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Introduction to Automotive Engineering

The BMW E46 – M3 and the enhancements in engineering disciplines
that led to its creation.

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1 Introduction

This report will give the reader an in-depth insight into the third generation M3 commonly referred to as the E46 (BMW's identifier), including the motorsport legacy and the vast improvements in the engineering industry leading up to its production. There will be six major factors discussed in this report and their impact of the design of the M3 and their current impact on the automotive and motorsport industry. With the first-generation BMW M3 being bred out of Munich motorsport division to meet homologation targets of 5000 road legal renditions were made for the 1987 World Touring Car Championships. (M, 2020) The instant success in motorsport and the commercial world proved BMW to be a fierce competitor for other manufactures at the time.

1.1 Aims

- Discuss the major engineering disciplines that aided in the creation of one of the best BMWs to date.
- Give the reader an understanding of each individual engineering field.
- Examine the implications of the selected engineering fields and how they can contribute and hinder the automotive industry.
- Show the history behind the BMW M division and its racing prowess that inspired the E46 M3

1.2 Objectives

By the end of this report, the reader will be able to distinguish some of the major engineering fields that relate to automotive and motorsport development cycles. This report will also give the reader a detailed view on BMW's racing legacy that has instilled it as one of the leading manufacturers for high performance vehicles.

2 The Legacy Behind the M3.

2.1 Previous iterations of the M3.

With the original M3 having a solid racing career totalling 1436 victories in just over four and a half years, including numerous touring car championships all through different drivers. This consistency solidified the first gen M3 as a proven road going race car, and further implemented BMW as a top tier manufacturer at the time. With the success that was brought through the original M3, BMW began to develop the second generation M3 commonly referred to as the E36. Produced from 1992 up until 1999, the E36 M3 saw numerous updates and upgrades to the platform to help it perform better in racing. Although this generation was primarily focussed on commercial sales, these updates would drastically change the way the E36 M3 is seen by enthusiasts. The biggest and most known update to the engine would be the development of the 'double vanos' system, a way of altering the intake and exhaust valve timing depending on the engine load. This system shifts the camshaft positions to maximise power delivery, torque and to lower emissions. With the E36 primarily marketed towards the consumer, the racing prowess gained from the original M3 wasn't as glorified or repeated, this can also be attributed to BMW withdrawing from DTM, Germany's production car championship.

2.2 The return of the M3 into motorsport.

Along with the release of the third generation M3, two notable versions were produced alongside referred to as the E46 CSL and the M3 GTR, these two versions are coveted as the best E46s ever produced by BMW.

The CSL was closer of the two to the base M3 but included several upgrades that put it ahead of its competition at the time, including but not limited to: Carbon fibre roof, lightweight rear view glass, aluminium bonnet, increased track width and semi slick tires, this provided the CSL with a lower centre of gravity and therefore faster cornering speeds. At the time of production only two models from BMW came with the CSL name, the 3.0 CSL and the E46, and the now current M4 CSL, considering of all the production models BMW has brought to bear, only 3 having the CSL branding it can be seen how special of a car the E46 was. Produced with an SMG (Sequential Manual Gearbox) as the only transmission option, further leaning into similar mechanical technologies to what is commonly used in motorsport.

Commonly referred to as a homologation special, the GTR was developed as the first M3 sporting a V8 engine paired to a 6-speed manual gearbox, the GTR edition became an enthusiast's dream. The production run for the GTR began with a tuned version of the S54 engine (The same 3.2 litre inline 6 from the standard E46 M3) but unfortunately had little success in the 2000 American Le Mans series beaten by Porsche with a result of 3rd in the tenth round (Ward, 2020) before the 2001 series, BMW decided to convert the inline-6 engine with a 4.0 litre V8 producing 330Kw (442 brake horse power, this can be calculated by multiplying the power in kilowatts by 1.341 – $330 \times 1.341 = 442.53\text{bhp}$) this iteration only had a production run of 10 unit to meet the homologation targets set for the GT series, but due to pressure from other manufacturers, the governing body ALMS was forced to increase the homologation target to 100 units for the 2002 series, ending the GTR's domination of the second half of the American GT series.

(Okulski, 2018)



Figure 1 shows a BMW M3 GTR sporting the Stars and Stripes livery at a Pit Lane in Ohio 2018

3 Major Engineering Fields and their implications on the current and future automotive and Motorsport industries.

Since it's inception, there have been numerous advancements in the technology and the design that was used to create the BMW M3, here these fields will be examined for the impact these disciplines impacted the design and the development of the M3 and the advancements that have been utilised in the subsequent models that BMW have created.

3.1 The internal combustion engine.

Beginning development in the late 19th century, the Four-stroke engine has seen several major changes and advancements in its design and the mechanical principles that it has relied on for over a century. As the M3 uses the four-stroke, spark ignition configuration, this will be discussed within this section. The four-stroke engine utilises four basic principles to transfer the chemical energy from fuel into kinetic energy, these principles are as follows: intake, compression, ignition, and exhaust. This cycle completes two revolutions of the crankshaft per cycle and four strokes of the piston (Haywood, 2018) This cycle has been a fundamental constant for the four-stroke engine and the major refinements to its design have included the materials used in the manufacture, the combustion timing and the replacement of carburettors in favour of direct injection. As the timing on the combustion stroke can be tuned by programming the ECU in modern vehicles, it can be optimised for certain scenarios such as using less fuel while cruising or providing more torque at lower speeds. This has been essential in the use of the double vanos system used on the M3 as the engine's computer can determine the best time to send the spark into the combustion chamber by altering the intake and exhaust timing, optimising power at higher revolutions and decreased emissions.

3.2 Chassis design using computational methods.

In the interest of human safety and the numerous deaths in motorsport and traffic accidents, major manufacturers and suppliers developed countless computer systems to be able to determine the structural rigidity of components to test their interactions and their forces limits. Using computer programs such as Matlab or Solid works, manufacturers can determine the tensile stress a component can be put under before failure. This is fundamentally useful as it negates the major cost of developing a full-sized prototype that will eventually fail, engineers are able to view the specific areas of component failure and determine the most suitable solution to fix the issue. Another major benefit of using computer simulation, is the ability to determine the crashworthiness of a chassis and design crumple zones to maximise the safety of the occupants. Another feature of the computation methods used by manufacturers is finite element analysis or FEA, this is a detailed visual representation of a model using points called elements. Although this way of design is faster and more cost effective compared to trial and error, the analysis can be time consuming due to the sheer number of elements involved in a major chassis. An increased use of simulations compared to physical models has drastically reduced the development cycle in the automotive industry and has enabled many teams in motorsport to be able to rapidly develop prototypes, fit them to a physical model, get performance data and then develop the design further in order to finalise a design. As with any simulation the accuracy of the data inputted or the number of elements used, has a huge effect on the precision of the of the simulation. (Ryberg, et al., 2015)

3.3 Automotive Sustainability

A growing number of manufacturers are switching their line-up to be completely electric and are either discontinuing their former ICE (internal combustion engine) vehicles in favour of electric and hybrids, this is beginning to put mounting pressure on motorsport development especially in F1. Although Electric cars are viewed to be environmentally friendly as there are no carbon emissions, this cannot be the case. A major contention with the electric vehicle is the rare earth metals such as lithium and cobalt that are used in the creation of the batteries. This has a similar record with the way diesels were first introduced, referred to as the wonder fuel for fuel economy, as technology developed the actual harm that they caused to the environment started to appear. With the vast majority of lower-class families relying on older cars, they simply cannot afford to convert to either full electric or hybrid due to the cost up front regardless of savings acquired from the tax-free incentives. Although electric cars can be viewed as carbon neutral after they have been built, the use of older cars can be seen as better for the environment, we can show this by the below equation:

$$\text{g/km} * \text{Annual Milage (11,430)} * 1.6 / 1000$$

As the E46 M3 produces 287g/km of carbon emissions and the average milage of a car in the UK is 11430 miles (Transport, 2022) we can assume that the average carbon emissions for the M3 can be 5284.656kg of carbon per year. From this we can see that the carbon output of a performance car can be seen to be lower than the carbon output of 7300kg to produce the lithium for a Tesla battery ((PhD), 2022)

Year	Car type	Petrol cars mileage	Diesel cars mileage	Business mileage	Commuting mileage	Other private mileage	Total mileage	Unweighted sample size: all cars
2002	Private car	8,000	10,900	800	2,500	5,100	8,400	6,881
2002	Company car [note 4]	18,800	23,800	9,000	5,700	5,700	20,500	457
2002	All cars	8,600	12,900	1,300	2,700	5,100	9,200	7,338
2003	Private car	8,000	11,400	800	2,600	5,100	8,500	7,353
2003	Company car [note 4]	18,200	24,200	8,100	6,600	5,700	20,400	460
2003	All cars	8,500	13,300	1,200	2,800	5,100	9,200	7,813
2004	Private car	8,000	11,300	700	2,600	5,100	8,400	7,075
2004	Company car [note 4]	18,400	24,700	8,200	7,600	5,500	21,300	370
2004	All cars	8,300	13,300	1,100	2,800	5,200	9,100	7,445
2005	Private car	7,800	11,000	700	2,500	5,100	8,300	7,743
2005	Company car [note 4]	17,000	22,700	7,900	7,000	5,200	20,100	410
2005	All cars	8,100	12,900	1,100	2,700	5,100	8,900	8,153
2006	Private car	7,600	10,800	700	2,500	4,900	8,200	7,658
2006	Company car [note 4]	14,200	22,800	7,500	6,800	5,300	19,600	406
2006	All cars	7,800	12,800	1,000	2,800	4,900	8,700	8,064
2007	Private car	7,600	11,000	700	2,500	5,000	8,300	7,513
2007	Company car [note 4]	16,000	22,300	8,300	6,100	5,800	20,200	398
2007	All cars	7,800	12,800	1,100	2,700	5,000	8,900	7,911
2008	Private car	7,400	10,500	700	2,500	4,900	8,000	6,977
2008	Company car [note 4]	13,000	23,100	7,900	6,800	5,100	19,800	322
2008	All cars	7,500	12,300	1,000	2,700	4,900	8,600	7,299
2009	Private car	7,100	10,600	700	2,400	4,800	7,900	7,454
2009	Company car [note 4]	13,100	21,200	7,000	6,700	5,200	18,900	278
2009	All cars	7,200	11,700	900	2,600	4,800	8,300	7,732
2010	Private car	7,000	10,400	600	2,500	4,700	7,900	7,175
2010	Company car [note 4]	12,700	21,000	7,700	6,200	4,800	18,700	304
2010	All cars	7,100	11,600	900	2,700	4,700	8,300	7,479
2011	Private car	6,900	9,900	600	2,400	4,700	7,700	6,760
2011	Company car [note 4]	15,300	20,500	8,000	6,600	4,800	19,400	252
2011	All cars	7,000	11,000	900	2,600	4,700	8,100	7,012
2012	Private car	6,700	10,000	600	2,400	4,700	7,700	7,205
2012	Company car [note 4]	9,700	22,200	7,600	6,900	4,700	19,200	253
2012	All cars	6,800	11,200	800	2,500	4,700	8,100	7,458
2013	Private car	6,600	9,800	500	2,600	4,400	7,500	7,115
2013	Company car [note 4]	12,500	19,900	6,300	7,600	4,700	18,600	234
2013	All cars	6,700	10,700	700	2,800	4,400	7,900	7,349
2014	Private car	6,600	9,600	400	2,700	4,400	7,500	6,941
2014	Company car [note 4]	10,900	21,500	7,200	7,400	5,000	19,500	236
2014	All cars	6,700	10,700	700	2,800	4,400	7,900	7,177
2015	Private car	6,500	9,700	400	2,700	4,400	7,500	7,113
2015	Company car [note 4]	9,400	20,100	5,500	8,200	4,600	18,300	270
2015	All cars	6,500	10,700	600	2,900	4,400	7,900	7,383
2016	Private car	6,500	9,500	400	2,600	4,400	7,500	7,105
2016	Company car [note 4]	8,900	20,900	7,100	6,700	5,100	18,900	221
2016	All cars	6,500	10,400	600	2,800	4,400	7,800	7,326
2017	Private car	6,500	9,400	400	2,600	4,500	7,500	6,545
2017	Company car [note 4]	10,100	19,800	4,500	9,100	4,400	18,000	202
2017	All cars	6,500	10,100	500	2,800	4,500	7,800	6,747
2018	Private car	6,600	8,900	300	2,500	4,600	7,400	6,501
2018	Company car [note 4]	11,300	19,500	5,100	7,600	4,700	17,500	158
2018	All cars	6,600	9,400	400	2,600	4,600	7,600	6,659
2019	Private car	6,300	8,900	300	2,500	4,400	7,200	6,468
2019	Company car [note 4]	11,000	20,800	4,200	9,400	4,900	18,400	139
2019	All cars	6,300	9,400	400	2,700	4,400	7,400	6,607
2020	Private car	5,900	8,300	200	2,400	4,100	6,700	3,150
2020	Company car [note 4]	11,900	14,400	1,600	7,900	3,700	13,200	56
2020	All cars	5,900	8,400	200	2,400	4,100	6,800	3,206
2021	Private car	4,600	6,300	200	1,700	3,300	5,200	4,555
2021	Company car [note 4]	6,900	12,900	1,200	6,000	3,000	10,200	95
2021	All cars	4,600	6,500	200	1,800	3,300	5,300	4,650

Table 1 shows the annual mileage of taxed vehicles in the UK provided by the office for national statistics.

3.4 Composite materials used in the M3.

Through the various iterations of the E46 M3 several different panels were designed to be manufactured using composites, these include fibreglass wings on the GTR, a carbon fibre roof panel and boot lid on the CSL model. Since the end of its production, more advancements have been made such as carbon-ceramic brake disks used on the Porsche 911 GT2, although they carry an enormous cost, they can increase the braking performance of a given vehicle and generally have an estimated lifetime much longer than what is feasible for a car. The manufacturing process for carbon fibre has become more mainstream in recent years, reducing the cost towards the consumer. Due to this, carbon fibre is more commonly used on cars as a design choice rather than a performance upgrade such as carbon interior panels or general plastic hydro-dipped to mimic carbon.

3.5 An example of failure within the automotive industry.

Premature failure has been an issue that has plagued the automotive industry since its beginning, from the Ford Pinto recall to the subframe cracks that can be seen on all versions of the BMW E46, these issues continue to cause disruption and have been noticed to appear at different points within a cars lifetime. The Ford Pinto suffered from a failure point in the rear of the car, in the event of a rear-end collision, the fuel tank would rupture and engulf the car in flames. This resulted in the entirety of the cars life cycle being cut short due as it was determined by Ford that the cost of a settlement for all consumers involved would be more cost effective than a recall and repair of all the cars produced with that issue. A catastrophic failure like this has been investigated by the correct authorities and has initiated changes to the laws surrounding automotive manufacturing as can be seen from this quote: The decision was then made to increase the speed of the crash tests to at least 35 miles per hour beyond the Pinto's "fire threshold" (and beyond the federal minimum) - so that fuel-tank integrity would be compromised and sufficient leakage would occur to justify the application of the label "safety defect." (Lee, 1998)

3.6 Evolution of aerodynamics as a result of FEA methods.

With the advancements in computing technology, FEA (Finite Element Analysis) has been able to generate data that is more accurate to a real situation without the influx of noise from the computer. Noise is commonly referred to as interference from the computer having to take an average of the data provided, the limitations of this are that the data gathered from a FEA simulation that doesn't have as accurate data. With the increase of computing power over recent decades in accordance with Moore's Law - Moore's Law is a prediction made by Gordon E. Moore in 1965, stating that the number of transistors on a microchip will double every 18 to 24 months, resulting in an exponential increase in computing power. (Moore, 1965) with the increase of more computing power, more elements are able to be used in any given simulation in a shorter amount of time prior to any prototyping taking place. This specific advancement has drastically increased the production speed of aerodynamic parts, especially in motorsport.

4 Conclusion

From the information discussed within this report we can conclude that although there have been numerous significant advancements within the engineering fields, but due to the E46 M3 being ahead of it's time during its production cycle, by the time these advancements could be fully utilised the M3 had already finished production. Further to this, the BMW E46 can still perform competitively with other vehicles that have utilised these advancements. Being the last hand drawn BMW and the last generation of BMW to feature hydraulic power steering, the E46 has been labelled as the last true analogue BMW and fulfils their slogan as the ultimate driving machine. These advancements have given the manufacturers a shorter and more cost-effective development and design cycle and further to this the first-hand consumer a shorter ownership cycle. With the inclusion of home computers being able to simulate fluid motion and aerodynamics, the electronic achievements have also aided the enthusiast market and second-hand markets to further develop their own cars.

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