engine, the main necessity is to develop components and processes for improving the cold start.

However, before current types of drive trains, such as internal-combustion engines, will be able to meet the SULEV-legislation limits all of their components will have to be improved in order to reduce their cold-start emissions.

2. COMPONENTS FOR REDUCTION OF COLD START EMISSIONS

Numerous publications that have appeared over recent years [6] – [17] have reported major advances toward reducing cold-start emissions.

Included among those advances are:

- Catalysts installed close to engine
- HC-traps
- Electrically heated catalysts
- Latent-heat storage systems
- Burner systems
- "Low-light-off" catalysts
- Exhaust-gas ignition (EGI)
- Bypass Catalysts

- **Catalysts installed close to the engine:**

Passive catalysts installed close to engines, particularly such with substrates with reduced heat capacities and improved coatings, substantially reduce cold-start emissions and are currently generally regarded as a means for meeting European Stage III and Stage IV and California's LEV and ULEV-regulations, at least for

vehicles equipped with small and moderate displacement engines [6], [7].

- **HC-traps:**

HC-traps [8], [9], [10] represent ideal, highly efficient, means for temporarily storing HC-emissions. However they have the disadvantage - still unresolved - that hydrocarbon desorption already begins at temperatures before the catalytic light-off temperature of oxidation-type or three-way catalytic converters is reached. This negative effect increases with ageing. If only a fraction of the hydrocarbons is stored - by dividing the stream of exhaust fumes - and the rest is used for heating the downstream oxidation or three-way catalytic converter, the emissions accompanying a cold start are indeed reduced. But such an arrangement cannot apparently reach the SULEV values owing to *Aleakages*, as evidenced by published the test results. So-called combined coatings, with both the adsorption and the catalytic function carried out simultaneously on one carrier, bring an improvement. But the adsorption no longer provides the heat sink (a cooling thermal mass) to the same extent, and hence there is still a need to develop resistance to high-temperature ageing for use close to the engine.

- **Electrically heated catalysts:**

The electrically heated catalytic converter has already proved itself ready to go into production as a component or sub-system with the converter close to the engine.

Extensive tests have shown it to have both the thermodynamic/catalytic effectiveness and the necessary mechanical durability [11], [12], [13]. However it has the disadvantages of requiring additional power for active heating and a more expensive electrical system with an electronic power switch and electronic control with OBD monitoring.

- **Latent-heat storage systems:**

Latent heat store systems which keep either the engine or the catalytic systems [14] at operation temperature show clear improvement potential, although the time is at present limited to 12 to 24 hours. Large-scale use, particularly of the insulated catalytic converter, depends partly on the judgment of local authorities (are increased emissions to be allowed after longer standing times?) and partly on the durability of the vacuum insulation over 10 years or 100 000 miles in the exhaust system.

- **Burner systems:**

Burner systems have already been tested successfully in the past [15]. The large amount of thermal energy obtained was helpful particularly with large-volume *Acold* engines. But apart from the question of reliability over the life of the vehicle the main aspect discussed is that of

safety in the event of a crash.

- **“Low-light-off” catalysts:**

New types of coatings that exhibit catalytic effects even at room temperature [16] are currently under development. However, initial experiences with them indicate that they tend to age rather rapidly, particularly in conjunction with current fuels.

- **Exhaust-gas ignition (EGI):**

Exhaust-gas ignition [17] represents an extreme approach to active thermocatalytic conversion of engine exhaust emissions. Under this approach, engines are run on fuel-air mixtures that are so rich that exhaust gases entering their catalysts constitute combustible mixtures that are then ignited either by using a retarded engine ignition timing or by an auxiliary ignition system incorporated into their exhaust systems. Large quantities of energy that may be used for heating their catalysts may be released over short periods. However, the risks involved here are that catalysts may be thermally damaged by the resultant extremely high temperatures and that levels of raw emissions will increase due to unintended late ignition of exhaust gases or misfiring.

- **Bypass catalysts:**

Bypass catalysts may be shut off once they reach their normal operating temperatures in order to prevent them from reaching too high temperatures. However, due to their finite thermal masses, the bypass valves employed represent heat sinks that lengthen the times they need to reach “light-off”. Yet another question that remains to be answered is their mechanical durabilities when installed close to engines.

Although all of the components of exhaust systems mentioned are capable of reducing cold-start emissions, at present, none of them would seem to be effective enough to allow reaching the SULEV legislation limits when used alone. Employment of a combination of several different technologies would seem to offer the best prospects for improvement. One example of what can be accomplished is Honda’s ZLEV, which is equipped with a catalyst with an optimized coating installed close to its engine and an HC-trap followed by an EHC [18].

3. DESIGNING SULEV SYSTEMS

Modern motor vehicles equipped with optimized lambda-controllers already attain HC and NO_x conversion rates of nearly 100 % running at their normal operating temperatures. Negative emissions, i.e., conversion rates exceeding 100 %, may even be attained for certain environmental-pollution levels, which is why, at least for the time being, engineering efforts are largely aimed at

reducing cold-start emissions.

However, even optimized catalyst systems are merely post-treatment systems. Reduction of engine out emissions and lambda-controllers that take control as early as possible represent the prerequisites for arriving at systems that will qualify as SULEV-systems. Fig. 1, below, depicts the raw emissions from 2 different types of engines and the associated latest “light-off” times needed for attaining the maximum-tolerated SULEV-emissions, assuming a conversion rate of 100 % subsequent to a cold-start.

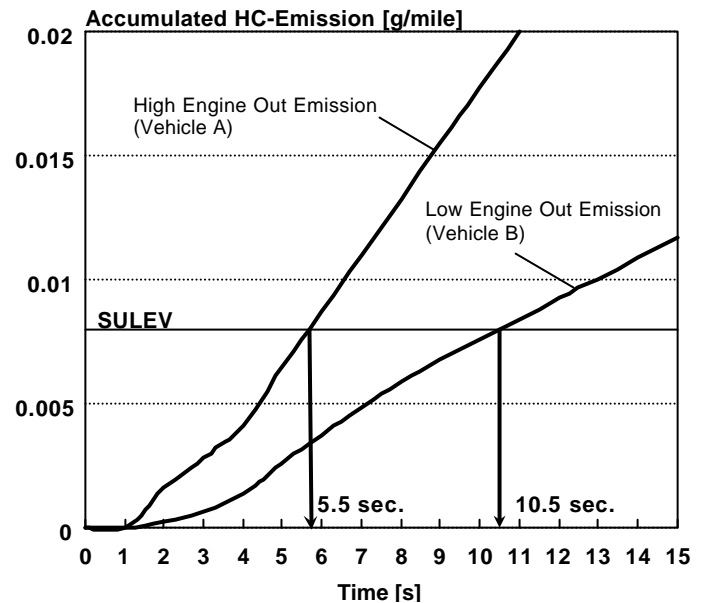


Fig. 1: Raw emissions of 2 different types of engines and the latest “light-off” times that will allow maintaining compliance with SULEV-limits

It may be seen that “light-off” times ranging from about 6 seconds to 11 seconds are required, depending upon the levels of raw emissions involved. If we consider the engine with a “light-off” time of 6 seconds, it would seem to be highly unlikely that any catalyst will be able to warm up to temperatures in excess of 300°C - 400°C over such a brief period. Need for temporarily storing hydrocarbons is readily apparent. Better engines that need “light-off” times of 10 - 15 seconds should allow using optimized catalyst systems that, under some circumstances, might require active engine-heating or employment of auxiliary heaters.

In view of the extremely short time remaining in which to complete development efforts (the systems required would have to be ready for mass-production applications in the fall of 2002), the question confronting development engineers is which systems should they try out and subject to road testing.

4. EMITEC'S "CATPROG" CATALYST DESIGN SOFTWARE

The "CatProg" catalyst-design software developed by Emitec allows simulating the performances of various components in conjunction with given applications, and will now be briefly explained based on the example of the operation of an HC-adsorber. The model is based on a 2-dimensional finite-volume network of gas and solid meshes, which uses engine out data (mass flow, gas temperature, HC- and CO-concentrations) as input. By them, the temperatures and concentrations within the converter are estimated. For ad- and desorption, a langmuir model was chosen.

Extensive correlation testing is required before the operation of a catalyst may be simulated to a sufficiently high degree of accuracy. The boundary conditions of temperature and HC-concentration, as well as cell density and the type, total volume, and design of the adsorber employed were checked for each HC-adsorber module involved. Testing was conducted on a flow test bench (cf. Fig. 2, below).

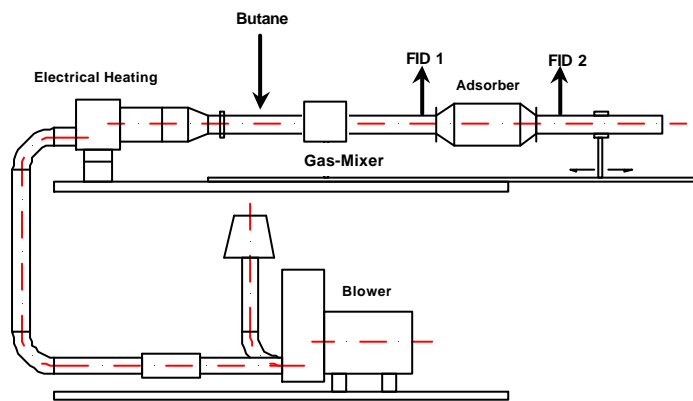


Fig. 2: A flow test bench for determining HC-adsorber operating parameters.

The gas mass flow rate, gas temperature, and HC-concentration were preset and reproducibly regulated by an electronic controller. Butane was employed as the test hydrocarbon. The allowances needed to account for realistic raw HC-emissions were determined from a second series of FTP-tests.

Figs. 3 and 4, below, show sample results obtained for the effects of cell density on adsorption and desorption at a temperature of 50°C for an HC-concentration of 1000 vpm. HC-adsorbers having cell densities of 50 to 600 cps were tested. The total mass of adsorber coating (Zeolite coating) employed was independent of trap volume, and thus remained constant to 150 g/l for all traps tested.

Both plots show HC-concentrations exiting the HC-traps. The areas enclosed between each curve, their y-axes and

the line for the inlet concentration thus are equivalent to the quantity of hydrocarbons stored.

The efficiency of the HC-adsorbers increases with increasing cell density, particularly over the first second of exposure, i.e., immediately after the engine is started up. The maximum storage capacity was identical for all test traps, since the total quantity of adsorber coating employed was the same for all. Since high adsorber efficiency is essential if the SULEV-legislation limits are to be met, particularly during cold starts, higher cell densities are of great benefit.

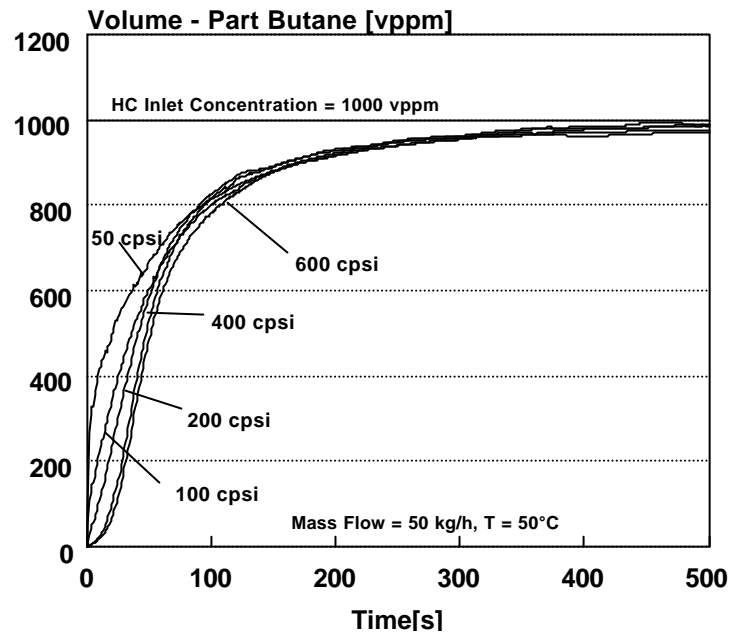


Fig. 3: HC-adsorption as a function of cell density

During desorption of HC-traps installed in vehicles, their engines must either be run on a lean mixture or an auxiliary flow of air must be fed in upstream of their HC-traps. Since compliance with forthcoming SULEV-legislation requires that conversion of oxides of nitrogen must commence as soon as possible after their engines are started up, their exhaust-gas mixtures must be regulated at a lambda of 1. The time intervals that elapse before their entire catalyst systems are able to operate while regulated at a lambda of 1 are thus directly related to desorption rates in their HC-traps. Short, complete, desorption is desired. An alternative solution would be using an HC-trap on a bypass line regenerated by recirculating exhaust gas.

Fig. 4 shows the desorption curves for the various cell densities involved. It may be seen that higher cell densities allow using shorter desorption cycles due to the faster mass transport through the smaller flow channels they provide.

A relatively short disk with a high cell density seems the best way to meet the mentioned set of requirements on HC-adsorbers, where the length of the disk will vary with the raw-emissions involved.

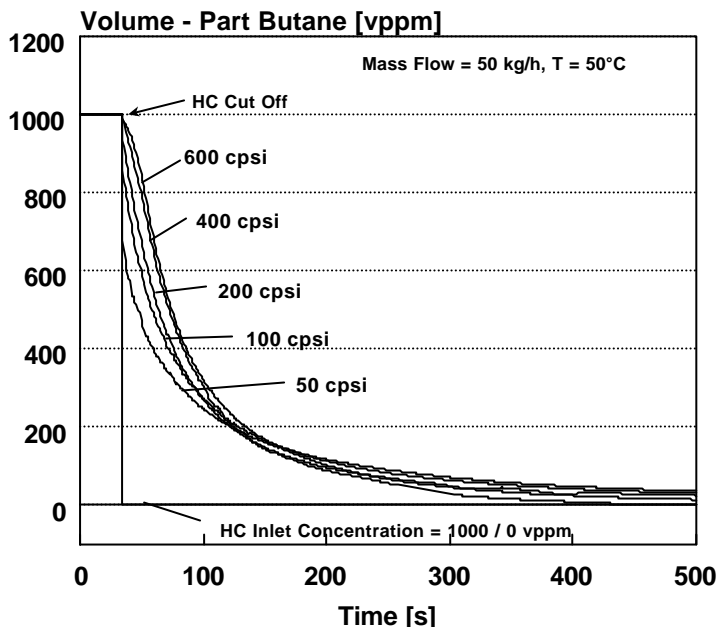


Fig. 4: HC-desorption as a function of cell density.

The effects of temperature on adsorption and desorption efficiencies were investigated for a constant mass flow rate of 50 kg/h and an HC-concentration of 500 vpm (cf. Fig. 5, above) in another run in which measurements were conducted at temperatures of 30°C, 50°C, 100°C, and 150°C.

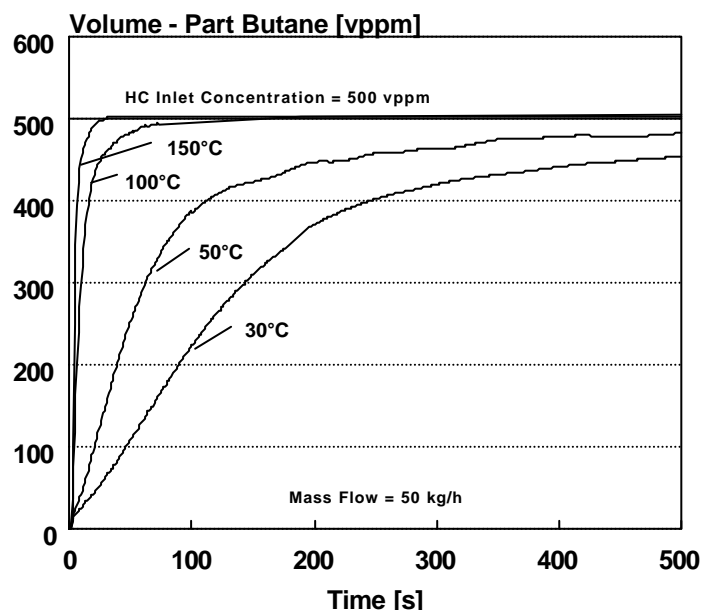


Fig. 5: HC-adsorption as a function of temperature.

Adsorption efficiencies fall off sharply with even slightly elevated temperatures (100°C and 150°C).

The effects of HC-concentrations on adsorption and desorption efficiencies were investigated in yet another run (cf. Fig. 6, below) in which the adsorber was initially saturated by exposing it to a constant HC-concentration of 500 or 1000 vpm at 30°C. The HC-concentration was then cut off to 0 ppm at constant temperature in order to

simulate a catalyst system in which a catalyst situated upstream of the HC-adsorber begins to operate.

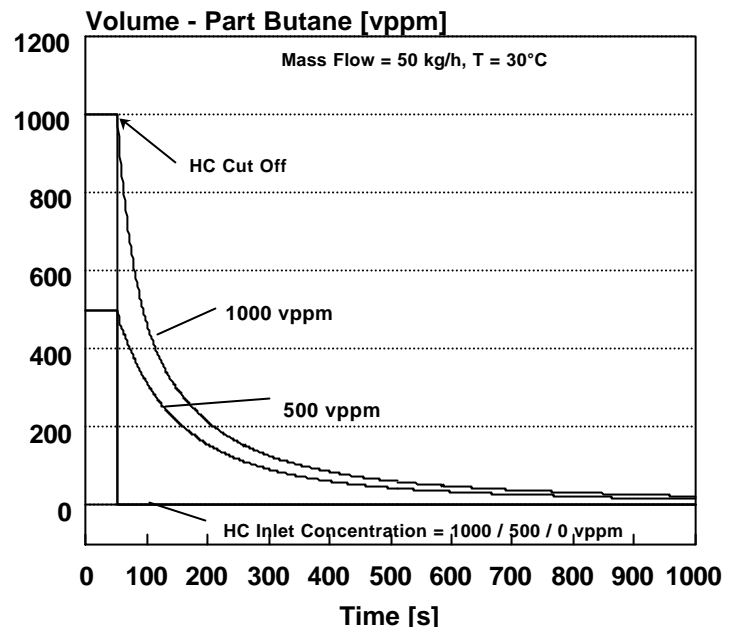


Fig. 6: HC-desorption as a function of HC-concentration.

It may be seen that desorption commences as soon as the inlet HC-concentration is cut off to zero, regardless of the temperatures involved. This implies that catalyst systems incorporating close coupled catalysts followed by HC-traps must be equipped with a second catalyst downstream from their HC-traps that must be ready for operation as soon as the former catalysts reach their "light-off" temperatures. Since this cannot occur for passive catalyst systems due to the heat sinks represented by the substrates of the former catalysts, an active catalyst, such as a preheated catalyst, will be required.

Further investigations were conducted in order to determine the effects of adsorber design (adsorber diameter/length ratios), exhaust-gas mass flow rates, and varying HC-concentration on HC-emissions.

Parameters determined from tests conducted on the test stand were subsequently verified by conducting FTP-tests. Fig. 7, below, depicts the results of a direct comparison of the results obtained from FTP-tests conducted on an HC-adsorber to data computed using the "CatProg" software, where a medium-sized passenger car was employed as test vehicle. The adsorber, which had a volume of 0.32 liters, was installed as close as practicable to the vehicle's engine.

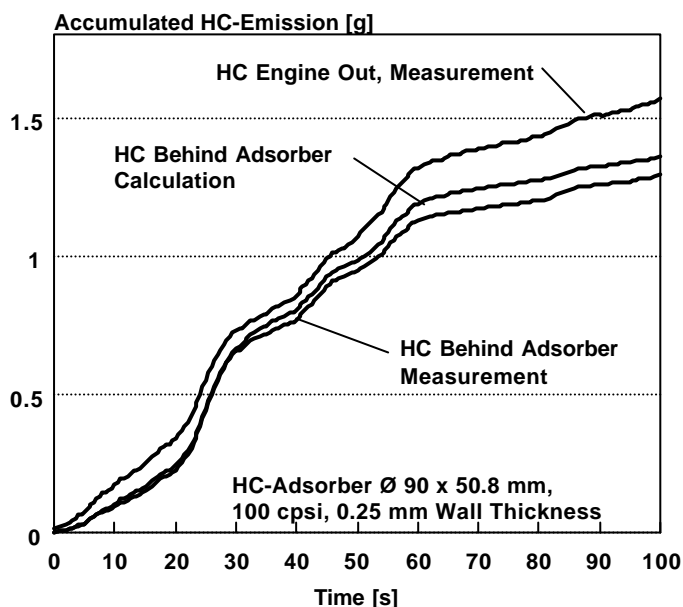


Fig. 7: A comparison of empirical and computed HC-emissions during the cold-start cycle of an FTP-test.

This direct comparison shows that there was a close correlation between measured and computed HC exhaust emissions, and it was found that even pure adsorber coatings (zeolites) also have slight catalytic potential.

In the following, we shall show that catalyst systems complying with forthcoming SULEV-legislation may be designed to suit both vehicles that have favorable raw emissions and vehicles that have unfavorable raw emissions. The cumulative raw emissions from Vehicle A and Vehicle B were depicted in Fig. 2, above.

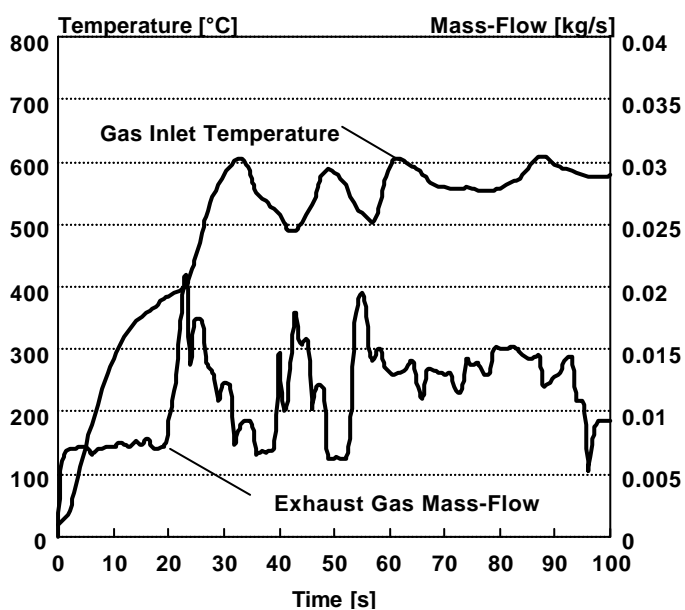


Fig. 8: Gas-inlet temperatures and exhaust-gas mass flow rates for the various computational models employed.

For better comparability, the same gas inlet temperatures

and the same mass flow rates were employed for all vehicles, regardless of their raw emissions. The data are shown in Figure 8.

a) Close Coupled Main Converter: A close coupled catalyst system served as a basis. The catalyst for computational purposes was a standard 110-mm diameter x 110-mm substrate with 400 cpsi and a foil thickness of 0.05 mm and a 800-cpsi catalyst with the same dimensions and a foil thickness of 0.03 mm. The resultant cumulative HC-emissions are shown in Fig. 9, below.

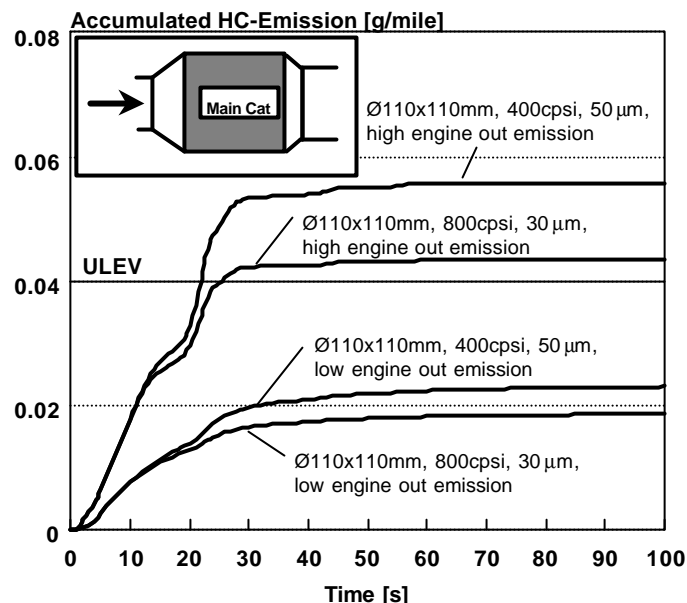


Fig. 9: Cumulative HC-emissions of two vehicles having differing raw exhaust emissions and equipped with two different types of catalyst.

Those catalysts with 800 cpsi yielded clearly better results. Those vehicles with less raw emissions remained well below the ULEV-legislation limits. Based on these results, the model was used to design a system complying with SULEV-emission limits. The first step was designing a catalyst system similar to that employed by Honda's ZLEV system [18].

b) Passive 3-Monolith Adsorber Inline System: HC-adsorbers are available in types that have adsorption actions only and types equipped with hybrid coatings that also act as oxidation catalysts. In view of the fact that the abilities of such hybrid coatings to withstand high temperatures remains to be established, the computations to be described below were confined to HC-adsorbers having adsorption actions only.

A converter system consisting of the following components was considered in the cold-start computations:

1st monolith: A three-way catalyst of 110-mm dia. x 110 mm with 800 cpsi and a foil thickness of 0.03 mm.

2nd monolith: A HC-adsorber of 110-mm dia. x 50.8 mm with 600 cpsi and a foil thickness of 0.04 mm.

3rd monolith: A three-way catalyst of 110-mm dia. x 50.8 mm with 600 cpsi and a foil thickness of 0.04 mm.

Fig. 10, below, shows the HC-conversion rates for the various individual substrates for the first 125 seconds of FTP-tests.

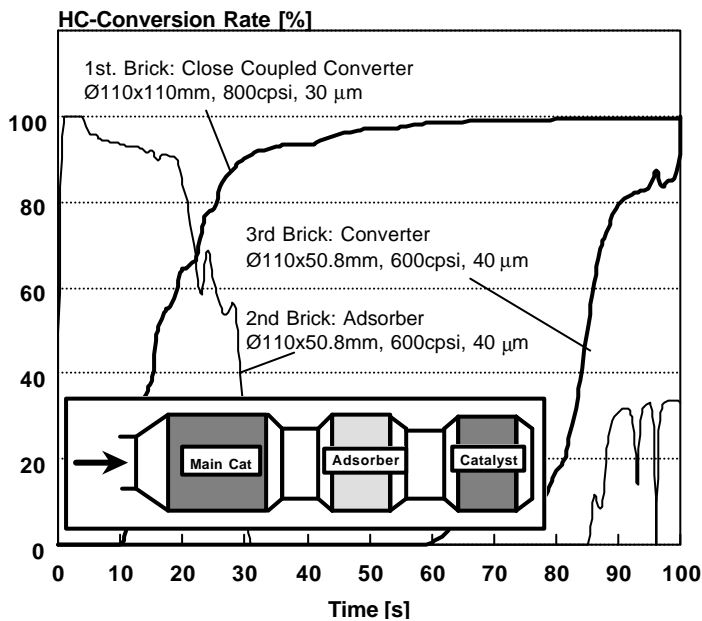


Fig. 10: HC-conversion rates for various types of catalysts and HC-traps during the first 100 seconds of cold-start cycles for Vehicle B.

It may be readily seen that the vehicle's HC-trap commenced desorbing as soon as the catalyst on its engine began to work. Since the three-way catalyst downstream of the HC-trap will not yet be ready to respond due to the heat sink represented by the upstream substrates, desorbed hydrocarbons will not be converted, and will reappear in the form of delayed tailpipe emissions. The cumulative HC-emissions after 100 seconds were 0.018 g/mile, and thus correspond to those for the case of the vehicle equipped with a close coupled catalyst (cf. Fig. 9, above).

c) Passive 2-Monolith Adsorber Inline System: Another computation considered the case of a catalyst system consisting of an close coupled HC-trap, followed by a three-way catalyst, where the HC-trap was regarded both as a pure adsorber and as an adsorber that also had a catalytic function (hybrid adsorber). Since test results showed that even zeolite coatings also have slight catalytic actions, this sort of behavior was taken into account in the computations. Fig. 11, below, shows the

HC-conversion rates for the various substrates and catalyst configurations.

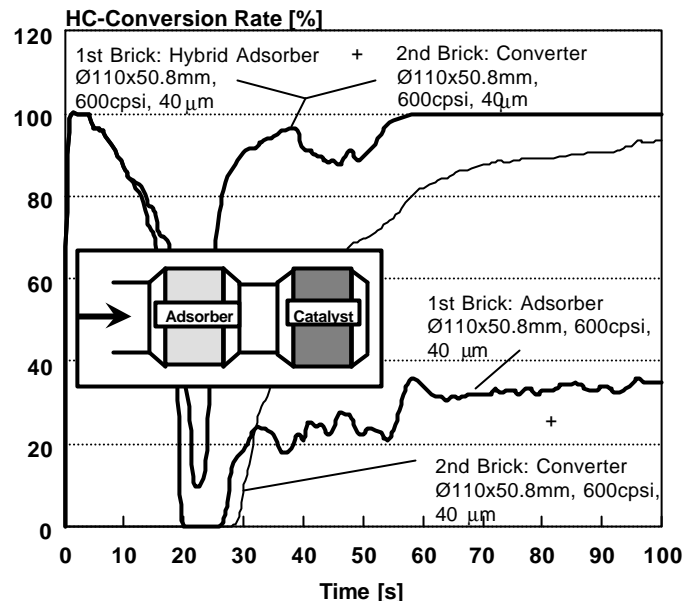


Fig. 11: HC-conversion rates for 2 different types of HC-traps and the subsequent catalysts during the first 100 seconds of a cold-start cycle for Vehicle B.

The HC-trap that had exclusively adsorption actions increased HC-emissions by 125 % compared to the close coupled main catalyst (Fig. 12), which may be explained by the fact that the downstream catalyst had not reached its normal operating temperature by the time thermally induced desorption occurs. The hybrid adsorber exhibited a correspondingly improvement in HC-conversion rates of 28 %, i.e. 0.013 g/mile within the first 100 seconds of FTP-tests compared to the close coupled option.

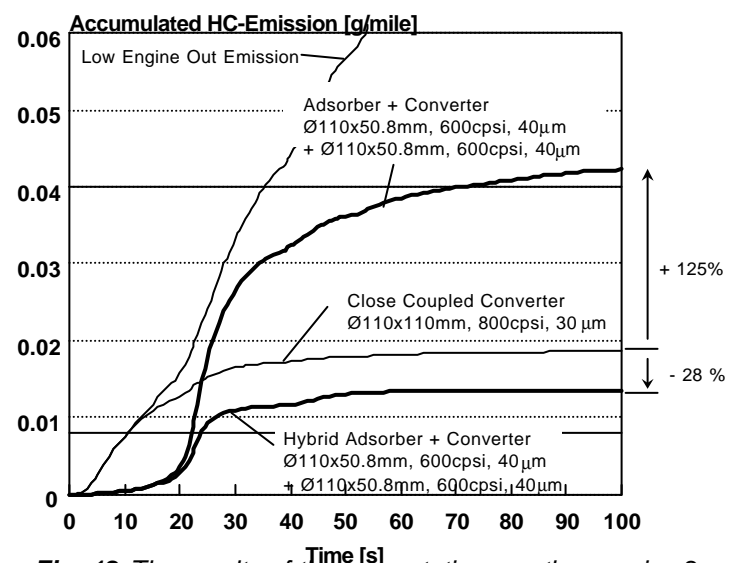


Fig. 12: The results of the computations on the passive 2-monolith adsorber inline system, expressed in terms of cumulative HC-emissions.

Fig. 12, above, summarizes the results of these computations, expressed in terms of cumulative HC-emissions. The computations indicated that overly low gas inlet temperature of the catalyst downstream from the HC-trap is the major reason why reductions in HC-emissions could not be achieved. Hybrid adsorbers installed close to vehicles' engines exhibited potential reductions in HC-emissions of 28 %.

d) Active 2-Monolith Adsorber Inline System: A heated catalyst with a heating capacity of 2 kW or 4 kW was added in order to increase temperature profiles downstream of the HC-trap. The heated catalyst had a diameter of 80 mm and a heated length of 10 mm joined to a 74.5 -mm long supporting catalyst [19]. The EHC was activated for 60 seconds after the vehicle's engine had been started up. Fig. 13, below shows the gas temperatures upstream and downstream of the individual bricks and the substrate temperature predicted by model on the axial centerline of the HC-adsorber.

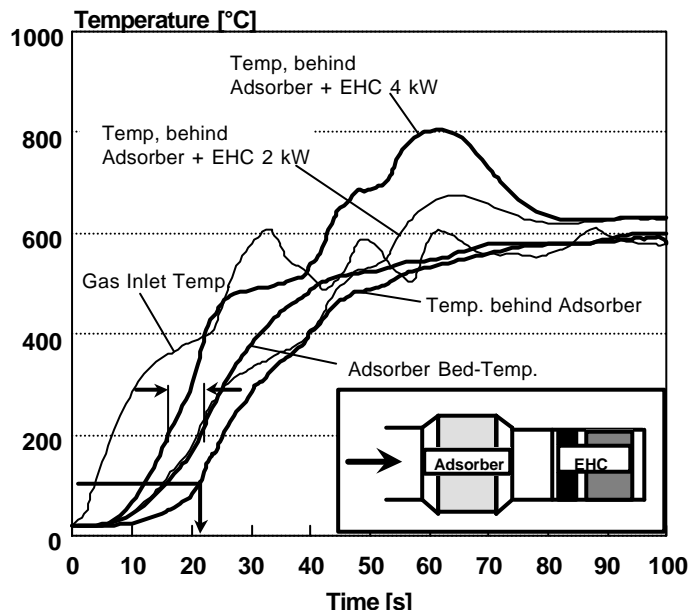


Fig. 13: Gas temperatures upstream and downstream of the individual bricks and HC-adsorber substrate temperature.

It may be seen that, due to the thermal mass of the HC-trap, gas temperature behind adsorber failed to rise above the 100°C line for as long as 22 seconds. Only the heated catalyst with a heating capacity of 4 kW was able to warm up the three-way catalyst up to its normal operating temperature before the desorption temperature (a substrate temperature of 200°C on the HC-adsorber's centerline) was reached.

Fig. 14, below, shows the associated HC-conversion rates for the various components of this catalyst system. The more rapid response of the heated catalyst system with a heating capacity of 4 kW is immediately apparent. This more rapid response yielded HC-emissions of 0.003 g/mile, i.e., a reduction in HC-emissions of 83 %, compared to the case of the close coupled main converter, while the heated catalyst with a rated heating capacity of 2 kW reduced them by only 65 %.

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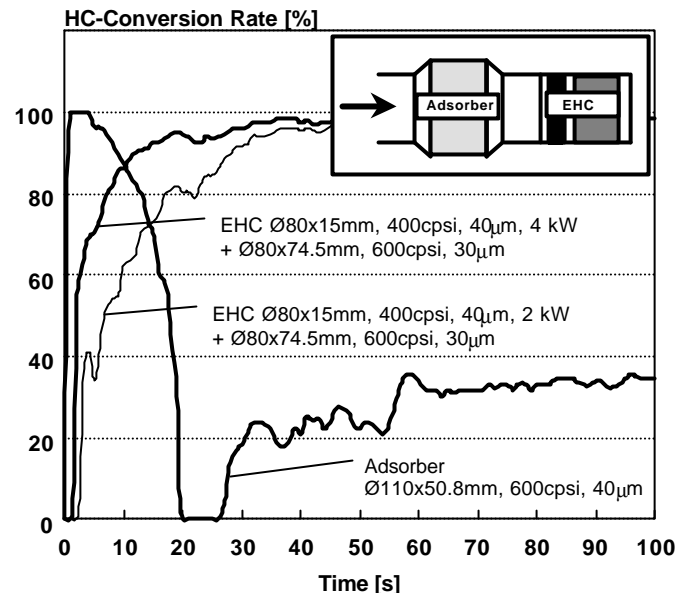


Fig. 14: HC-conversion rates for the various components of the HC-adsorber / EHC system

e) Active 2-Monolith EHC System: Since the adverse effects of the thermal mass of the adsorber could only be offset by using higher heater power dissipations, the case of an close coupled EHC was simulated in a subsequent simulation, where the heated catalyst was identical to those in the computations described above. The main converter employed (110-mm dia. x 110 mm, 800 cps, with 0.03-mm foil thickness) was assumed to be installed immediately downstream of the heated catalyst for computational purposes.

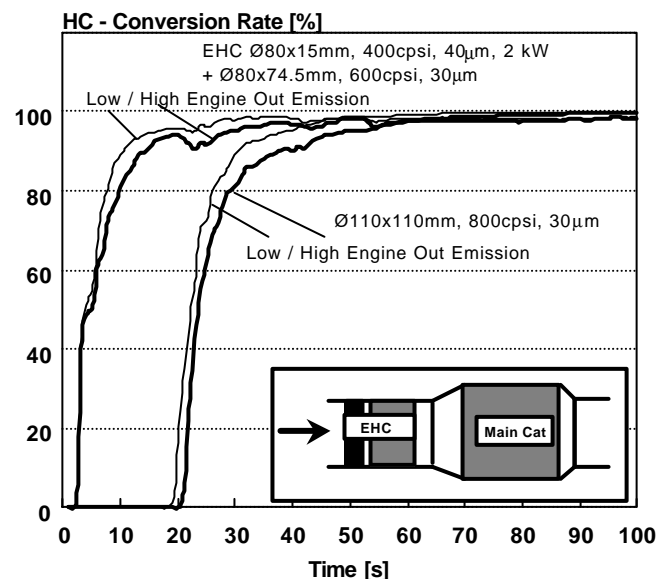


Fig. 15: HC-conversion rates for the different components of the close coupled EHC- system

Heater power was set at 2 kW for 20 seconds, and the computation was performed for both Vehicle A and Vehicle B.

Fig. 15, above, shows the HC-conversion rates for activation of the catalyst after 3 - 4 seconds for both vehicles A and B for the case where identical mass flow rates and gas inlet temperatures were applied.

However, the resultant HC-emissions, which are shown in Fig. 16, below, indicate that there is a difference in their behaviors corresponding to the difference in their raw emissions. The curve representing the SULEV-emission limitation clearly shows that it should be possible to obtain compliance with forthcoming SULEV-legislation limits using a heated-catalyst system installed close to vehicles' engines in conjunction with low raw emissions during cold starts. The vehicle with high raw emissions failed to attain the emission levels needed for compliance with forthcoming SULEV-legislation. In the event that the necessary reductions in cold-start raw emissions should prove impossible in real-world applications, employment of an HC-adsorber installed on, e.g., a bypass line, or preheating the heated catalyst will be required.

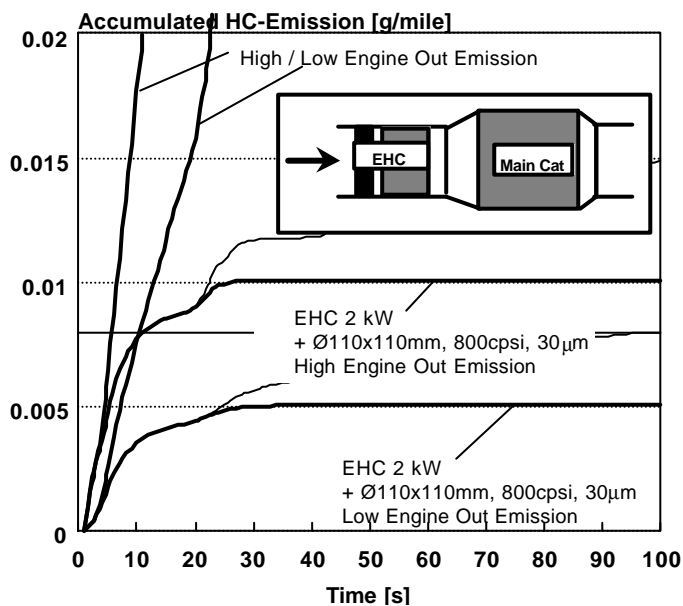


Fig. 16: Cumulative HC-emissions for the different components of the close coupled EHC-system

f) Emissions in Warmed-Up Conditions: In actual practice, it will be essential to both reduce cold-start emissions and provide that catalysts reach their full catalytic efficiencies under warmed-up conditions, which requires using both a lambda-controller with excellent regulation characteristics and the option of monitoring / regulating the lambda of each single cylinder.

Mixing of exhaust gases from individual cylinders sufficient to offset the effects of variations in lambda will usually fail to occur, particularly in cases where catalysts are installed close to vehicles' engines, due to the overly

short lengths of flow channels where mixing might take place. Emission tests were conducted using various average values of lambda in order to elucidate the adverse effects that even slight variations in lambda can have on emissions.

The results of those emission tests and the average values of lambda involved are summarized in Table 2, where the measurements involved were performed on the exhaust gases from a 4-cylinder engine run on a dynamometer test stand equipped with a catalyst installed close to the engine and all testing was based on the FTP-test cycle.

Lambda	HC	CO	NOx
0.99	2.60	8.39	2.8
1.0	2.19	5.05	2.44
1.01	2.06	2.19	8.88

Table 2: HC-, CO- and NOx-emissions [g] obtained for various average values of lambda

HC-emissions for the case where the catalyst was run at its normal operating temperature in the FTP Bag 2 were grouped and coordinated to the associated values of lambda in order to elucidate the influence of variations in lambda on HC-emissions. The results obtained are shown in Fig. 17, below.

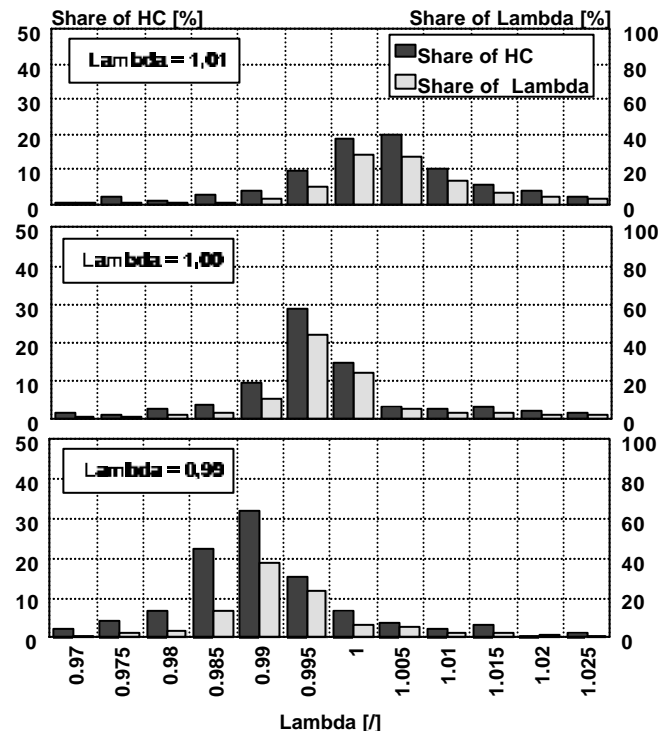


Fig. 17: Tailpipe HC-emissions as a function of lambda in the FTP-cycle bag 2.

As indicated by Fig. 17, a Lambda shift from 1.01 to a value of 0.99 results in both the increase of the amount of tailpipe HC-emissions during FTP bag 2 and a shift of the probability of the emission appearance towards richer lambda values.

5. SUMMARY AND CONCLUSIONS

Emitec's "CatProg" catalyst-design software represents a highly sophisticated tool for computing the cold-start emissions of future catalyst systems. Computations for widely varying types of exhaust-gas post-treatment systems equipped with three-way catalysts, HC-traps, hybrid adsorbers, and heated catalysts have made it clear that optimized combinations of known technologies tailored to suit their cold-start emissions will allow vehicles powered by internal-combustion engines to comply with SULEV-legislation. The following results have been computed for the various individual components of such systems:

- **HC-Traps:**

HC-traps represent an excellent choice of means for temporarily storing hydrocarbons. Desorption will commence either when temperatures rise or once HC-concentrations upstream from their adsorbers have dropped due to, e.g., the startup of catalytic conversion by an upstream startup catalyst. However, since HC-traps represent heat sinks, it has proven impossible to warm their downstream catalysts up to their normal operating temperatures prior to the commencement of desorption using currently known catalytic coatings without employing auxiliary heating.

- **Hybrid adsorbers:**

Hybrid adsorbers installed close to vehicles' engines markedly reduce exhaust emissions compared to the case where HC-traps are employed, which is due to the fact that both only one substrate (= heat capacity) is required and adsorption / desorption actions occur very close to the place where catalytic conversion takes place, so that desorbed hydrocarbons may be immediately converted, provided that temperatures are sufficiently high. Their catalytic-ignition fronts may even overtake their desorption lines if they are very rapidly warmed up to their normal operating temperatures, which implies that part of the catalyst upstream from the desorption zone will remain catalytically active.

- **Heated catalysts:**

Heated catalysts represent both a means for increasing gas temperatures, thereby offsetting the thermal mass downstream from HC-traps, and a means for shortening the "light-off" times of catalysts. Employment of optimized heated-catalyst systems installed close to vehicles' engines may allow attaining cold-start emissions that comply with SULEV-legislation if their raw emissions

are suitably low.

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