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BMW

The Exhaust System for the New BMW M3

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Rear end view of BMW M3

By Christian Eichmueller, Gerhard Hofstetter, Winfried Willeke and Peter Gauchecl

In connection with BMW, the letter M has stood for exceptional sports vehicles since 1978. This tradition is being continued with the new BMW M3, which is a sport coupe absolutely tuned for everyday driving and at the same time performing like a thoroughbred sports car. BMW M GmbH, a company within the BMW GROUP, has developed the M3. At the heart of the M3 is the equally new, high-revving inline six cylinder naturally aspirated engine. From a displacement of 3,246 cc, the engine achieves a power output of 252 kW (343 bhp) at 7,900 rpm. With a specific output of 105.7 bhp/litre and a broad usable speed range, this high-speed engine represents the very best in naturally aspirated engine design. The realization of the high engine-speed concept required highly innovative development of the engine's specific functional elements. The design of the new exhaust system was therefore perceived as a special challenge.

1 Introduction

The new BMW M3's exhaust system began with the premise of justifying the special vehicle concept. The new BMW M3's dynamic road performance and the high-speed design of the engine represent a major stress factor with regard to the strength of the exhaust system. The exhaust system's necessary lightweight construction and the confined assembly situation on the vehicle **(Figure 1)** also complicate the design. The engineers therefore set themselves the task of mitigating conflicts of objectives and developing technical solutions that match the vehicle concept, as well as appeal to customers. Development of the new M3 exhaust system was defined by BMW M and brought to series-production readiness in cooperation with the manufacturer ArvinMeritor. ArvinMeritor develops and manufactures exhaust systems for the automotive industry at its production center in Finnentrop (North-Rhine Westphalia, Germany).

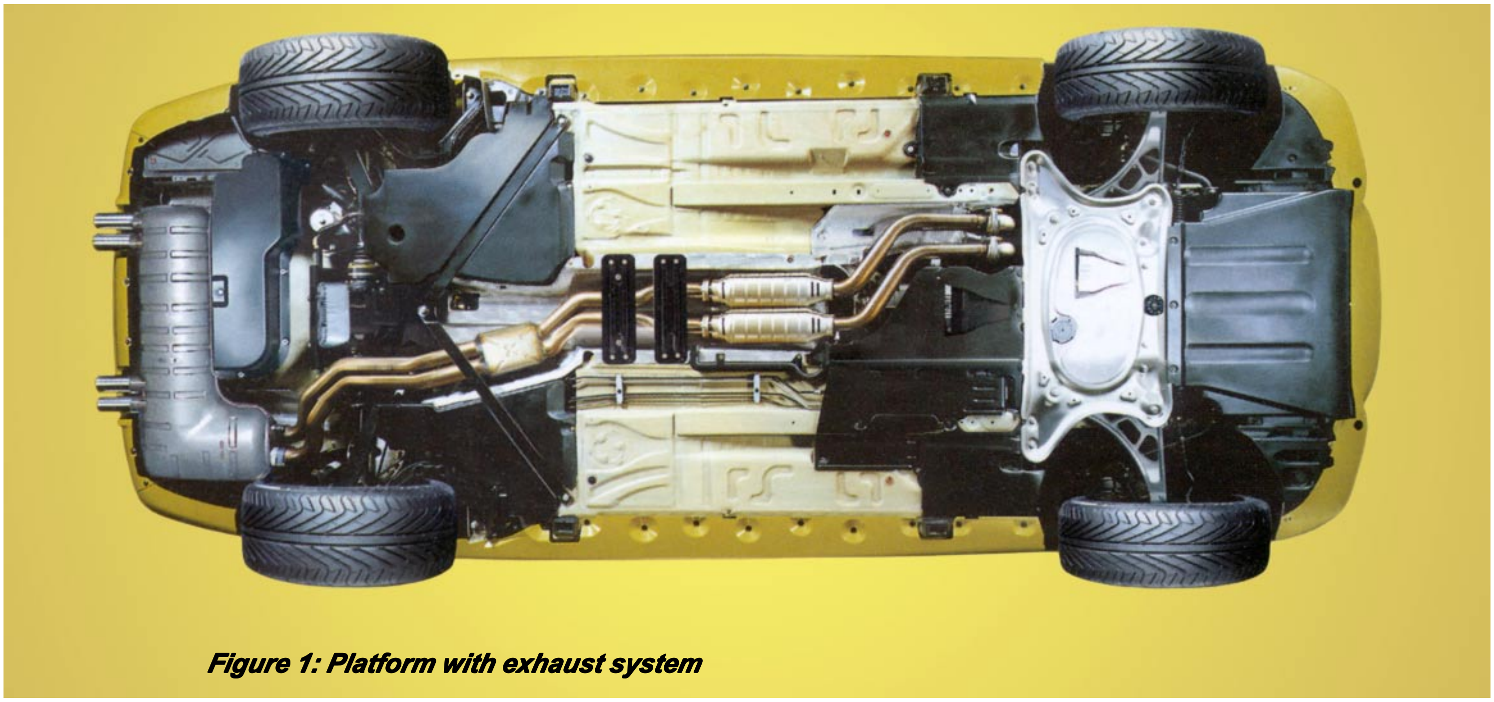

Figure 1: Platform with exhaust system

2 Development Aims

The following development aims were defined for the new exhaust system:

- Optimizing the gas exchange with the exhaust system
- Consistent lightweight construction (target weight < 50 kg)
- Limitation of the heat capacity in the manifold, down pipe and catalytic converter areas
- Compliance with emission regulations (exhaust, noise)
- Characteristic sporting exhaust sound
- Restrained, but sporting interior acoustics
- Crash-optimized exhaust tailpipes in BMW M look
- Long-term BMW quality
- Economical manufacture
- Exhaust manifold and catalytic converter usable as identical parts on the BMW M3, BMW M Roadster and M Coupe

3 Design

To achieve these development aims, the exhaust manifold and exhaust system as well as all the mounting and attachment elements were newly designed. The 3D data created at BMW M with the CATIA CAD system is used throughout the process chain (analysis, DMU, manufacturing, quality assurance). The direct further application of CAD data served as a basis for a short, effective development period.

4 Component Design

4.1 Exhaust Manifold

The design of the exhaust manifold was consistent with calculated gas exchange requirements. The M3 engine therefore has tubular exhaust manifolds, such as are normally only to be found on racing engines. **(Figure 2)**

The exhaust gas flow from the exhaust ports to the collector pipes is in six individual primary pipes of identical length. A succession of pressure and induction waves in the exhaust pipe correctly phased to the valve timing is the precondition for good gas exchange. Exhaust from

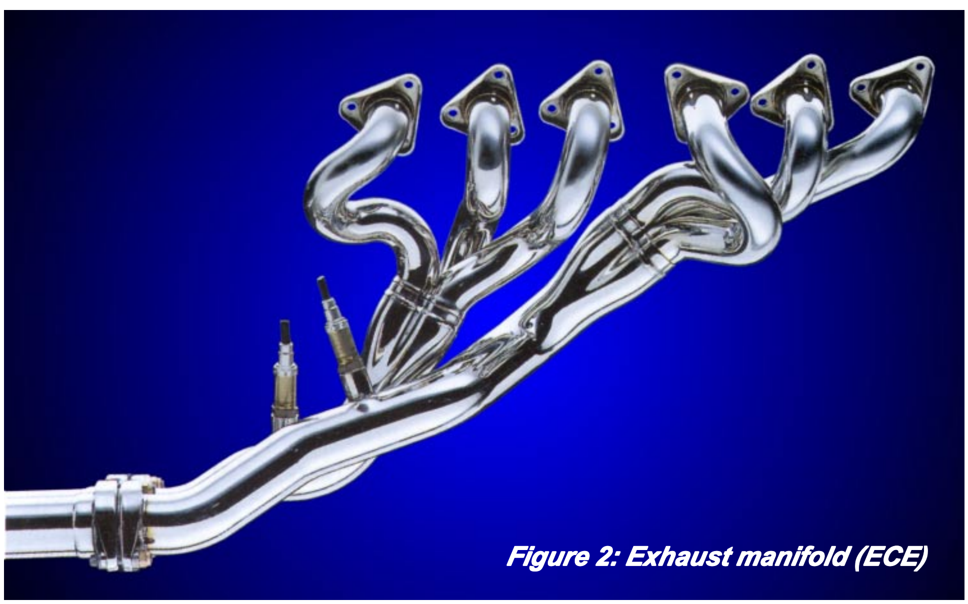

Figure 2: Exhaust manifold (ECE)

cylinders or primary pipes is therefore only led to common collector pipes if the relevant exhaust valve opening times do not overlap at all or only slightly. Because of the engine's firing order (1-5-3-6-2-4), the three cylinders 1-2-3 and 4-5-6, respectively, were therefore led to a common collector pipe.

The exhaust manifold pipes are manufactured by internal high-pressure molding (IHU). In cooperation with ArvinMeritor, the world's first tubular manifold was produced by this process back in 1992 for the M3 model then being manufactured.

This prior knowledge was drawn on and further refined for the new BMW M3's exhaust manifolds. All primary and secondary pipes are in one piece, despite the complex molding, so that many sockets and their weld seams disappear, and, conversely, fewer obstructions arise in the exhaust flow. In addition, a cross-sectional reduction in the pipes is avoided, since nether folds nor flattened bends occur in manufacture.

The considerable cold hardening in the IHU process yields a stable, lightweight construction. A wall thickness of only 1 mm is sufficient for the exhaust manifold. The thin-walled design limits thermal inertia when heated up. This was a major precondition to improve the light-off performance of the catalytic converter.

Figure 3: Mounting flanges (old / new)

To avoid further heat reduction and reduce component weight, all connecting flanges were of new, lightweight design. The flanges are formed in such a way that the lowest amount of mass is directly coupled to the piping. The patented flanges for attachment to the cylinder head were, in contrast to the previous model, converted from precision castings to sheet metal, and the number of mounting screws for each reduced from four to three. **(Figure 3)** This results in a weight saving in detail of more than 66%, as well as better pressure distribution at the sealing face.

Sheet metal flanges instead of forged flanges are also used at the connection to the exhaust system. Here, a weight saving of 50 percent is achieved. By integrating linear and angular compensation for the absorption of heat expansion and assembly tolerances an expensive corrugated pipe compensator can thus be avoided.

As the sheet metal flanges represent a completely new development, they first had to prove their worth with regard to strength, distortion and sealing.

Despite its complex shape, the exhaust manifold is suitable for use in both left-hand and right-hand drive vehicles. As the BMW M3's new engine will also be installed in the future in the BMW M Roadster and M Coupe, the installation conditions for these vehicles also had to be taken into account.

For the U.S. model, a different exhaust manifold was developed. Because of the position of the catalytic converter next to the engine, a different pipe layout from the ECE model has been developed, but the design features resemble the ECE version.

4.2 Exhaust System and Silencer

The twin-pipe exhaust flow was maintained up to the rear silencers,

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Figure 4: Entire exhaust system

in view of the resulting gas exchange benefits. In order to reduce exhaust backpressure, the components were designed to be as free of throttling effects as possible.

4.2.1. Front Pipes with Catalytic Converter

A closed-loop, three-way catalytic converter is integrated into each of the two pipe runs for the purification of exhaust emissions. Two cylindrical metal monoliths from the company EMITEC are arranged in sequence for each catalytic converter. The main design priorities were the conversion rate, rapid light off and limitation of pressure losses. These requirements were met with a low number of cells (200 per square inch), reduced foil gauge (40µm) and a three-metal coating from the Engelhard Company.

In order to permit a reduction in foil thickness without affecting strength, the winding of the metal monolith (SM design) was improved. The catalytic converter's endurance is considerably higher as a result of a higher natural frequency, a greater axial secondary moment of inertia, more homogeneous radial rigidity and the larger brazing surface between the matrix and the jacket.

IHU pipes are used for the flow to the catalytic converters. This technology enabled the required cross-section for the twin-flow exhaust system and free-flowing transitions (diffusers) to be realized.

After the catalytic converters, an interference pipe connects the two pipe runs. This cross-coupling point leads to an increase in torque at medium engine speeds.

4.2.2. Exhaust Pipe with Intermediate Silencer

The required cross-sections in the rear axle area could only be obtained by means of special IH molded pipes. Because of the high degree of cold hardening during manufacture, there is no reduction in strength despite the thin walls. A further step in the direction of lightweight construction can thus be achieved. The intermediate silencer has a volume of 1.8 dm^3. The one-piece outer casing is double-walled.

4.2.3. Rear Silencer

To improve the gas flow, gas column oscillations of broad amplitude are necessary, whereas, the silencing requires the smoothing out of these vibration in the exhaust flow to be as uniform as possible. The M3's rear silencer was therefore mainly designed as an absorption silencer, since this construction best unites both requirements. Selection of the silencer volume is coupled to the swept volume ($V_{SD}=V_{HUB}$) and the engine's target values. For effective silencing without loss of performance, the facto "X" should not be less than 12 times the swept volume.

Only be means of a modification of the floor pan specific to the M3 could a large-volume rear silencer (40 dm^3) be located across and behind the differential at the rear of the car.

The rear silencer housing consists of two deep-drawn sheet metal half-shells. These are welded together after the internal components have been installed. In order to avoid structure-borne noise, curved, but relatively large, boundary surfaces are strengthened by swage-lines and panels. Only glass (Advantex) is used as an absorption material for the M3. This material combines high acoustic silencing properties with lasting quality at low weight. To attenuate the ignition frequencies, one chamber of the rear silencer acts as a resonator. The twin exhaust flows are divided to obtain the four tailpipes in this chamber. It was necessary in particular to test the new form and installation of the large-volume, transverse rear silencer. **(Figure 4)**

4.2.4. Exhaust Tailpipes

Two pairs of cylindrical, chrome-plated exhaust tailpipes in two cutouts of the bumper trim emphasize the car's sporting character.

In a rear-end collision, the exhaust tailpipes almost inevitably suffer damage due to their exposed position. In order to avoid damage to the exhaust system, new tailpipes were therefore designed and patented especially for the BMW M3. In a rear-end crash at up to 15 km/h, the new tailpipes are prevented from retracting towards the exhaust system and causing further damage. This is achieved by a crumple zone of suitable length inside the tailpipes. **(Figure 5 and Figure 6)** If necessary, the tailpipes can be easily replaced individually. Thanks

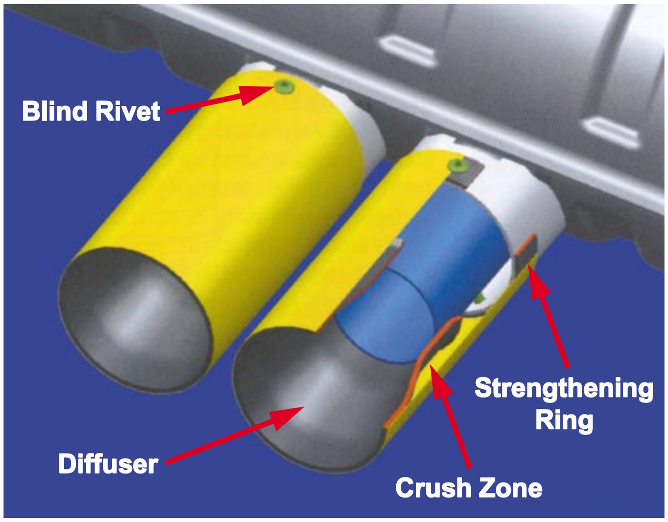


Figure 5: Section view of exhaust tail pipes

Figure 6: Comparison of exhaust tail pipes (new / after crash)

to this customer-friendly solution, the new BMW M3 qualifies for a less expensive insurance category. The new tailpipes were additionally tested in corrosion and crash tests, as well as in thermal shock tests.

4.2.5. Mountings

The load is distributed through several points, namely two rubber mountings located at the center of the exhaust system and three at the rear silencer. The combination of high temperatures and transverse acceleration forces, in connection with the confined installation conditions, requires the rubber mountings to be very durable. The mountings in the central area of the exhaust system are particularly exposed to high dynamic and thermal stresses.

In order to reduce transverse displacement, these rubber mountings are equipped with a metal insert. These mountings not only give the exhaust system the necessary transverse rigidity, but also prevent irritating vibration in the passenger area. Because of their relative proximity to the exhaust pipe, the rubber mix for the central mountings was also optimized for greater resistance to high temperatures. At constant stress and maximum velocity, temperatures of up to 200 degrees C are reached at the mounting.

Definition of the Shore hardness in combination with the spring steel sheet-metal insert and the contour of the rubber mountings were partly carried out mathematically (FEM calculation) and also empirically in cooperation with the WEGU Company. The conflict of objectives between strength and acoustics was ideally solved.

4.2.6. Material and Weight

With the exception of the metal monoliths in the catalytic converter, all metal components in the entire exhaust system are made of high-temperature resistant austenitic stainless steel. Thanks to its high corrosion and acid resistance, the durability of the exhaust system has been extended to match the car's life expectancy.

Although the volume of the silencer has been increased by over 50 percent compared with the previous model (E36 M3), the weight of the exhaust system (including the exhaust manifold) has been keep down to the previous level, i.e. under 50 kg, by systematic weight-saving design.

5 Exhaust Back-pressure

Due to the largely throttle-free exhaust pipes and generous dimensioning of the catalytic converters and silencers, pressure loss has been kept down to 300 mbar at 8000 rpm (in standard operating conditions), which is actually 40 percent better than on the previous model (E36 M3).

6 Exhaust Emissions

With the measures described here applied to the new BMW M3, a major contribution has been made to exhaust emission control. The BMW M3 is well below the EU3 exhaust emission limits. **(Figure 7)**

	HC	**CO**	**Nox**
BMW M3 Emissions (g/km)	**0.095**	**0.717**	**0.026**
Emission Limit for EUS	**0.20**	**2.30**	**0.15**
% of Limit	**47.7**	**31.2**	**17.4**

Figure 7: Chart of certificated emissions

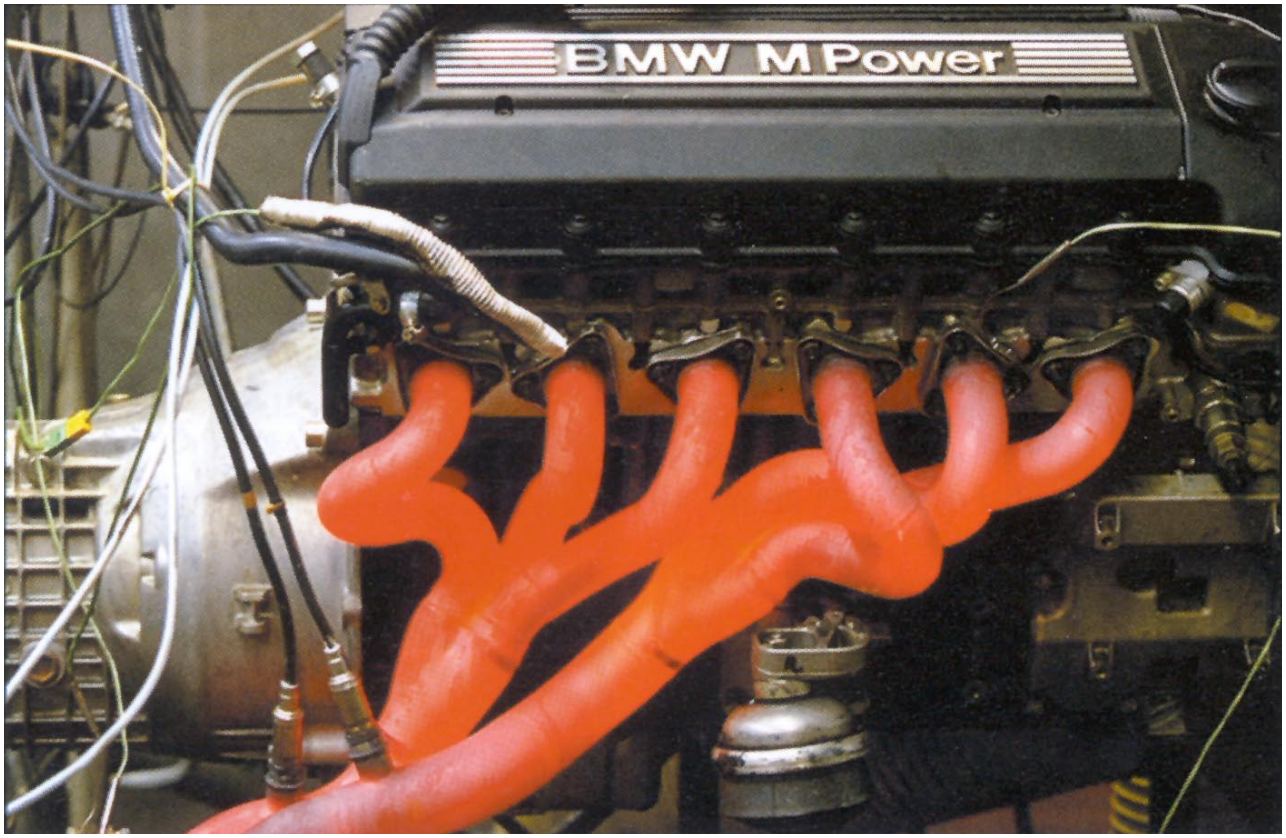


Figure 8: Test bed

For the USA, placing the catalytic converters near to the engine enables it to meet LEV I compliance.

7 Endurance Testing

The new M3's exhaust system with all its new features had to prove itself time and time again in special BMW M-specific long-term testing profiles, both installed on the vehicle as well as in complex rig testing. **(Figure 8)**

Heavy-load testing at the BMW proving ground in Miramas in Southern France, (corresponding to about 200,000 km of motorway) and 8,000 km under racing conditions on the northern loop of the Nuremburgring had to be completed successfully several times. Acceleration and deceleration values of up to 1.1 g occur in the longitudinal or transverse directions. Nuremburgring testing represents 20 times the stress encountered in normal road use.

The suitability of the exhaust system for day-to-day use, as well as for the requirements specific to each country were tested and validated in numerous long-distance road tests, in situations likely to be encountered by a customer. After endurance testing, the function of individual components of the exhaust system was tested. The weld seams, sliding fits, the fit of the partitions, the volume of the absorption material in the rear silencer and the newly developed flange seals were scrutinized.

By means of operational vibration analysis, a statement on the exhaust system's resistance to fatigue vibration could be made even at an early stage of development and any deficiencies removed.

8 Acoustics

The new BMW M3 was required to possess and indeed enhance the specific features of its predecessor with regard to exhaust system acoustics, i.e.: a fairly robust, sporting sound, without sacrificing comfort.

The following development aims were set up from this standpoint and known requirements taken into account:

- Compliance with an external noise limit of 75 dB(A)
- Lower outlet noise level
- Minimizing structure-borne noise
- Restrained, but sporting interior acoustics

8.1 External Noise

An added difficulty regarding the external noise pattern on the new BMW M3 was the additional requirement for performance optimized gearbox/axle ratios. The high engine speed in the drive-by measurement is generally reflected in the results as a higher drive-by noise level. To comply with the external noise limit valued according to Lex Ferrari of 75 dB (A), it was therefore necessary to optimize all noise sources on the BMW M3 and aim for a balanced distribution between them.

The silencing volumes necessary for exhaust system acoustics were made possible by adopting a transverse rear silencer. Through specific division into reflection and adsorption sections, the advantages of broadband and narrow-band silencing were combined.

With the aid of the reflection chamber, it was possible in particular to optimize the outlet noise level, i.e. to adapt it in the best possible way to the firing frequency for the accelerated drive-by. **(Figure 9)** Tuning of the resonance chamber took place empirically in several development stages.

The motor-sport type of exhaust sound that is a feature of the new BMW M3 was obtained at the intermediate silencer within the framework of the regulations currently in force. The size and position of the intermediate silencer were ascertained with close-field noise level measurements. The lack of adsorption wool makes an additional contribution to the robust sound.

Radiated noise from the component surfaces was reduced considerably by careful location of swage-lines. Elliptical or circular component geometries increase the inherent stability of these components. With the exception of the intermediate silencer, all pipes and silencer units are single-walled.

8.2. Interior Acoustics

A sports car like the new BMW M3 does not claim to have the quiet interior acoustics of a family car. However, clearly sensed vibration and unpleasant resonance in the interior are undesirable. By matching the effective tailpipe length to the rear silencer volume, low frequency drumming (< 100Hz), which mainly irritates rear-seat passengers, was considerably reduced. This measure resulted in a synthesis of sound and comfort requirements.

Under load, the exhaust system's acoustics provide the driver with powerful, sporting feedback. This clear acoustic feedback of the engine's load and speed status is backed by full-bodied air intake noise.

However, the new M3's exhaust system displays its acoustic suitability for everyday driving in all other operating conditions. The M3 can thus be driven comfortably without unpleasant noise levels for longer distances, when necessary.

The mountings have been designed so that no undesirable vibration and noise reach the interior.

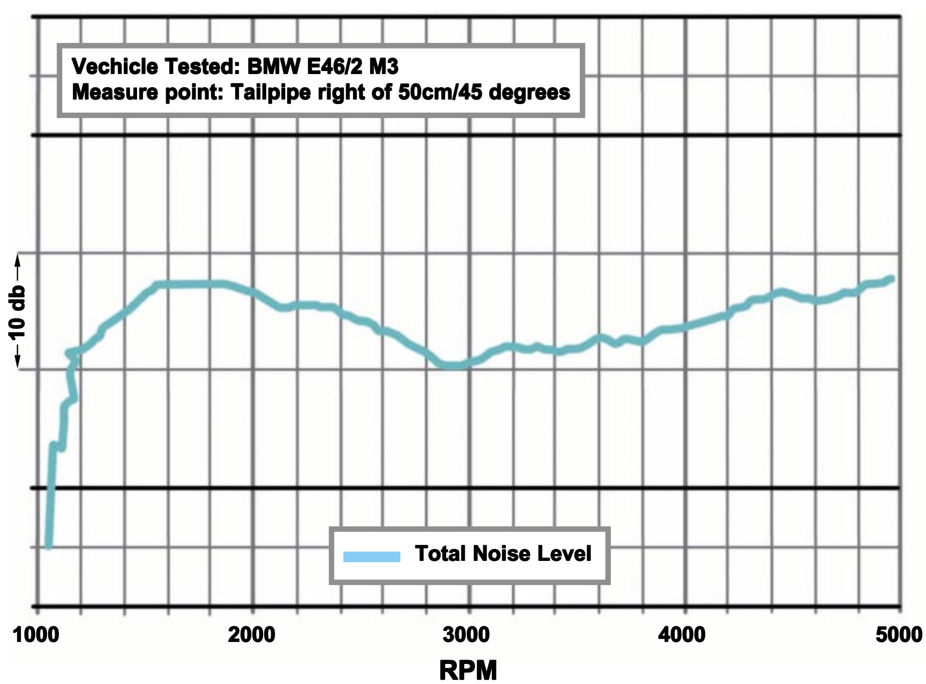


Figure 4: Entire exhaust system

9 Production

In order to meet structural requirements, to attain the lowest possible exhaust back pressure and to make maximum use of the available underfloor space, all the pipes from the manifold to the rear silencer have had to be produced by hydroforming. This technology is currently the only method of ensuring that the high qualitative demands on a sports-tuned exhaust system can be met. As well as fulfilling design specifications, hydro-forming technology ensures that the pipe cross-section can, for example, be matched to the available installation space and that very fine tolerance are adhered to. These can be guaranteed by robot welding, even with low wall thicknesses.

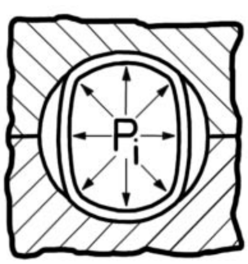
9.1. Bending Technology

In the first production stage, the pipes must be bent before hydro-forming, Low radii and very thin walls necessitated the development of electric bending machinery with a CNC-controlled tool changer. These machines were developed in close cooperation with ArvinMeritor and Addison, and brought to series-production maturity.

A total of 21 different bent components with the smallest of radii and precision dimensions are needed for the ECE and U.S. versions. This is achieved by using a fully electric compression/bending machine. The machine is equipped with 13 CNC-controlled shafts and a tool magazine with 16 sets of contour tools. Each shaft can be programmed individually. The bending process is the preparatory production step before hydro-forming and plays a key role in it.

9.2. Internal High-Pressure Molding

Section View



Calibrate

Figure 10: Calibration prinziple

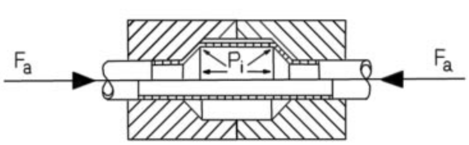


Figure 11: Flaring prinziple

In this process, the pipes are molded from within by hydraulic pressure in the tool. Depending upon the material and wall thickness, the pressure is between 2000 and 2800 bar. Two types are principally used for the M3 exhaust system:

Calibration:
Pre-formed pipes are forced against the tool wall in a closed tool by inner pressure (e.g. 2500 bar), **(Figure 10)** to reach the required forming level, the pre-formed pipes are normally annealed before reshaping.

Flaring:
In this process, additional material is brought into the remolding zone by axial compression, and very large amounts of expansion can be achieved. **(Figure 11)**

Combination of calibration/ flaring:
Combination of the two methods enables complex components to be produced, partly with a calibrated pipe section, but with greater flaring at one or both ends. This process has been used successfully, for example, on the cones of the catalytic converters. In this way, welded shells with a welded-on pipe have been replaced by a single component.

All 21 pipes are given their final form by internal high-pressure molding. Internal high-pressure presses with a locking pressure of 2,500 tons and 10 CNC axes are used. All components are transferred to the internal high-pressure molding process by robots. The expansion levels achieved are 80 percent more than in catalytic converter cones. **(Figure 12)**

From an economic point of view, the use of IHU is equally successful. Costs have been optimized by

Figure 12: Internal high-pressure component of the exhaust manifold (US)

minimizing the number of weld seams necessary and by the integration of the required shaping process. Thus, there is a considerable cost benefit compared to conventional construction from split shells or multi-stage processes.

An example of an integrated component is the collector for the ECE manifold. The two collectors are pre-bent as one header pipe, annealed and subjected to internal high-pressure molding. After reshaping, the component is sawed into the two separate parts required.

In conventional production, this component would consist of at least 6 separate parts joined together by welding. As well as the high number of separate parts to be manufactured, the many weld seams would present a high risk factor for the component's lifespan.

9.3. Assembly

For further processing of what are now high precision, internal high-pressure molded pipes and shaped parts, only the latest welding robots and special welding machines are used. All weld seams are carried out by machine to ensure consistent high quality. The welding processes used are pulsed TIG and MAG. A highlight of the whole process is the welding of the rear silencer. All outer seams in this component are welded in a single clamping. The surrounding seal seam of the two shells is welded without removal in a locking press modified to serve as a manipulator (10 tons clamping force). In order to ensure freedom from slip and torsion on the still loose shells at the start of the welding, both tool halves are driven separately by a CNC controlled motor. The motors are digitally connected here as an “electrical axis” and synchronized by the robot controls.

The requirements imposed by the very confined space in the car’s floor pan could thus be met. The tailpipes, as an important design feature, must be aligned with the rear body apron and follow the line of the bumper. All these points proved practicable with the method described.

10 Summary

The perfect combination of a powerful engine and the newly developed exhaust system on the BMW M3 creates an extremely spontaneous flow of power, accompanied by a sporty, robust sound. As well as offering the enjoyment of driving a sports car such as the M3, the car takes environmental protection requirements fully into account.

Compared with the exhaust system of the previous model, several basic changes were made to achieve the main goals of low exhaust backpressure and lightweight construction. Special attention was devoted to the major new features, such as sheet metal flanges and seals, thin-walled IHU components, metal catalytic converter monoliths with a foil thickness of 40µm, rear silencer and tailpipes, and the rubber mountings.

Thanks to innovative production methods, economical manufacturing with a high level of quality was achieved.

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