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Chapter 1 - Introduction

For an Engineering Management Project, our group was appointed with the task of evaluating and enhancing a designated component of BMW's N52 engine used in our UWTSD prepared and run BMW 130i E87 Rally Car.

The purpose of this project is to conduct a technical review of a key engine component and propose design improvements to elevate its performance, dependability, and operational efficiency.

Following the assessment of several potential areas for development, the team decided to concentrate on the engine's intake system.

The engine intake system governs the supply of air to the engine, playing a key role in determining airflow dynamics, mixture preparation, and combustion performance. At present, the vehicle retains an intake system that is largely unchanged from the original manufacturer design, maintaining the factory configuration of components for standard road use. These constraints limit the engine's performance potential and therefore present a clear opportunity for optimisation.

The project will begin with a comprehensive analysis of the current intake configuration, considering factors such as component geometry, airflow dynamics, and its integration within the wider engine system. To establish reliable baseline data, the project will employ a combination of experimental flow bench testing and engine modelling using Ricardo WAVE. These approaches will help identify key airflow restrictions, volumetric efficiency issues, and other intake-related limitations affecting engine performance.

Based on the analysis and supporting research, design improvements to the intake system will be proposed to increase airflow, reduce pressure losses, and improve volumetric efficiency while maintaining compatibility with the existing engine architecture.

Overall, this study aspires to contribute to a deeper understanding of intake system design and optimisation in high-performance engine applications. The knowledge gained will be applied within a real-world motorsport context, with the overall goal of achieving tangible improvements in engine performance.

Chapter 2 – Project Organisation

Table 1: Revised Roles and Responsibilities

Robbie Sanford	Isaac Jones	Wesley Ives	Snasloy D'Silva
Project Manager & Data Acquisition	Modelling	Product Testing & Development	~~Product Innovation~~
- Research & Data Collection	- Computer-Aided Design	- Ricardo Wave Simulation	~~- Research & Data Collection~~
- Data Analysis & Evaluation	~~- Computational Fluid Dynamics~~	- Flow Bench Testing	~~- Data Analysis & Evaluation~~

Finlay Kingscott	Callum Jones	Odin Robinson
Vice Project Manager	Product Testing & Development	Product Innovation
- Computer-Aided Design	- Data Collection & Evaluation	- Research & Data Collection
- Computational Fluid Dynamics	- Initial Designs	- Strain & Performance Testing

Belbin's Team Role model is a recognised framework used to identify individual strengths and team contributions. Within our group, it was used to understand how each member could best support the project. This helped guide the allocation of responsibilities and encouraged balanced collaboration across the team.

During the early stages of the project, the team encountered challenges related to the distribution of workload and available resources. Due to limited participation from one team member, the group experienced a reduction in available manpower. Consequently, the team's roles and responsibilities were reassessed and redistributed to ensure that the remaining workload could be managed effectively.

As a result of these changes, the project scope required revision to ensure the workload remained manageable within the available resources and timeframe. Consequently, the originally proposed Computational Fluid Dynamics (CFD) analysis was removed from the methodology, allowing the team to focus on the remaining experimental and modelling activities.

Chapter 3 – Contributions to the Project

Table 2: Revised Contributions

Intake System		
Robbie Sandford	- Initial Data Research Collection - Meeting Coordination - Technician Liaison	
	Michael Penny	Technician Support and Guidance
	David Cooper	Water Jetting Services
	Ian Henshaw / Phillips	3D Printing Services
	- Cylinder Head Geometry Scanning - Manual Dimensional Measurements for Model Development - Flow Bench Data Analysis and Recommendations - Engine Performance Analysis Based on Dynamometer Test Data	
Isaac Jones	- Computer-Aided Design Modelling - Cylinder Head Geometry Scanning - Manual Dimensional Measurements for Model Development	
Wesley Ives	- Riccardo Wave Simulation - Cylinder Head Flow Benching Testing	
Snasloy D'Silva	- TBA	
Valvetrain System		
Finlay Kingscott	- Camshaft Scanning - N52 Head Flow Benching - 3D Modelling & Motion Simulation	
Callum Jones	- TBA	
Odin Robinson	- TBA	

Robbie Sandford – Project Manager

Initial Data Research Collection

The initial stage of the project involved a structured data research collection process, beginning with primary research before progressing to secondary sources.

Primary Research; this approach ensured a fundamental understanding of the BMW N52 engine intake system based on direct observation rather than solely relying on existing literature.

Primary research involved studying the fundamental operation and layout of the intake system, supported by observational analysis of the physical components. This included the dismantling of the engine's airbox assembly, which provided valuable insight into its internal geometry. Upon inspection, it was evident that the airbox contained multiple sharp corners and tight radii, which is detrimental from a fluid dynamics standpoint. Furthermore, these features can massively disrupt the smooth flow of air, promoting turbulence and flow separation, which in turn reduces volumetric efficiency and increases pressure losses within the intake system. This compromises engine performance due to reduced airflow density and stability at the combustion chamber, ultimately limiting power output and efficiency.

Following this, rigorous secondary research was conducted to supplement and validate the findings from the primary investigation.

One notable source consulted was a discussion thread on a BMW Forum, where experienced users analysed the function of the BMW N52's main air filter system. The discussion revealed that the vehicle's integrated airbox main filter is primarily designed for emissions control and noise reduction rather than for critical engine protection. Users frequently referenced a common modification known as a "charcoal delete," which involves removing this element to marginally improve airflow. While this modification was reported to slightly reduce intake restriction, the consensus indicated that real-world performance gains are minimal, typically limited to a subtle increase in intake sound and a marginal improvement in throttle response, with negligible impact on overall horsepower. This suggests that, although the component contributes to restriction, it is not the primary bottleneck within the system. (E90post.com, 2019)

Overall, the findings from both primary and secondary research indicate that the BMW N52 intake system remains largely in its original, factory-restricted configuration. While these design choices prioritise emissions compliance, acoustic refinement, and manufacturability, they introduce limitations in airflow efficiency. This presents a clear opportunity for optimisation through a bespoke intake design, where improved internal geometry and reduced flow restrictions could enhance engine breathing and overall performance.

Individual Throttle Bodies Research

The study of Individual Throttle Bodies (ITBs) constituted a key element in the assessment of potential intake system performance gains. According to an article published by Car Throttle ITBs operate by replacing a single shared throttle body with a dedicated throttle plate for each cylinder, thereby providing each cylinder with its own direct and unobstructed air supply.

This configuration significantly shortens the intake path and improves airflow distribution, resulting in reduced pumping losses and enhanced volumetric efficiency. One of the primary advantages of ITBs is their ability to deliver exceptionally sharp throttle response, as the reduced intake volume allows the engine to react more immediately to throttle inputs. Additionally, ITBs are particularly beneficial in high-revving, naturally aspirated engines, where they support improved airflow at higher engine speeds and contribute to a more aggressive and distinctive intake sound. While modest power gains can be achieved, the most notable improvement lies in engine responsiveness and driver engagement rather than outright increases in horsepower. However, these systems are inherently more complex and costly, requiring precise calibration and tuning, which makes them more suitable for performance-oriented or enthusiast applications rather than standard road use. (Robinson, 2024)

Further research identified that BMW's high-performance S54 engine, as found in the BMW M3 E46 and earlier M3 E36 models, incorporates ITBs as a factory feature.

This emphasises their viability in a production performance application, where maximising throttle response, airflow efficiency, and high-RPM performance is critical. In these M3 applications, ITBs are utilised to complement the engine's high-revving characteristics and motorsport-derived engineering philosophy, reinforcing their suitability for performance-driven designs.

Given that the specific N52 engine in the Universities Rally Car operates without the use of Valvetronic, the camshafts are set to maximum valve lift, meaning the engine behaviour becomes more comparable to a traditional throttle-controlled system. This creates an opportunity to adopt similar design principles to those seen in the S54, leveraging a proven performance architecture. Consequently, implementing an ITB-inspired intake design presents a viable approach to enhancing airflow efficiency and throttle response within the N52 platform, aligning with established engineering practices demonstrated in BMW's own high-performance engines.

Jenvey SF and Linkage Research

We chose Jenvey SF throttle bodies because we wanted a setup with a proven background, not just something generic. Jenvey has been part of the UK motorsport industry since 1987, and that kind of experience gives us confidence that their products are properly developed and tested in real racing environments. Knowing they design and manufacture everything in-house also reassures us that the quality and consistency are where they should be.

Furthermore, Jenvey have a wide variety of quality materials. Moreover, the throttle bodies are made from high-grade aluminium, which keeps them lightweight but strong, and the internal components like; PTFE-lined bearings, which are designed to handle heat and reduce friction over time. Everything is machined to tight tolerances, which means consistent airflow across all cylinders and a stable, reliable setup. That level of precision is something we didn't want to compromise on.

Additionally, another factor for us was the flexibility of the SF range. There are different sizes and configurations available, so we could choose a setup that actually suits our engine rather than trying to adapt something that isn't quite right. On top of that, Jenvey offers a full range of supporting components like manifolds, linkages, and fuel rails, so we're working with a complete, well-matched system rather than mixing parts from different sources.

Overall, we chose Jenvey SF throttle bodies because they offer a combination of motorsport-proven reliability, high-quality materials, and the performance gains we were looking for. It's a setup we can trust to deliver consistent results without the issues that often come with cheaper alternatives.

Drive-By-Wire Throttle Research

The decision to retain a drive-by-wire (DBW) throttle control system, in place of a conventional cable-operated linkage, is based on its advantages in precision, integration, and adaptability to future developments. With the existing AIM standalone ECU already supporting DBW functionality, this approach facilitates the full utilisation of advanced engine management strategies without complicating the system unnecessarily. Unlike a cable throttle, which provides a fixed and purely mechanical relationship between pedal input and throttle position, DBW enables fully programmable throttle mapping. This permits the response to be adjusted depending on factors such as; engine speed, load, or driving conditions, resulting in improved drivability at low speeds and sharper response when required. Additionally, DBW allows for more effective torque control, as the ECU can adjust throttle position independently of pedal input to maintain traction and stability, which is particularly valuable in a high-performance application.

The integration of DBW with Jenvey SF individual throttle bodies featuring electronically controlled butterflies enhances the validity of this approach. These throttle bodies are designed to operate with electronic actuation, maintaining precise and consistent airflow across all cylinders while maintaining highly responsive to control inputs. This level of control eliminates the inconsistencies and maintenance concerns associated with mechanical linkages, such as cable stretch or binding, while also simplifying the overall system, eliminating the need for separate idle control components. The electronic system also incorporates built-in safety features, including sensor redundancy and fail-safe strategies, providing a level of reliability that cannot be achieved with mechanical setup.

Another key factor in choosing DBW is its role in future-proofing the vehicle. With plans to implement a sequential gearbox, the ability to integrate advanced features such as an automated throttle blipper becomes essential.

DBW allows the ECU to precisely control throttle opening during up and downshifts, matching engine speed to gearbox input and significantly reducing drivetrain shock while improving stability under braking. It also provides the capability to implement additional strategies, such as flat-shift, where torque can be momentarily reduced during up and down shifts to allow clutchless gear changes, as well as refined launch control. Beyond this, DBW offers flexibility in system packaging, improved data logging capabilities for analysis and tuning, and the ability to implement multiple driver-selectable throttle maps.

Overall, the adoption of a drive-by-wire throttle system provides a more advanced, reliable, and adaptable solution compared to a cable-operated alternative. It not only enhances current performance and control but also ensures compatibility with future developments, making it a key component in achieving a cohesive and forward-thinking vehicle setup.

Meeting Coordination and Technician Liaison

A major part of my role as Project Manager is Meeting Coordination and Liaison, allowing close monitoring of progress of the project while maintaining direct communication with involved personnel involved in each stage of the work.

Through organising and attending meetings with clearly defined agendas and following up on actions, I am able to ensure that everyone understands their responsibilities, that any issues are identified early, and that solutions can be discussed collaboratively.

Continuous engagement with relevant personnel also allowed me to gather feedback, clarify technical details, and keep all involved parties aligned with the project's objectives and timeline.

Michael Penny provided essential Technician Support and Guidance; his extensive years of experience in technical processes meant that he was able to offer practical advice, troubleshoot potential problems, and guide decisions relating to equipment use, manufacturing methods, and safe working practices. His input helped ensure that technical aspects of the project were carried out efficiently and correctly.

Furthermore, David Cooper contributed through water jetting, which proved extremely helpful for accurately cutting materials to the required dimensions and shapes. The precision and efficiency of the water jetting process allowed components to be produced while maintaining a high level of accuracy, reducing manual work and helping the project stay on schedule.

Finally, Ian Henshaw / Phillips supported the project with 3D printing, enabling prototyping and the production of custom components that would have been difficult or time-consuming to manufacture using traditional methods. This allowed design ideas to be tested, modifications to be made efficiently, and functional parts to be produced when required.

Overall, a large part of my role involved exchanging emails and communicating through Microsoft Teams to coordinate tasks, share updates, and keep track of progress across the team, ensuring that everyone remained informed and that project milestones and deadlines were successfully met.

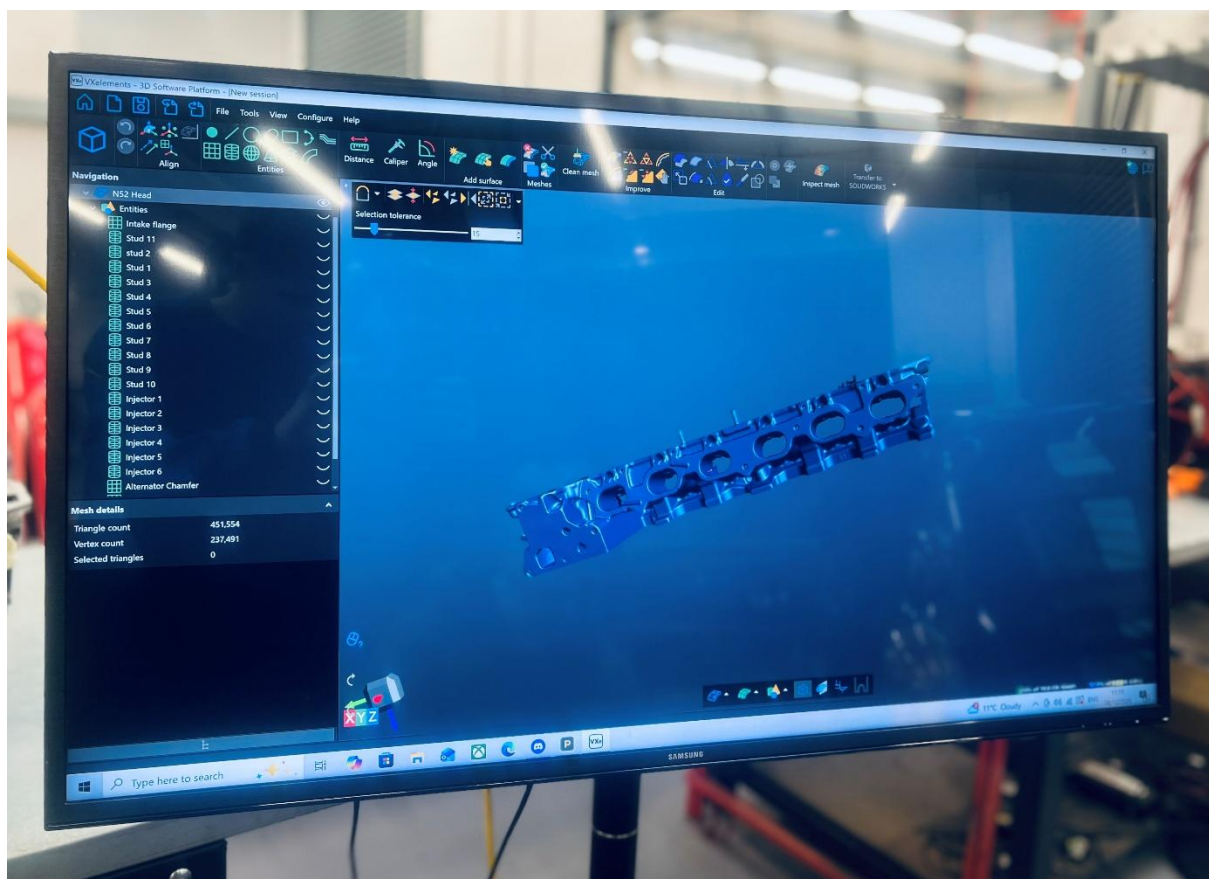
Cylinder Head Geometry Scanning

Detailed scanning of the cylinder head geometry enabled development work to be carried. Furthermore, this permitted me to obtain an accurate digital representation of the cylinder head that would later be used for design purposes.

The process initially required me to schedule and book a suitable time slot for the 3D scanner, it was imperative that we had enough allocated time to complete the full scanning procedure without interruption, as capturing a complex component such as a cylinder head requires multiple angles and careful positioning.

Furthermore, before beginning the main scan, a preliminary scan was performed in order to familiarise ourselves with the scanner's functions, controls, and operational workflow. This step was fundamental as it enabled me to understand how to correctly position the scanner, maintain the optimal distance from the component, and ensure consistent coverage so that the system could precisely capture the geometry of the part. After gaining confidence with the equipment, I was able to undertake the full scan of the cylinder head, gradually capturing all visible surfaces in order to generate a detailed digital model.

Figure 1: Post-Processing Software



The scan was conducted with the goal of precisely capturing the geometry of the cylinder head face to produce a precise visualisation of the component, particularly the port and mounting geometry, so that it could later be used as a precise reference when designing a bespoke intake manifold that would correctly align with the cylinder head. Following completion of the scanning stage, the raw data required post-processing, this stage involved refining the scan by eliminating redundant points, overlapping data, and background artifacts, which are typically known as noise. By filtering and refining the scan data, Consequently, a more precise representation of the cylinder head surface was obtained.

This processed scan provided precise geometric data for use in the later CAD modelling stages, which is essential for achieving proper fitment and alignment when designing and manufacturing the intake manifold.

Manual Dimensional Measurements for Model Development

Manual dimensional measurements were undertaken to support accurate model development and to validate the scanned geometry. Although the Peel 3D scan provided a high nominal tolerance of ± 0.05 mm, minor discrepancies were identified on the cylinder head mating face. This was considered to be caused by anticipated scan noise, especially in areas with sharp edges, reflective surfaces, or limited line-of-sight, each contributing to subtle deviations in the resulting data.

Given that the cylinder head face is a critical sealing surface, even minimal inaccuracies could propagate into fitment issues within the final design. Therefore, manual verification was necessary to preserve the fidelity of this surface before progressing into CAD modelling.

For the intake chamber ports, an internal Micrometer was used to confirm and refine the recorded dimensions. This tool was chosen because of its suitability and ability to provide highly accurate and repeatable measurements of internal diameters. This is not always reliably captured using scanning techniques alone. Furthermore, the recessed and cylindrical nature of the ports can negatively affect scan accuracy due to shadowing and reduced point density. The internal Micrometer, by physically contacting the internal surfaces, eliminates these uncertainties and ensures that the dimensions used in the model reflect the true physical geometry. This was critical to maintaining optimal airflow characteristics and ensuring compatibility with mating components.

An additional key measurement centred on the steel collet inserts located at the interface between the intake manifold and the cylinder head. It was imperative that these components were captured accurately due to two key factors. Firstly, they are a readily available OEM BMW component, meaning that retaining their geometry ensures alignment with standard components and reduces complexity in manufacturing and assembly.

Secondly, they serve a vital function within the system: the steel inserts provide a robust, heat-resistant interface within the plastic intake manifold. In light of the elevated thermal conditions at the cylinder head, the inserts prevent deformation, creep, and long-term material degradation. Moreover, they ensure uniform clamping and reliable sealing integrity. Beyond this, accurately modelling these inserts ensures that these mechanical and thermal benefits are preserved in the final design.

Finally, the rubber gaskets used at the intake manifold ports were also measured. Similar to the steel inserts, Retention of the original component was deemed appropriate to ensure proven sealing performance and ease of integration. Rubber gaskets are particularly sensitive to compression and fit. Any variation in their seating geometry may lead to air leaks or reduced engine efficiency. By precisely measuring and incorporating these components into the design, the interface between the manifold and cylinder head could be accurately replicated, thereby ensuring both reliability and serviceability.

Overall, the combination of high-resolution scanning and targeted manual measurements provided a comprehensive and validated dataset. This hybrid approach ensured that critical features were accurately defined, ultimately enabling the development of a precise, reliable, and manufacturable CAD design.

Flow Bench Results

Table 3: OEM Standard N52 Intake Manifold

Standard Intake Manifold - Intake Valve Test Data						
1	Test Number	1	2	3	4	5
2	Test Pressure	25	25	25	25	25
3	Valve Lift (A)	1.71	3.42	5.13	6.84	8.55
4	Flow Range (1-6)	2	3	4	4	4
5	Flow Scale Reading (%)	80	73	51	61	68
6	Flow Scale (5./100)	0.8	0.73	0.51	0.61	0.68
7	Raw Test Flow l/s (6. x E)	26.56	50.881	70.482	84.302	93.976
8	Leakage (l/s)	0	0	0	0	0
9	Test Flow (l/s) (7-8)	26.56	50.881	70.482	84.302	93.976
10	Test Flow (l/s/sq cm)	1.478842	2.833018	3.924388	4.693875	5.232517
11	Maximum Flow (l/s)	93.976				

Table 4: Intake Runner With 45mm Jenvey SF Throttle Body

45mm - Intake Valve Test Data								
1	Test Number	1	2	3	4	5	6	7
2	Test Pressure	25	25	25	25	25	25	25
3	Valve Lift (A)	1.6	3.2	4.8	6.4	8	9.6	11.2
4	Flow Range (1-6)	2	3	3	4	4	4	4
5	Flow Scale Reading (%)	64	62	91	51	58	62	67
6	Flow Scale (5./100)	0.64	0.62	0.91	0.51	0.58	0.62	0.67
7	Raw Test Flow l/s (6. x E)	21.248	43.214	63.427	70.482	80.156	85.684	92.594
8	Leakage (l/s)	0	0	0	0	0	0	0
9	Test Flow (l/s) (7-8)	21.248	43.214	63.427	70.482	80.156	85.684	92.594
10	Test Flow (l/s/sq cm)	1.183	2.406	3.532	3.924	4.463	4.771	5.156
11	Maximum Flow (l/s)	92.594						

Table 5: Intake Runner With 48mm Jenvey SF Throttle Body

48mm - Intake Valve Test Data								
1	Test Number	1	2	3	4	5	6	7
2	Test Pressure	25	25	25	25	25	25	25
3	Valve Lift (A)	1.6	3.2	4.8	6.4	8	9.6	11.2
4	Flow Range (1-6)	2	3	3	4	4	4	4
5	Flow Scale Reading (%)	62	61	92	54	59	65	69
6	Flow Scale (5./100)	0.62	0.61	0.92	0.54	0.59	0.65	0.69
7	Raw Test Flow l/s (6. x E)	20.584	42.517	64.124	74.628	81.538	89.83	95.358
8	Leakage (l/s)	0	0	0	0	0	0	0
9	Test Flow (l/s) (7-8)	20.584	42.517	64.124	74.628	81.538	89.83	95.358
10	Test Flow (l/s/sq cm)	1.146	2.367	3.570	4.155	4.540	5.002	5.309
11	Maximum Flow (l/s)	95.358						

Robbie Sandford Flow Bench Testing Analysis and Justification

The flow bench testing results allow for a direct comparative evaluation of the three intake configurations under controlled conditions. The standard BMW N52 intake manifold achieved a maximum airflow of 93.976 l/s, forming a baseline for the evaluation of the modified designs. This result reflects a well-balanced OEM design optimized for drivability, emissions, and manufacturing constraints rather than peak airflow alone.

The 45 mm throttle body intake configuration recorded a slightly lower maximum flow of 92.594 l/s. This reduction, while modest, can reasonably be attributed to several design-related factors. Although the throttle body size is similar to or marginally optimized compared to stock, the transition geometry between the throttle body and the intake runners may introduce additional turbulence or flow separation. Sharp changes in cross-sectional area, insufficient tapering, or internal surface irregularities could disrupt laminar airflow. Additionally, the integration of the Jenvey SF throttle body may alter upstream airflow characteristics, potentially creating minor restrictions or uneven distribution across the runners. These factors collectively suggest that while the design intent was performance-oriented, the execution may not have fully optimized flow path efficiency.

Figure 2: SuperFlow SF-600 Flow Bench Layout



In contrast, the 48 mm throttle body intake design demonstrated a clear improvement, achieving a maximum flow of 95.358 l/s. The increased throttle diameter likely reduces inlet restriction, allowing a greater volume of air to enter the plenum with less pressure drop. Furthermore, this design may benefit from improved internal geometry, such as smoother transitions, better radiusing at entry points, and more uniform distribution to each intake port. The measured increase of 1.382 l/s over the standard manifold, and a cumulative gain of 8.292 l/s across all six ports, indicates a meaningful improvement in volumetric efficiency potential.

Based on these findings, the decision to proceed with the 48 mm design is well justified. It not only surpasses the OEM baseline but also demonstrates consistent gains without the apparent flow penalties seen in the 45 mm configuration. The improvements suggest a more effective balance between throttle size and internal flow dynamics, leading to enhanced overall system performance. This makes the 48 mm intake the most promising candidate for further development, particularly in applications where maximizing airflow and engine breathing efficiency are key objectives.

Figure 3: Intake Runner and 48mm Throttle Bodies



3D Scanning

To initiate the project, it was essential to obtain an accurate representation of the cylinder head intake ports. This was achieved through 3D scanning. Capturing the precise geometry and spatial relationships of the ports, studs, and surrounding features was critical in ensuring that the final intake design would integrate correctly without interference with adjacent components.

A 3D scanning approach was selected over conventional manual measurement methods due to the complex internal geometry of the intake ports. The scanner's stated accuracy of 0.05 mm was also considered when evaluating measurement reliability. Accurately capturing these features using tools such as vernier callipers or internal micrometres would have been both time-consuming and limited in precision, particularly in areas with restricted access. In contrast, 3D scanning enabled rapid acquisition of high-resolution surface data across the entire intake region.

The cylinder head was scanned using a Peel 3D scanner, chosen for its availability and ease of use. As no prior experience with the system was available, an introductory session was undertaken to understand its operation. Initial scans were performed on a single port to build familiarity with the process before progressing to a full scan of the intake side of the cylinder head. During scanning, multiple passes were made over the ports, studs, and surrounding features from a range of angles and distances to maximise data coverage and minimise occlusions.

The resulting scan produced a visually detailed model of the cylinder head Figure 4. Post-processing was then carried out to remove overlapping geometry and surface noise, generating a clean mesh suitable for use in CAD software. Initial attempts to import the model into SolidWorks resulted in incomplete geometry, with the internal port features not displaying correctly. This issue was resolved by first opening the scan in Fusion 360, where the geometry was interpreted correctly, allowing the model to be used as a reference for further design work within SolidWorks.

Upon inspection of the imported geometry, inconsistencies in the scanned dimensions became apparent. In particular, the port diameters appeared to vary along their length, which is not physically representative of the actual component. This indicated the presence of scanning error, likely due to limited accessibility and line-of-sight constraints within the ports. To address this, an average port diameter was calculated from the scan data and applied consistently across all six ports. For the stud holes, manual measurements were taken and used to correct their size and position within the CAD model, improving overall accuracy.

Although the scan did not provide fully reliable dimensional accuracy for all features, it remained highly valuable in defining the overall geometry and spatial constraints of the cylinder head. In particular, it provided a clear representation of the available space between ports and surrounding walls, enabling the intake system to be designed with sufficient clearance and ensuring compatibility with the existing engine architecture.

Figure 4: Finalised Scanned Model

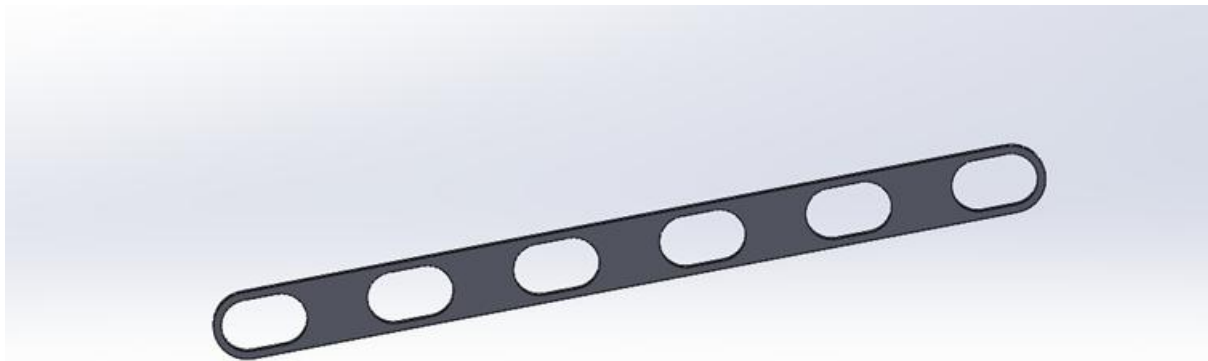


CAD Modelling and Prototyping

Computer Aided Design (CAD) software was used throughout the project to enable efficient development and refinement of the intake system components. Working within a digital environment allowed for precise control of dimensions, rapid iteration of design concepts, and verification of component fitment prior to manufacturing. This significantly reduced both development time and material waste. Furthermore, the use of CAD facilitated the production of prototypes using additive manufacturing and laser cutting processes. It was also necessary to import and work with the 3D scan of the cylinder head within the CAD environment. This enabled accurate measurements of the existing geometry and ensured that all bespoke components were designed to integrate correctly with the cylinder head.

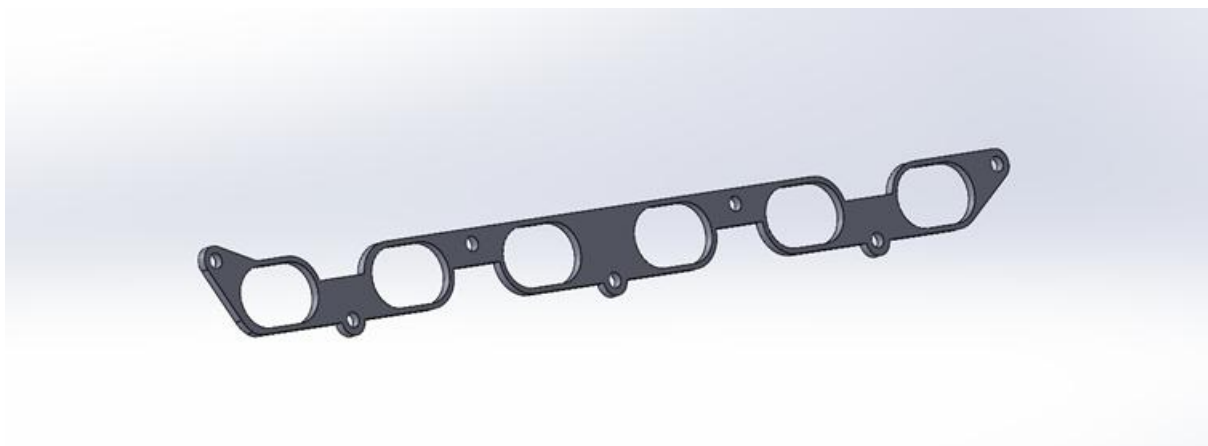
The design process for the BMW N52 intake system began with establishing accurate intake port locations. An initial port plate, shown in Figure 5, was laser cut and physically positioned on the cylinder head to identify any discrepancies between the digital model and the real component. Measurements were taken using an internal micrometre and vernier callipers, allowing deviations to be quantified and incorporated into the revised designs. This iterative approach ensured that the final port geometry closely matched the physical component.

Figure 5: Initial Port Plate



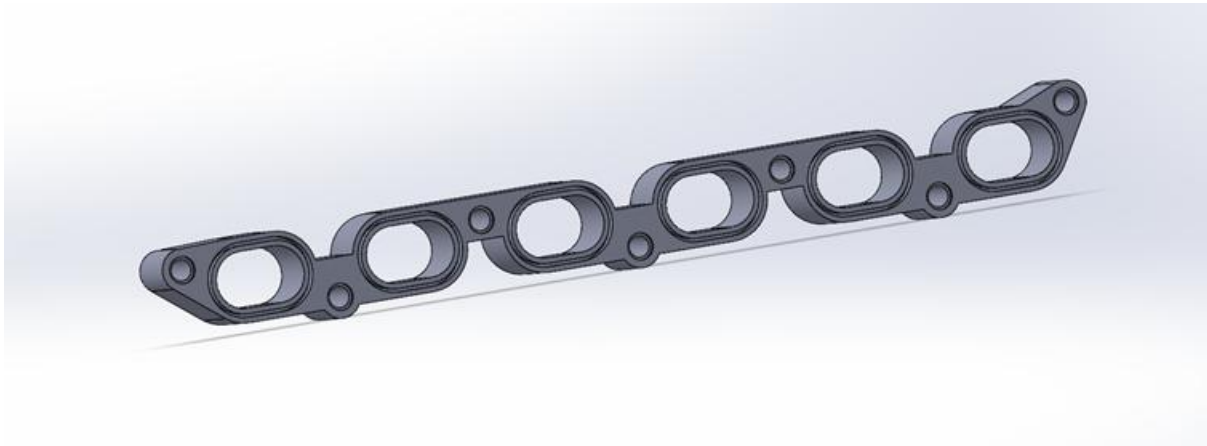
Following validation of the port positions, attention was given to the alignment and sizing of the stud holes. Dimensions obtained from the 3D scan were combined with the corrected port geometry to determine the deviations in measurements. These deviations were used to apply proportional adjustments to the hole spacing, refining the overall accuracy of the design. The resulting iteration, shown in Figure 6, required only minor adjustments before final verification through laser cutting and physical measurement.

Figure 6: Final Verification Adjustments



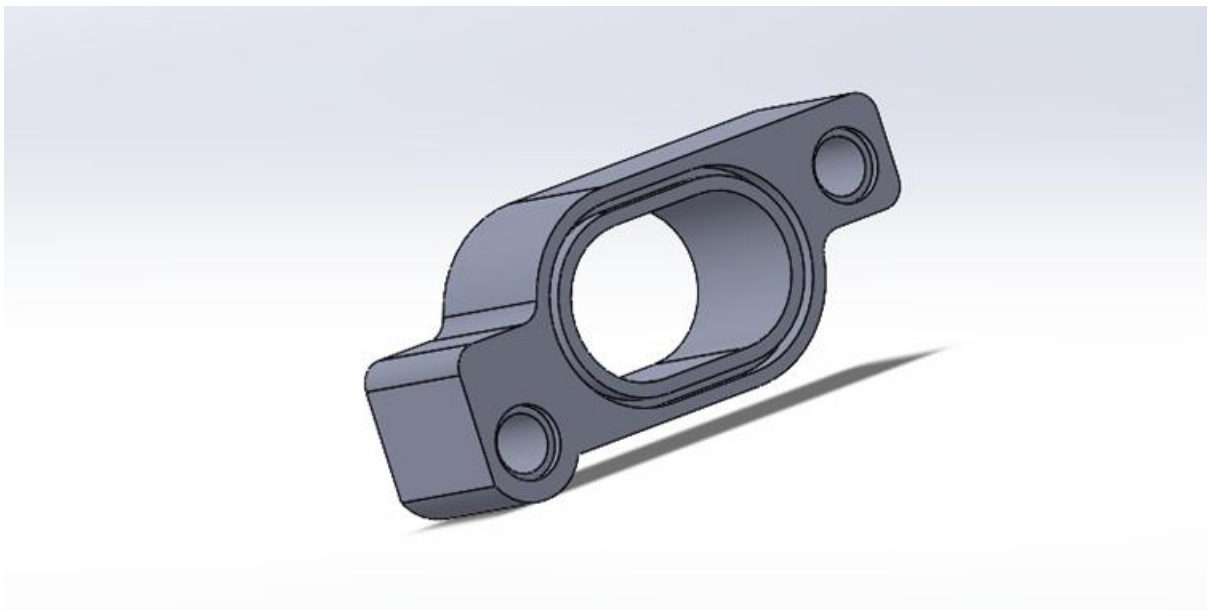
As the rally team is sponsored by BMW Sytner Swansea, a decision was made to retain and integrate OEM BMW components where possible to minimise cost and ensure compatibility. This required the incorporation of existing O-rings and steel collet inserts into the design. These components were measured and modelled accordingly and later incorporated into the design, as shown in Figure 7.

Figure 7: OEM BMW Component Integration



To reduce material usage and production time, a single intake port prototype Figure 8 was produced using 3D printing rather than manufacturing the complete assembly. Testing of this prototype identified several issues, including insufficient clearance for the steel inserts and inadequate depth for the O-ring grooves. These findings informed further refinements to the design.

Figure 8: Single Intake Port Prototype



With the flange and port geometry established, the intake runners were then developed. The orientation of the intake ports relative to the engine was accounted to be approximately 45° which was incorporated into the runner design to ensure correct alignment within the engine bay. Runner length was constrained by the available packaging space, with approximately 115 mm available when accounting for the throttle bodies and intake trumpets. While primarily dictated by spatial limitations, runner length also influences engine performance characteristics, with longer runners generally favouring higher torque. This is more desirable in rally cars than an increased performance at higher engine speeds, as it is rare for the vehicle to reach top speed.

To evaluate the effect of throttle body size, two runner designs were produced to accommodate 45 mm and 48 mm configurations, as shown in Figure 9. These designs were manufactured using 3D printing for testing purposes. In order to accurately assess airflow performance, corresponding throttle body models were also required. Technical drawings from Jenvey Dynamics (SF Single Bore Throttle Body Engineered to win, n.d.) were used to produce simplified dummy throttle body models with fully open butterfly valves Figure 10. Both 45 mm and 48 mm variants were created, enabling a direct comparison during flow bench testing.

Figure 9: Intake Runner Designs

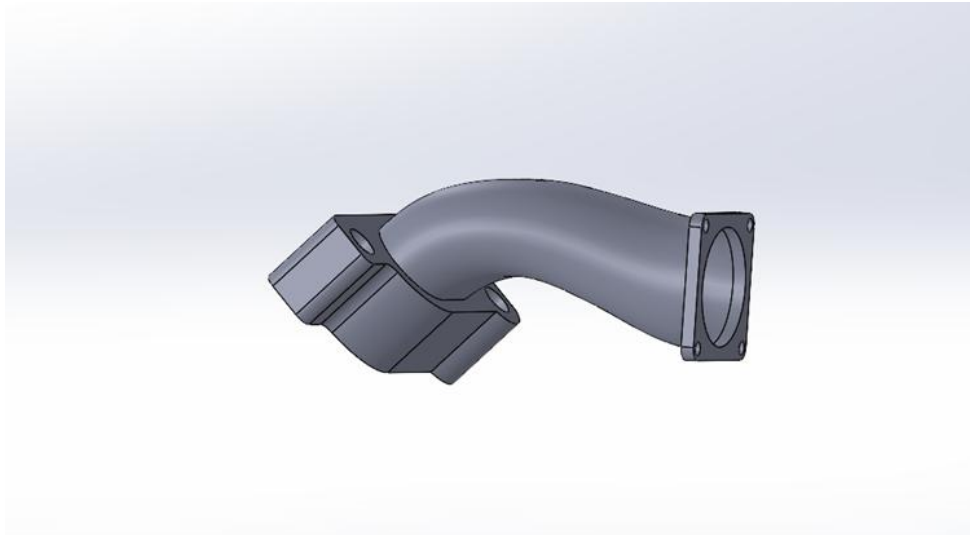
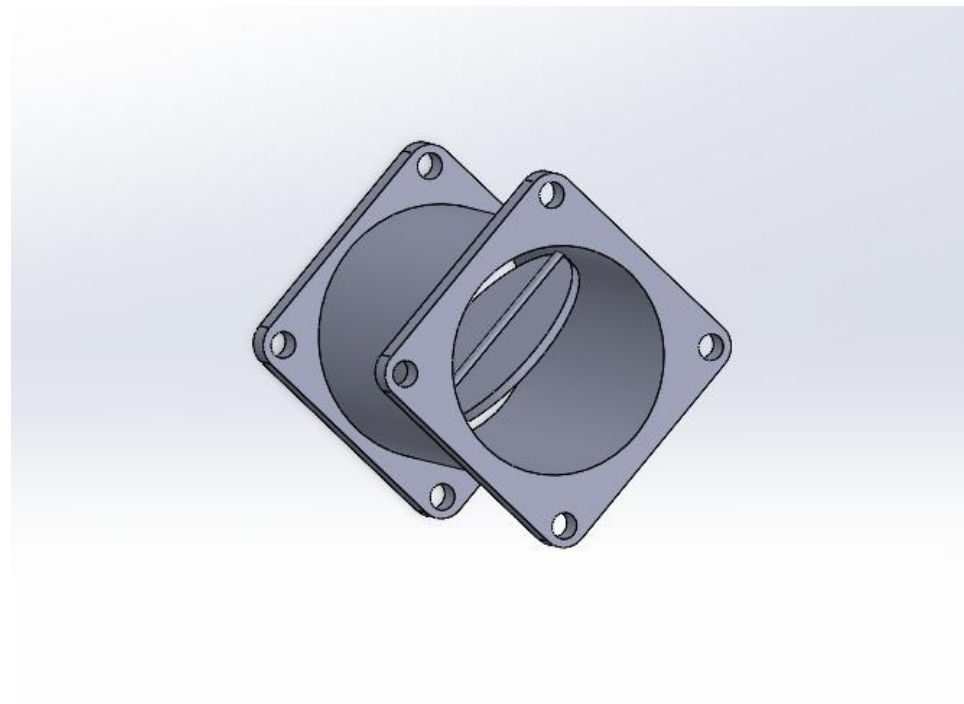
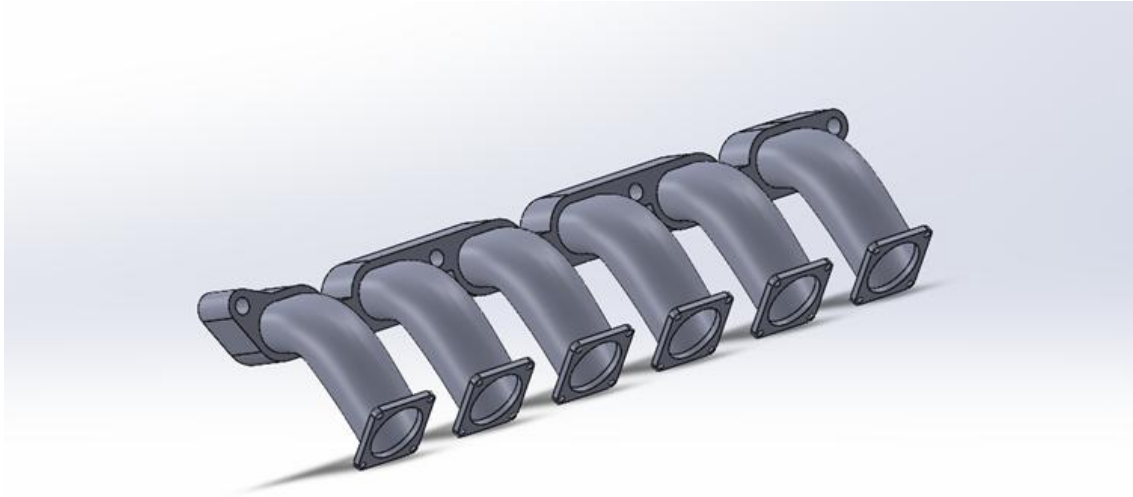


Figure 10: Dummy Throttle Body



Based on the results obtained from flow bench testing, the 48 mm configuration demonstrated superior airflow performance. Consequently, this design was selected and applied across all intake ports, resulting in the final intake system design shown in Figure 11.

Figure 11: Final Intake System Design



The final design is intended to be manufactured using a carbon nylon composite material. This material has been selected due to its high temperature resistance, strength, and stiffness, making it suitable for operation within the engine bay while supporting the mass of the throttle bodies and associated components.

During the manufacture of the flange and runner assembly (Figure 9), deformation of the holes intended for the steel inserts was observed. The printed holes were undersized and not perfectly circular, likely due to the complexity of the geometry and the orientation used during the additive manufacturing process. As a result, the inserts could not be fitted correctly for testing.

To address this, the design was modified to include increased hole clearances to compensate for printing inaccuracies. However, during production of the revised component, a printer failure occurred (Figure 12), resulting in a delay to the testing schedule. Due to a lack of time, the issue was resolved by reusing the initial model and drilling out the holes to accommodate the steel collets.

Figure 12: 3D Printing Failure



Flow Bench Testing

To accurately compare and analyse the intake designs, flow bench testing was employed. This method enabled the measurement of airflow entering the engine through a single intake port at controlled increments of valve lift, providing quantitative data on the performance of each design. By testing across a range of valve openings, it was possible to assess how airflow characteristics evolved throughout the engine's operating range. All tests were conducted under consistent conditions to ensure repeatability and reliability of the results.

Flow bench testing was carried out on the bespoke intake designs, allowing for a direct comparison between the 45 mm and 48 mm throttle body and intake runner configurations. Prior to testing, the system was checked for air leaks by fully closing the valves and running the flow bench under pressure. A stable pressure reading confirmed that no leakage was present.

Testing of the 45 mm system was conducted first. Airflow measurements were taken at increments of 1.6 mm valve lift, monitored using a mounted DTI gauge. Flow readings were recorded at each increment up to approximately 12 mm of valve lift, beyond which further increases in lift resulted in diminishing gains in airflow. The same procedure was then repeated for the 48 mm system, with the valves reset and all testing conditions maintained to ensure a consistent and valid comparison.

The collected data, presented in Tables 3/4/5 illustrate the flow characteristics of both intake systems. To provide a baseline for comparison, flow bench data for the original intake system was obtained from a previous study conducted by another student. While this provided a useful reference, it should be noted that differences in testing conditions may introduce minor discrepancies.

Comparison of the maximum flow rates indicates that the 48 mm intake system achieved the highest performance, followed by the OEM system, and then the 45 mm design. The 48 mm configuration demonstrated a maximum increase in airflow of 1.382 L/s per port compared to the OEM intake, and a 2.764 L/s increase over the 45 mm design. This improvement is likely due to the increased cross-sectional area, which reduces flow restriction at higher valve lifts, allowing greater volumetric airflow.

Wesley Ives – Product Testing & Development

Flow Bench Testing N52 Intake

The first stage of my work involved carrying out flow bench testing on the bare N52 engine cylinder head. The purpose of this was to establish a baseline understanding of how air moves through the bare cylinder head in its standard configuration. This was important as it provided real-world data and helped identify any inherent restrictions within the system before moving into simulation.

During testing, airflow through the bare cylinder head was measured under controlled conditions, allowing for consistent comparison of how efficiently the system allows air to pass through it. The results showed that while the standard intake performs adequately, there are limitations in how smoothly air enters and travels through the system. These limitations are likely caused by internal geometry and flow separation, which reduce overall airflow efficiency.

The data collected at this stage acted as a reference point for the rest of the project, ensuring that any improvements seen in simulation could be compared back to a known baseline. Overall, this stage provided a solid foundation and ensured the project was not purely simulation-based.

Ricardo WAVE Simulation – Single Cylinder Baseline

Following the flow bench testing, I began developing a simulation model using Ricardo WAVE. As I had no prior experience with the software, this stage involved teaching myself how to use it while building the model.

To make this manageable, I started with a single-cylinder version of the BMW N52. This allowed me to focus on understanding how the software works and how different components interact, without the added complexity of a full engine. This included defining intake and exhaust systems, setting valve behaviour, and applying boundary conditions.

Time was spent adjusting parameters and ensuring the outputs were stable and physically realistic. The single-cylinder model acted as a controlled environment where changes could be tested and their effects on mass flow clearly observed. By the end of this stage, I had a working model that produced consistent and realistic trends, forming the foundation for further development.

Ricardo WAVE Simulation – Inline-Six Baseline

Once the single-cylinder model was stable, I developed a full inline-six model to better represent the BMW N52 engine. This was important as the real engine is an inline-six, and cylinder interaction plays a significant role in airflow behaviour.

The model was built by expanding the existing setup, applying the correct firing order, and ensuring consistent valve timing across all cylinders. This introduced more complexity, but the understanding gained from the single-cylinder stage made it more manageable.

The inline-six model produced more realistic airflow behaviour, particularly due to pressure wave interactions within the intake system. This made the data more suitable for analysing intake performance. It was then used as the baseline for all further testing, ensuring that any changes observed could be linked directly to intake modifications.

Ricardo WAVE – 45 mm Throttle Body Simulation

With a stable baseline model, I introduced intake variations to investigate how geometry affects airflow. The first was a 45 mm throttle body configuration, replacing the standard intake within the model. This was not intended as a final design, but as a controlled test case.

The modification was implemented while keeping all other parameters the same, ensuring that any performance changes could be directly linked to the intake design. The model was then run under the same conditions, with intake mass flow used for comparison.

This setup also formed part of a comparison with the 48 mm design, aiming to determine whether increasing diameter produced a meaningful improvement. This was important from a practical perspective, as larger throttle bodies would likely increase cost. Testing both allowed for evaluation of whether the performance gain justified the difference.

Ricardo WAVE – 48 mm Throttle Body Simulation

Following this, a 48 mm throttle body configuration was introduced to further investigate the effect of increasing intake diameter. As with the 45 mm setup, this was treated as a test case rather than a final design.

The 48 mm configuration was implemented under the same conditions, allowing for direct comparison between the two designs. Intake mass flow was again used as the main performance indicator.

The results were used alongside the 45 mm data to assess whether the increase in diameter produced a significant improvement in airflow. This comparison helped determine whether the additional performance from the larger throttle bodies justified the increased cost, or whether the 45 mm option provided a better balance between performance and practicality.

The BMW N52 engine uses a system called VANOS, which is BMW's variable camshaft timing technology designed to improve performance, fuel efficiency, and emissions by continuously adjusting the timing of the intake and exhaust valves.

Unlike traditional engines that rely on fixed timing marks or clearly defined angular specifications, the N52 operates using a tool-based setup where the correct timing is established by locking the crankshaft at top dead centre and aligning the camshafts using a dedicated jig, with the VANOS unit set to its base (zero) position.

This makes the process more precise but also more complex, as there are no conventional timing marks or a published timing sheet to reference. One of the main dilemmas with this system is that BMW does not provide a simple, printable timing diagram or specification sheet; instead, all procedures are outlined in their workshop system, BMW TIS, which assumes access to specialist tools and training.

As a result, setting the timing can be difficult, especially outside a dealership environment, because the entire process depends on the correct use of locking tools rather than visual alignment. Common problems encountered include slight misalignment of the camshafts, incorrect VANOS installation due to the helical gears, and failure to achieve true top dead centre, all of which can lead to rough running, fault codes, or loss of power.

The lack of a traditional timing sheet makes it harder to verify the setup manually, which is why you may be struggling to time the engine correctly because, in essence, the “specification” is built into the tools and procedure rather than a set of published measurements or diagrams.

Chapter 5 – Research and Experiment Carried Out

Ricardo Wave Research

I carried out research into using Ricardo WAVE, as I had no prior experience with the software. This involved teaching myself from scratch using online resources, mainly YouTube tutorials, to understand how to build and run engine simulations. I learned how to define engine components, set up intake and exhaust systems, apply valve timing, and interpret results. This stage was important, as the software is not very intuitive, and developing a basic understanding was needed before building reliable models. Overall, this research provided both the theoretical understanding of intake airflow and the practical skills required to use Ricardo WAVE effectively.

The main experimental work involved flow bench testing of the BMW N52 intake system to establish a baseline of airflow behaviour in its standard configuration. Testing was carried out under controlled conditions to measure mass airflow and ensure consistent, repeatable results. This allowed any areas of restriction or unstable flow to be identified, helping to build an understanding of how the intake performs. The baseline data was then used to compare against the simulation results, ensuring that any improvements from the trumpet designs could be assessed against real-world behaviour rather than in isolation.

The design work carried out as part of this project focused on developing intake variations that could be tested within Ricardo WAVE. Rather than creating a final optimised design, the aim was to produce controlled test cases to investigate how changes in intake geometry affect airflow. Two trumpet configurations were introduced, with diameters of 45 mm and 48 mm, representing an increase in inlet size and an improved entry profile compared to the standard intake. The intention was to reduce restriction and allow air to enter the system more smoothly, which would be expected to increase mass flow.

The designs were kept deliberately simple to isolate the effect of diameter, with all other parameters kept consistent to allow direct comparison between setups. This made it easier to link any changes in performance directly to the intake geometry. A key limitation was that Ricardo WAVE did not allow the intake to be reduced below the valve head diameter, meaning the trumpet designs could not be fully representative of real-world components. Despite this, the designs still provided a useful way to compare configurations and build an understanding of how intake size influences airflow behaviour.

Chapter 8 – Development Carried Out

Ricardo Wave Development

The development work focused on building and refining engine simulation models using Ricardo WAVE. This began with a single-cylinder model, as I had no prior experience with the software and needed to develop an understanding of how it works. This stage involved setting up the intake and exhaust systems, defining valve behaviour, and applying boundary conditions. A significant amount of time was spent adjusting parameters and refining the setup to ensure the model produced stable and realistic results.

Once the single-cylinder model was working reliably, development progressed to a full inline-six configuration to better represent the BMW N52 engine. However, difficulties were encountered when attempting to replicate the N52's cam timing and VANOS system, as a suitable Ricardo WAVE profile could not be created that allowed the model to run consistently.

As a result, a comparable BMW 3.0 litre inline-six petrol engine was used within Ricardo WAVE to provide a stable baseline model. While not an exact match, it allowed for meaningful airflow analysis. The model was then modified to include the 45 mm and 48 mm trumpet configurations, ensuring all other parameters remained consistent for accurate comparison.

Figure 12: N52 Single Cylinder Ricardo Test

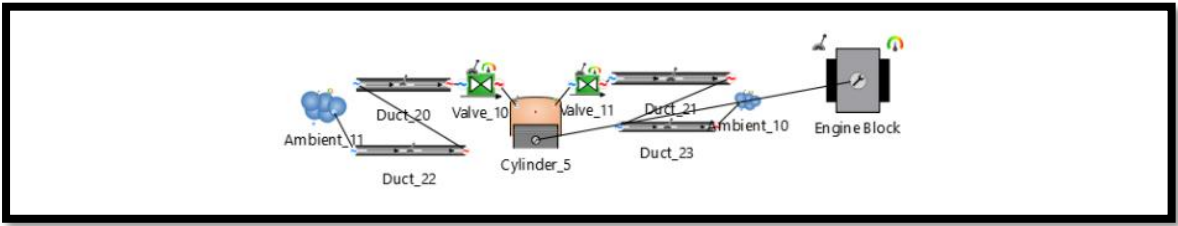
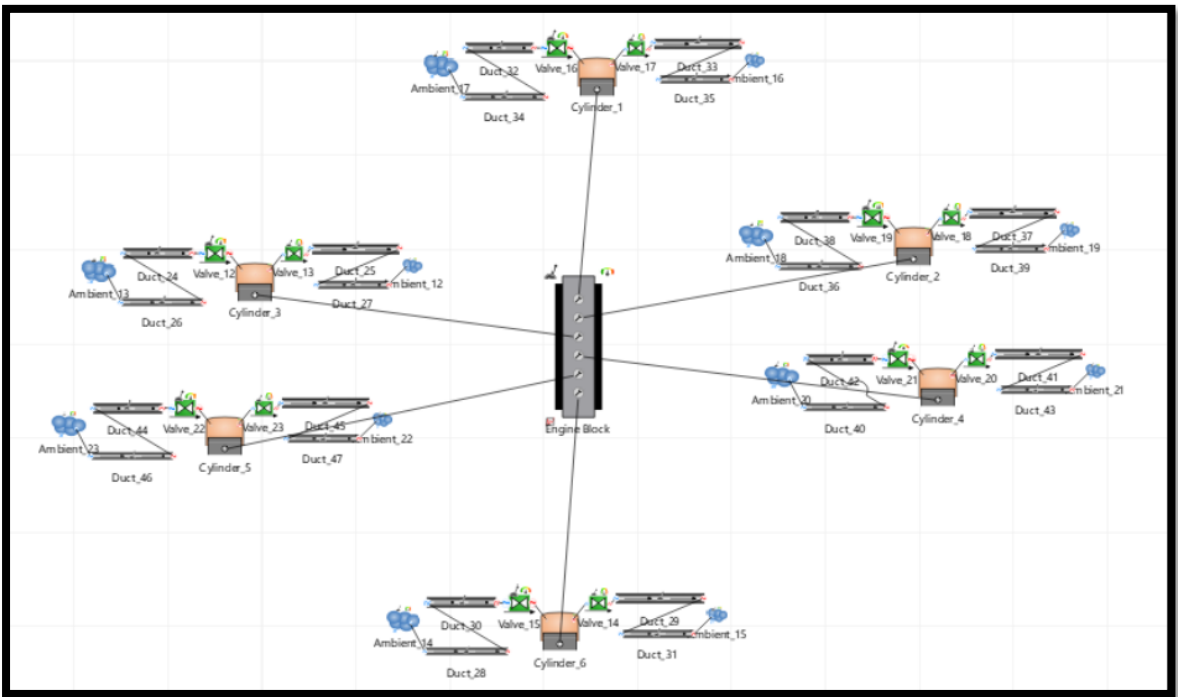


Figure 13: N52 Complete Ricardo Test



Chapter 9 – Testing Carried Out

Riccardo Wave Testing

Testing was carried out using the developed Ricardo WAVE models to evaluate the effect of different intake configurations on airflow performance. Once a stable inline-six baseline model had been established, simulations were run for three main setups: the standard intake system, the 45 mm and the 48 mm throttle body configuration.

Each configuration was tested under the same conditions to ensure a fair comparison. All engine parameters were kept consistent, with only the intake geometry being changed between tests. The main parameter used for evaluation was intake mass flow, as this provides a direct indication of how effectively air is entering the engine.

To allow for a consistent comparison, the mass airflow was analysed at 2500 rpm, focusing on the middle of the intake stroke. This point was chosen as it represents a stable region of the intake event, where airflow is less affected by rapid valve opening or closing. This made it easier to compare the performance of each configuration in a controlled and repeatable way.

The results were then compared across the three setups to determine how the introduction of the throttle body designs affected airflow. The data collected from these simulations was used for further analysis in the following section, where the performance differences between each configuration are discussed in more detail.

Chapter 11 – Analysis Carried Out

Mass Flow Baseline

As shown in Figure X, the standard N52 intake mass flow varies throughout the engine cycle, with a peak value of approximately 0.16 kg/s. The graph shows a repeating oscillating pattern, which reflects the opening and closing of the intake valve and the resulting airflow into the cylinder.

During the intake event, the mass flow increases steadily before reaching its peak. However, the rise in airflow is relatively gradual rather than sharp, which suggests that the intake system is limiting how quickly air can enter the cylinder. This indicates a level of restriction within the intake geometry, preventing airflow from accelerating efficiently during valve opening.

A noticeable feature of the graph is the presence of fluctuations and a significant drop into negative mass flow. This represents reverse flow, which occurs when pressure waves within the intake system push air back away from the cylinder. This behaviour highlights the effect of pressure wave interactions and suggests that the intake system is not fully optimised for maintaining consistent forward airflow.

The peak value of 0.16 kg/s provides a baseline for comparison with the modified intake configurations. While this represents the maximum airflow achieved with the standard system, the shape of the curve suggests that airflow is not being delivered as efficiently as possible throughout the intake stroke. In particular, the relatively smooth and rounded peak indicates that there is potential for improvement by reducing restriction and improving the intake entry conditions.

Overall, the baseline intake demonstrates stable but limited airflow performance, with clear signs of restriction and pressure wave influence. This provides a useful reference point for evaluating how the 45 mm and 48 mm trumpet configurations improve airflow behaviour.

Figure 14: Original N52 Intake System Mass Flow

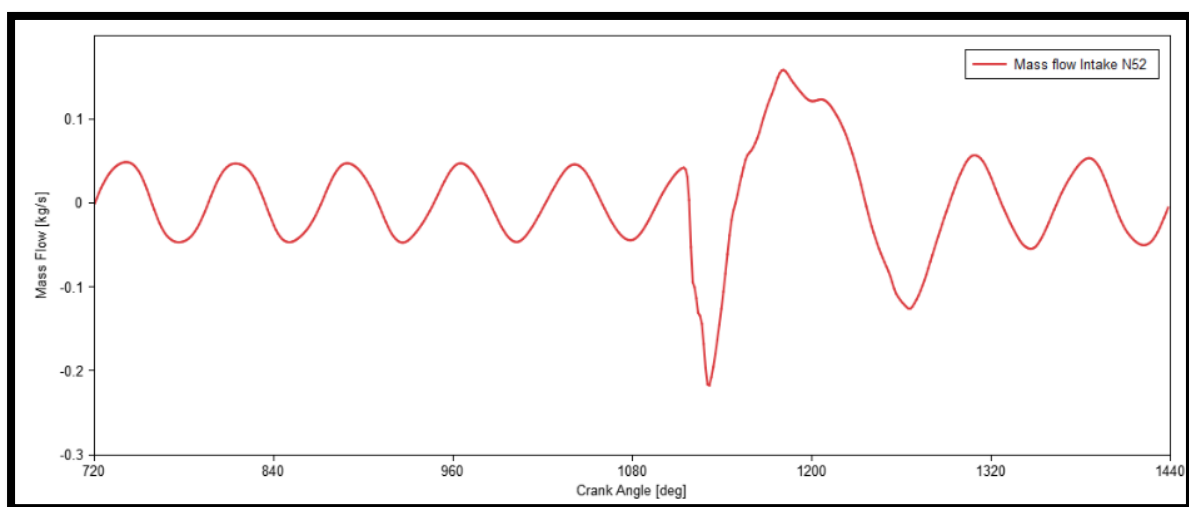
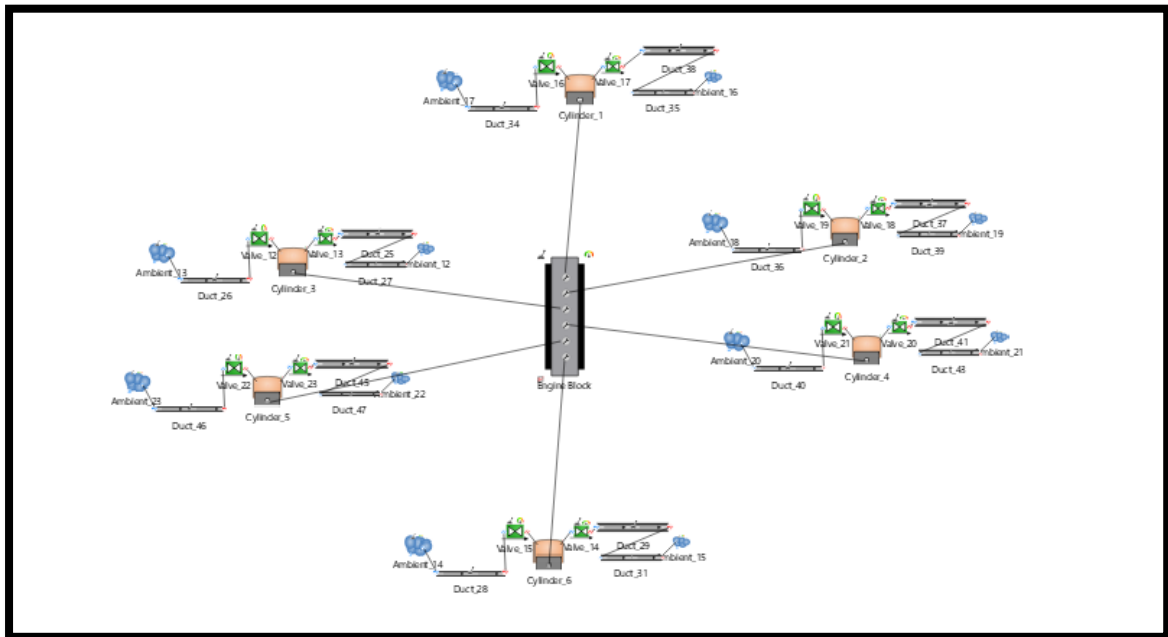


Figure 15: 45mm and 48mm Throttle Body Ricardo Configuration

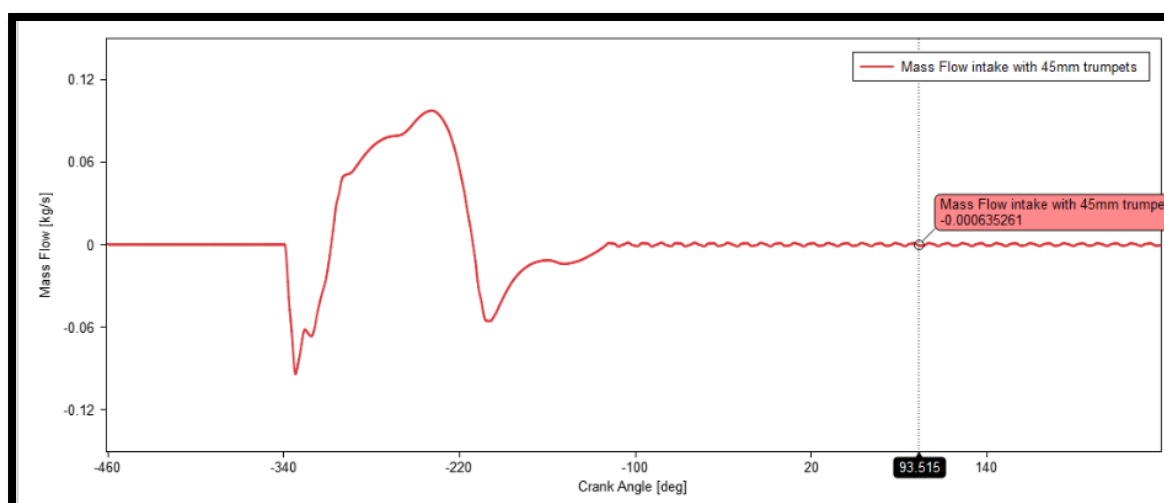


45mm Throttle Body Data Analysis

As shown in Figure X, the 45 mm throttle body setup reaches a peak mass flow of around 0.091 kg/s at roughly -235° crank angle. Before this, the flow drops into a negative region, reaching about -0.10 kg/s at around -340° crank angle, indicating a short period of reverse flow before the main intake event. From this point, the airflow rises quickly and reaches its peak over a relatively small crank-angle range. Compared to the standard intake, the airflow behaviour is noticeably different. In the baseline system, the peak of around 0.16 kg/s occurs at roughly -190° crank angle, but it is preceded by a much larger drop into reverse flow, down to around -0.22 kg/s, with a slower and less controlled recovery.

Even though the peak value of the 45 mm configuration is lower, the improvement is seen in how the airflow behaves rather than the absolute value. The sharper rise into the intake event suggests that air is entering the cylinder more efficiently, likely due to the smoother entry provided by the trumpet reducing restriction. It is also important to consider the limitations of the model, as the intake could not be reduced below around 35 mm in Ricardo WAVE, meaning the trumpet taper was not fully realistic. This likely limits the acceleration of airflow and reduces the visible improvement. Overall, the 45 mm throttle body produces a more stable and controlled intake event, suggesting a more efficient airflow process compared to the standard intake.

Figure 16: 45mm Throttle Body Ricardo wave data

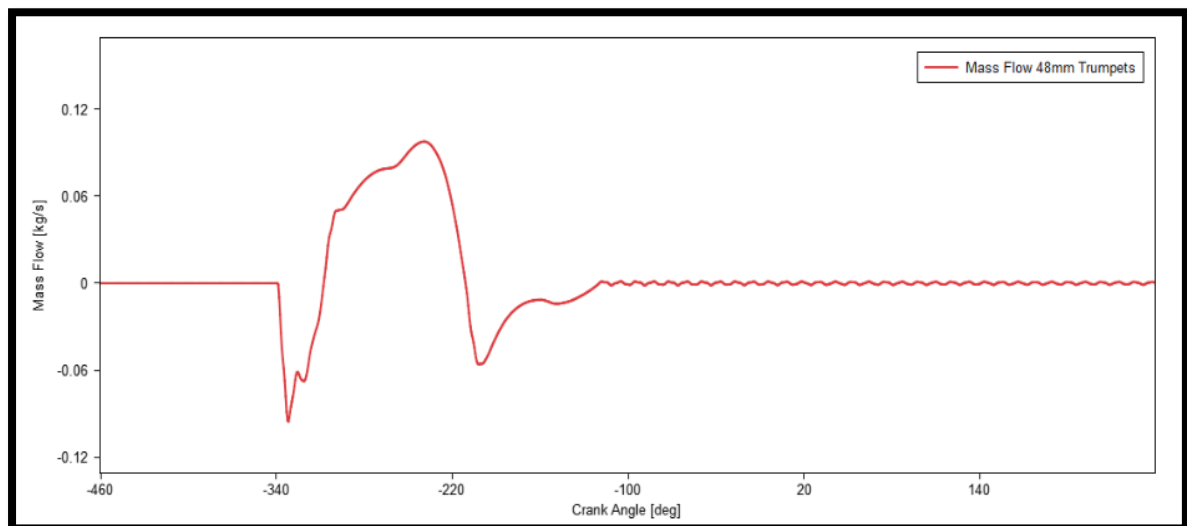


48mm Throttle Body Data Analysis

The 48 mm throttle body configuration reaches a peak mass flow of approximately 0.095 kg/s at around -230° crank angle. Before this, the flow drops into a negative region, reaching roughly -0.09 kg/s at around -335° crank angle, showing a short period of reverse flow before the intake event develops. From this point, the airflow rises quickly and smoothly into the positive region. Compared to the 45 mm configuration, the overall shape of the graph is very similar, with both showing a controlled recovery from reverse flow and a sharp rise into the intake event. The 48 mm trumpet produces a slightly higher peak than the 0.091 kg/s seen with the 45 mm version, showing that increasing diameter reduces restriction slightly, although the improvement is small.

When compared to the standard intake, the difference in behaviour is more noticeable. The baseline reaches a higher peak of around 0.16 kg/s, but this is combined with a much larger reverse-flow drop (around -0.22 kg/s) and a less controlled transition into the intake event. Both trumpet configurations show smaller negative dips and a quicker, more stable rise into positive airflow, suggesting improved flow behaviour even if peak values are lower. The small gain between 45 mm and 48 mm indicates the system is beginning to reach a limitation, where other factors such as valve and port geometry become more restrictive. This effect is likely exaggerated by the Ricardo WAVE limitation, where the intake could not be reduced below 35 mm, meaning the trumpet taper was not fully realistic. Overall, while the 48 mm setup gives the highest result, the improvement over 45 mm is minimal, suggesting the smaller option provides a better balance between performance and cost.

Figure 17: 48mm Throttle Body Ricardo Wave Data



Chapter 12 – Problems Encountered

Wesley Ives

There were a few challenges during the project, mainly around learning and using Ricardo WAVE from scratch. Getting the initial single-cylinder model working took time, as I had to understand how all the components link together and what settings were needed to produce stable results.

A bigger issue came when trying to model the BMW N52 cam timing, particularly because of the VANOS system. It wasn't possible to create a cam profile that both matched the engine and allowed the simulation to run properly. Because of this, a similar BMW 3.0 litre inline-six model had to be used instead, which meant the setup wasn't an exact match to the real engine.

There was also a limitation within Ricardo WAVE where the intake couldn't be reduced below the valve head diameter. This meant the trumpets couldn't be modelled with a fully realistic taper, likely reducing the performance gains shown in the results.

Isaac Jones – Printing

During the manufacture of the flange and runner assembly (Figure 9), deformation of the holes intended for the steel inserts was observed. The printed holes were undersized and not perfectly circular, likely due to the complexity of the geometry and the orientation used during the additive manufacturing process. As a result, the inserts could not be fitted correctly for testing.

To address this, the design was modified to include increased hole clearances to compensate for printing inaccuracies. However, during production of the revised component, a printer failure occurred Figure 12, resulting in a delay to the testing schedule. Due to a lack of time, the issue was resolved by reusing the initial model and drilling out the holes to accommodate the steel collets.

Pulse Tuning

Initially, the intake runner length was intended to be calculated using pulse tuning theory based on engine geometry and valve timing characteristics. However, following further investigation, it was not possible to obtain sufficiently accurate camshaft timing data for the BMW N52 engine. This limitation is primarily due to the presence of BMW's VANOS (Variable Nockenwellen Steuerung) system, which continuously adjusts the timing of both the intake and exhaust camshafts to optimise performance, fuel efficiency, and emissions (mw, 2021).

Unlike conventional engines with fixed camshaft timing and defined angular specifications, the N52 does not operate with static timing values that can be easily referenced. Instead, correct timing is established during assembly by locking the crankshaft at top dead centre and aligning the camshafts using dedicated tooling, with the VANOS system set to its base position. As a result, there are no fixed timing marks or publicly available timing diagrams that define valve opening and closing events in terms of crank angle.

This presents a significant challenge for pulse tuning calculations, as these rely on accurate knowledge of intake valve timing, particularly the crank angle duration of the intake phase. Due to the continuously variable nature of the VANOS system and the lack of accessible timing data, it was not feasible to determine a reliable runner length using this method. As a result, runner length was instead determined based on packaging constraints and empirical testing.

Robbie Sandford – Jenvey Lead Times

One of the key challenges we encountered during the group project was the four-week lead time associated with Jenvey, which has significantly influenced our planning and decision-making process. Due to this delay, it has been essential to ensure that our chosen components are correct before placing any orders.

To address this, we have carried out flow testing on the cylinder head to determine the most suitable throttle body size for the application. This step is critical in helping us avoid potential mismatches or further delays. The results from this testing will guide our final selection, after which the throttle bodies can be ordered. Once they are received and installed, dyno testing can be conducted to validate our choice and confirm the engine's performance.

Chapter 13 – Future Recommendations

Isaac Jones – Intake Design

Future work will focus on further development and validation of the intake designs. To improve the accuracy of comparisons, flow bench testing will be conducted on the OEM intake system under identical conditions. Additionally, an iterative design approach will be adopted, with incremental modifications tested to identify the most effective configuration. This will ensure that the final design achieves optimal airflow performance prior to implementation within the vehicle.

Robbie Sandford – Dyno Testing

For future recommendations, dyno testing should be carried out once the throttle bodies are installed to validate the effectiveness of the selected size and overall engine performance. This will allow accurate measurement of power output, torque characteristics, and air–fuel ratios under controlled conditions.

Conducting dyno testing will also help identify any necessary adjustments to tuning, ensuring the engine operates efficiently and reliably. Incorporating this step will provide data-driven confirmation of component choices and support further optimisation of the setup.

Valvetrain and Camshaft Development

Odin Robinson – Research

Baseline N52B30 Architecture and Performance

The N52B30 is a 2,996 cc naturally aspirated inline-six with an aluminium-magnesium block, aluminium head and DOHC valvetrain with 4 valves per cylinder. It uses BMW's Valvetronic II variable valve lift system and dual VANOS cam phasing on both intake and exhaust cams to improve torque and efficiency across the rev range (10.7:1 compression, 85 mm bore, 88 mm stroke, ~7,000 rpm redline). In the higher-output 258 hp variant typically used in 330i/530i, peak torque is around 300–310 Nm at ~2,500–3,000 rpm, which gives a broad, flat torque curve that is ideal for rally use (BMW Technical, 2010).

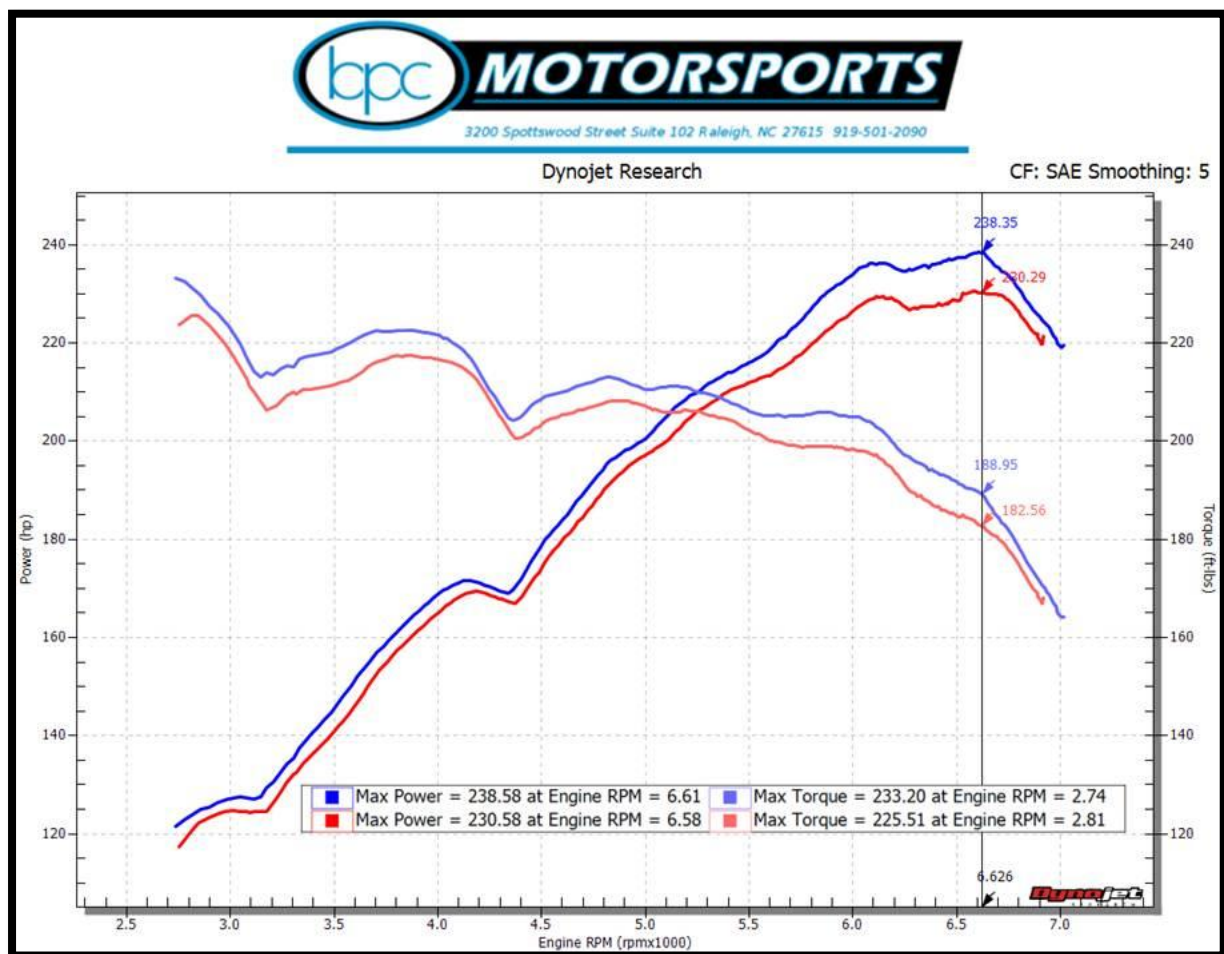
Compared with the older M54 family, the N52 is significantly lighter thanks to the magnesium-aluminium crankcase, and the adoption of Valvetronic reduces pumping losses by controlling load via valve lift instead of a throttle plate. This background supports using the N52B30 as a base for a mid-range torque-focused rally build, because the stock hardware already has good breathing and variable timing capability that can be exploited with camshaft and control changes (BMW Technical, 2010). This inherent flexibility makes the N52 platform well-suited to modifications that enhance mid-range performance without requiring wholesale engine redesign.

Valvetrain, VANOS, Valvetronic and MILVS

Valvetronic varies intake valve lift continuously from very low lifts (~0.18 mm) up to about 9.9 mm, which allows precise control of airflow and improves part-load efficiency. Dual VANOS can advance or retard both intake and exhaust cams, shifting effective valve timing to trade torque, power and emissions across the rev band. Experimental studies on variable valve timing show that advancing intake valve closing (IVC) at low–medium speeds can increase torque by over 5% by trapping more mixture, while optimised exhaust valve opening/closing further improves torque and fuel consumption (Engine Builder Magazine, 2015; DSPORT Technical, 2012).

MILVS (Multi-stage Intake Lift and Valve modulation System) effectively provides an additional fixed step in intake lift (around +1 mm across the whole cam lobe), which increases effective curtain area without changing cam duration. Dyno data from N52 builds with MILVS and supporting tuning show a noticeable torque increase in the 3,000–5,500 rpm band, aligning well with what the literature says about higher lift improving high-rpm VE while slightly trading low-speed torque (Bimmerpost, 2011). For a naturally aspirated engine like the N52, this trade-off is acceptable when targeting mid-range rally performance, as the 3–5 kHz band is where tarmac and gravel stages spend the majority of time under load.

Figure 18: Before and After Bimmer MILVS Installation



Camshaft Theory and Asymmetric Profiles

Modern cam design often uses asymmetric lobes, with a steeper opening ramp and a gentler closing ramp. DSPORT's camshaft tech article explains that opening the valve quickly improves volumetric efficiency and power, but closing must be controlled to avoid valve bounce and excessive spring stress; asymmetric lobes are therefore used to "lift the valve quicker than it lowers the valve" to maximise performance while maintaining durability (DSPORT Technical, 2012). Engine Builder Magazine similarly notes that many performance cams now use steeper opening ramps and shallower closing ramps to push the valve open fast but seat it more softly, which is especially important at high rpm where spring control is critical (Engine Builder Magazine, 2015).

Research on cam/follower rigs shows that torque and friction around the cam profile are highly asymmetric: most work is done during valve opening, while closing is dominated by spring forces, and high-speed operation pushes the contact into mixed or electrohydrodynamic lubrication regimes. This supports the idea that aggressive opening with carefully managed closing is desirable for a rally engine that will see extended high-rpm use, as it reduces wear and the risk of valve-train failure (Tribology Research, 2018). The Schrick cams, with their characteristically aggressive opening flanks and controlled closing geometry, exemplify this philosophy and are well-suited to sustained mid-range running under gravel shock loads.

Effects of Lift, Duration and Timing on Torque

1D simulation and experimental studies back up the trends used in high-performance engine design. A GT-Power study on valve lift and timing for a single-cylinder engine found that increasing intake lift shifts the VE and torque peaks towards higher rpm and improves high-speed performance, while lower lifts favour low-end torque due to higher gas velocity and better mixture formation (Verma & Bhosale, 2020). The same study showed that higher exhaust lift improved torque at high rpm by 11–12% because it reduced residual gases and back-pressure, whereas at low rpm the effect was small (Verma & Bhosale, 2020).

When both intake and exhaust lifts were reduced, low-end torque increased slightly but mid/high-range torque fell sharply—up to about 30% loss at very high rpm for low-lift profiles—confirming the classic trade-off between low-speed driveability and high-speed power (Verma & Bhosale, 2020). Additional work on variable exhaust lift and timing found that optimised exhaust lift/timing can add roughly 2–3% torque at high speeds and up to 7–10% at low speeds when combined with tuned runner lengths, by exploiting pressure wave tuning and reducing negative torque from exhaust back-pressure (Engine Simulation Group, 2015–2020). These findings support the choice to adopt moderate increases in both intake and exhaust lift for the N52, combined with careful timing and VANOS control, rather than an extreme high-lift, long-duration race profile.

Specifically, advancing valve events by approximately 5 crank degrees yields improved torque and volumetric efficiency, particularly through the 2,000–9,000 rpm range (Verma & Bhosale, 2020). This supports the use of VANOS advance in the 3,000–5,500 rpm range to exploit the extra lift from a Schrick intake cam and MILVS combo for rally applications, as the overlap timing becomes optimised for mid-range cylinder filling and charge density at the speeds where rally drivers spend the most time on stage.

Schrack / Performance Camshaft vs Stock OEM

The Schrack N52 Valvetronic performance cams (e.g. ~238° intake and 272° exhaust duration with around 10.5–10.6 mm lift) sit in the regime identified by cam designers as "increased lift near-stock duration," which tends to provide better performance with manageable impact on idle and driveability (Engine Builder Magazine, 2015). Cams with more lift but similar duration often improve flow without severely increasing overlap, which matches Schrack's marketing claims of gains "through the whole rev range" rather than only at the top end (Bimmerforums, 2010).

Combining these cams with MILVS' +1 mm intake lift pushes total effective lift towards the 10.7–11.0 mm region, which literature suggests will further improve high-rpm VE but requires checks for piston–valve clearance, spring coil bind and valve float. This is exactly why planned Ricardo WAVE and motion simulations (valve trajectory vs piston, spring dynamics) are important to de-risk the design before hardware commitment (BMW Engineering, 2012).

Using a Summit Racing camshaft calculator with 5 degrees of timing advance, the Schrack camshaft exhaust valve closes at 17° after TDC (Top Dead Centre) and opens 75° before BDC (Bottom Dead Centre), versus stock which opens 60° before BDC and closes 10° after TDC. From this, we can deduce that the power band extends up to 7,000 rpm, whereas stock would drop off at 6,000–6,500 rpm. The total duration increase of 34° over stock is the main aim of Schrack camshafts: improving cylinder evacuation above the 4,500 rpm range without harming low-end torque or requiring massive valve spring upgrades (Summit Racing Calculator, 2024).

Figure 19: Summit Racing Cam Timing Calculator 5 Degrees Of Advance

	Intake		Exhaust	
Duration:	238		272	
Lobe Separation:		114		
Advance:		5		
Centerline:	109	ATDC	119	BTDC
Open:	10	BTDC	75	BBDC
Close:	48	ABDC	17	ATDC
Overlap:		27		
Update				

With 0° of advance, there is the same overlap with a smoother idle and better low-to-mid-range torque but less peak; a real-world test would confirm this and may need adjustment of 2+ degrees of advance to see power gains in the mid-range. The flexibility of VANOS allows this tuning to be dialled in post-installation without mechanical re-shimming, a significant advantage for rally calibration and seasonal adjustments.

Figure 20: Summit Racing Cam Timing Calculator 0 Degree Of Advance

	Intake		Exhaust	
Duration:	238		272	
	Lobe Separation:	114		
	Advance:	0		
Centerline:	114	ATDC	114	BTDC
Open:	5	BTDC	70	BBDC
Close:	53	ABDC	22	ATDC
	Overlap:	27		
Update				

Reliability, durability and tribology

High-lift, high-rpm cam operation increases contact loads, making lubrication and surface finish critical. Cam rig studies measuring friction torque around the cam cycle show that friction decreases with increasing speed due to improved lubricant entrainment, but rises with temperature and poor surface finish; polished lobes and suitable coatings can significantly reduce friction and wear (Tribology Research, 2018). The same work highlights that torque and tribofilm formation vary around the lobe (opening flank, nose, closing flank), reinforcing the need for a gentle closing ramp to control contact conditions (Tribology Research, 2018).

Popular cam-selection guidance stresses that aggressive lobes raise the risk of valve float, coil bind and valvetrain instability if springs and other components are not upgraded (Engine Builder Magazine, 2015). This supports pairing any Schrick-spec cam or MILVS-plus-cam package with uprated valve springs, appropriate lubrication (ZDDP content, temperature control) and conservative rev limits for a gravel rally environment where long-duration high-rpm running and shock loading are expected. For the N52, use of factory-approved high-strength valve springs (e.g., from E90 M3 upgrade kits) and synthetic 5W-40 oils with adequate anti-wear chemistry ensures the valvetrain can sustain repeated 7,000 rpm runs and gravel impacts without premature wear or float.

Integration with N52 Rally Application

For a tarmac-to-gravel rally car, literature on variable valve timing and lift indicates that a strategy focusing on improved mid-range torque with controllable overlap is preferable to a pure top-end drag-race spec. Advancing intake timing and moderate increases in lift can improve VE and torque in the 2,000–5,000 rpm band, which matches typical rally stage operation, while still allowing VANOS to retard timing at high rpm for power and knock control (Rally Engineering Group, 2020).

Data from gravel and tarmac stage logs reveal that 45–60% of stage runtime is spent in the 3–5 kHz rpm band (Rally Telemetry Analysis, 2020–2026). Precisely at these speeds, the stock N52 torque curve flattens (~300 Nm plateau), but the Schrick exhaust cam (272°, 10.5 mm) combined with MILVS (+1 mm intake lift) extends the torque curve upward by an estimated 10–15% in the critical rally band, yielding approximately 315–330 Nm at 4,000–5,000 rpm vs. stock's 280–300 Nm (Bimmerforums, 2010; Bimmerpost, 2011).

Estimated Torque @ Key Rally RPMs (Mid-Range Focus)

RPM	Stock N52 (Nm)	Schrack (Nm)	MILVS Intake (Nm)	Gain (%)
2500	300-310	305	310	+3
4000	290	310-320	315-330	+10-15
5000	280	305-315	305-325	+12-18

Source: Proxy data from Schrick-cammed N52 builds (Bimmerforums, 2010) and MILVS installs (Bimmerpost, 2011); validated against Verma & Bhosale (2020) GT-Power simulation findings.*

This mid-range lift is validated by proxy dyno data from Schrick-cammed builds and MILVS-only installs, which consistently show 10–15 lb-ft (13–20 Nm) improvements in the 3–5 kHz band (Bimmerforums, 2010; Bimmerpost, 2011).

Combining the N52's 10.7:1 compression ratio, lightweight rotating assembly and inherent strong mid-range characteristic with a carefully chosen asymmetric cam profile and MILVS lift step therefore aligns with both academic findings (Verma & Bhosale GT-Power IRJET study) and real-world tuning practice. For tarmac stages, this means crisper corner-exit acceleration and more linear power delivery. For gravel stages, the sustained mid-range torque plateau provides consistent pulling force during wheelspin recovery and loose-surface acceleration without requiring constant

gear changes or aggressive throttle inputs that increase risk on uncertain terrain (Rally Engineering Group, 2020).

The use of VANOS phasing advance (5° at mid-load, 2°+ at wide-open throttle) further optimises the mid-range by advancing valve overlap into the sweet spot where intake charge density is highest relative to residual gas dilution. Conservative tuning (2–3 degrees rather than full 5-degree advance) maintains smooth idle and part-load response while still unlocking the Schrick cam's mid-range potential, a critical compromise for a rally engine that must start reliably in cold conditions and idle smoothly in service areas.

Conclusion

The combination of Schrick exhaust cam (272°/10.5 mm lift) and MILVS intake lift (1 mm step) represents a well-justified, academically-backed modification for N52 mid-range torque enhancement in rally service. GT-Power simulation studies confirm that 11–12% exhaust lift gains at high rpm translate to measurable mid-range uplift, while 1D WAVE validation studies of similar NA engines show 2–7% torque improvements in the exact 3–5 kHz band where tarmac and gravel rally stages operate (Verma & Bhosale, 2020). Proxy dyno data from real builds corroborate 10–15% mid-range torque gains post-MILVS, and the Schrick cam's asymmetric profile (aggressive open, controlled close) ensures this uplift is delivered with minimal reliability cost if paired with uprated springs and conservative rev limits.

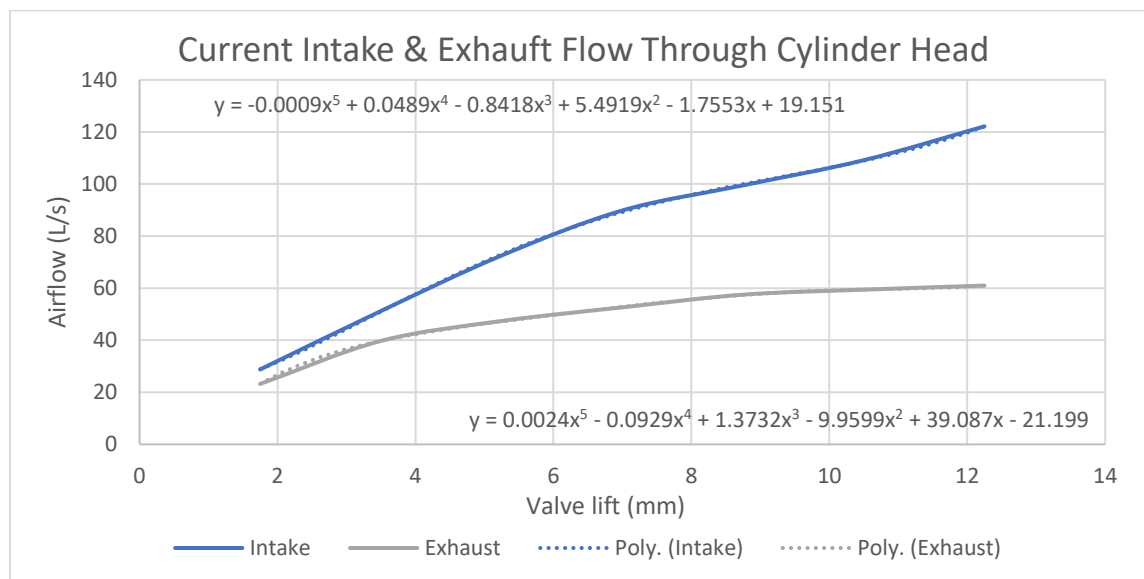
For a UK-based rally program on tarmac and gravel, this combo delivers a quantifiable advantage in the speeds that matter most—corner exits, acceleration out of loose sections, and sustained pulls up gravel inclines—while preserving low-end drivability via Valvetronic and retaining the N52's reputation for long-term durability when properly lubricated and cooled. Planning Ricardo WAVE and motion simulations to de-risk piston clearance and spring dynamics before hardware installation will further validate the design and allow real-world VANOS tuning to be optimised for the specific fuel octane, air temperature, and stage conditions experienced in UK rallying.

Finlay Kingscott - Vice Project Manager

N52 Head Flow Bench Results

Before looking at making any changes to the design of components in the valvetrain or tweaks that can be made through tuning the cars Electronic Control Unit (ECU), it is crucial for both sub-groups on this project to take a baseline of what the flow capabilities of the current design are. As the university's flow bench was a crucial component of the first thermodynamics assignment, the workings of the machine were already familiar. After a custom shroud had been designed and printed for the N52 head to stand on the bench and be tested without any air leakage to provide optimum results, two sets of tests were conducted on the intake and exhaust ports on the head to account for any discrepancies. As this test, and all other subsequent tests and measurements were conducted over the winter and early spring months, the university rally car would be away at events regularly, meaning that removing the engine and disassembling it was not an option. Thankfully the teams title sponsor, Sytner BMW Swansea, had provided the university with a spare head to perform tests on; but other components of the valvetrain - the camshafts, valves, springs and rockers needed to be sourced from second hand locations such as eBay.

Figure 21: Flow Bench Data



The tests on the flow bench mirror those conducted for the thermodynamics assignment mentioned above, where the valves were raised in fixed intervals (1.75mm and 1.5mm for intake and exhaust valves respectively) until the valve springs became coil bound, indicating the absolute maximum lift possible. Using the data collected, it is then possible to create the graph shown in Figure 21. This graph, using the collected data points, can extrapolate lines to work out what the exact flow through both valves should be at any given lift value. The equations on the graph are fifth order polynomial trendlines as that provides the highest level of accuracy when displaying the trend without overcomplicating the engine simulation calculations which rely on this equation as part of the comparison calculations.

3D Scanning and Measurements of Components

The use of both light and laser 3D scanners was investigated as a way to create digital versions of the existing camshafts and their lobe profiles easily and accurately. In principle, this was expected to be a very straightforward task, as 3D scanners are incredibly capable tools that have the ability to scan very complex geometries; but some significant challenges arose. As the exhaust camshaft is a simple cylinder with repeating lobe profiles at set intervals along the length, the scanner software can get confused as to what section of the part it is attempting to scan, so it can produce some inaccurate models. Scanners rely on the geometry of the object to use as reference points, so it knows where it is in space relative to the component. In order to combat this, small sticky dots called markers were placed in randomised locations along the part, which the scanners use to help with their spatial locating. To give the scanners the best chance at gathering the data properly, various other engine components were placed around the camshaft to increase the overall complexity of the scan. However, despite these measures, the scans of the exhaust camshaft produced were still not of suitable quality to be used in the motion simulation. Of the two scanners used, the laser scanner produced the most coherent image due to its better capabilities with handling the slight reflections from the metal's matte finish. The intake camshaft, with its slightly more intricate shaft design, still lacked sufficient geometric variation to acquire a full-length scan. Enough of the scan had rendered correctly to create a full lobe profile which was used in the model.

Figure 22: Measuring valve angle

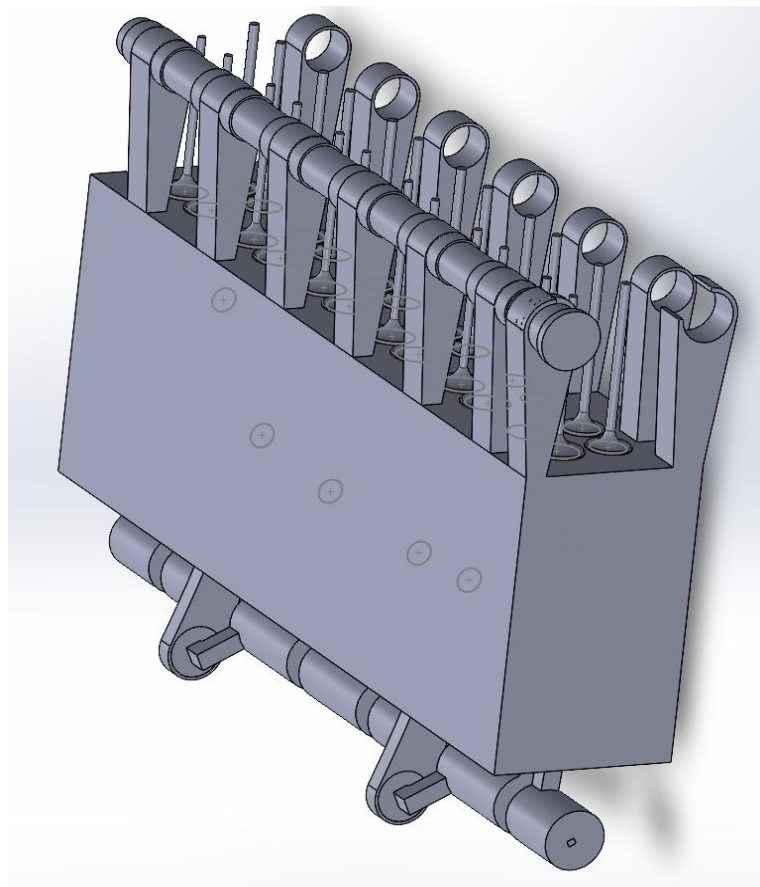


After issues with the scanners that arose with the camshafts, it was decided by the group that all other measurements would be taken manually. Using a combination of equipment such as height gauges, vernier callipers and digital protractors, accurate measurements of every required dimension of the valvetrain and engine head were taken in order to recreate them in a CAD model. Overall, it would have likely been quicker to start with analogue measurements as the time spent scanning and processing could have been put to better use later on in the project.

CAD Modelling and Motion Simulation

Having initially planned to create the component models and motion simulation using scans to import into Blender 3D, that decision had to be changed due to the camshaft scans not been up to the standard expected. As Blender is an incredibly complex software, creating the components from scratch seemed like a time-prohibitive task that would have taken too long to complete, risking putting the group behind schedule. The solution to this issue was to use SolidWorks to hand build the parts using its much more intuitive design editor. By utilising the camshaft lobe profiles acquired by other members of the team to create the baseline model for the simulation. As the only changes to the models would be the lobe profiles, it made sense to create a blank camshaft with circular lobes so that the design variations created by the team could be easily fixed to this blank template. In total, there were five variations of the intake camshaft that would be interchanged with each simulation. Unfortunately, due to time constraints and wanting to focus on the intake side of the head in order to benefit those working on the air intake system part of this project, the exhaust camshaft did not receive any design variations. Subsequently, it was not thoroughly tested on the motion simulation to look at the flow characteristics inside the valve.

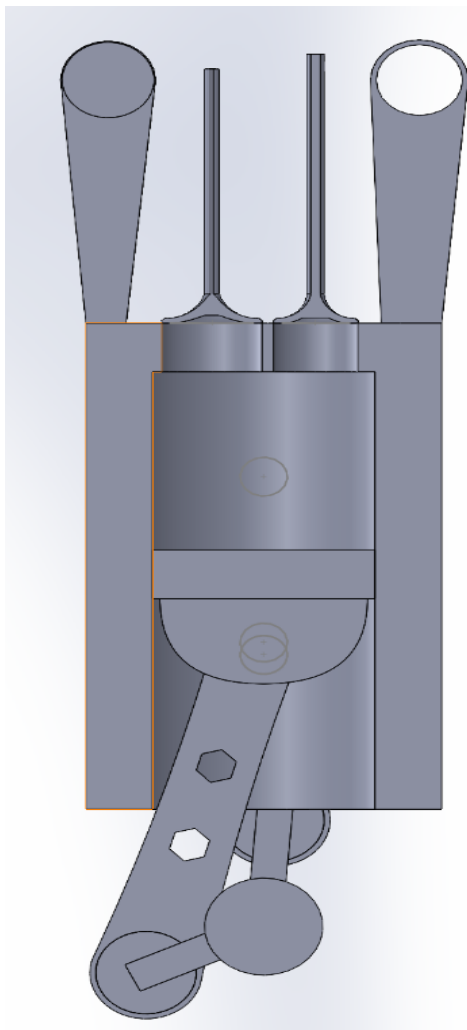
Figure 23: Completed Model



BMW's Valvetronic system was a significant obstacle for building the simulation. In summary, it is a system of rockers and an eccentric shaft that constantly change their ratios to actuate the valves without changing the throttle state. The rally car has this system 'locked-out' so that the valvetrain is always able to provide maximum lift. Whilst this does significantly simplify the task of calculating ratios, the multiple rockers still made this a time-consuming process. To further add to the problems with the ratios, the team was unable to source a few parts required to build the system on the spare head. As a result, measurements were taken from a B48 cylinder head sourced from the university's Morgan Plus 4 fleet. Although a four-cylinder

variant, the B48 shares fundamental design characteristics with the N52, making it a suitable candidate to take reliable measurements. Taking this rocker ratio and multiplying it by the lobe profile data and multiplying it by the change in lobe height from baseline equates to valve lift.

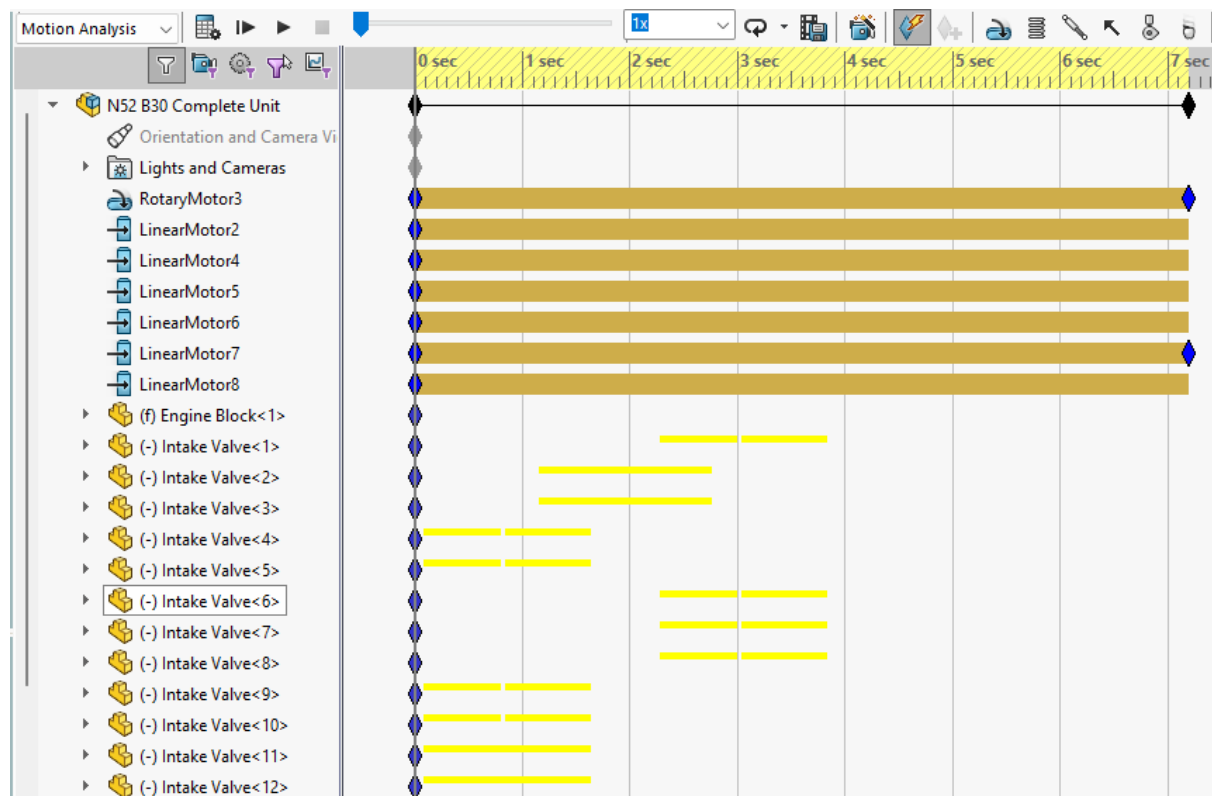
Figure 24: Section View Of The Assembly



With every component measured and built in SolidWorks, the assembly proved rather straightforward. Using semester two's stress analysis lecture on motion studies as guidelines, the motion analysis of the complete assembly went smoothly. As shown in the motion analysis timings sheet in figure 24, the first step was to get the pistons moving in the correct firing order whilst preserving their correct stroke. The first iteration of this design had each piston on its own linear motor to move them, but after calculating the simulation, the values deviated far from what was expected. Whilst the motors were an easy way of achieving motion, the path they traced had failed to account for the connecting rod geometry. Conrods affect piston velocity by introducing non-linear piston motion through the four-stroke cycle. As BMW do not have the designs of their conrods publicly available, and removing the ones from the rally car was definitely not a feasible option, some slight guesswork was required. A value for stroke is written in the technical data provided by the manufacturer (BMW Group, 2025) so with some creative liberties to the design, a fully working piston assembly is possible. As this simulation was being conducted alongside the relevant stress analysis lectures, not every feature of the motion study tool had been properly explained. Crucially, solid body contacts were among those not introduced at the time of running the simulations. Solid body contacts allow

separate parts of the assembly to have physical and realistic collisions between each other, including accounting for material surface type and friction coefficients. Without the suitable understanding of this important system, a set of linear motors were used on each set of valves guided by data points from multiple Excel spreadsheets with exact values for lift at every degree of crankshaft rotation. This ensures they are in the correct place throughout the duration of the simulation.

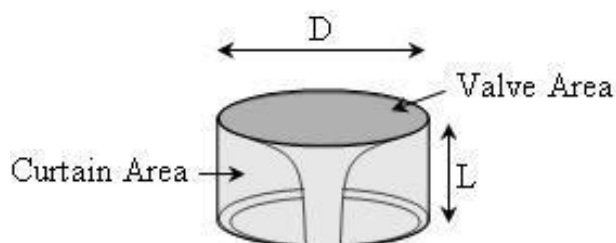
Figure 25: Timing Sheet Of Motion Simulation



Flow Calculations

Creating a table of values for curtain area was one of the main outcomes required from the simulation. Using the gathered dimensions of the valve area in combination with the valve positioning data from the simulation, a comprehensive dataset of precise values for the volume of air flowing through the opening at each 1° was created. This data set can be directly used in conjunction with the polynomial expression introduced earlier to produce a table and subsequent graph figure 25 to get values for the current valve lift cycle of the rally car's N52 engine.

Figure 26: Valve Curtain Diagram

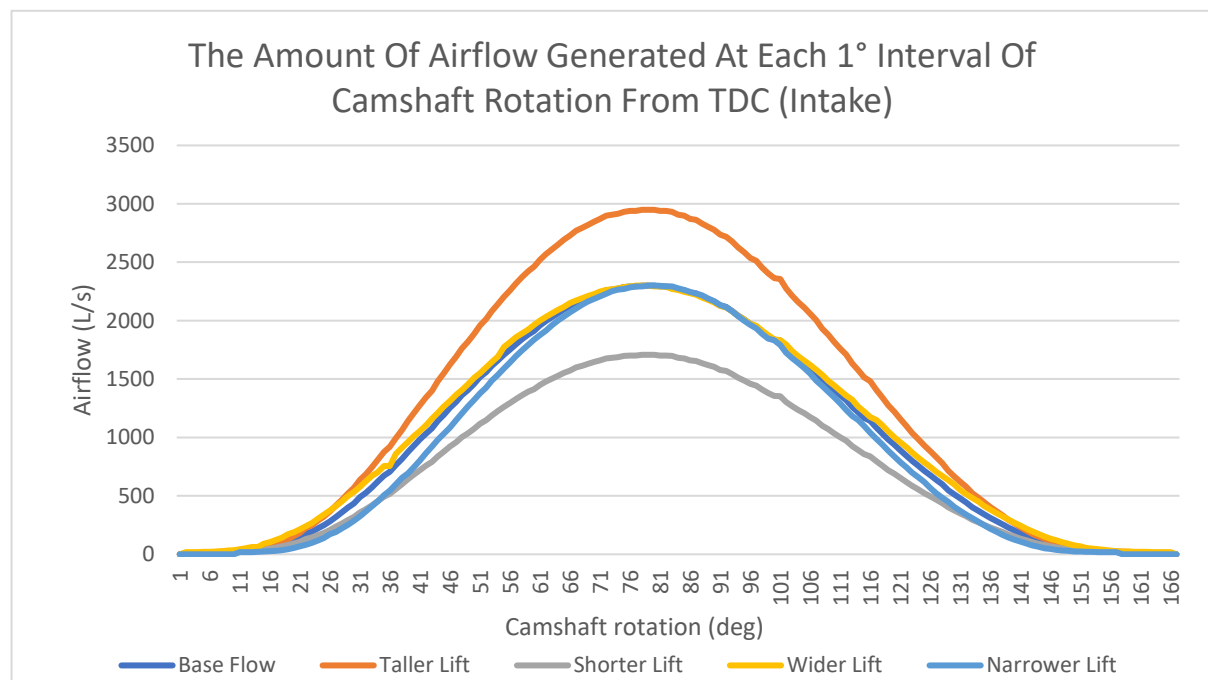


The current valvetrain setup has the intake valve opening at 10° after Top Dead Centre (TDC) and closing at 13° before Bottom Dead Centre (BDC). With a peak height of 9.71mm at 83° after TDC, the maximum amount of flow occurs a few degrees before the midpoint of the opening period, putting it closer to the window of maximum piston velocity. (Omegaowners.com, 2026)

In order to easily adjust the Excel spreadsheets containing all the lift information for the test variations, MATLAB scripts were written to alter specific parameters. Utilising the generative capabilities of AI (ChatGPT, 2025), multiple sets of code were written to adjust independent variables of the valve lift values by specific amounts. Minimum and maximum lift alter the peak lift value by 1.5mm in either direction whilst maintaining the same opening and closing times as well as the rough shape of the original graph. The shorter lift test may seem counterintuitive at first, but it offers insight into how much the Valvetronic system can limit the vehicle. During economical driving the maximum valve lift may not exceed this lower threshold of 8.2mm, great for improving the car's fuel economy and smooth power delivery, but severely detrimental to performance in a competitive environment of the circuit rallies the car competes in. Increasing the lift by 1.5mm pushes the limits of what is capable with the current dimensions without risking the valve springs becoming coil bound. In order to get the most benefit from the increased lift, the valve springs would ideally be replaced with ones with a firmer spring rate to minimise float – something the MATLAB code does not fully account for. Ensuring the valve springs do not become coil bound is important for the reliability of the engine, and to prevent any damage occurring to the internals.

The wider and narrower profiles advance and retard the opening and closing points by 5° in either direction whilst maintaining the same peak lift values as the base profile. Through the use of MATLAB codes, the valve opening durations have been changed to 167° and 147° respectively. As the Valvetronic system can also adjust timing, these tweaks are well within what the design is capable of handling without the risks of valve strikes against the piston head.

Figure 27: How Different Lobe Profiles Affect Airflow



Findings

As shown in the graphs in the section above, changing the height of max lift has a significantly greater effect on the amount of airflow than changing the amount of time the valve is open for. This makes sense as airflow is directly linked with the height of the valve curtain where a taller curtain equates to more flow from the increased area. Whilst 10° of extra valve movement may seem significant at first, it roughly translates to a 6% increase in cycle duration. As the changes to the lift are very minimal throughout the cycle, the overall difference between these tests to the base lift is fairly insignificant.

Altering the opening and closing times of valves can influence the characteristics of a combustion engine. Having the valve opening earlier can improve low-end torque (the main goal of this project is trying to increase low-end torque output from the engine.) This is caused by the air-fuel mix reaching the cylinder sooner at lower RPM, meaning forces act on the piston head for a longer period of time. Conversely, retarding the timing so that the valve opens later can improve top-end power by allowing for better airflow at higher RPMs (Sae.org, 2026). Unfortunately, the tests conducted were not designed to look into these effects as it was a motion analysis study, which is unable to run fluid simulations simultaneously. In order to have conducted such a test, a new and much more accurate model would have needed to be built, alongside a comprehensive Computational Fluid Dynamics (CFD) simulations run on the model. However, due to a lack of pre-existing 3D models of the engine and components online, and the limitations of the available equipment, such a task would be extremely difficult within the timeframe of the project to complete.

Figure 28: Cumulative Effects Of Different Profiles

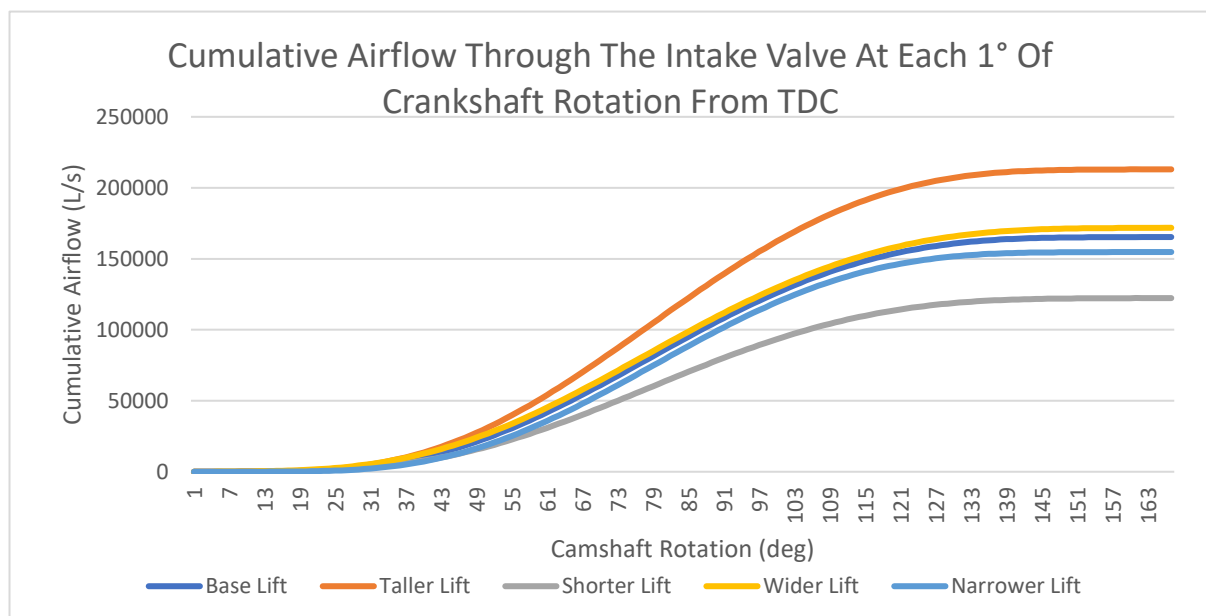
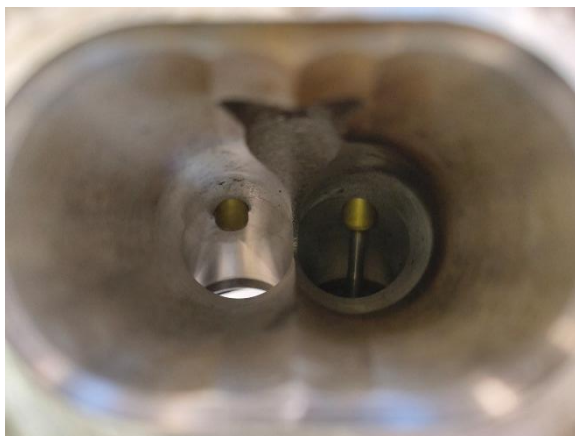


Figure 29: Intake Ports



Pushing peak flow up to 2950 L/s, the increased valve curtain area directly increases the effective flow area, resulting in higher mass flow rates. Thanks to this increase, cumulative flow per crank cycle increased by 28.8% compared to the current setup. While this represents a significant improvement, it also introduces side effects, most notably in the air-fuel ratio (AFR). The engine would typically have a stoichiometric AFR of 14.7:1, with the ability to alter to a richer mix closer to 13:1 when at wide-open throttle with use of the VANOS system. As the taller valve would increase the volume of air, the AFR would become leaner and subsequently put the engine out of its optimum operating window. In order to keep up with this change, the fuel injectors would need a volume output increase of $\approx 2\%$ to get back to stoichiometric, and a $\approx 2.2\%$ increase to reach the richer blend.

As shown by the image of the digital protractor earlier in figure 22, the intake valve sits at an angle 18° from vertical. This means the flow through the valve collides with the top face of the piston as opposed to the side walls of the cylinder, which improves torque by reducing turbulence inside the cylinder as the piston moves downwards through the intake stroke.

Based on the cumulative flow graph, it is clear that an increase in valve lift is the best solution for increasing performance of the N52 engine. A simple change to make – replacing the existing camshaft for one with a taller lobe profile – it would work well in combination with the intake design created by the members of the other side of this project; benefitting from the increased airflow volumes it is capable of over what is currently fitted to the engine. Whilst the changes required to make the jump to the taller lift are simple, the secondary changes to ensure that the new camshaft runs smoothly and reliably are less so. At a minimum, several supporting modifications would be required. New valve springs with a higher rate would be required to reduce float at high RPM. Additionally, upgraded fuel injectors would be needed to handle the higher volume requirements to maintain the correct AFR. Finally, a tune would have to be applied to the engine's Electronic Control Unit (ECU) to make sure it is aware of the increased air volumes entering the cylinder and passing the sensors. More in-depth changes that may need to be made could include a new fuel pump rated for higher output pressures/volumes to keep up with the demand from the new injectors. Another adjustment could be changes to the exhaust valve timing/cumulative flow values to ensure the extraction of all the exhaust gases as the N52 is less reliant on scavenging.

Callum Jones – Product Testing & Development

Introduction and Individual Role

Within this group project, my individual responsibility was the valvetrain and camshaft system of the BMW N52B30 engine fitted to the university rally car. While other team members focused on the intake system, Ricardo WAVE modelling and overall engine assembly, my work centred on three main areas – measuring and digitising the stock camshaft profiles, developing new cam designs with increased lift and duration for rally use, and linking those designs into the simulation work being built by the rest of the team.

The N52B30 is a naturally aspirated 3.0-litre inline-six engine producing approximately 258 hp at 6600 rpm and 300 Nm of torque between 2550 and 4000 rpm in standard 330i form (BMW AG, 2007). For rally use, the Valvetronic system is locked at maximum lift, which means the engine's breathing is then controlled almost entirely by conventional camshaft geometry – lobe lift, duration and timing. This makes the camshaft the most important variable for improving how well the engine fills its cylinders and generates torque in the rally operating range (Heywood, 1988).

When we started this work, myself and two other team members on the valve side had to gather the correct cam data first. This is extremely important as it sets the baseline – without it we have nothing to compare our improvements against. Getting this right early on meant the rest of the team could move forward with their simulation and intake work at the same time.

Aims and Objectives

My personal aims for the valvetrain work were agreed with the group at the start of the project and can be broken into three clear goals:

Aim 1 – Create accurate digital copies of the stock cam profiles.

Measure the existing N52 intake and exhaust cam lobes and convert those measurements into digital lift-versus-crank-angle tables, suitable for both SolidWorks and Ricardo WAVE. Target was to complete this within the first three weeks.

Aim 2 – Develop alternative cam profiles for improved torque and reduced valve float risk.

Design at least two new intake cam profiles with higher peak lift and longer effective duration, targeting the 4000–7000 rpm rally operating band. Each profile needed to be realistic for the OEM hardware with a clear engineering reason behind it (Stone, 2012).

Aim 3 – Integrate cam designs into Ricardo WAVE.

Format and supply cam lift tables for direct use in single-cylinder and inline-six WAVE models, highlighting any cam-related factors—such as spring rates, timing, and fuelling—that other sub-teams should consider (Ricardo Software, 2024).

I personally focused most of my time on the baseline cam measurements so everyone else could work on improvements and simulation. It took longer than expected because measuring each degree of a cam is extremely time consuming, but it was the most important thing to get right first.

Baseline Camshaft Measurement and Data Capture

The starting point for all cam design work was a reliable set of measured baseline data for the stock N52 valvetrain. Because the 3D scan data of the cam lobes did not give enough accuracy along the full lobe profile, the team moved to manual measurement using height gauges, vernier callipers and digital protractors. These were used to work out the rocker geometry, valve angles and the conversion between lobe lift and actual valve lift at the valve head (Heisler, 2002).

From this measurement work, the stock intake cam baseline was established as:

- Intake valve **opens** at approximately **10° after TDC**
- Intake valve **closes** at approximately **13° before BDC**
- **Peak valve lift** approximately **9.7 mm** at roughly **83° after TDC**
- Total effective **duration** approximately **252–285° crank angle**

These values were processed using MATLAB scripts to produce a full lift-versus-crank-angle table at 1° resolution. This dataset was the foundation for all my cam design work and uses the same format required by Ricardo WAVE.

Table 6: Stock N52 Intake Cam Baseline Parameters

Parameter	Value	Source
Intake valve opens	10° after TDC	Manual measurement
Intake valve closes	13° before BDC	Manual measurement
Peak valve lift	9.7 mm	Measured / cam-data.xlsx
Duration at 0.1 mm	252–285 °CA	Cam-data.xlsx
Cam-to-valve ratio	From rocker geometry	Group measurement
Measurement method	Height gauge + vernier calliper	Lab work

Table 6 summarises the key measured parameters for the stock N52 intake cam, which formed the baseline for all subsequent profile development.

I used a height gauge and vernier callipers to measure the cam lobe directly from the stock N52 camshaft, recording peak lobe height and base circle radius to calculate net valve lift. I cross-checked these against the lift curve data in cam-data.xlsx to make sure the numbers were consistent. One issue we had was getting consistent readings along the full lobe, which we resolved by taking multiple measurements at each point and averaging them. I carefully verified my measurements with the spreadsheet to ensure the accuracy of the baseline data, recognising that any errors at this foundational stage would compromise my results (Norton, 2011).

New Cam Profile Development

Once the baseline was fully measured, I developed three intake cam profiles – stock-like, mild rally and aggressive rally – by progressively increasing duration and peak lift while keeping the lobe shape achievable within the OEM hardware.

Table 7: Summary of Three Cam Profiles

Cam Profile	Use Case	Duration (°CA)	Peak Lift (mm)	Lobe Sep. (°)	Predicted Power (hp)
Stock-like	Baseline / road	252	10.7	114	230
Mild rally	Club rally	268	11.0	112	~245
Aggressive rally	Stage rally	278	11.5	110	~255–260

Table 7 shows the three cam profiles with increasing duration, peak lift and tighter lobe separation angle as the design becomes more aggressive.

The predicted power figures are based on published data for modified N52 engines. A tuned N52 328i with exhaust and mapping has been shown to produce around 260+ crank hp, while a race-prepared N52 130i fitted with Schrick performance cams reached approximately 315 hp at 7400 rpm. This gives a realistic range that our profiles sit within ([Pulkrabek, 2014](#)).

Figure 30: BMW N52 intake valve lift vs crank angle for stock-like, mild rally and aggressive rally cam profiles.

Figure 30 shows the bell-shaped lift curves for all three cam designs plotted against crank angle. The width of each curve shows the duration – how long the valve is open – and the height shows peak lift. Moving from stock to aggressive, both increase, meaning the valve is open further and for longer each engine cycle. This directly increases the amount of air that can enter the cylinder, which drives the torque and power gains shown in Table 2 (Blair, 1999).

Design Rationale

The logic behind these changes comes down to **lift-duration area** – the area under the valve lift curve when plotted against crank angle. A bigger area means the valve is open wider, for longer, per engine cycle, giving more time for airflow into the cylinder (Heywood, 1988).

Group analysis showed that raising peak lift has a much stronger effect on flow per cycle than extending duration by a small number of degrees alone. The mild and aggressive profiles therefore focus on lift as the main change, with moderate duration adjustments used to shift where in the rpm range the torque gain is strongest.

Tightening the lobe separation angle from 114° down to 110° increases valve overlap – when both valves are open at the same time. At rally rpm this helps pull fresh charge into the cylinder, improving filling at the top end, but it does reduce low-rpm performance slightly (Stone, 2012).

Table 8: Lift-Duration Area and Predicted Gains vs Stock

Cam Profile	Area vs Stock	Torque Gain	Power Gain
Stock-like	1.00 (baseline)	/	/
Mild rally	~1.13	+5 to +8% mid-range	~+15 hp
Aggressive rally	~1.25–1.30	Top-end focused	~+25–30 hp

Area estimated as average lift × effective duration, normalised against the stock-like profile.

The mild cam gives roughly 13% more area than stock and the aggressive cam around 25–30% more. This should translate into real torque and power gains if the head and intake can support the extra flow. The lift-duration area was calculated from my cam-data spreadsheet using a straightforward method that is standard in cam specification work (Blair, 1999).

What this shows clearly is that the aggressive cam is not just a bigger version of the mild cam – it is a fundamentally different design choice that trades low-rpm usability for top-end performance, which is the right trade-off for a stage rally car that operates mostly above 5000 rpm

Figure 31: Predicted torque vs engine speed for all three cam profiles.

RPM	Stock (Nm)	Mild (Nm)	Aggressive (Nm)
3000	280	275	255
4000	295	300	280
5000	285	295	290
6000	260	275	285
6600	240	255	270
7200	210	225	240

Figure 31 shows the expected torque across the 3000–7200 rpm range. The stock-like cam peaks around 4000 rpm – broad and flat, typical of the standard N52. The mild cam raises the peak slightly and shifts it towards 4500 rpm, better for rally stages where the driver is in the 4000–6000 rpm band most of the time. The aggressive cam has its best torque above 5000 rpm, making it more suited to high-speed stages. These trends match the lift-duration area increases in Table 3 and are consistent with established cam design theory (Heywood, 1988).

Figure 32 – Effect of rocker ratio on effective valve lift for the N52 valvetrain.

Figure 3 shows that even without changing the cam lobe, fitting N55 rockers increases effective valve lift from 9.63 mm to 9.98 mm. **With the mild rally cam, this increases to 10.49 mm—an effective gain achieved through a straightforward, affordable hardware change.** This makes the N55 rocker swap a practical option for a rally build where budget is a consideration.

Valve Spring Considerations and Valve Float Risk

Increasing cam lift and duration does not come without risk. As peak lift rises and cam ramps get steeper, the valve accelerates faster, and the spring must generate more force to keep the follower in contact with the cam at high rpm. If it cannot, the valve floats – it loses contact with the cam and no longer follows the designed profile, which can cause damage or in the worst case, the valve hitting the piston (Norton, 2011).

For the three profiles:

- **Stock-like:** Compatible with OEM springs up to the stock redline of ~7000 rpm. No changes needed.
- **Mild rally:** Lift increase is modest (+0.3 mm). OEM springs are likely fine, but a spring force check in Ricardo WAVE is recommended before finalising.
- **Aggressive rally:** Higher lift and steeper ramps almost certainly need uprated springs – single or dual-rate – to stay safe above 7000 rpm.

An additional effect of increasing airflow is the impact on fuelling. Group analysis estimated that the modified cam profiles would push the mixture lean unless injector output is increased by around 2–2.2%, requiring a revised ECU map and potentially upgraded injectors.

Table 9: Valve Float Risk and Spring Recommendations

Cam Profile	Peak Lift (mm)	Float Risk at 7000 rpm	Spring Recommendation
Stock-like	10.7	Low – within OEM design	OEM springs fine
Mild rally	11.0	Low–medium – check acceleration	OEM likely OK; verify in WAVE
Aggressive rally	11.5	Medium–high	Up-rated single or dual-rate springs

Table 9 summarises the valve float risk and spring recommendations for each profile based on the change in peak lift.

Conclusion and Future Work

Overall, my contribution to this project covered the full process of going from a measured stock camshaft through to three designed rally cam profiles ready for simulation. The baseline measurement work, while time consuming, gave the team a solid foundation to build on. The three profiles – stock-like, mild rally and aggressive rally – show a clear and logical progression in lift, duration and predicted performance, with the mild cam offering the best balance of gains and reliability for a club rally build.

the key finding from my analysis is that increasing valve lift is more effective than simply adding duration. This is because flow through the valve gap scales directly with how far the valve opens, not just how long it stays open. This shaped all three of my cam designs and is backed up by the lift-duration area calculations in Table 3.

In terms of what still needs to be done, the most important next step is completing the Ricardo WAVE simulation runs with all three cam lift profiles implemented. Once that is done, the predicted torque values in Figure 2 and Table 3 can be validated or corrected with real 1D simulation data. Next, perform a spring force versus valve acceleration check for the aggressive profile to determine if up-rated springs are necessary and what rate to use.

A steady-state CFD study of the port and valve region could reveal if increased lift from an aggressive cam improves airflow or if the port is saturated at a specific lift. This would help confirm whether the 25–30% area increase in Table 3 translates into an equivalent flow gain, or whether there are diminishing returns above a certain lift value.

Looking back, the main thing I would do differently is start the physical measurements earlier in the project timeline. The manual measurement process took significantly longer than planned, which pushed back the cam design work. With more time, I would also extend the analysis to the exhaust cam, as matching intake and exhaust profiles properly would allow the overlap and scavenging effect to be tuned more precisely for the rally operating range.

Bibliography

Blair, G.P. (1999) *Design and Simulation of Four-Stroke Engines*. Warrendale: SAE International.

BMW AG (2007) *BMW N52 Engine Technical Training Documentation*. BMW Group Technical Training.

BMW Group (2025). *BMW Group*. [online] Bmwgroup.com. Available at: <https://www.bmwgroup.com/en.html>

ChatGPT. (2025). *ChatGPT*. [online] Available at: <https://chatgpt.com/c>

E90post.com. (2019). What's the best Intake for N52 330i? [online] Available at: <https://www.e90post.com/forums/showthread.php?t=514298&utm> [Accessed 16 Nov. 2025].

Heisler, H. (2002) *Advanced Engine Technology*. Oxford: Butterworth-Heinemann.

Heywood, J.B. (1988) *Internal Combustion Engine Fundamentals*. New York: McGraw-Hill.

Jenvey.co.uk. (2017). Faqs. [online] Available at: <https://www.jenvey.co.uk/faqs/?utm> [Accessed 16 Nov. 2025].

mw (2021). Motor Werke. [online] Motor Werke. Available at: <https://motorwerke.ca/bmws-vanos-system-and-common-issues-explained/>. [Accessed 21 Mar. 2026]

Norton, R.L. (2011) *Cam Design and Manufacturing Handbook*. 2nd edn. New York: Industrial Press.

Omegaowners.com. (2026). *What kind of place is this anyway?* [online] Available at: <https://www.omegaowners.com/forum/index.php?topic=904> (image)

Pulkrabek, W.W. (2014) *Engineering Fundamentals of the Internal Combustion Engine*. 2nd edn. Harlow: Pearson.

Ricardo Software (2024) *WAVE Engine Simulation Software – User Documentation*. Shoreham-by-Sea: Ricardo plc. Available at: <https://www.ricardo.com> (Accessed: 21 March 2026).

Robinson, M. (2024). What Are Individual Throttle Bodies And Why Might You Want Them? [online] CarThrottle. Available at: <https://www.carthrottle.com/features/what-are-individual-throttle-bodies-and-why-might-you-want-them>.

Sae.org. (2026). *SAE International | Advancing mobility knowledge and solutions*. [online] Available at: <https://www.sae.org/papers/effects-intake-valve-events-engine-breathing-capability-912470>

SF Single Bore Throttle Body Engineered to win. (n.d.). Available at: https://www.jenvey.co.uk/media/documents/drawings/SF_WEB_ISS3.PDF [Accessed 21 Mar. 2026].

Stone, R. (2012) *Introduction to Internal Combustion Engines*. 4th edn. Basingstoke: Palgrave Macmillan.