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Metallic Substrates for Catalytic Converters in 2 & 3 Wheelers
Turbulent Catalysts meet the Requirements of the Future

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ABSTRACT
The 2 & 3 wheeler industry is using worldwide metallic substrates for catalytic converters in their production. To achieve higher efficiencies of metallic catalytic converters, progressive developments in the area of turbulent foil structures have taken place. First results show, that 15 % smaller volume of the catalysts with turbulent structure offers higher conversion efficiencies applied to smaller size 2 & 3 wheeled vehicles.
The design details of so called TS and LS structures as well as catalytic converter performance behavior will be reported in this paper. Especially the influence of these new structures and the new catalyst performance improvement applied to smaller size 2 & 3 wheeled vehicles are discussed.

INTRODUCTION
Within the next years, more severe exhaust emission limits will come into force for the 2 & 3 wheeler vehicle class. The strengthened legislation on the one side and cost pressure on the other side force the catalyst producer to the development of more efficient and cost effective converters, such as turbulent TS and LS structure catalytic converters from EMITEC.
Earlier studies of TS and LS structures [1, 2] with experimental results for automobile application have shown improved catalytic performance. Analyses were made for representative sizes of TS and LS structures applicable for 2 & 3 wheelers. It can be seen that TS as well as LS structure improves the catalytic converter performance for smaller sizes which has been tested during stationary and dynamic tests. This improvement can be utilized to reduce catalytic converter volume and precious metal loading for the same or even better performance as compared to regular substrate. Reduced size offers improved light-off characteristic compared to regular substrates and a significant reduction of the cost of precious metal.

TURBULENT CATALYSTS
Mass transfer for regular catalyst shows a laminar flow after intrusion in the catalytic converter after a short time. If the change in the metallic substrate allows the change from laminar flow into turbulent one, longer residence time and more unconverted gases from the core of the channel come closer to the catalyst surfaces and more reaction takes place. The higher flow velocity corresponds to a higher mass transfer. The correspondence between flow velocity and mass transfer is shown in Figure 1.

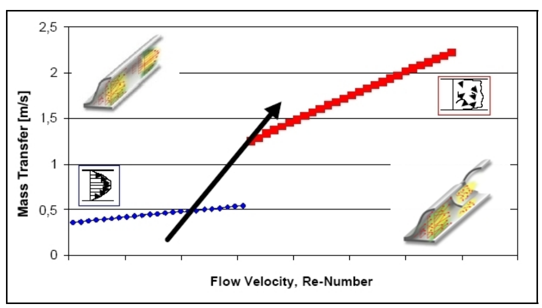

Figure 1: Flow velocity - Mass transfer diagram

The scope of work in this publication covers the analysis of turbulent catalyst with transversal foil structure (TS) and longitudinal foil structure (LS) with the focus for use in 2 & 3 wheeler vehicles [3].

TS – Structure

Transversal Foil Structure (TS) catalyst is the second generation of metallic substrates. The first generation had straight and unstructured channels.

This TS design is commercially produced and widely used in regular mass production for automobile application.

In this type, the corrugated foils are embossed with secondary micro- corrugations (Figure 2), which are provided transverse to the direction of flow i.e. at 90 degree to the flow direction (see above described mass transfer to the wall).

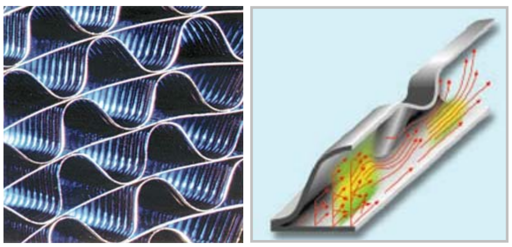

Figure 2: TS structure design with flow details

These micro-corrugations help intense exchanges of unconverted gases in the core of channel with the converted gases close to the walls.

LS – Structure

Longitudinal Structure (LS) is the third generation of metallic substrate structure, which has been developed by EMITEC. In the LS design the corrugated foil is characterized by additional cuts and depressions to provide shovel like shapes (Figure 3).

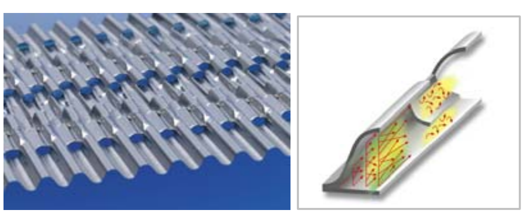

Figure 3: LS structure design with flow details

These counter corrugations projecting into the basic channels create the effect of additional channels within the same given volume, which results in turbulent mass transfer to the channel walls and an increased catalytic reaction.

Thus, without increasing the actual surface area of a catalyst, a higher catalytic efficiency is achieved by the LS design.

TEST BENCH ANALYSIS

During stationary and dynamic tests catalysts with applied TS as well as LS metallic substrate structure have been analyzed. To exclude the influence of production, all converters were preconditioned 4 hours under 950°C ambient air.

Converters with dimensions as defined in table beneath were analyzed on test bench:

Dimension (Diameter x Length)	cpsi	Structure	Volume [cc]	Delta V	Coating Pt:Rh	Loading(g/ft^{-3})
33x60	100	Std	51	-	4:1	25
33x60	100	TS	51	-	4:1	25
33x50.8	100	TS	43	-15 %	4:1	25
33x50.8	100	LS	43	-15 %	4:1	25

Table 1: Dimensions of tested catalytic converters

All substrates had the same diameter, cpsi, coating and loading. Coating was provided from W.C. Heraeus GmbH. For analyzing the influence of the structure in combination with the substrate length, two shorter metallic substrates were applied. Besides, the benefit of 15% reduction in substrate volume could be achieved.

All catalysts were conditioned at 950°C, 4h in ambient air.

Stationary Measurements

The main task of the engine test bench analysis was to define the exact conversion rates for several lambda values and different engine speed and load.

Lambda, according to [4], is defined as the actual air-fuel ratio divided by the stoichiometric air-fuel ratio. If λ is smaller than 1, the engine runs with air deficiency or rich mixture, if λ is more than 1, the engine is running lean. The definition of lambda is shown in the equation below:

$$\lambda = \frac{\text{AFR}}{\text{AFR}_{\text{st}}} \, [\text{-}]$$

Equation 1: Lambda

λ .... lambda [-]

AFR ……….. air-fuel ratio in the cylinder [-]

AFR_{st} …...… stoichiometric air–fuel ratio [-]

Thus a 50cc 4-stroke engine with a free applicable ECU with the possibility to focus on the selected operation points was mounted on the test bench (Figure 4).

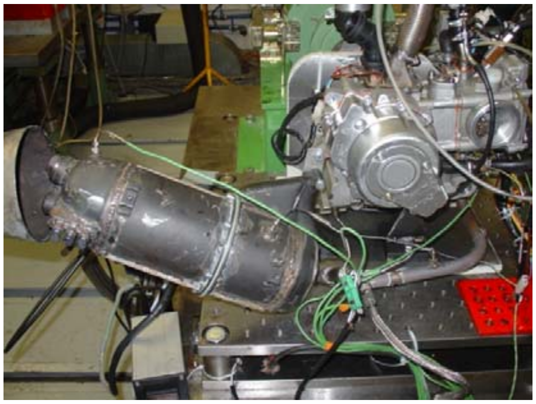

Figure 4: Engine with special exhaust system mounted on engine test bench

The engine configuration is listed in Table 2.

Prototype 1 cylinder 4-stroke engine	
Displacement [cm^3]	49.8
Bore x Stroke [mm]	40 x 39.8
Compression ratio [-]	11:1
Cooling system	liquid
Valve train	2 Valves , OHC, chain
Carburetion	Fuel injection

Table 2 Engine operation points driven on engine test bench

In addition, a special assembly of the exhaust system to meet all the measurement conditions was designed. An important requirement was the possibility to measure the exhaust gas components before and after the catalytic converter at the same time during engine operation. Thus, special heated exhaust pipes, for simultaneous measurement before and after the catalytic converter, were applied between the exhaust system and the exhaust gas analyzer. The temperatures before and after catalyst were examined in the same areas

In Table 3 representative engine operation points, as driven on the engine test bench, can be seen. These points represent the most common operating engine speed and load points for a scooter vehicle during the ECE-R47 homologation cycle.

Lambda	Engine speed [rpm] - BMEP [bar]
0.9	5000 rpm – 8 bar 7000 rpm – 8 bar
1.0	5000 rpm – 8 bar 7000 rpm – 7 bar
1.1	5000 rpm – 8 bar 7000 rpm – 5 bar

Table 3: Map points for stationary measurements

Lambda 0.9

The results of rich operation points represent acceleration phase of 2 & 3 wheeled vehicles. Turbulent catalysts with different substrate lengths were compared with the standard catalyst between 5000 and 7000 rpm engine speed.

The standard catalyst shows moderate conversion rates for all three emission factors at 5000 rpm operation point (Figure 5). Turbulence in the substrate improves the conversion efficiency for more than 100% in the case of HC and CO emission factors. Even better conversion rates are represented for NOx, where a conversion rate of about 50% can be reached. The best results are presented for the Ø 33 x 60 mm catalyst with TS substrate.

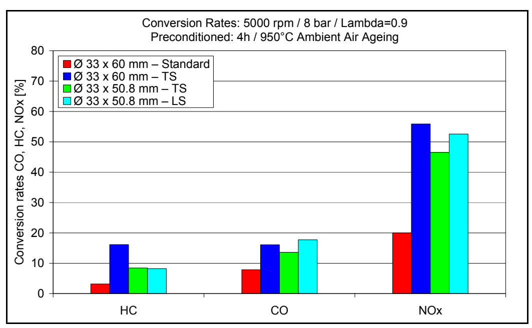

Figure 5: Conversion rates 5000 rpm / 8bar / Lambda 0.9

Figure 6 shows the results of the 7000 rpm rich operation point. The best HC conversion is achieved by TS Ø 33 x 60 mm substrate;

all other turbulent substrates show lower conversion rates. A conversion improvement for TS as well as LS substrate is seen for the CO and NOx emission factors.

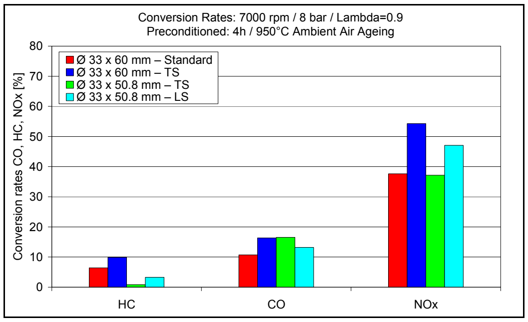

Figure 6: Conversion rates 7000 rpm / 8bar / Lambda 0.9

In general, all conversion rates for rich operation points could be improved with the turbulent catalysts. The eye catching improvement is visible for the NOx conversion rates.

Lambda 1.0

Lambda 1.0 is a typical operation point for the 20 km/h section in the ECE R47 homologation cycle (see Figure 16). This driving point has about 32% share of the emission factors in the homologation cycle.

Standard catalyst reaches approximately 30% conversion rates for HC and CO, whereas all turbulent converters exceed these conversion efficiencies (Figure 7). Compared to lambda 0.9, all catalysts reach much higher conversion rates for HC and CO.

NOx conversion for turbulent substrates reaches remarkable 60%.

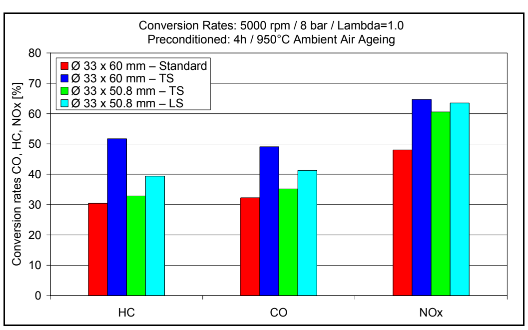

Figure 7: Conversion rates 5000 rpm / 8bar / Lambda 1.0

A similar behavior than at the operation point with lambda 1.0 and engine speed 5000 rpm and at lambda 1.0 / 7000 rpm operation point (Figure 8) can be observed. Higher conversion efficiencies were reached for all three emission factors.

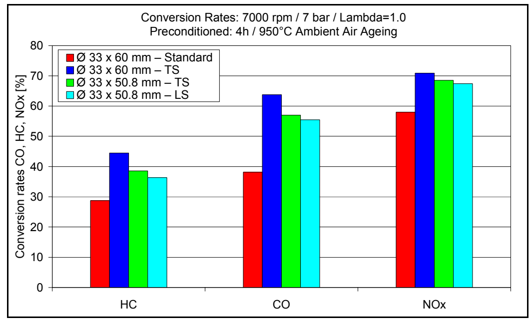

Figure 8: Conversion rates 7000 rpm / 7bar / Lambda 1.0

Also at this operation point the TS Ø 33 x 60 mm substrate shows the best overall conversion efficiency, compared to other converters.

Lambda 1.1

Engines mounted in a scooter vehicle usually reach their break away point at lean engine operation to allow use of oxidation catalysts. Therefore these results represent typical engine operation at wide open throttle and break away point.

The conversion rates for HC and CO show respectable results. Compared to the standard catalyst (Figure 9), TS Ø 33 x 60 mm substrate reaches 25 % improvement of conversion efficiency. The NOx conversion of TS and LS substrates stagnates.

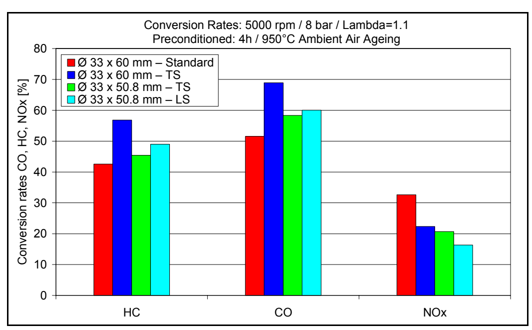

Figure 9: Conversion rates 5000 rpm / 8bar / Lambda 1.1

In the case of high engine speed and lean operation (Figure 10), high CO conversion is representative for all catalysts. Moderate NOx conversion for two turbulent Ø 33 x 50.8 mm substrates can be seen. TS Ø 33 x

60 mm substrate shows much higher HC conversion rates than the standard one.

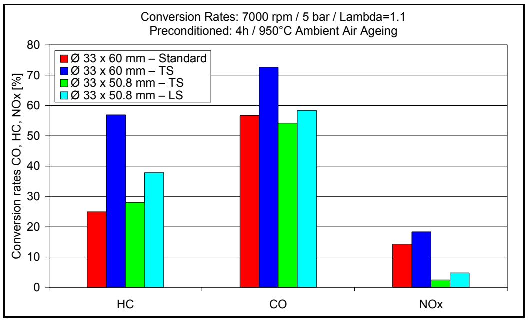

Figure 10: Conversion rates 7000 rpm / 5bar / Lambda 1.1

It can be stated, that the turbulence in the channels (TS substrate) improves the overall efficiency of all operating points about 33% at the same substrate length compared with standard substrate. Shorter TS substrate (Ø 33 x 50.8 mm) shows similar or slightly better conversion rates than the standard one. LS substrate with Ø 33 x 50.8 mm dimensions enhances the conversion efficiency compared to the same dimensioned TS substrate.

Turbulent catalyst backpressure

Exhaust gas mass flow of the small capacity engines rarely reaches values over 20 kg/h. Figure 11 shows, that the backpressure for these values is the same for turbulent as well as for standard substrates. The backpressure for significantly increased mass flow values shows a disadvantageous backpressure behavior of turbulent substrates. No increase in fuel consumption would be observed for turbulent structures (see Fig. 18).

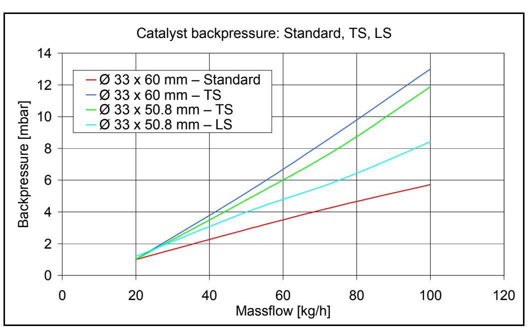

Figure 11: Catalyst backpressure as function of the mass flow

Dynamic measurements

The modified exhaust system, already used for stationary measurement, has been applied in a series 50cc 4-stroke scooter vehicle (Figure 12). The technical data of the tested vehicle are presented in Table 4; the homologation measurement results are available in [6]. The dynamic measurements were carried out on a chassis dyno test bench with a **C**onstant **V**olume **S**ampling (CVS) device to detect the exhaust emission characteristics.

Figure 12: Measurement setup for dynamic tests

Series 50 cc vehicle with 1 cylinder 4-stroke engine (Euro 2 homologation)	
Carburetion system	Constant pressure carburetor
Cooling system	Air
Exhaust gas after treatment	Oxidation catalyst and secondary air
Cold start system	Thermo switch choke
Transmission	CVT, secondary gear
Vehicle reference mass	170 [kg]
Power output	2.54 [kW] at 7250 [rpm]
Mean fuel consumption in the homologation cycle	42.7 [km/l]
Homologation	Euro 2

Table 4: Technical data of the test vehicle

The standard ECE R47 driving cycle was used for the testing program, in which the same catalysts were tested during the stationary measurements. The road resistance

and reference vehicle mass were defined as specified by the Directive 97/24/EC [5].
The complete homologation cycle ECE R47 consists of eight identical cycles. The first four cycles are warm up cycles for the homologation procedure and are at the same time used for sampling the exhaust emissions for the hypothetical cold start phase for Euro 3. The complete ECE R47 homologation cycle is shown in Figure 13.

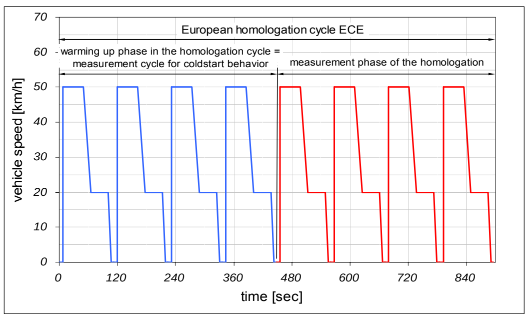

Figure 13: ECE R47 homologation cycle with defined cold start phase

All emissions, measured separately for the warm and the cold start cycle, were collected in the emission bags as well as recorded with an online measurement tool. The emission factors (HC, CO and NOx), resulting of the bag measurements, were analyzed for each catalytic converter separately. The online measurements provided an insight into cold start behavior and allowed detailed analysis of the warm-up phase for tested catalysts.

Results

The standard catalyst serves as basis for the comparison with turbulent converter. In the cold start cycle (Figure 14) slightly improved CO emission factors of the TS and LS substrate (Ø 33 x 50.8 mm) can be seen. TS substrate with the dimensions Ø 33 x 60 mm shows the best CO emission factor of all substrates. HC+NOx are for both catalysts, LS and TS with dimensions Ø 33 x 50.8 mm, about 18% lower compared to the standard catalyst. TS substrate with dimensions Ø 33 x 60 mm shows 38% better HC+NOx values than the standard catalyst.

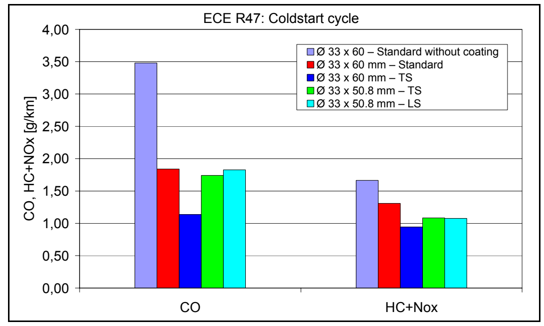

Figure 14: ECE R47 cold start cycle results

The emission factors in the homologation cycle (Figure 15) are limited according to the Euro2 legislation to 1.0 g/km CO and 1.2 g/km HC+NOx.
The focus of the analysis was not put on the achievement of homologation limits, but to clearly point out the difference in the catalyst performance. Due to the fact, that standard catalyst exceeds the limited CO value, a standard catalyst without coating has been used to make the analysis of turbulent catalyst possible. Nevertheless the standard catalyst with coating reduces the CO emissions to the half and lowers the HC+NOx. The TS and LS substrates with the dimensions Ø 33 x 50.8 mm show moderately higher CO values for both short type turbulent catalysts. As expected, the TS Ø 33 x 60 mm substrate shows a 48% better CO emission factor than the standard substrate and is the only one that falls below the limited Euro 2 value.

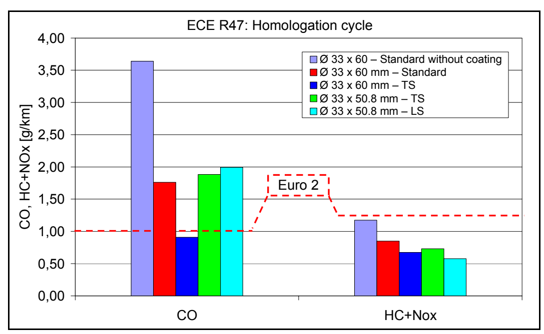

Figure 15: ECE R47 homologation cycle results

The HC+NOx factor of the Ø 33 x 50.8 mm TS is 14% lower and of the Ø 33 x 60 mm LS 32% lower in comparison with the standard catalyst. TS substrate with the dimensions Ø 33 x 60 mm shows 21% improvement in HC+NOx conversion.

Online recorder measurement

The online recorder measurement of lambda as function of the time is shown in Figure 16. With this tool the exact duration of the cold start enrichment phase and the calibration of the carburetion with secondary air induction were observed. Furthermore, the pre-defined lambda values for stationary measurements could be defined according to the dynamic measurements.

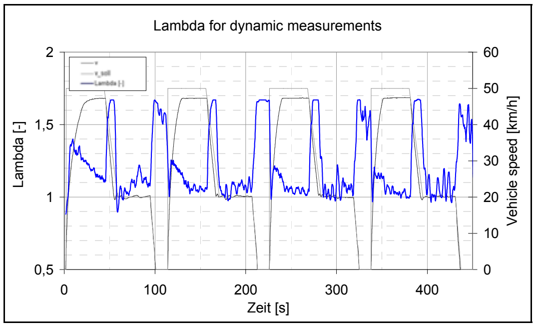

Figure 16: Lambda history in the ECE R47 cold start cycle

With the help of online measurement temperatures progression before and after catalytic converter was recorded too. Delta T, presented as substitution between the temperature after and before the catalyst, shows the starting time of conversion in the catalyst, which directly impacts the cold start emission factors in the cycle. The results show, that the turbulent LS substrate starts the conversion after 150 s in the second cycle followed by the TS (Ø 33 x 50.8 mm) substrate. The standard converter starts with conversion after 400 s in the fourth cycle. The eye-catching effect is the peak of the delta T for LS substrate that is twice as high as for the standard converter, which can be traced back to higher turbulence in the substrate channel and subsequently a higher mass flow to the substrate walls. The TS Ø 33 x 60 mm substrate shows the highest peaks of delta T in the cycle. It starts with the conversion at the same time as LS substrate.

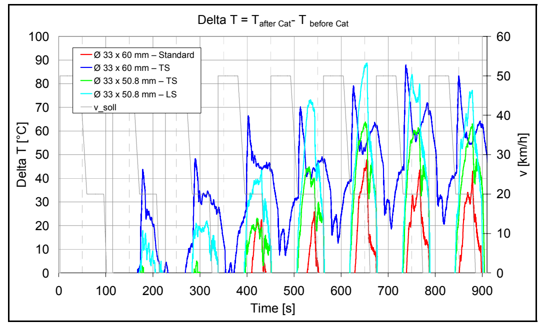

Figure 17: Delta T flow during the ECE R47 homologation cycle

The fuel consumption in the ECE R47 homologation cycle can be seen in Figure 18. Due to the fact that similar fuel consumption values can be seen for all converters,, no influence of the turbulent substrates on the engine operation compared to the standard catalyst was detected. This can be attributed to the backpressure results, which are shown in Figure 11, where no significant backpressure change at maximum engine mass flow (20 kg/h) was measured.

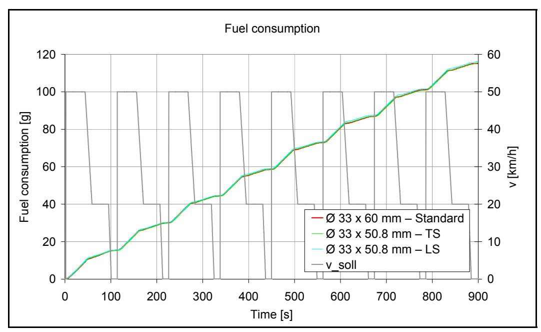

Figure 18: Fuel consumption in the ECE R47 homologation cycle

CONCLUSION

Experimental results show that the turbulent catalysts have a future perspective and will dominate the application in the future.

The results presented in this publication show that a 15 % smaller catalyst with turbulent structure offers the same or even better conversion efficiency than the reference catalyst with 100 % volume. Thereby gained volume reductions of up to 25 % offer significant lower consumption of precious metal (PGM); advantageous especially at times when it is expected that the PGM costs will further increase in the future.

The production technology of the second generation TS-structure is mature and ready to be launched.

Catalysts equipped with turbulent LS-structure substrates show an even higher potential than TS-structure and are ready to leave the R & D status with proven durability [7, 8].
The new turbulent substrate technology should be accompanied by a new coating technology being introduced as a worldwide standard.

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