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Group Project Report

ACHA5014

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1 Introduction

1.1 Justification

The Restoration and modification of the FZR represents a valuable engineering project. By blending contemporary mechanical and modern performance principles with a classic motorcycle foundation. This presents a challenge to us beyond the technical outcome by providing significant personal and educational value. It derives from a substantial theoretical and mechanical challenge that requires us to initiate hands on fabrications, material determinations, experimenting and optimisation, pushing the teams' skills beyond that of normal comfort zones. This will enable us to acquire and develop skills that weren't already present.

1.2 Aims

The aim of this project is to restore and enhance a Yamaha FZR1000 motorcycle through targeted engineering modifications, transforming it into a competitive and reliable machine suitable for participation in endurance-based circuit racing, specifically within the No Limits Racing category. The project seeks to improve overall performance, efficiency, and data acquisition capability while maintaining compliance with racing regulations and practical manufacturing constraints.

1.3 Objectives

- To assess the current condition of the motorcycle and identify key areas requiring improvement in terms of performance, safety, and reliability.
- Investigate and redesign selected mechanical and electrical systems of the motorcycle, including engine components, suspension, structural elements, and supporting systems.
- Apply engineering principles and analytical techniques to improve the performance and efficiency of individual subsystems.
- Utilise modern engineering tools such as CAD modelling, simulation, and data analysis to support design decisions.
- To ensure the motorcycle complies with relevant racing regulations and safety requirements.
- Developing practical solutions that consider real-world constraints such as manufacturability, cost, and time limitations.
- Implement and, where possible, test modifications to evaluate their effectiveness.
- Work collaboratively as a team, effectively allocating tasks and integrating individual contributions into a cohesive outcome.

-To critically evaluate the success of the project, identifying strengths, limitations, and opportunities for further development.

2 Background



Figure 1(Yamaha FZR 1000 1989) [Staticflickr.com. 2026]

For our group project, we will be restoring and modifying a 1989 Yamaha FZR1000 motorcycle. This report retrospectively documents the collective group efforts and individual processes carried out by each team member. Our overall goal is to fully restore and upgrade the already existing motorcycle through rigorous calculations and team efforts, to ensure the motorcycle is prepared for No limits Endurance Racing.

3 Project Organisation and Tasks

3.1 Daniel Briggs

The primary role for Daniel is to research the sensors that will need to go on the motorcycle to keep the motorcycle compliant with the regulations for the endurance race. The secondary role for Daniel is to redesign the yokes on the motorcycle and try to lose weight, but at the same time keep the structural strength. The third role is to support others in the group for their task on the motorcycle.

3.2 Finn Flye

Finn will begin by inspecting the engine clearances, ensuring the valves and camshaft are within the motorcycle's specifications. Furthermore, a deep analysis will be conducted on the strength and potential structural issues of the welded steering column. Finally, a CAD model of a rear shock will be created. Following this, a MATLAB script will be produced against the gathered dyno data of the shock and optimized versions.

3.3 Lars Milner

First check if the play in the rear suspension system is within tolerance. Accurately measure the dimensions of all parts of the rear suspension and, importantly, the relative positions of all pivots and mounting points. Model the rear suspension system and establish its characteristics. Then attempt to redesign the linkage keeping in mind the bikes intended purpose. Finally, structurally analyze the redesigned parts.

3.4 Moses Adair

Moses will be looking at the exhaust system with potential for redesign. Also, Moses will be looking at the headers and collectors for the motorcycle. The third part of the motorcycle Moses will be looking at electrical wiring.

3.5 Oska Robertson

Oska will review the race regulations and ensure the motorcycle complies with the required standards set by the ACU (Auto Cycle Union Bike Sport GB). This will entail replacing the brake light with a rain light, oil sealing, removal of indicators, removing the glass and examining the chain guard for compliance.

4 Daniel Briggs

4.1 Completed Tasks

I have investigated what sensors are required for the endurance race and where the sensors should go on the motorcycle.

I have redesigned the yokes on the motorcycle and run basic simulations on the motorcycle.

4.1.1 Support work

I have supported Oska with some research in finding out some of the regulations for the endurance race.

I have helped with disassembling the motorcycle and removing the engine from the chassis.

I have supported Moses in measuring the exhaust system for a potential redesign.

I have helped with taking the chassis apart, looking at whether the chassis can be fixed, or if the group needs to replace the chassis.

I have supported Finn with the reassembly of the motorcycle engine after Finn had finished measuring the clearances and valves.

4.1.2 Extra Work

Finn and I Striped parts of the engine and vapour blasted the casing to remove dirt and paint.

After vapour blasting, I cleaned up the casing and prepped the parts for painting

I painted the parts and let them dry.

Finn and I reinstalled the painted parts to the engine and reinstalled the engine to the frame of the bike.

4.2 Research

To find out the endurance race requirement Oska and myself researched the regulations and found out that it only allows two types of transponders, which are:

- AMB TranX 260
- MYLAPS X2

The MYLAPS X2 has been updated and is now the MYLAPS TR2. This is the sensor that the group will use on the motorcycle. The sensor must be mounted on the side of the motorcycle below 600mm

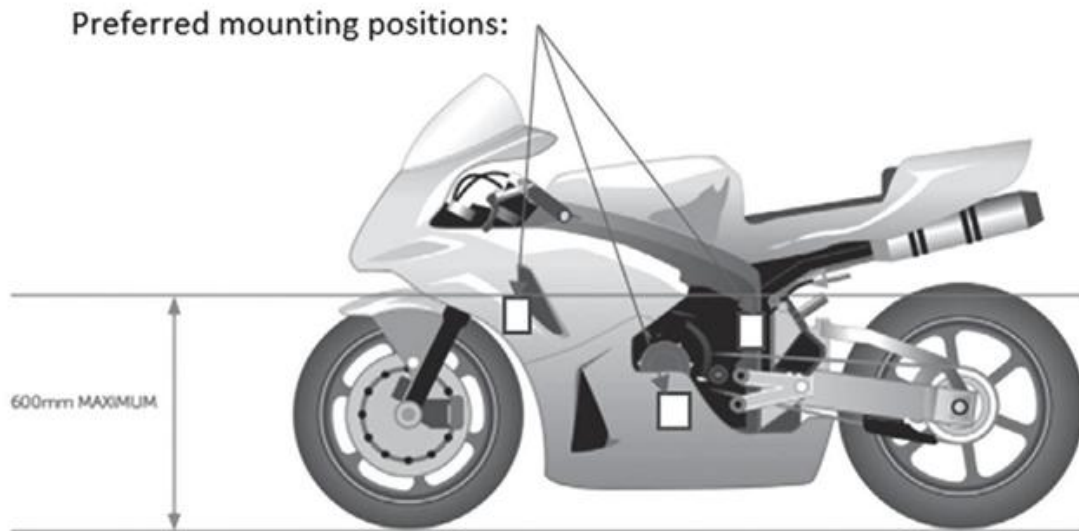


Figure 2 (The Mounting Position for the transponder) [Moto Performance. 2025]



Figure 3 (MYLAPS Transponder) [ROAD RACING STANDING REGULATIONS. (n.d.)]

Another research area is in the yokes, what material is used for the yokes and why.

6061 T6 aluminium: This is a very popular material used for general-purpose alloy used in many billet-machined motorcycle parts, such as yokes. It offers good strength, excellent corrosion resistance, and is easier to machine than the 7000 series.

6082 T6 aluminium: A common, slightly stronger European alternative to 6061 that is widely used and anodises well.

7075 T6 aluminium: this material is becoming popular for being used in high-performance or racing triple clamps due to its superior strength-to-weight ratio. It is an aircraft-grade alloy with strength comparable to many steels, making it ideal for high-stress applications, however it is more expensive than the other grades of aluminium mentioned above.

4.3 Designs

The images below show the different designs and concepts. All the designs are based on the yokes that were on the motorcycle when the project started; however, after an accident, the bottom yoke was destroyed.

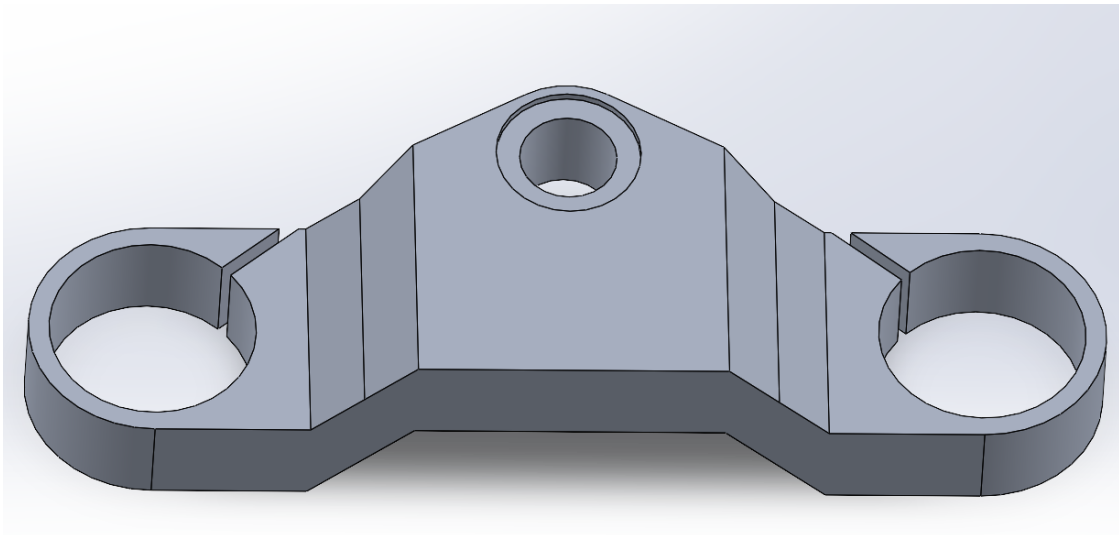


Figure 4 (Standard Yoke CAD Design) [D. Briggs 2026]

This image is the base template for the other designs below, in order to keep the designs symmetrical and have a base to make comparisons.

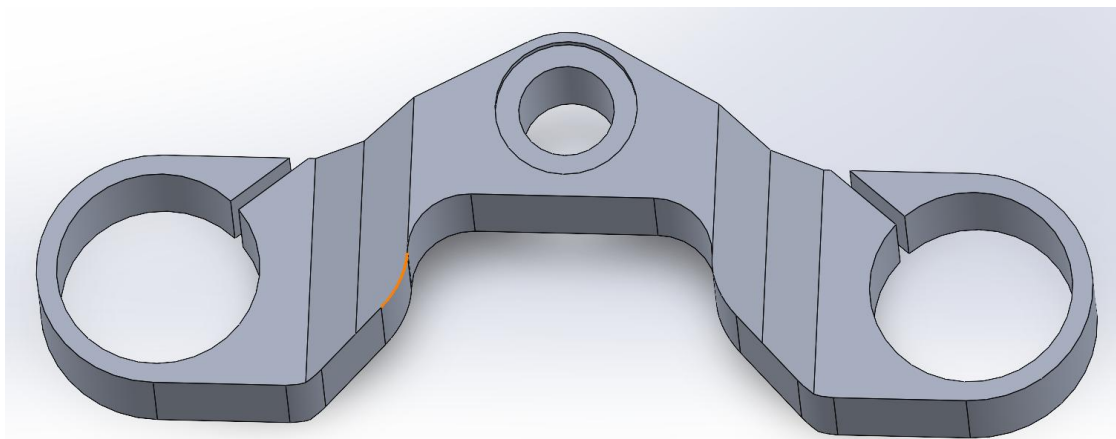


Figure 5 (Cut Away Yokes CAD Design) [D. Briggs 2026]

The Cut Away design was to see how much could be removed before the component failed; however, the design was interesting when the component went through the simulation.

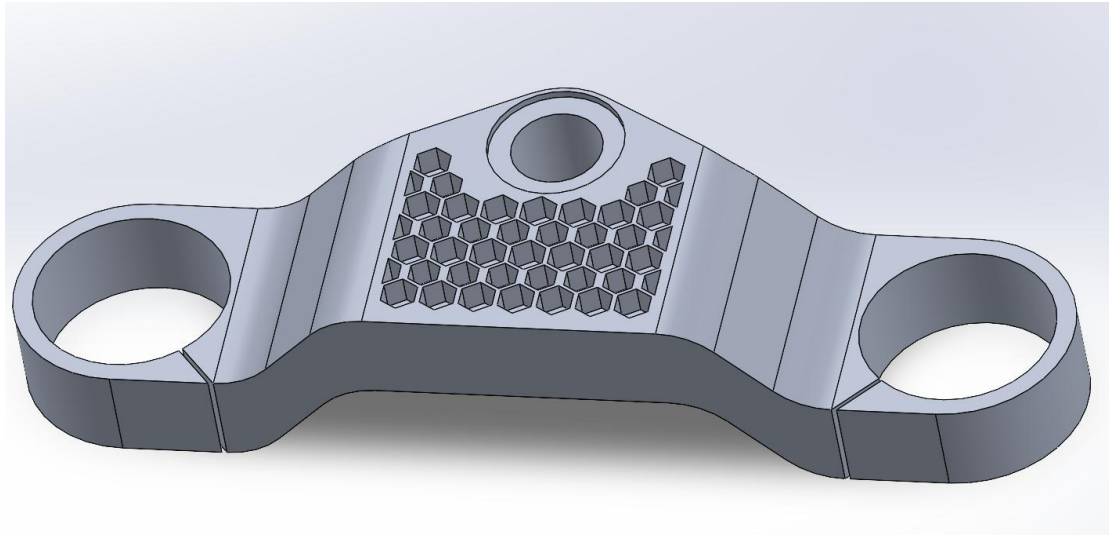


Figure 6 (Hex Hole Yoke CAD Design) [D. Briggs 2025]

The problem with the Hex design is that when the component is created, the corners of the hexagons would be very difficult to create with the CNC machines. However, this design keeps the component's tensile strength and removes weight.

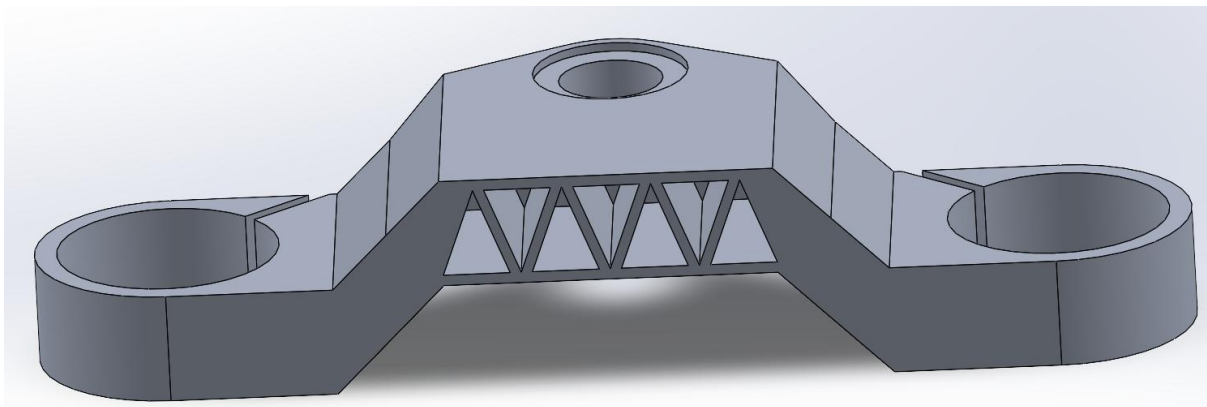


Figure 7 (Bridge Yoke CAD Design) [D. Briggs 2026]

The Bridge design was just a experiment to see if this type of structure could work in yokes and the results are surprising because the structure did hold.

4.4 Development

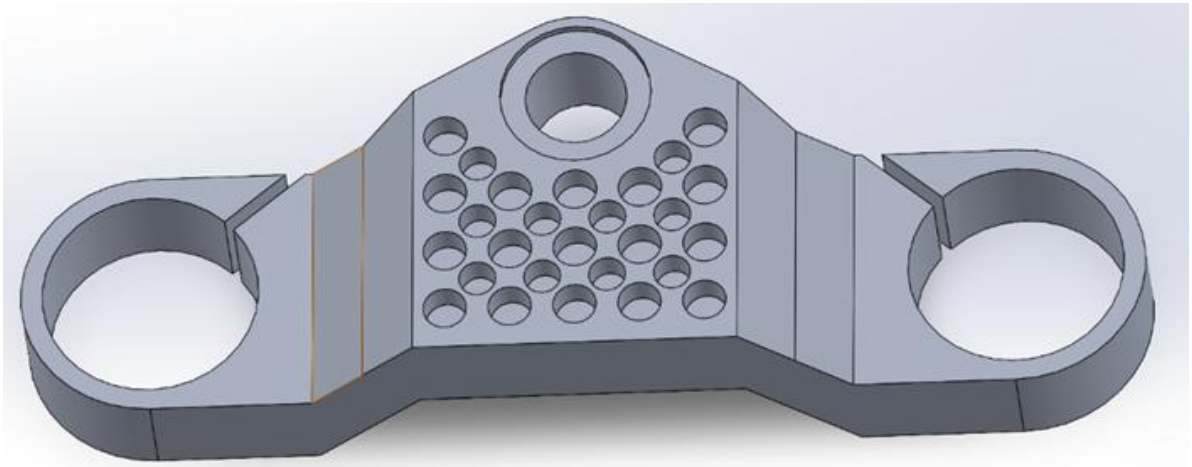


Figure 8 (Top Yoke CAD Model) [D. Briggs, 2025]

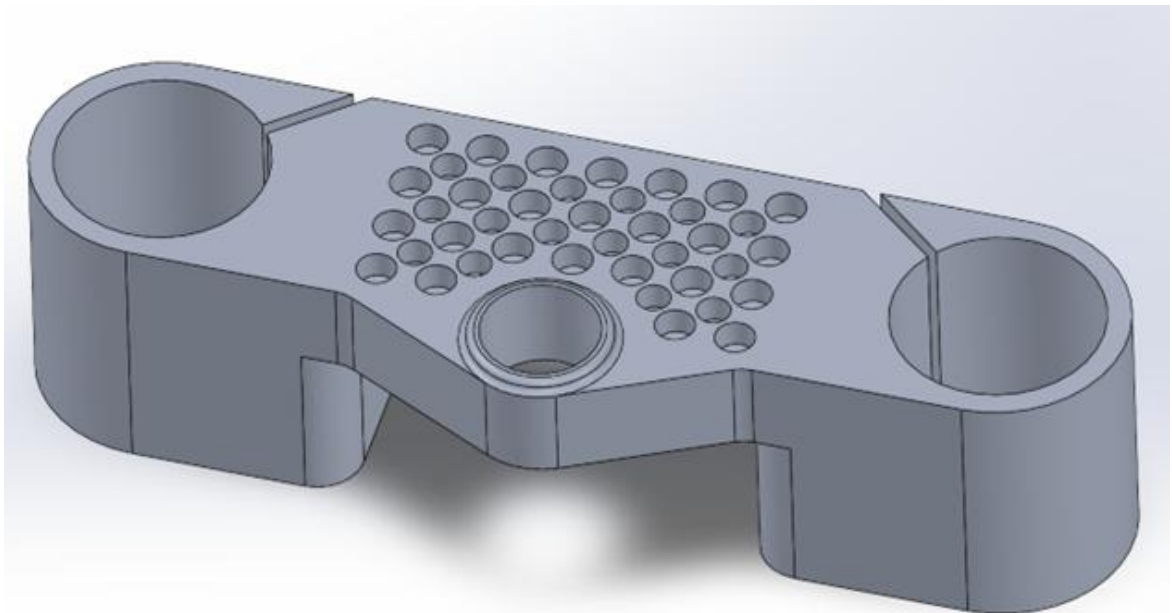


Figure 9 (Bottom Yoke CAD Model) [D. Briggs 2026]

The decision was made to go with this design because this design is easy to produce and works well in the simulations, as shown below.

4.5 Testing

After the CAD designs were completed, a simulation was used to see the Stress and strain on the parts with a load of 1000N of force

Below shows the results of the simulations

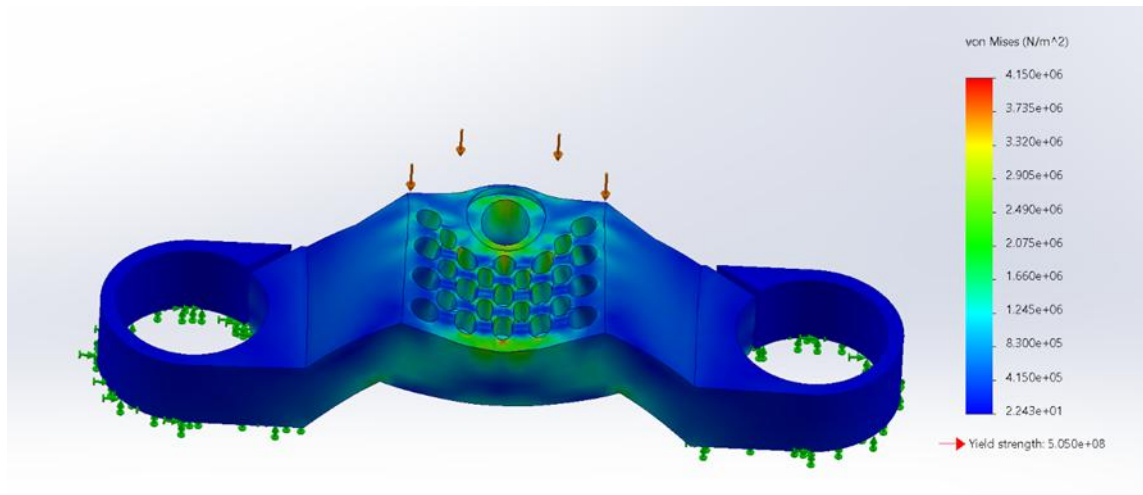


Figure 10 (Top Yoke Stress Simulation) [D. Briggs 2026]

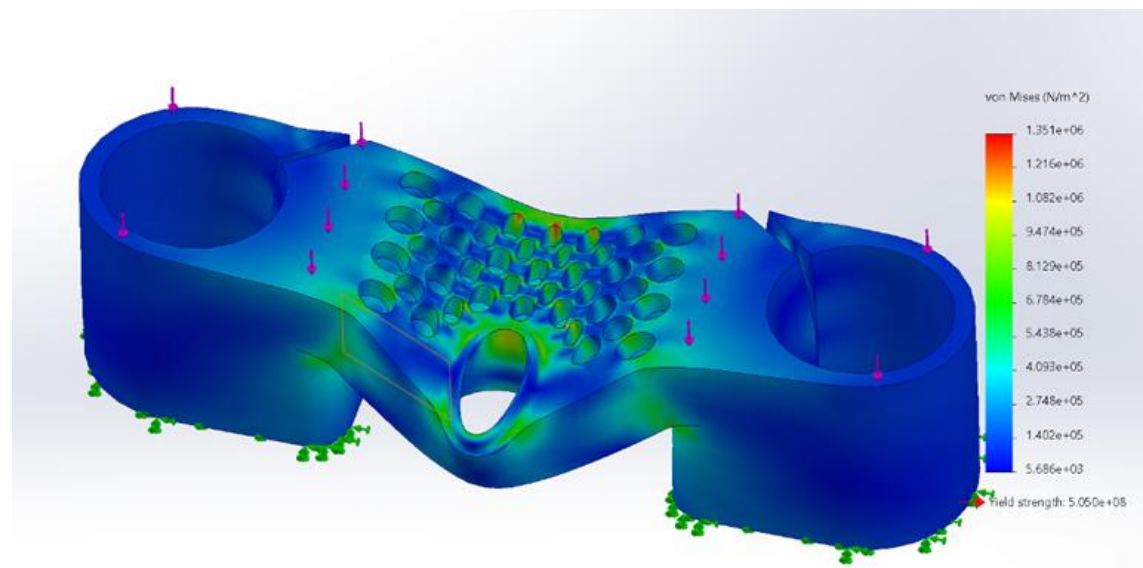


Figure 11 (Bottom Yoke Stress Simulation) [D. Briggs 2026]

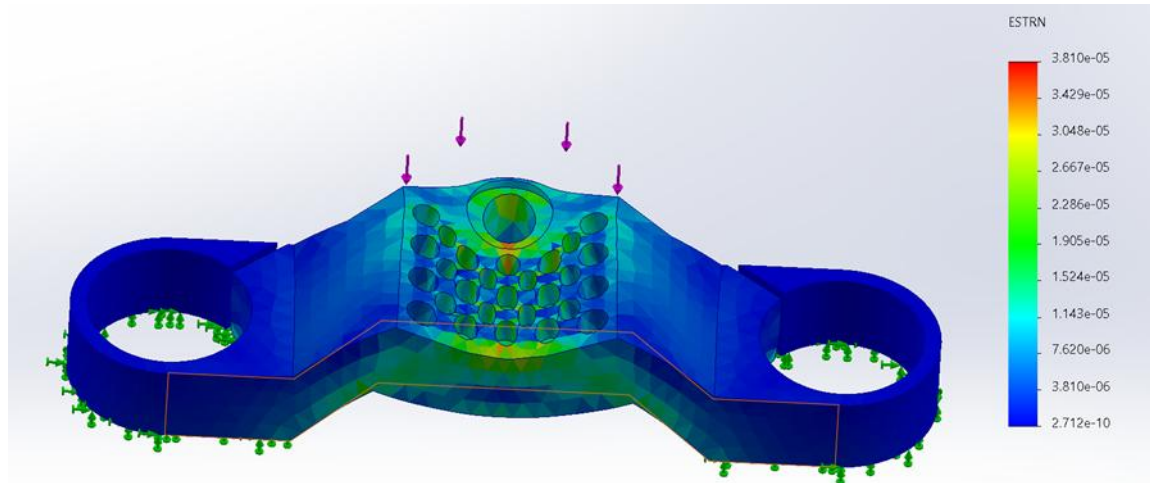


Figure 12 (Top Yoke Strain Simulation) [D. Briggs 2026]

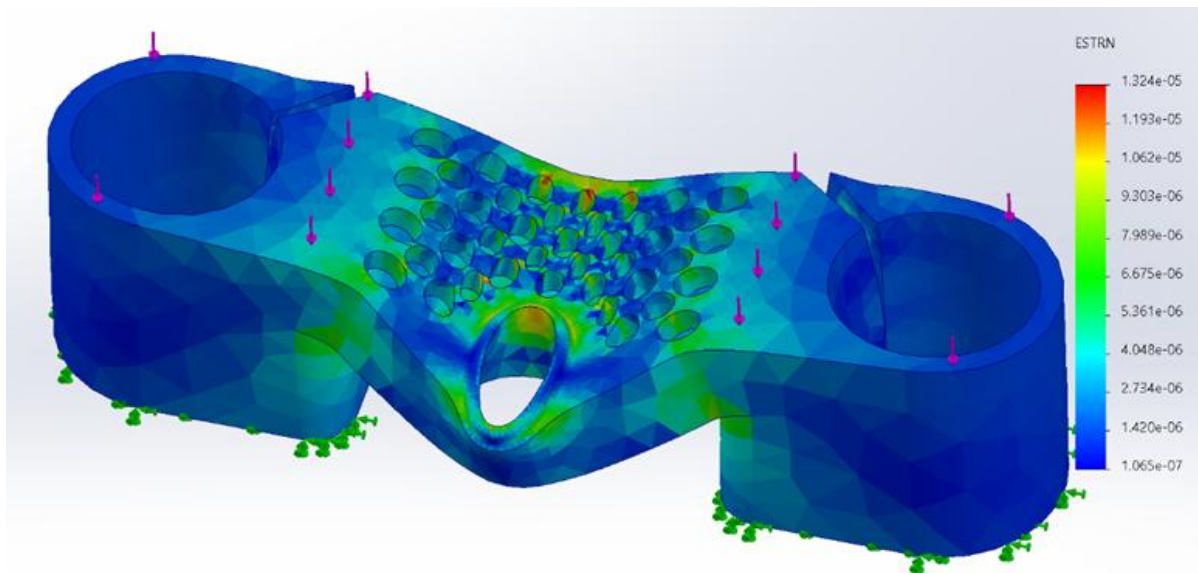


Figure 13 (Bottom Yoke Strain Simulation) [D. Briggs 2026]

4.6 Analysis

The material that would be used in the construction of the yokes would be aluminium 7075 T6 because this material offers a superior strength to weight ratio.

After the simulations were completed, the results showed that the aluminium material would fail before the components would deform. The preliminary simulation shows that the design would be an improvement to the standard component; however, there needs to be a few more simulations and tests done before the part can be used on the race motorcycle.

5 Finn Flye

5.1 Introduction

The primary goal of this section is to redesign the motorcycles currently fitted rear suspension. This begins with developing an informative CAD model of the proposed new design. Once the CAD model has been optimised and constructed a MATLAB script based on damper characteristics will be composed through parameterized real damper dynamometer data gathered from the original shock. This script will enable accurate calculations of the damper characteristics which include Rebound/Compression coefficients and ratios at high and low speeds, the natural frequency of the system.

Leveraging these parameters an enhanced and optimised version of the script can be written. This script will improve the original one by defining target performance values such as improving the performance around the track, including the bumps and rough terrain and increasing the chassis stability by increasing the rebound damping while keeping the compression low.

In Addition, another key objective includes the evaluation of the implications of welding repairs on an aluminium frame, specifically addressing the already existing crack on the steering column that necessitated prior welding. The subsequent analysis will assess the strengths and weakness inherent to the welding process of high stress areas such as the steering column.

The finding from this analysis will subsequently determine the action taken towards the motorcycle itself, whether to retain the welded frame or come to the decision to pursue a newer and treated aluminium frame for the motorcycle.

5.1.1 Support Work

Through conversing with fellow members instances of collaboration occurred regarding sharing data of MATLAB scripts with lars and him sharing motion ratio and wheel spring rates that will be taken into consideration for the improvements and accuracy of scripts.

To further this section collaboration occurred between Dan and Oska in the support of analysing and verification of the engine valve clearances. This ensured the intake and exhaust within the specified tolerances. While giving verbal measurements Dan and Oska assisted by recording the measurements and cross referencing to each other and the manual to ensure all areas were covered.

5.2 Research

5.2.1 Welding Strengths and Complications



*Figure 14 Photograph of weld on steering column
(F. Flye, 2025)*

This section examines the welding results in a key structural area of the motorcycles frame, that of which is the steering column. This location significantly influences the structural integrity of the front portion of the motorcycle while simultaneously effects the direct inputs of the rider.

One Key advantage of aluminium welding is the ability to control grain sizes, as stated by (Mathers, 2002) 'minimize the risk of hot cracking, controlling the strength of the metal and its notch toughness'. In Aluminium the strength lies in the boundaries between the layers of grains, when the grains are smaller this creates more boundaries, thus impeding dislocation movement and thereby increases the overall structural strength of the material. To optimize this process to reduce the sizes formed in the heating process, parameters can be optimised such as the heat affected zone (HAZ) can be limited while heat inputs and cooling rates can be changed accordingly.

Furthermore, once welding occurs the hot aluminium is exposed to air which rapidly forms a thin layer of aluminium oxide which is significantly resistant to corrosion and rust.

On the other hand, despite the benefits welding introduces many implications based on location especially in the high stress area of the steering column and the weld itself. A primary concern is 'gas porosity' as noted by (Fracchia, Gobber, Rosso, 2017) gas porosity is the occurrence when cavities form in the metal where hydrogen gas can become trapped underneath the material as highlighted by (Ardika, Triyono, Muhayat, 2021) 'they are dissolved in the welding process' this means the structural integrity is massively effected as the cross sectional area shrinks which means the strength decreases as its proportional to the area.

Further on this topic this induces further fatigue on the motorcycle as the front portion of the bike is under constant cyclic loads, these include vibrations, corner forces and road impacts. From this it can also be determined that there is a significant increase of potential cracking as pores provide areas that initiate cracking which can propagate swiftly under stress.

Finally, the location of the weld plays a vital role as this could affect steering as the racer that holds the bearing could be slightly off if the material pushes against the races meaning that all steering inputs can be construed and if the material fails this could cause sudden loss of control.

5.2.2 Design Inspiration



Figure 15 (Legend Suspension REVOARC Remote Reservoir Shocks) (revzilla, 2026)



Figure 16(YSS Rear Mono Shock External Reservoir) (Fc.moto, 2026)

These designs served as the initial foundation for developing the rear shock model. They feature distinctive reservoir canister concepts with the damping adjusters integrated into the design themselves, rather than using the more conventional remoter adjusters.

Building on these ideas, a new reservoir was constructed with a similar cylindrical surface and standard nitrogen repressurizing nipple. However, following the similar notion of having the adjuster on the body of the canister an innovative cog design was constructed mounted on the cylindrical profile. This mechanism allows for simulations or independent control over both high and low speed compression damping through this compact component.

5.3 Experiments

5.3.1 MATLAB Data

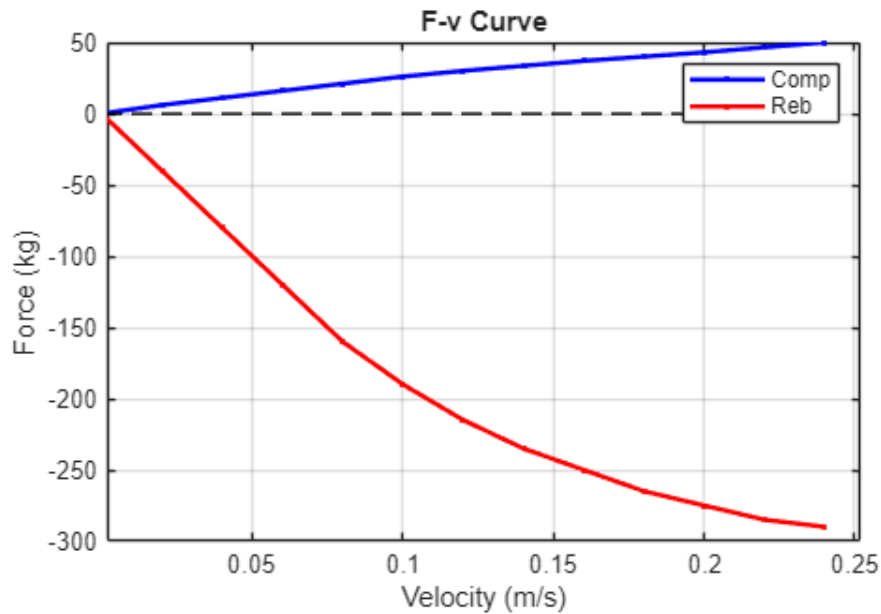


Figure 17 Force Velocity Diagram based off Dyno Data collected (F. Flye, 2026)

This graph is derived from actual damper dyno testing carried out on the rear shock from the Yamaha FZR; this illustrates the real behaviour of compression and rebound strokes across the shaft velocity. Furthermore, this data will undergo deeper analysis to calculate Damper coefficients, Damping ratios and with additional information the natural frequency of the system. In essence this conveys how a real damping operates which gives a further understanding into this research.

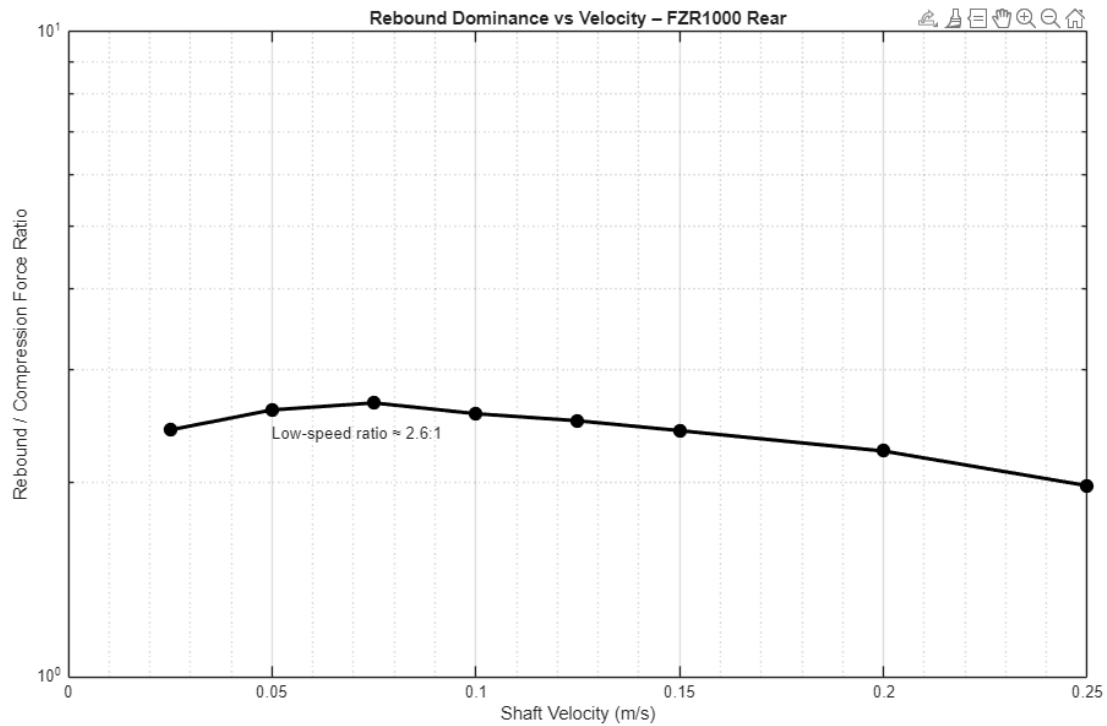


Figure18 Rebound Dominance vs Shaft velocity graph (F. Flye, 2026)

The rear damper from this bike illustrates a well balanced rebound dominance, with a rebound to compression ratio peaking a 2:6:1 in the low speed region before a smooth transition to 2:1 at the higher shaft velocities, which corresponds well to real world data as stated on (ShimRestackor, 2013) 'rule of thumb is 2:1 for rebound to compression ratios' this provides the motorcycle with strong stability and rapid settling under inputs. Following this the gradual reduction ensures traction friendly behaviour during swifter suspension events.

Table 1 Data Produced from MATLAB Script showing the Damper Values (F. Flye, 2026)

	FZR 1000 Rear Damper Analysis	
Shaft Damping Coefficient (low speed)	0.01-0.08	m/s
Compression	4415	N.s/m
Rebound	12361	N.s/m
Shaft Damping Coefficient (High speed)	≥ 0.12	m/s
Compression	2901	N.s/m
Rebound	3863	N.s/m
Wheel Rate Damping (MR)	2.6	
Compression low	653	N.s/m
Rebound low	1828	N.s/m
Sprung Mass	114	kg
Wheel Rate	30000	N/m
Critical Damping	3699	N.s/m
Damping ratios ζ		
Low speed Compression	0.098	
Low Speed Rebound	0.785	
High Speed Compression	0.064	
High Speed Rebound	0.245	
Natural Frequency	2.58	Hz

Table 1 highlights the calculated data from the MATLAB script; enabling crucial insights into how the characteristics of the damper really function on the FZR, this allows for ideas on how it can be tuned for finer riding and more stability. These results show a strong rebound bias at 12361 and 3863ns/m which in turn enhance the stability of the suspension as it counters the aggressive unloading force from the spring during its extension, this enacts a prevention to over oscillation of the system.

The lower rebound damping creates a low speed rebound ratio of 0.785 that equates to a quick and sharper response without overdamping as this would make recovery slower. The compression values are light which means that the rear can handle bumps well which is ideal for enduro racing.

To see the code that produced the graphs and calculated the data please see appendix 13.2.1

5.3.2 Optimised Data

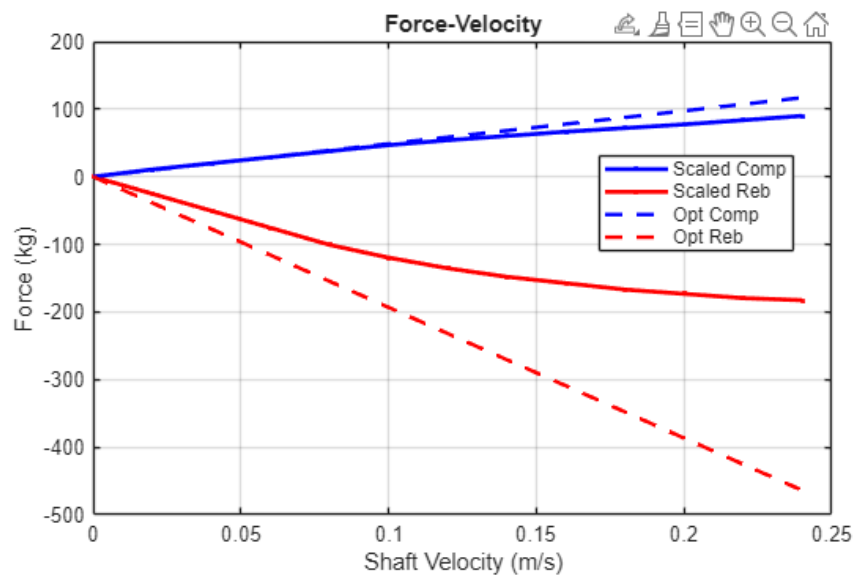


Figure 19 Graph Illustrating optimised data against original data (F. Flye, 2026)

The primary objective of the optimisation was to strengthen the rebound damping, while increasing the rebound to compression ratio and rebound ratio value, while keeping compression relatively soft as to create more chassis stability, quicker settling after bumps, reduce the pitch oscillation and the movement in the rear end post acceleration and during breaking. By prioritizing the rebound strength, the optimised data creates a confident rear end that recovers well and absorbs bumps efficiently which is ideal for the parameters of the endurance race.

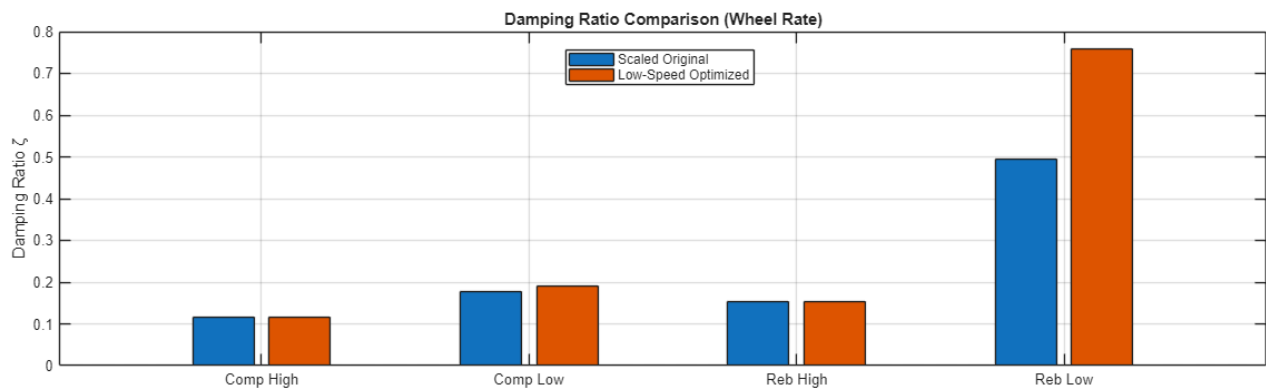


Figure 20 Bar graph showing the optimized against the original data (F. Flye, 2026)

Figure 18 conveys the optimised values of damping ratios that are correspondent to the values in Table 2 below, referring to the previous statement this was done to create a rapid response to settling and a better chassis stability. Regarding the code that produced this data please see appendix 13.2.2.

Table 2 Optimized data for Compression and Rebound (F. Flye, 2026)

Optimised Data		
Optimised Compression	4780	N.s/m
Optimised Rebound	18967	N.s/m
Rebound: Compression ratio	3.97:1	
Compression Ratio	0.191	
Rebound Ratio	0.759	

Table 2 presents the calculated data from the script showing the increased values for rebound and compression during low-speed damping. These values were produced from tragedized functions within MATLAB to create the desired characteristics.

5.4 Designs/ Prototypes

5.4.1 Preliminary Designs

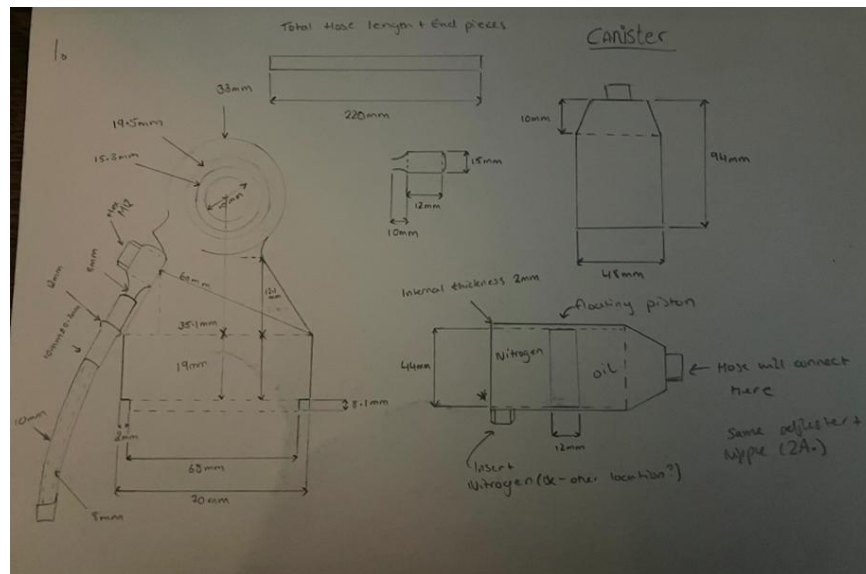


Figure 21 Preliminary Design 1, Rear Shock Head and Canister (F. Flye, 2025)

Figure 21 illustrates the initial constructed design of the upper portion of the rear shock, while representing a simplistic design for the remote reservoir. The inside of the reservoir is displayed to show the floating piston that will be implemented into the designs to maintain the isolation between the pressurized gas and the oil. The Dimensions of the shock were determined based on measurements gathered from the current shock on the motorcycle with a calculated hose length by running a string across the frame to acquire an accurate locale.

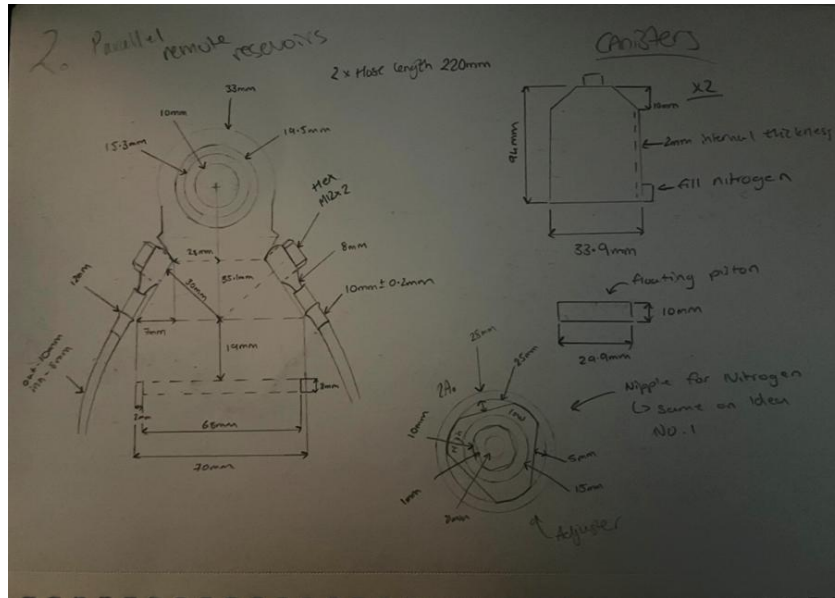


Figure 22 Preliminary Design 2, Twin Reservoirs (F. Flye, 2025)

In figure 22 it can be observed that the complexity of the initial design has increased through the introduction of a parallel function for two separate remote reservoirs, this then alters the required dimensions for both canisters and hose lengths, to account for this the initial parameters were halved. Finally, this design shows the parameters for the rebound and compression adjuster.

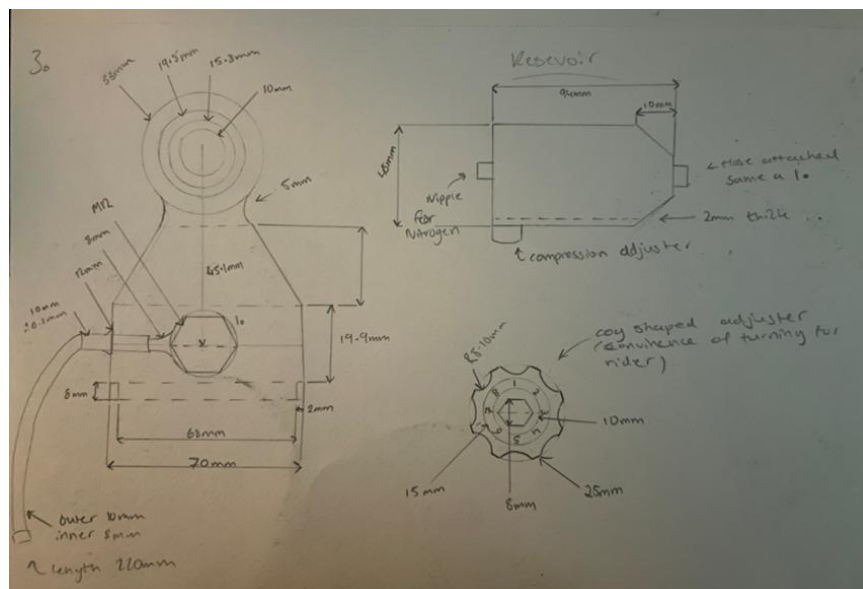


Figure 23 Preliminary Design 3, Hose located on side of head (F. Flye, 2025)

In addition to the previous designs this final drawing entails a singular remote reservoir with a more refined design, alongside a more practical and flexible adjuster configuration that improves compatibility with the rider as it is placed closer to the seat for easier access.

5.4.2 CAD Models

5.4.2.1 Rear Head CAD Model and Technical Drawing



Figure 24 CAD Model of Rear Shock Head (F. Flye, 2026)

The design shown in Figure 24 is based on preliminary design 3. The configuration was chosen due to the simplistic yet efficient design, which will be used on the complete full rear shock CAD model. This design features the top portion of the shock with the hose extension located on the outer ring of the body. This lets the hose slide over the 6mm extension using its inside diameter of 8mm, where the hose clamp can be later attached to fasten the hose down at both ends after the assembly. The hose extension will then be fastened with an M8x1.0 bolt with a central through hole to allow the oil to flow more freely through the fastening during the compression and rebound strokes.

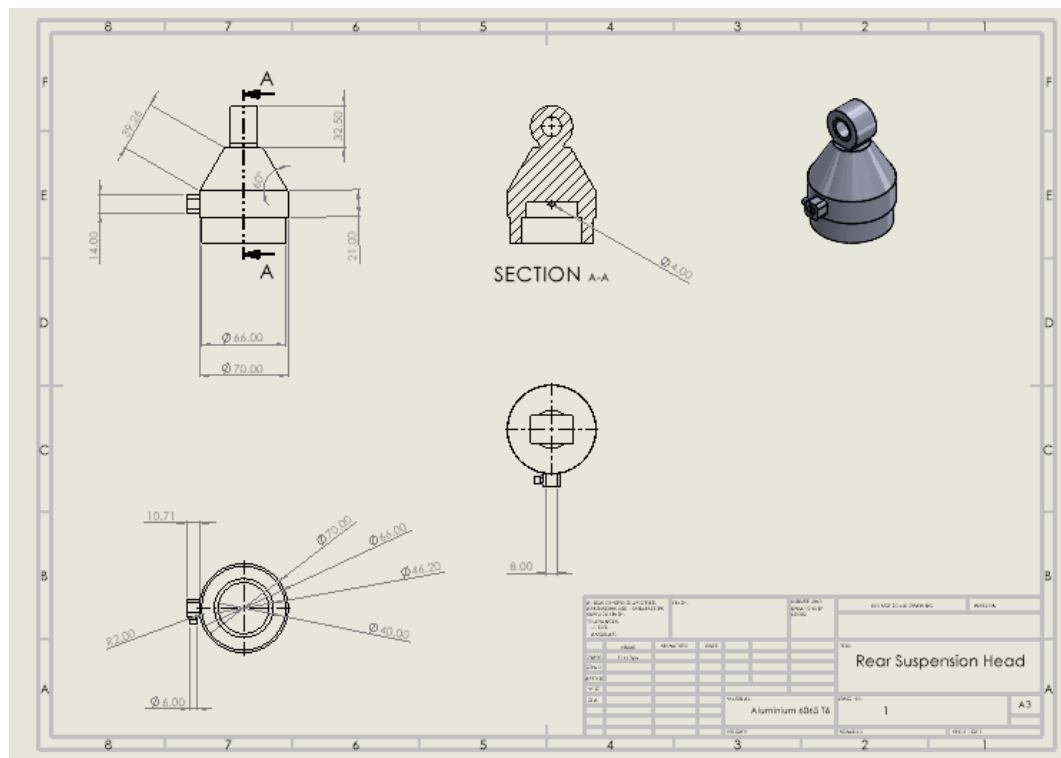


Figure 25 Technical Drawing of Rear Suspension Head (F. Flye, 2026)

Figure 25 illustrates the technical drawing generated by the model presented in Figure 22. This drawing clearly displays key dimensions, making it suitable for potential development through machining or possible collaborations with external companies. These dimensions shown in the Figure above were gathered from the current shock that is fitted to the motorcycle to ensure that if the design were to be produced that it would have full compatibility with the FZR.

The material for the shock will be aluminium 6061 T6 as a generalised and well-rounded material that is commonly used in shocks as highlighted by (AM Editors Team, 2026) 'Excellent corrosion resistance, exceptional machinability' which makes it well suited for this application. This provides exceptional protection against environmental damage and physical wear that can occur on the endurance race.

5.4.2.2 Complete Rear Shock CAD Model and Technical Drawing

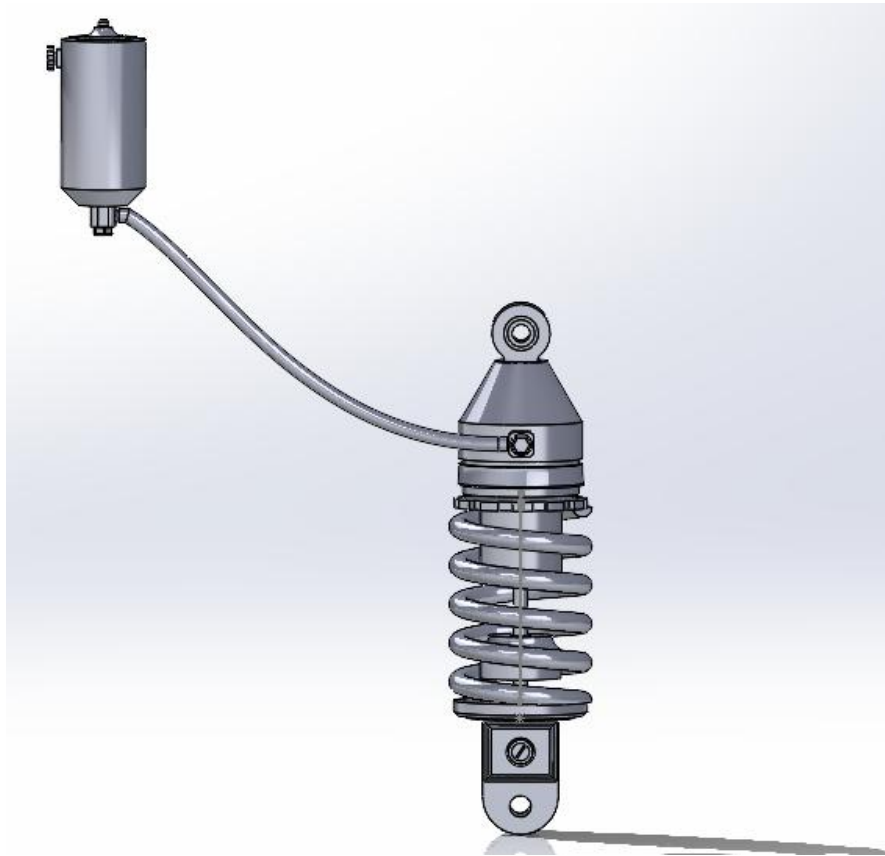


Figure 26 CAD Assembly of Rear Shock (F. Flye, 2026)

Presented in Figure 26 lies the complete rear shock assembly including the remote reservoir. Building on the material section above, the material for the hose will be Black Nitrile Rubber which is commonly used within bushings which is ideal for the application as the rubber provides excellent flexibility which allows it to transport oil across a wide range of temperatures while enabling smooth routing along the frame without risk of pinching or abrasion.

Furthermore, regarding the pistons and shims they will be made from aluminium as they are perfectly suited due to its wear and corrosion resistances. Finally, the bump will be made from polyurethane as highlighted by (polylabs, 2020) 'increased performance, protection and durability' this conveys that this material has a longer life than typical rubbers and preforms exceptionally well in physical wear resistances while helping the shock recover from bounces.

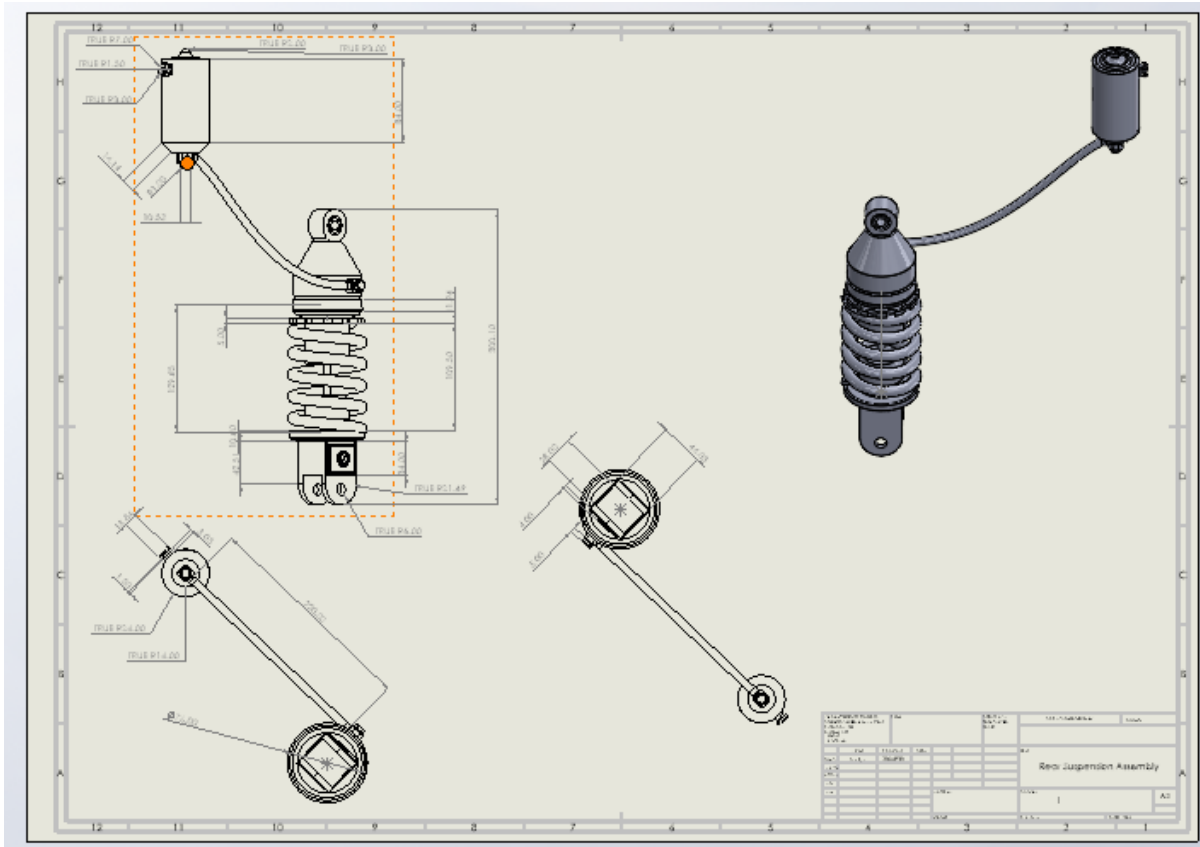


Figure 27 Technical Drawing of Assembled Shock (F. Flye, 2026)

Figure 27 conveys the technical drawing derived from the 3D model illustrated in figure 24. This drawing presents core dimensions, which align with the specifications noted in previous statements in the design section and incorporates the element of the remote reservoir as well as its dimensions.

The adoption of the remote reservoir design includes several important performance advantages in this rear suspension model; Optimised Airflow and heat dissipation through thorough calculations and converses with fellow members on where the reservoir should be placed. Heat dissipation arises from the travel that the oil undergoes through the hose between each body, due to this the oil remains cool, which in turn provides the retainment of peak performance in the system over a longer period.

Finally, the remote reservoir incorporates a floating piston that separates the pressurized gas from the oil. This separation maintains the pressurized gas without causing any mixture occurrences between the oil and gas, if not maintained correctly cavitation occurs causing the damper system to become decrease in damping effectiveness and inconsistent performance issues.

5.5 Conclusion

In conclusion, after thorough evaluation, the pursuit of an alternative frame has been declined. The existing weld has proven to be exceptionally robust, with post machining to further refine the weld into the correct parameters that there are no collisions between it and the bearing. The frame will continue in service under strict surveillance to ensure a new crack doesn't form this will be done by visual checks after each endurance race and immediate halting if there are signs of propagation of the crack which will result in reinforcement.

This surveillance approach balances practicality with the known fatigue issues associated with welded aluminium, this ensures reliable performance during the races and the safety of the rider.

Furthermore, the CAD modelling effort was successful, resulting in a comprehensive, fully detailed rear suspension model. The model incorporates the determined materials in preparation for potential production and cost determinations for the whole teams' concepts.

In addition, the MATLAB script was a success in conveying all the variables required to show the damper characteristics, which can be used to support the other members in their endeavours. Subsequently these can then be used to tune and optimize the original shock to have similar characteristics to the calculated data.

Finally, the optimised script shows the direction of characteristics we want the suspension to follow. These are presented by the direct increase to Rebound damping as this will create a stable chassis and quick response time without overdamping, while keeping the compression soft to enable the shock to absorb bumps smoother which is ideal for this application. However, the script can be further tuned as after thorough calculations and attempts the values for the rebound damping become substantially higher than intended.

5.6 Further Work

To further enhance and validate the rear shock redesign, a dedicated Motion analysis study can be conducted within SolidWorks. The simulation will simulate the linear movement seen on a spring under different forces that can equate to real world experiences, while being under the parameters of the known spring stiffness of the original shock and the calculated data from the MATLAB script. The study will compute plots for the linear displacement, velocity and acceleration of the spring. Additionally, the produced graphs and values can be compared to the MATLAB script outputs and against the linkage data that Lars has computed and measured to validate the kinematics of the design and data.

Finally, regarding the substantiality high values from the optimized code can be further refined with deeper analysis and conversing with suspension and MATLAB experts to ensure the code is outputting more realistic values in terms of increasing the base rebound damping coefficient.

Although these Configurations were initially planned to be incorporated into the work as a valuable insight, they were ultimately not incorporated primarily due to the time management constraints. During the project the development timeline proved more consuming than initially anticipated as significant time had been allocated to refining the designs and initial code to ensure the best possible quality of work. To reprimand this a stricter time management arrangement will be implemented while completing designs and risk assessments in earlier stages to ensure all work is conducted in accordance with the schedule.

6 Lars Milner

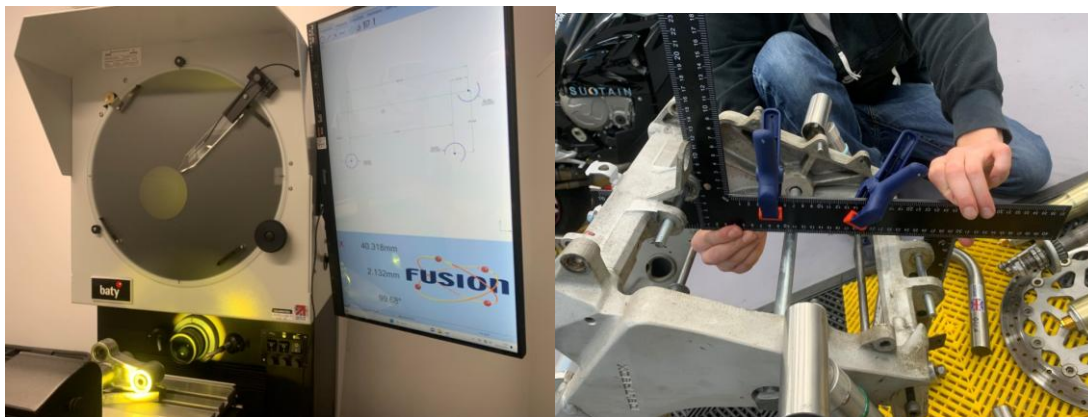
6.1 introduction

This section of the report analyses the rear suspension linkage of the yamaha. Important dimensions were recorded and a cad assembly built. This was used in a motion analysis to output motion ratio which can be used to determine wheel spring rates and damping. The linkage was then redesigned with regards to its purpose as a track bike and more modern trends in rear suspension linkages. Determined motion ratio values were communicated with the group, most importantly Finn, as his data at the rear wheel is very dependent on motion ratio and likewise his data for spring rate and damping at the shock is required for an accurate bump simulation. Finally, dynamic loads were imported into a design study testing the structural integrity of the new linkage.

6.2 Initial data gathering

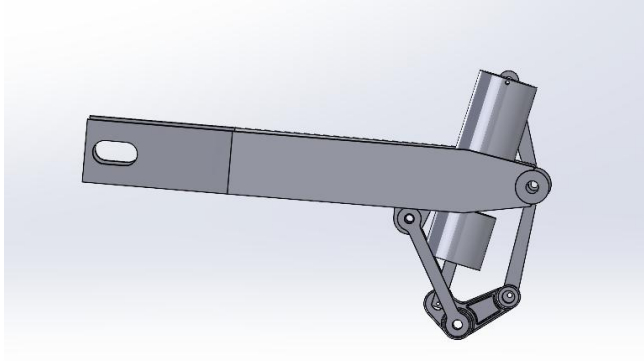
Measurements of the rear shock linkage and mounting points were taken using a shadow graph and for the more basic dimensions a tape measure or calipers. The points requiring measuring are all pivots and as such have bolts or pins that fit through and relative position measurements can easily be taken from these.

Figure 32



A CAD assembly with all the correct degrees of freedom was then constructed with the frame fixed in position. A motion simulation was used to rotate the swingarm through its travel and export data for the shock displacement and vertical wheel travel. The data was then manipulated in excel to find motion ratio. The assembly was also used to check for clearance issues in the new linkage.

Figure 33

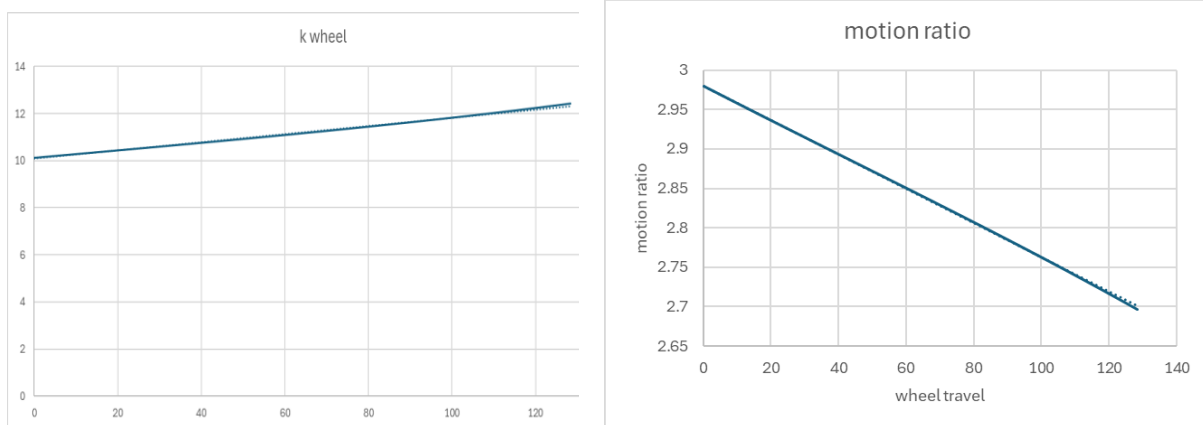


6.3 Initial results

Motion ratio was calculated as: *vertical wheel displacement / shock displacement*, for roughly every 0.25mm over 130mm of wheel travel. Figure 34 shows the linkage is

progressive and that the spring rate over the rear wheel rises 25% over the entire travel of the rear wheel.

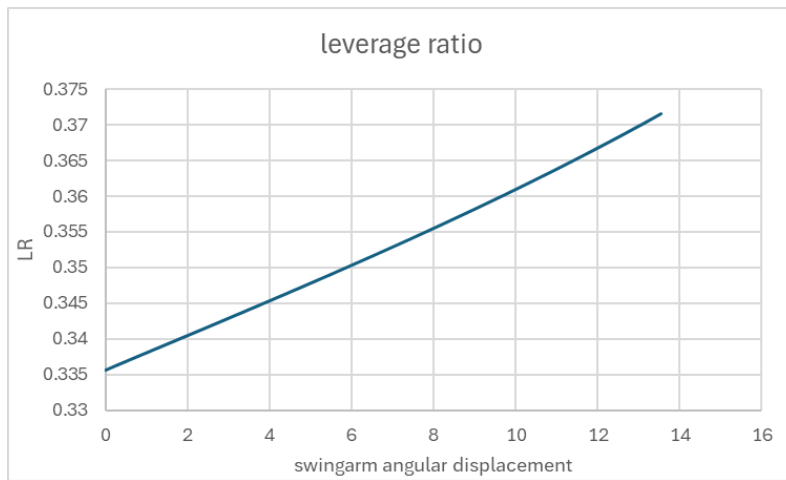
Figure 34.



6.4 Research

segľa , Antonescu , Orečný , elbaghar (2015) state in their paper about optimization of a Kawasaki zx6R rear shock linkage that the progressivity of the linkage enables the avoidance of bottoming out. This is especially important in racing applications where the bikes are ridden aggressively, the wheels are under high loads and bottoming would cause loss of grip and excessive loads. The initial softness of progressive suspension also absorbs smaller bumps well without jolting or upsetting the bike, an important parameter considering the surfaces of most British tracks. They also draw attention to the importance of the effect of the progressivity of the linkage on varying damper velocity and therefore damping force. Hwang and shih (1987) also mention that the progressivity of the linkage is very useful in altering damper curves in older shocks where adjustment is limited.

Figure 34



Hwang, shih (1987)

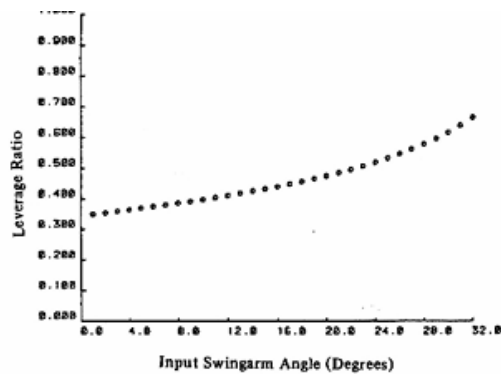
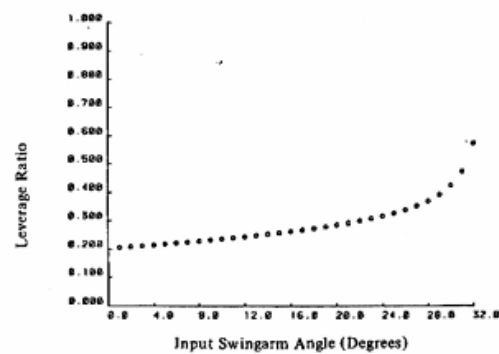


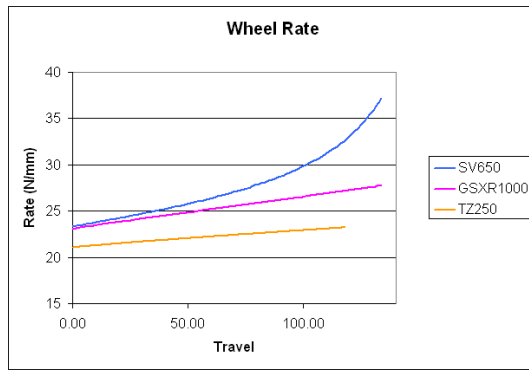
Fig. 3. LR of Suzuki VLRS mechanism.



Here are graphs of leverage ratio vs swingarm angular displacement for the Yamaha compared with Honda and Suzukis of the same era. It shows similar increases of around 0.05 over 12-14 degrees for each. These bikes all have progressively increasing spring rate.

Figure 35

Figure 35 shows spring rate vs travel for 3 more modern motorcycles. This shows a modern sports bike (GSXR 1000) and a 2003 Yamaha race bike with a linear increase in wheel rate with wheel travel. These bikes have modern suspension with more tuneable damping characteristics which can help avoid bottoming without unnecessarily increasing wheel spring rate at the end of travel.



Since our FZR will require a new, modern shock absorber to go racing my aim will be to straighten the motion ratio to get a more linear increase in wheel rate. This has some benefits in that the damper velocity will not increase exponentially for a

constant speed swingarm rotation, therefore making damper tuning simpler. It will also give more support in the initial part of the travel and resist squat and dive better.

6.5 Revised Design

The redesigned system is limited by being unable to alter any mounting points of the suspension system. This leaves only the wishbones and pivot/rocker to change. Over a few weeks a new assembly was produced with revised wishbones and pivot and the same motion analysis conducted. There is one design of pivot and an option of two lengths of wishbone. To keep the same average spring rate at the rear wheel the shock spring must be increased from 90Nmm to 140Nmm. the new components allow an extra 30mm of travel in the rear wheel with the same shock displacement or, with the wheel travel limited by larger bump stop to the original range, lower damper velocities.

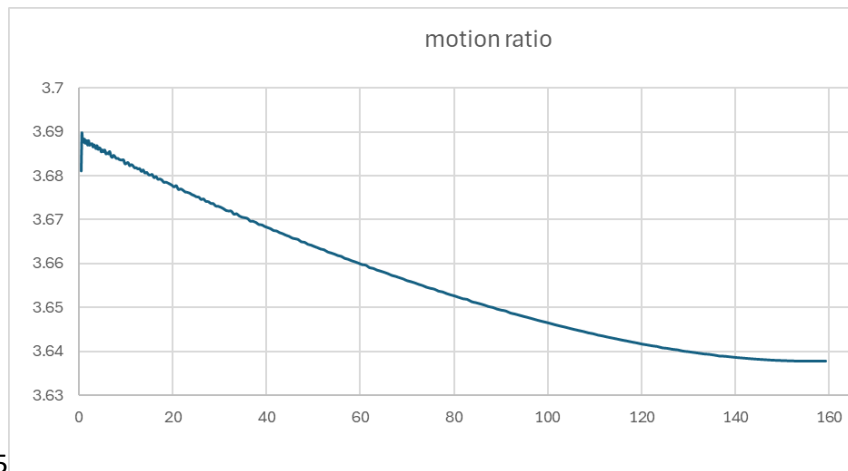


Figure 35

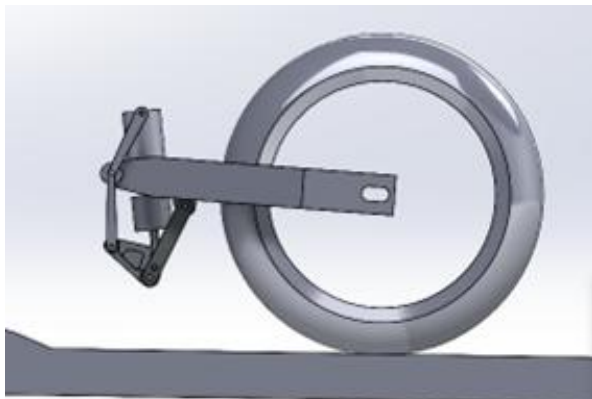
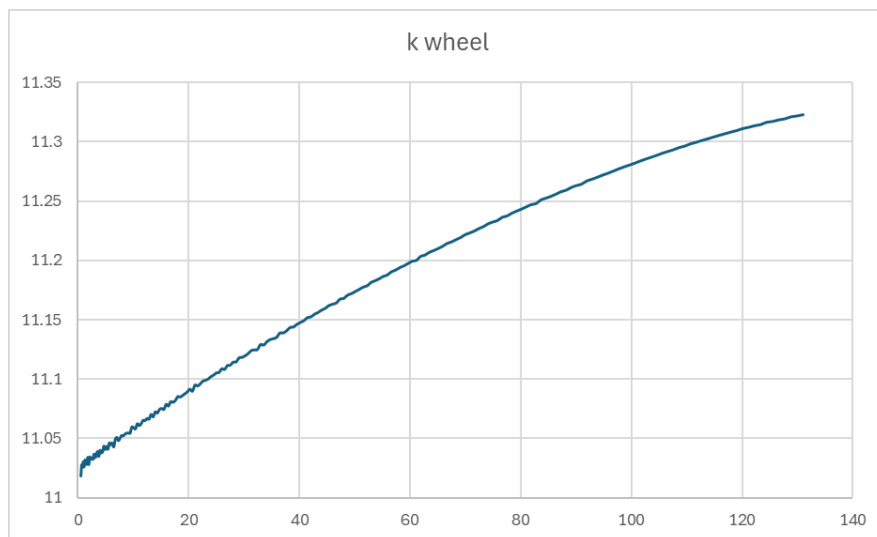


Figure 35 shows the motion ratio and wheel spring rate for the new pivot. The new components give a much more linear wheel spring rate and do not interfere in any way with the original ride height of the bike. In the first setup the wheel rate starts more progressively and ends flattening which is odd but not unheard of (2004 Kawasaki zx10r for instance). This is a result of the restriction of only being able to change the dimensions of the bones and pivot, (one dimension changes, so must another to compensate and keep the same mounting points) however the curve is still very close to a linear increase.

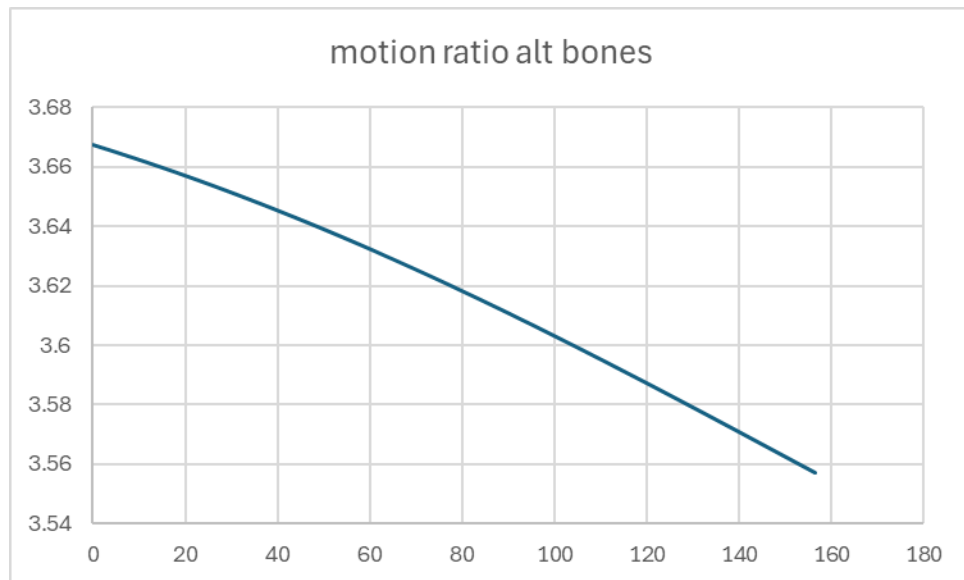


Figure 36

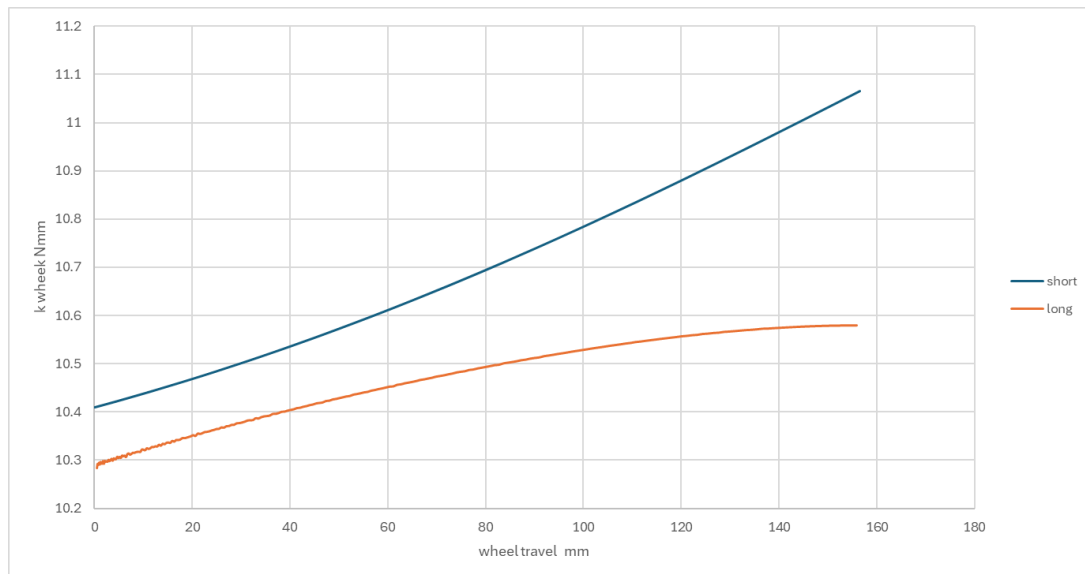
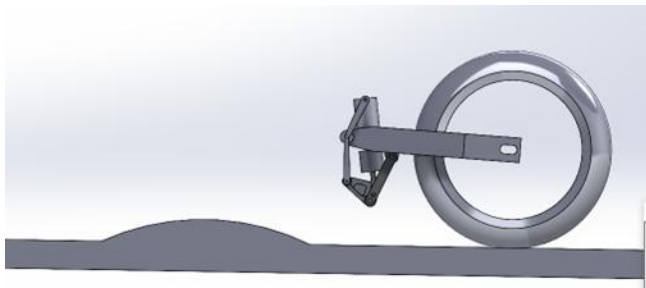


Figure 36 shows the motion ratio when the wishbones are connected at their shortened length. The next graph is a comparison of wheel spring rates for wishbones connected in their short and long positions. This shows the curve of the shorter wishbones is the traditionally favoured one, with the progressivity of the wheel spring increasing with wheel travel. However, to maintain structural integrity the mounting holes on the wishbones need to be a certain distance apart. Simply swapping these out would raise the rear ride height by 55mm which is rather a lot. Therefore, a shock absorber with length adjustable by 12mm is required to change the motion ratio curves with minimal change in ride height. Of course, with the shock and wishbone lengths adjustable rear ride height becomes massively adjustable providing the specific motion ratio curve is unimportant.

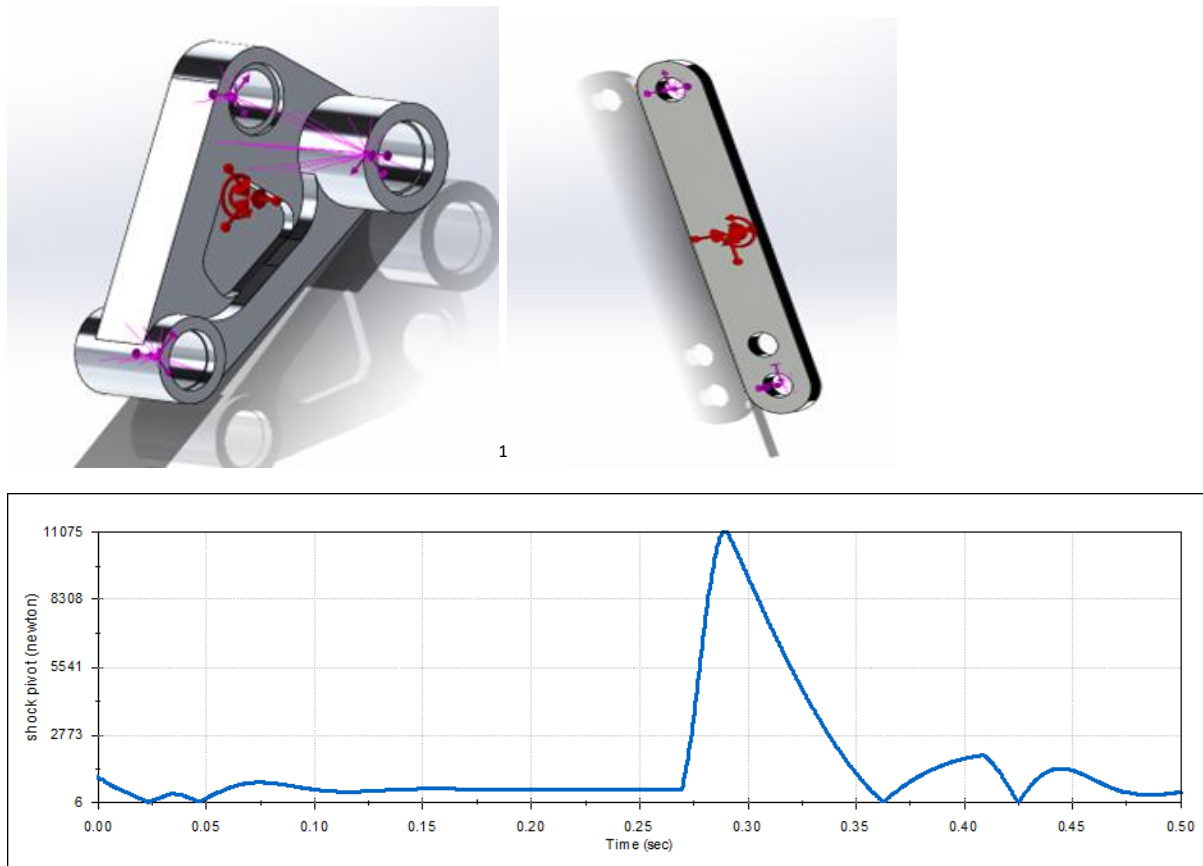
6.6 Structural analysis

Bump simulation variable	value	reference
Spring rate N/mm (linear)	140	Finn Flye
Preload mm	10	^
Damping Ns/mm (linear)	7.7	^
Tyre spring N/mm (exp 1.2)	200	Roberto Lot (2003)
Tyre damping Ns/mm (linear)	0.2	^
Impact velocity m/s	23	
Swingarm mass kg	5	
Wheel mass	17	
Frames per second	2500	

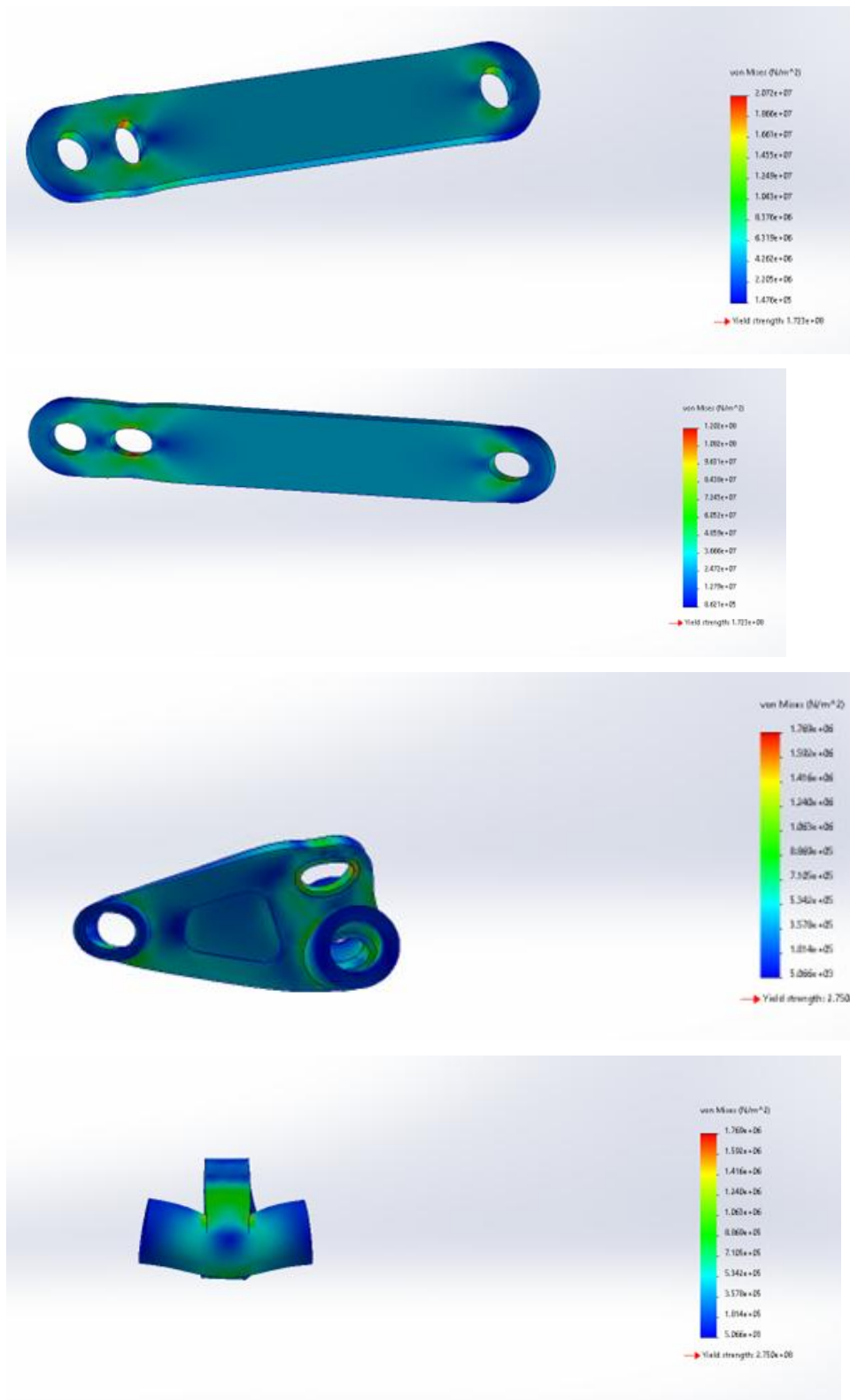


To structurally analyse the components a model of a road with a bump was moved by constant speed linear motor under the assembly. Variable values were calculated or researched (as displayed in the table) to ensure reasonably accurate load results and then the speed of the impact was increased until the suspension very nearly bottomed out. The load bearing surfaces of the pivot are the same size and position as the needle roller bearings pressed into them.

Figure 37 Shows the positions of the imported loads from the bump simulation and the load on the pivot at the face where the shock absorber attaches as an example.



Since the bump simulation took place without the bike leant over the loads on the pivot and wishbones could be considered two dimensional and acting in opposite directions depending on the vector of force on the wheel with some change with rotation of the pivot. Here are shots of the worst-case scenarios for each. The needle roller bearings are well within their limit for dynamic load (20.1KN, 27.7 KN, SKF, KOYO)



The material specified for the wishbones is chrome steel as the originals are. This is ideal and necessary to withstand the tensile and compressive stress and corrosion from water or salt but is not easy to machine. The pivot should be made from 6061 T6 aluminium. It is relatively cheap, easy to machine, and stands up to the stress well.

6.7 Limitations and possible improvements

To make the outputted forces more accurate the spring damping should be non linear. Currently it is an average of Finn's calculated ideal damping. Also instead of fixing the frame a sprung mass could be used. A side effect this new linkage could have is on swingarm lateral stiffness. Another bump simulation could be produced to study this with the bike leant over, suspension compressed and measuring sideways deflection. The lateral stiffness is important at high lean angles over bumps rather like Dans yokes.

7 Moses Adair

8 Introduction

Within the group motorcycle development project, my primary responsibility was the redesign and development of two key subsystems: the exhaust system and the electrical wiring harness. These areas were selected due to their direct influence on engine performance, system reliability, and suitability for a race-oriented application.

The primary objective of my work was to reduce exhaust restriction to improve engine performance and reduce overall system weight, while also redesigning the wiring harness to integrate additional data acquisition systems, improve reliability, and optimise routing and packaging for track use. These objectives required a combination of theoretical understanding, practical design considerations, and an awareness of real-world constraints such as cost, manufacturability, and time limitations.

The work carried out forms a critical part of the overall project, as both the exhaust system and the electrical system design significantly influence the performance and usability of the motorcycle in a competitive racing environment.

9 Exhaust System Redesign

9.1 Initial Assessment and Problem Identification

The Yamaha FZR1000 originally utilised an EXUP (Exhaust Ultimate Power Valve) system, designed to dynamically control exhaust backpressure and improve torque delivery across a wide engine speed range. However, the project motorcycle had previously undergone modifications in which the EXUP valve was removed, leaving behind a collector geometry that was no longer functionally optimised.

This resulted in several performance and design issues. The original collector, which had been designed to work in conjunction with the EXUP valve, became highly restrictive when the valve was removed. The internal geometry promoted turbulent flow and inefficient gas evacuation, reducing the effectiveness of exhaust scavenging. Additionally, the system was constructed from relatively heavy cast materials, contributing unnecessary weight to the motorcycle.

Given that the intended use of the motorcycle is for racing applications, where high engine speeds and efficient gas flow are prioritised, the existing exhaust system was identified as a major limitation. Improving this system presented a significant opportunity to increase engine efficiency and performance.

The performance improvements expected from the redesigned exhaust system can be further understood through the behaviour of pressure waves within the exhaust system. In a four-stroke engine, exhaust gases do not exit as a steady flow but rather as high-energy pulses each time the exhaust valve opens. These pulses travel through the exhaust system at high velocity and interact with changes in geometry such as bends, junctions, and collector regions.

In the original exhaust system, the collector geometry introduced abrupt changes in cross-sectional area and flow direction. This caused flow separation and the formation of turbulent regions, which dissipate energy and reduce the effectiveness of exhaust gas evacuation (Su, Zhao and Zheng, 2011). Additionally, the absence of the EXUP valve meant that the system no longer had any mechanism to control pressure wave reflection, further reducing efficiency, not only at low RPMs.

The redesigned 4–1 collector improves this behaviour by introducing a gradual merge angle. This allows pressure waves from each cylinder to combine more smoothly, reducing destructive interference between pulses (Ullah, Ahmed and Akhtar, 2021). According to Hidayanti, Adi and Wati (2020), as a result, the system promotes more effective scavenging, where the momentum of one pulse helps extract gases from another cylinder.

Furthermore, maintaining equal-length headers ensures that pressure pulses arrive at the collector at evenly spaced intervals. As written by Sawant, Warstler and Bari (2018), this consistency improves the predictability of wave interactions and reduces the likelihood of pulse overlap causing backflow/exhaust pulses into adjacent cylinders or oncoming pulses.

Although precise tuning of exhaust length to specific engine speeds was not fully achieved within this project, the design moves significantly closer to an optimised system compared to the original configuration.

9.2 Engineering Principles and Design Considerations

The redesign of the exhaust system was informed by several key engineering principles, primarily relating to fluid dynamics and thermodynamics. Exhaust gas flow within an internal combustion engine is highly dynamic, consisting of pressure pulses generated by the opening of exhaust valves (Plotnikov, Zhilkin and Osipov, 2020). The management of these pulses is critical to engine performance.

One of the most important phenomena considered in the redesign was exhaust scavenging. This refers to the process by which the momentum of exiting exhaust gases helps draw fresh gases out of the combustion chamber, improving volumetric efficiency (Mustapha Bordjane et al., 2011). Effective scavenging relies on careful tuning of pipe lengths, diameters, and collector geometry.

Backpressure was another key consideration. With reference to Murali et al. (2021), while some level of backpressure can improve low-speed torque, excessive backpressure restricts flow and reduces engine efficiency at higher engine speeds. For a race-oriented motorcycle, minimising restriction and promoting high flow rates is generally more beneficial, even at the expense of low-end torque.

Pulse timing also influenced the design. By maintaining equal-length headers, the timing of pressure waves reaching the collector can be synchronised, reducing interference between cylinders and improving overall flow efficiency (Worsztynowicz and Perek, 2018).

9.3 Design Development and Concept Evaluation

The development process began with the reverse engineering of the existing exhaust system using SolidWorks. This allowed a digital representation of the baseline geometry to be created, which could then be analysed and modified. The designs evidenced below (Figure 1.1 - Figure 3.8) display the original exhaust collector CAD model, prior to any modifications or re-designs.

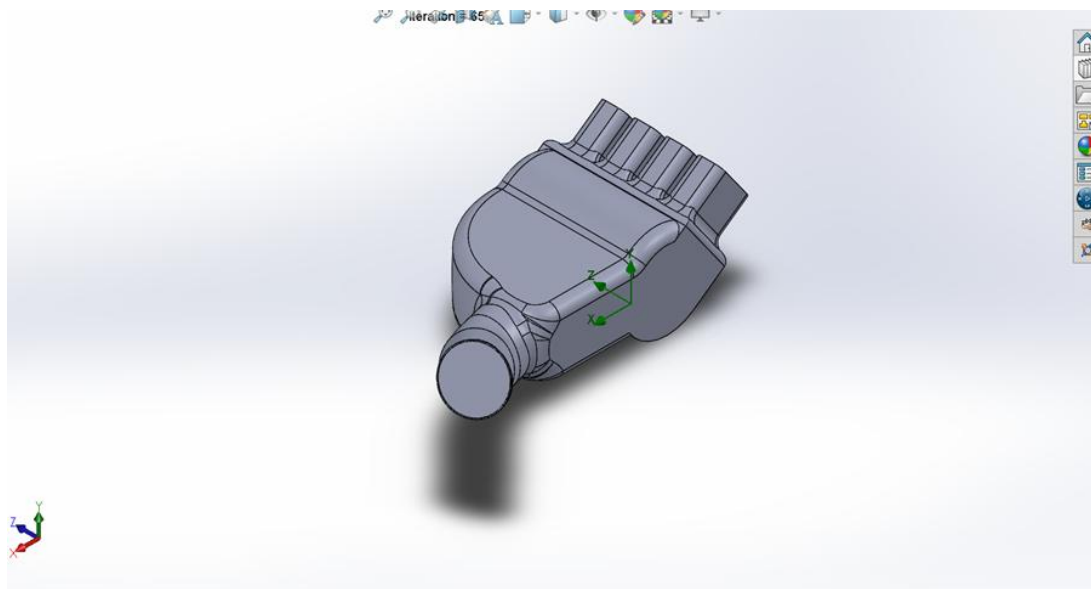


Figure 28 (original exhaust collector CAD model view 1 [Adair, 2026])

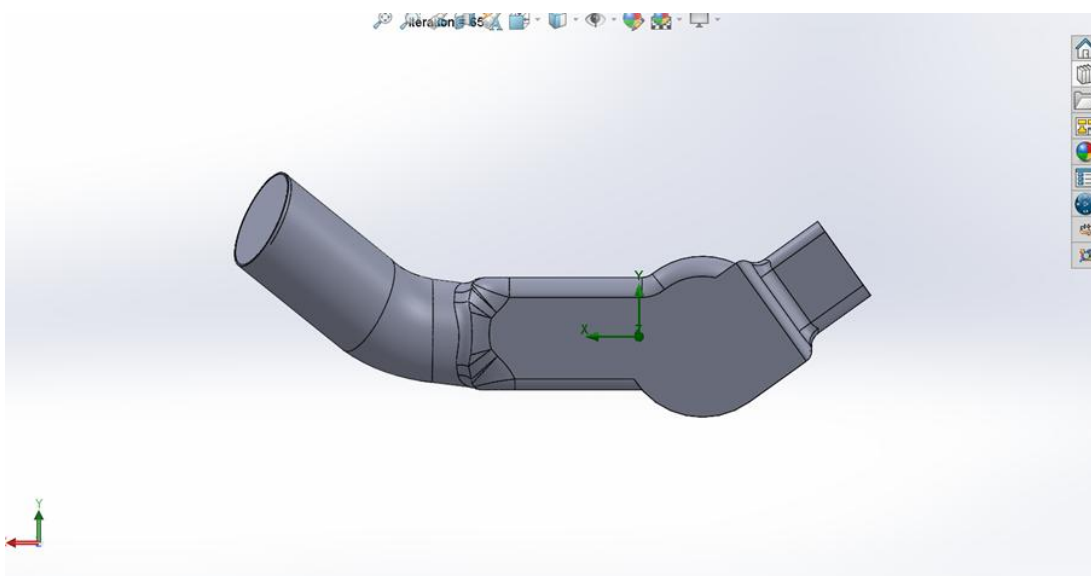


Figure 29 (original exhaust collector CAD model view 2 [Adair, 2026])

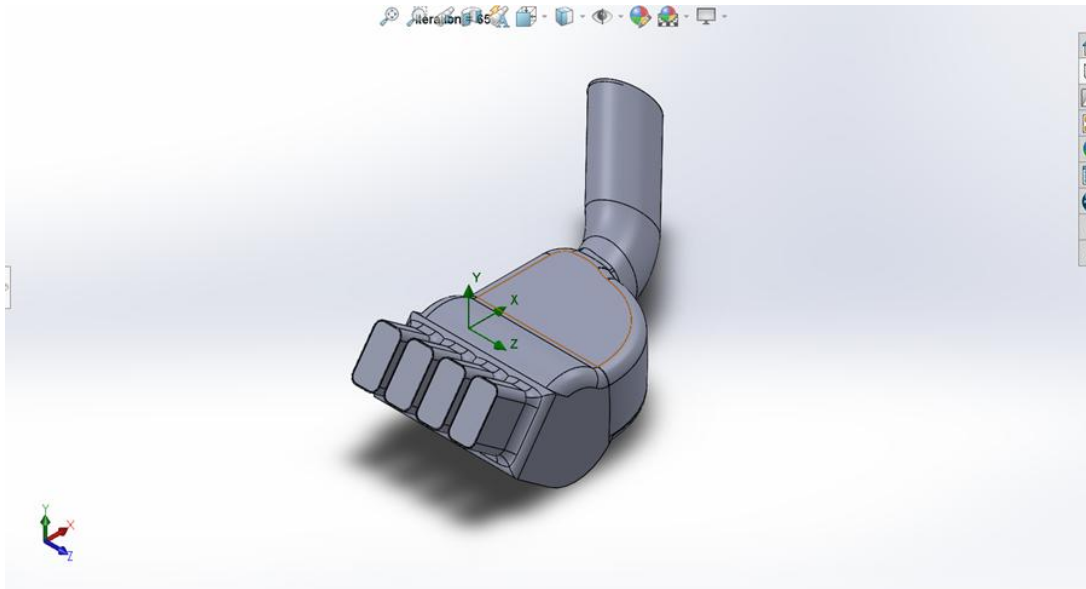


Figure 30 (original exhaust collector CAD model view 3 [Adair, 2026]).

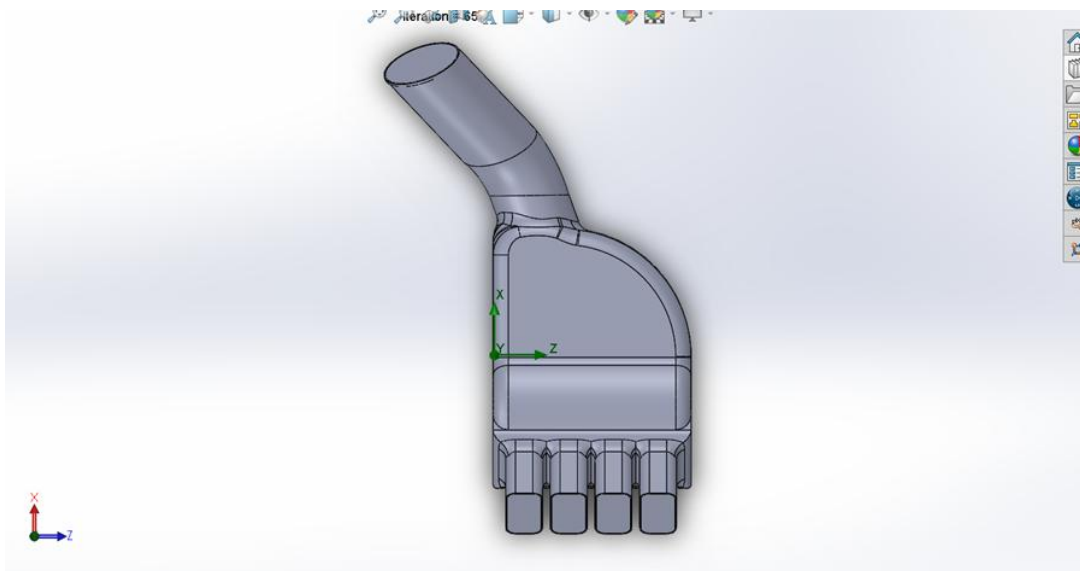


Figure 31 (original exhaust collector CAD model view 4 [Adair, 2026]).

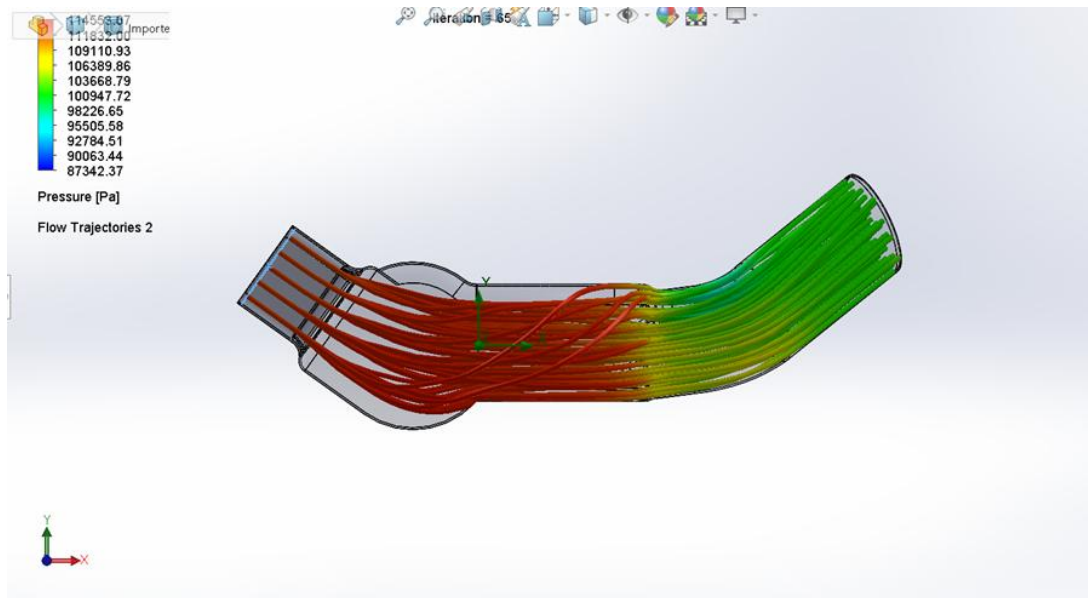


Figure 32 (original exhaust collector CAD model pressure flow simulation view 1 [Adair, 2026]).

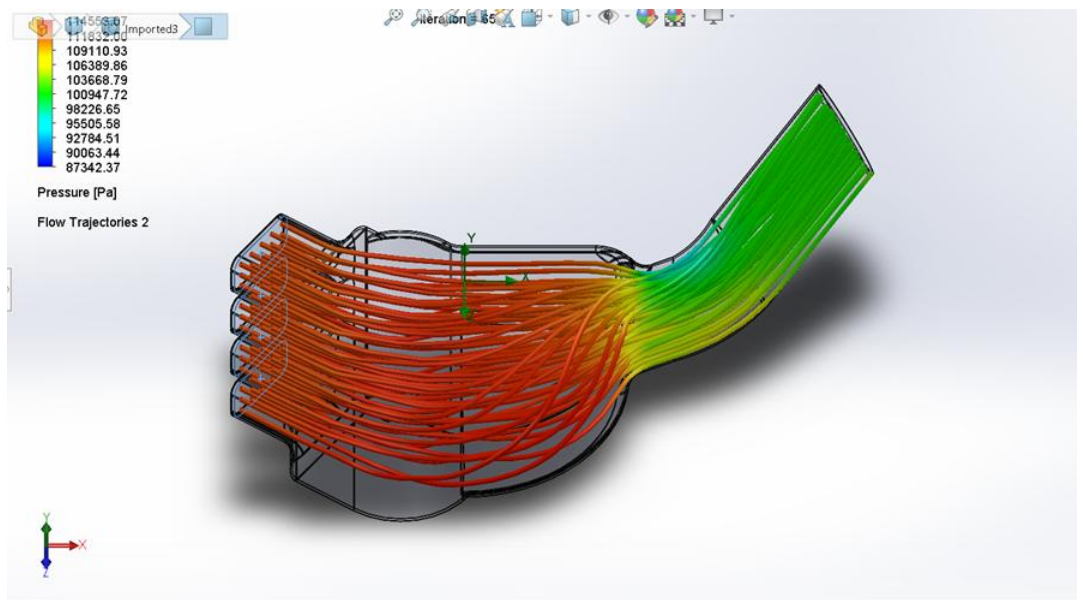


Figure 33 (original exhaust collector CAD model pressure flow simulation view 2 [Adair, 2026]).

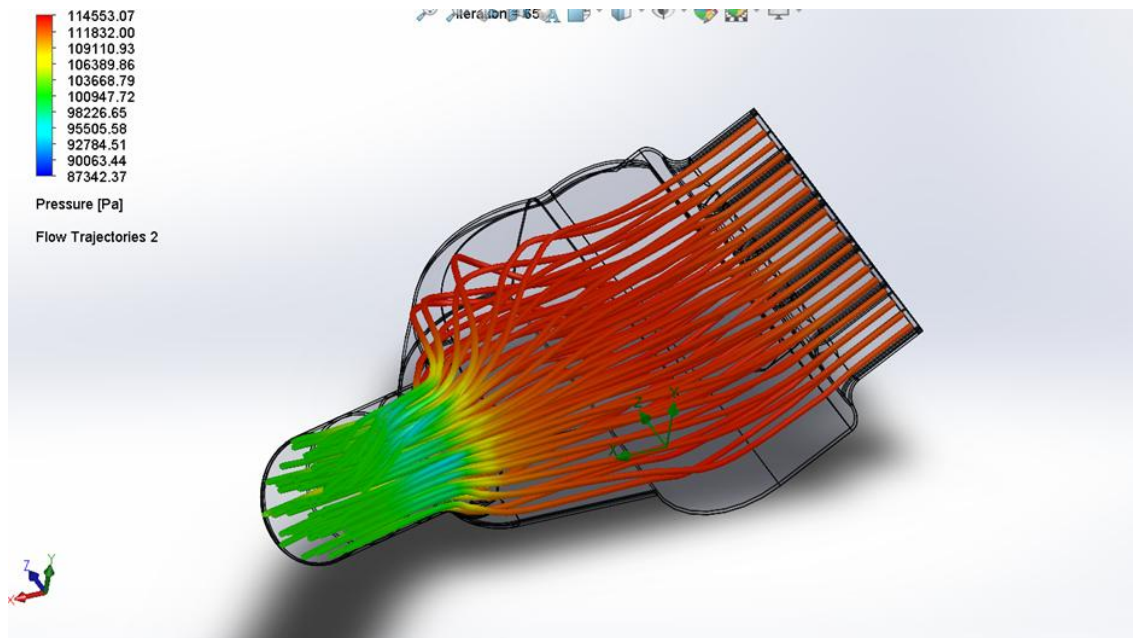


Figure 34 (original exhaust collector CAD model pressure flow simulation view 3 [Adair, 2026]).

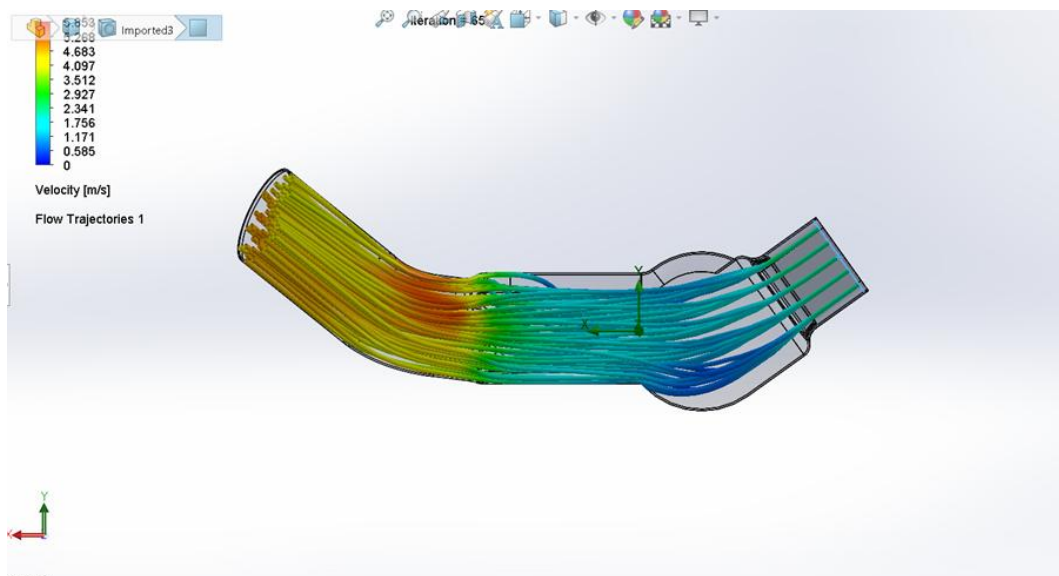


Figure 35 (original exhaust collector CAD model velocity flow simulation view 1 [Adair, 2026]).

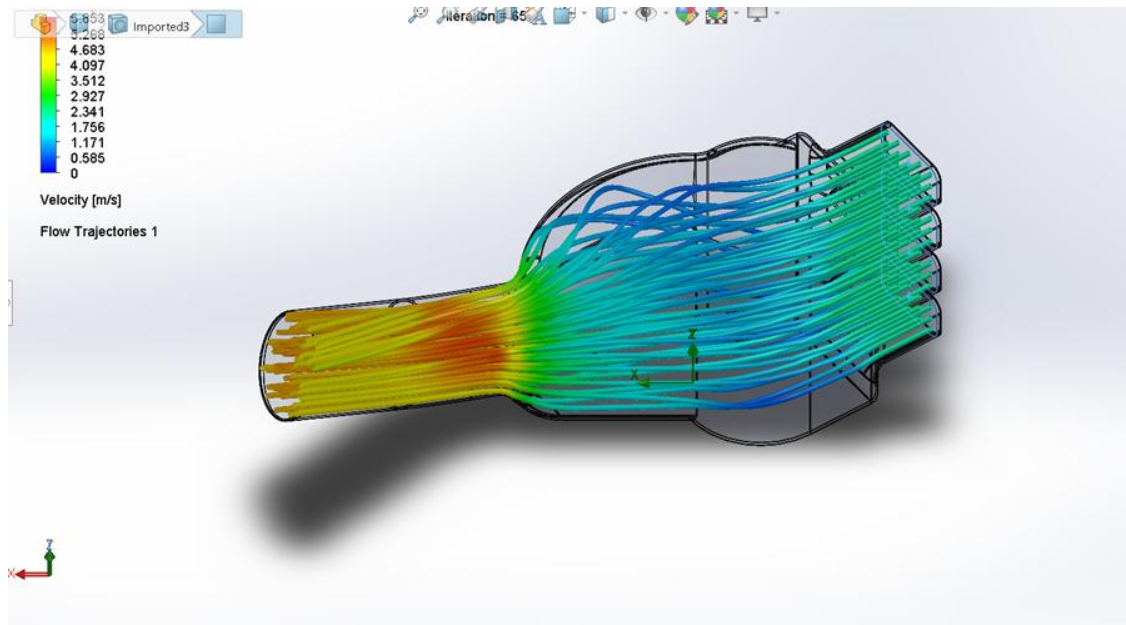


Figure 36 (original exhaust collector CAD model velocity flow simulation view 2 [Adair, 2026]).

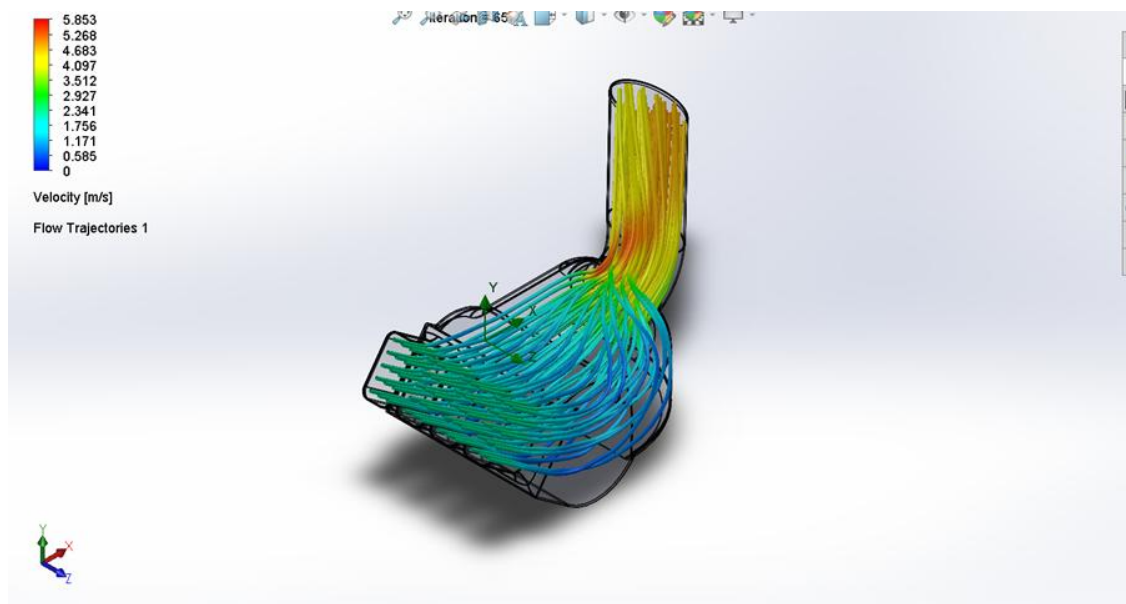


Figure 37 (original exhaust collector CAD model velocity flow simulation view 3 [Adair, 2026]).

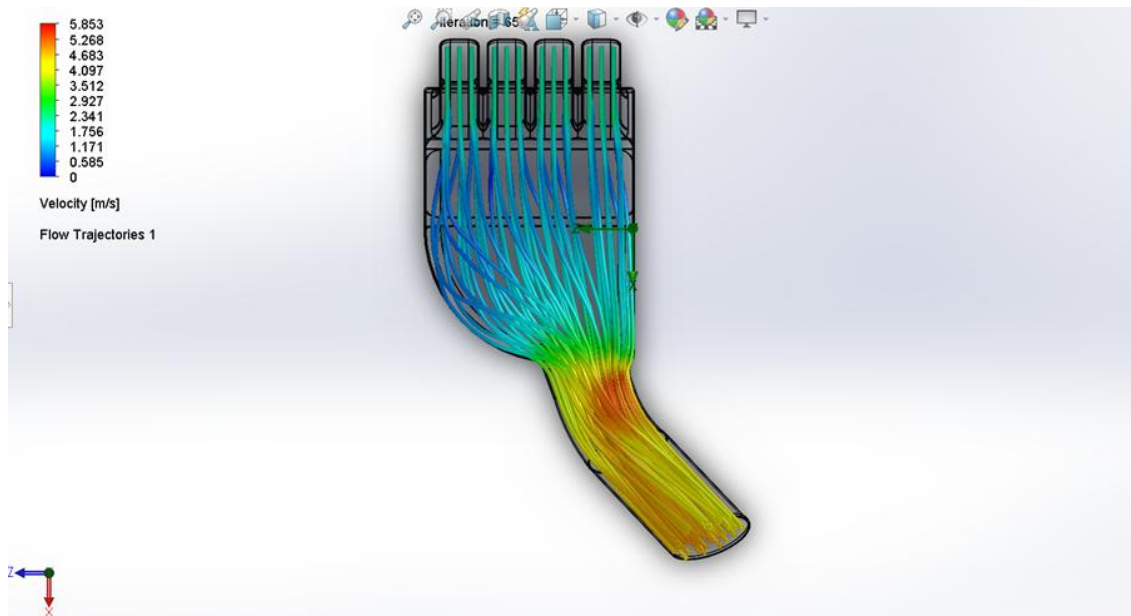


Figure 38 (original exhaust collector CAD model velocity flow simulation view 4 [Adair, 2026]).

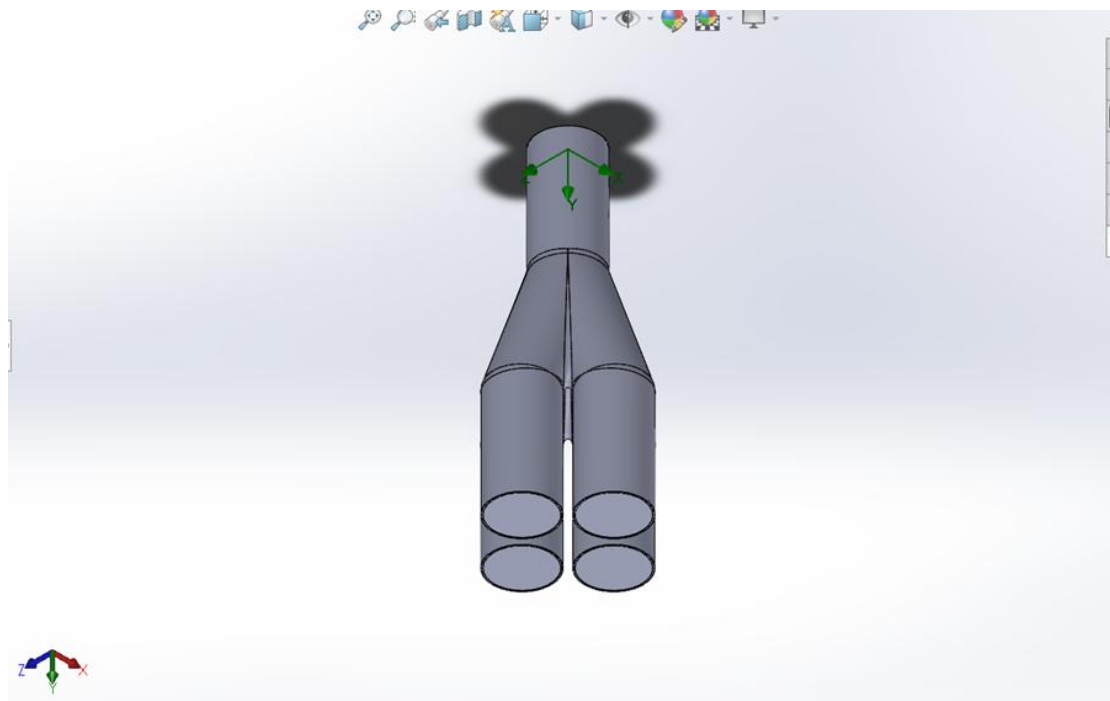


Figure 39 (4-1 collector CAD model view 1 [Adair, 2026]).

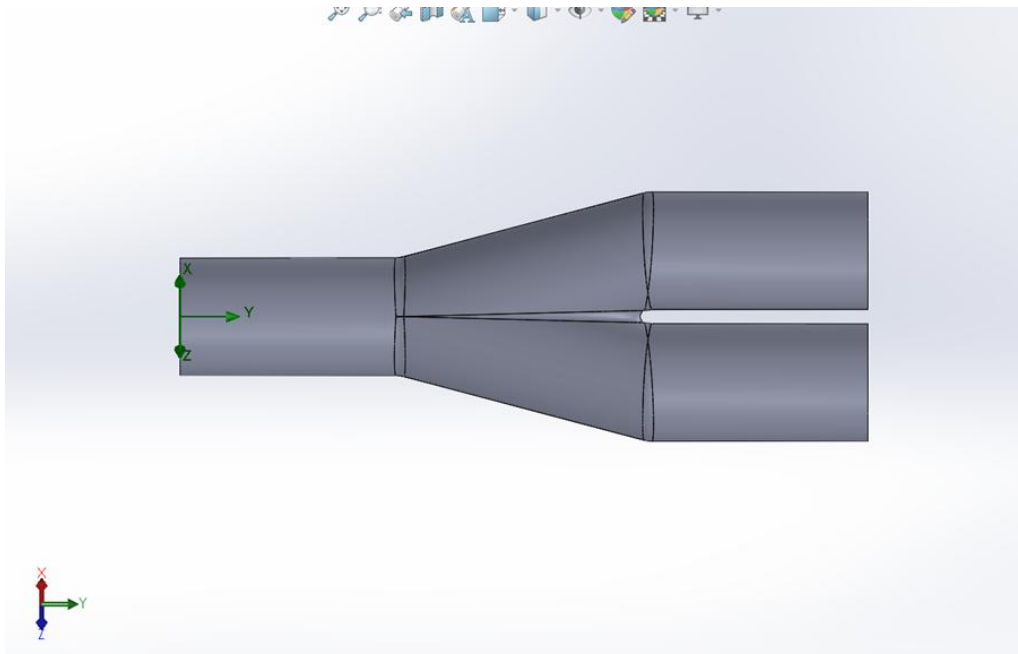


Figure 40 (4-1 collector CAD model view 2 [Adair, 2026]).

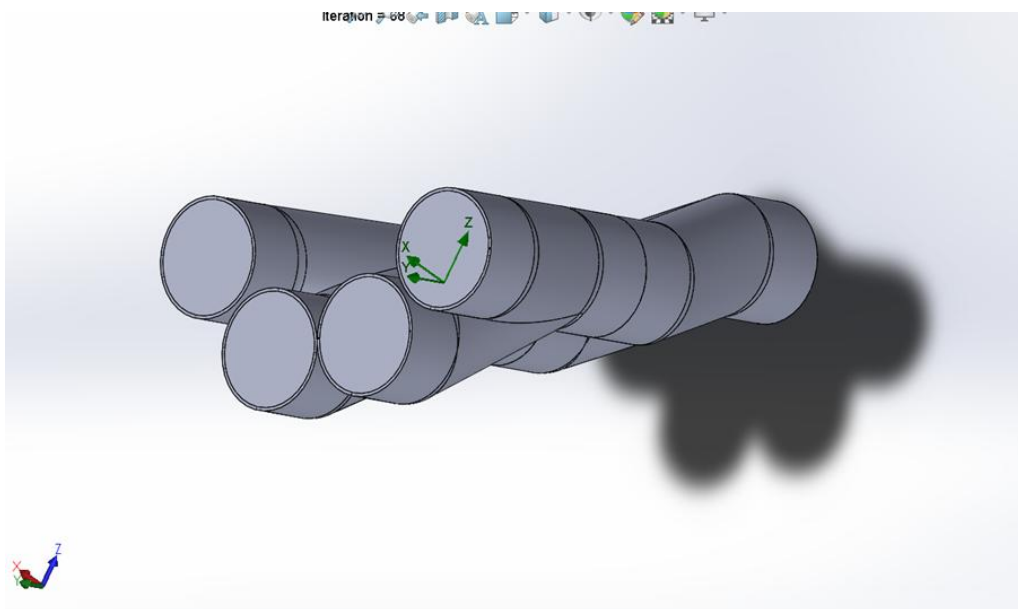


Figure 41 (4-2-1 collector CAD model view 1 [Adair, 2026]).

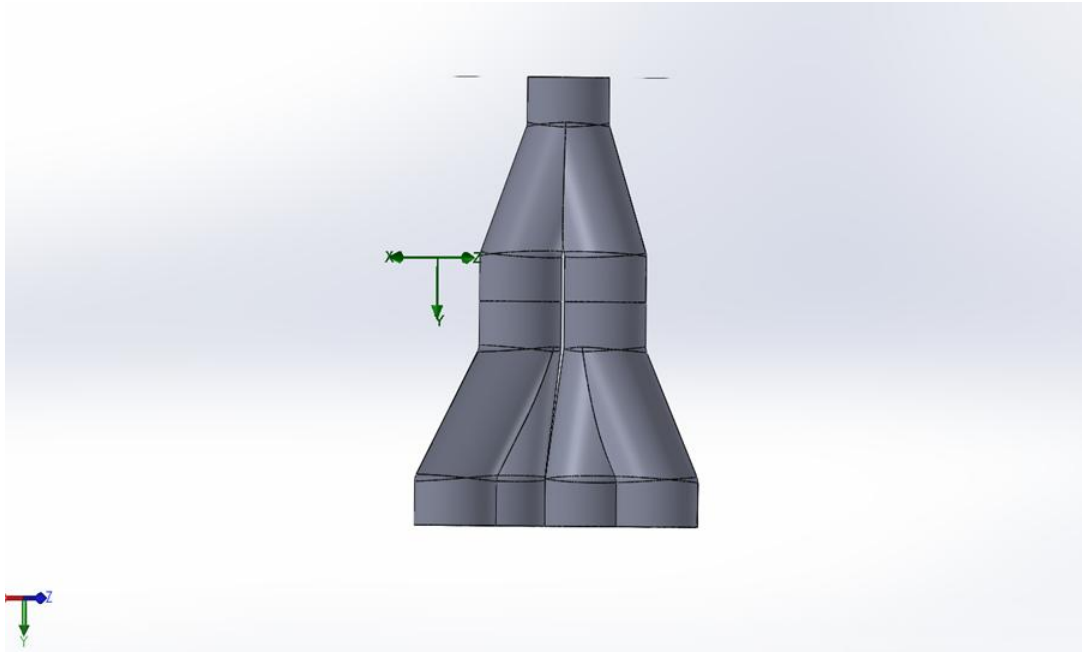


Figure 42 (4-2-1 collector CAD model view 2 [Adair, 2026]).

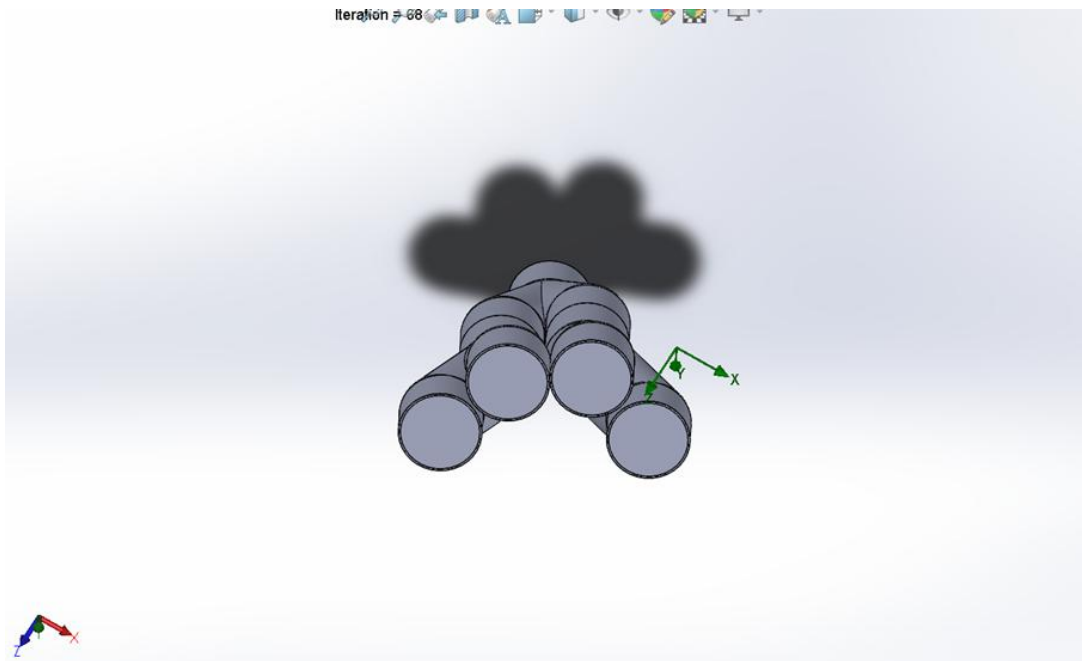


Figure 43 (4-2-1 collector CAD model view 3 [Adair, 2026]).

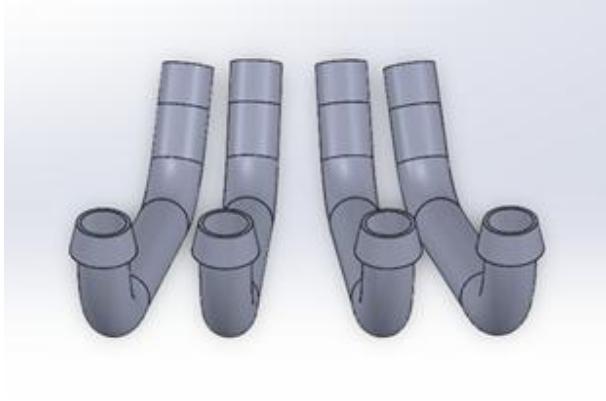


Figure 44 (original exhaust headers CAD model view 1 [Adair, 2026]).



Figure 45 (original exhaust headers CAD model view 2 [Adair, 2026]).



Figure 46 (original exhaust headers CAD model view 3 [Adair, 2026]).

Several alternative collector configurations were explored, including multiple 4–2–1 arrangements and a 4–1 collector design. Each configuration was assessed based on:

- Flow efficiency
- Packaging constraints within the chassis
- Ease of manufacturing
- Weight considerations

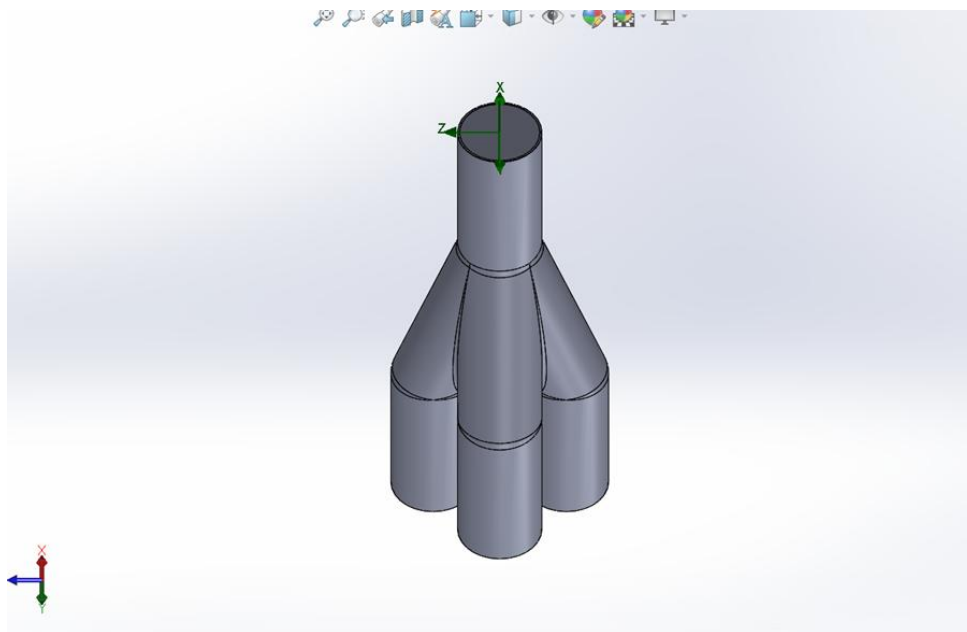


Figure 47 (original 4-1 collector CAD model view 1 [Adair, 2026]).

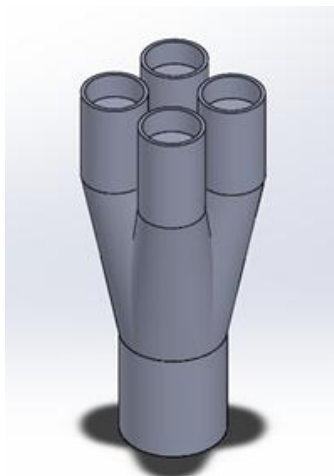


Figure 48 (original 4-1 collector 2 CAD model view 1 [Adair, 2026]).

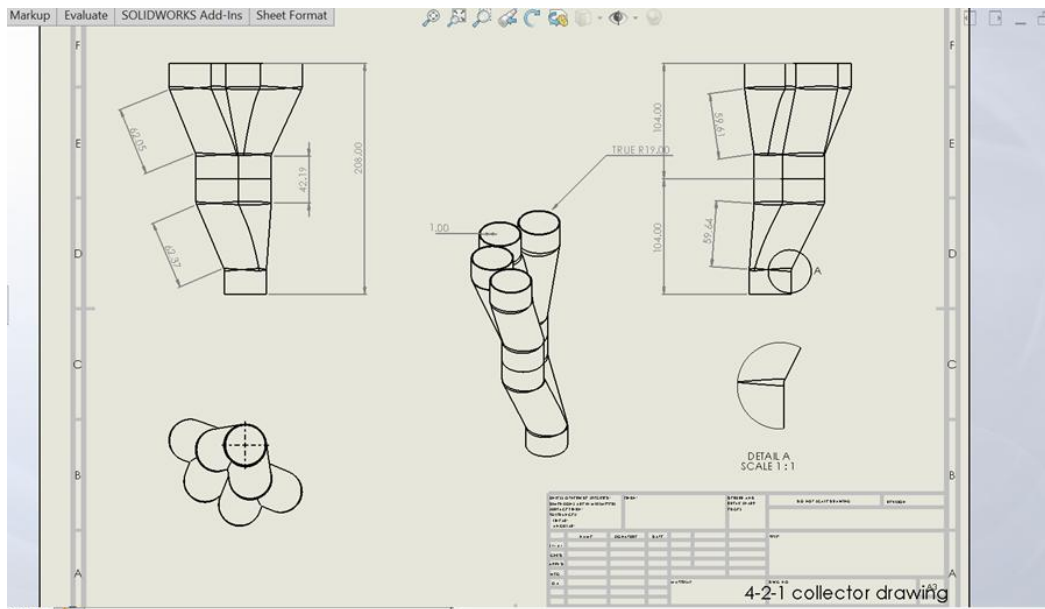


Figure 49 (4-2-1 collector engineering drawing [Adair, 2026]).

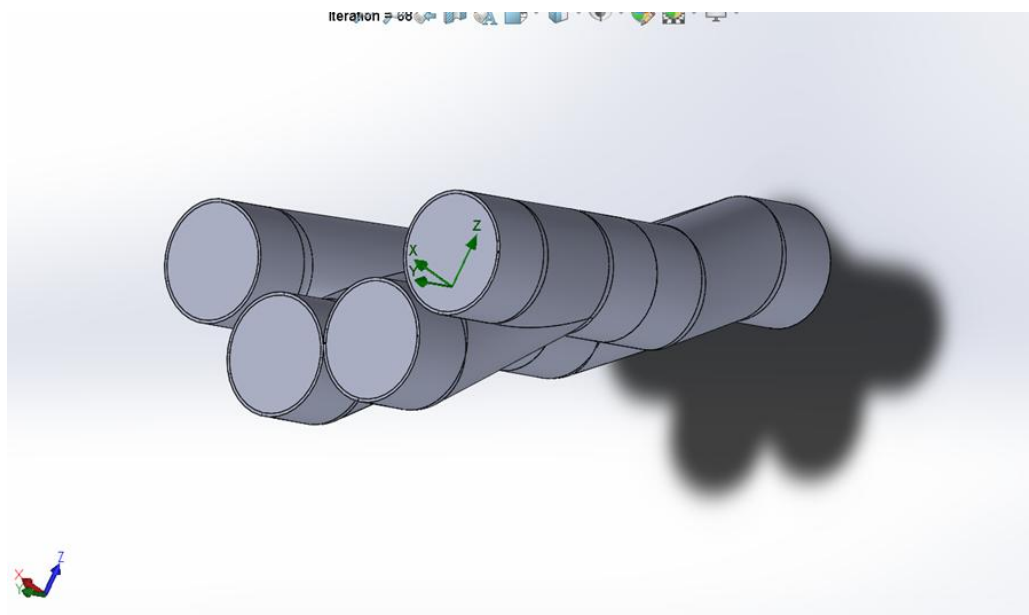


Figure 50 (4-2-1 collector CAD model view 4 [Adair, 2026]).

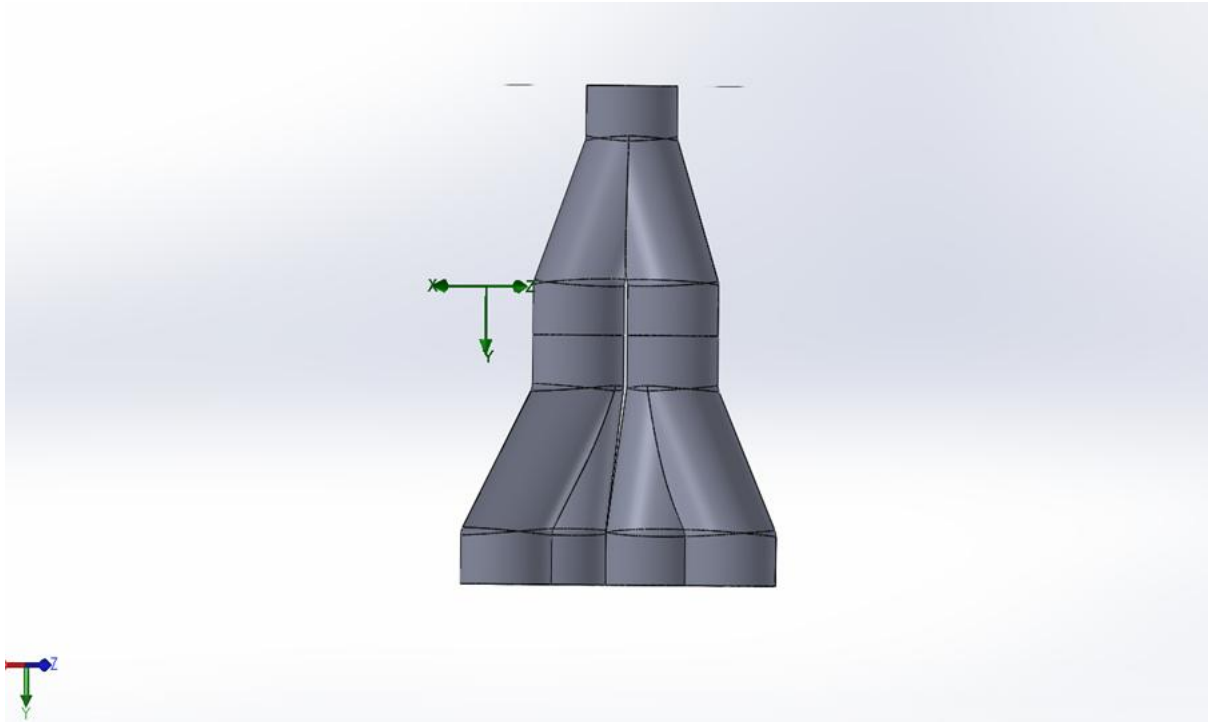


Figure 51 (4-2-1 collector CAD model view 5 [Adair, 2026]).

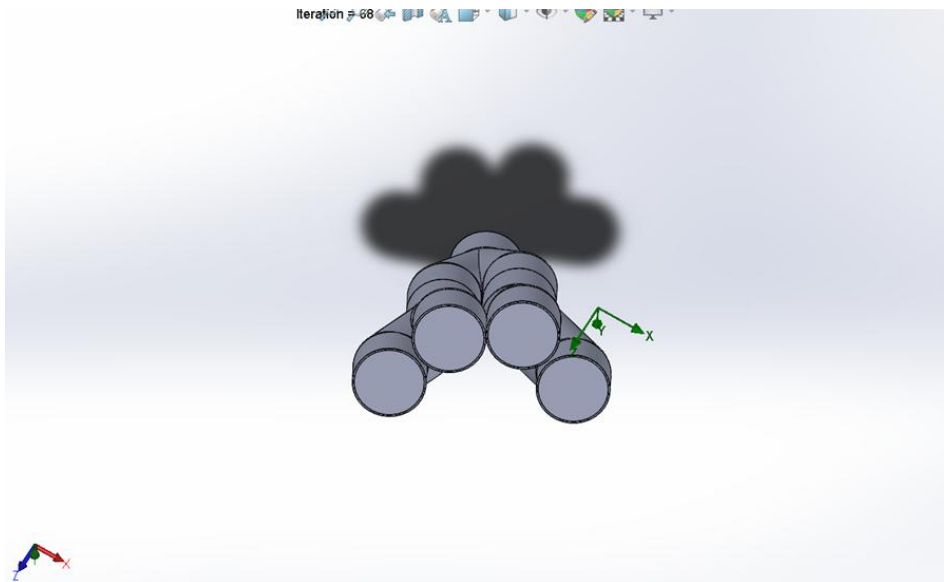


Figure 52 (4-2-1 collector CAD model view 6 [Adair, 2026]).

Computational Fluid Dynamics (CFD) simulations were conducted to analyse airflow through each design. These simulations provided insight into velocity profiles, pressure distribution, and areas of turbulence. The original collector exhibited significant flow disruption, particularly at junction points, confirming its inefficiency.

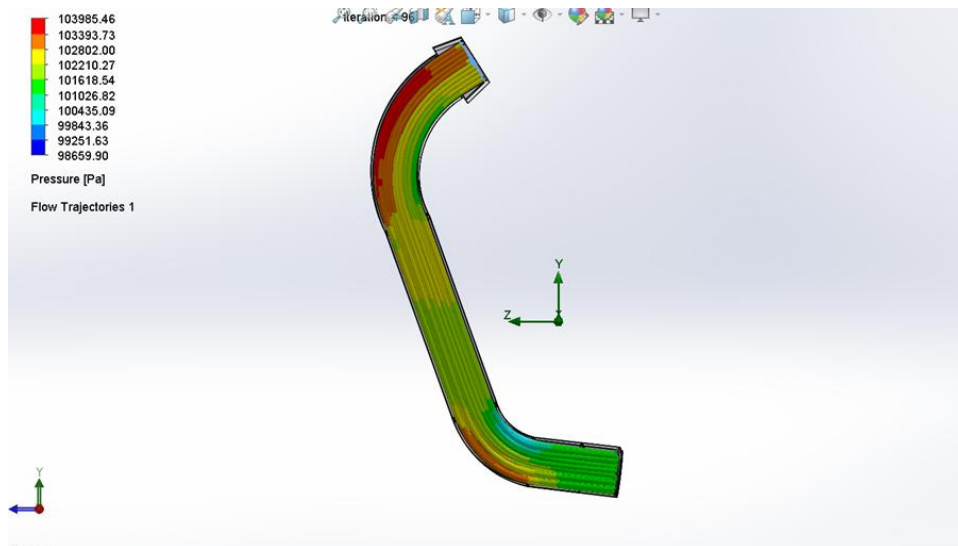


Figure 53 (original exhaust headers CAD model flow test (pressure) view 1 [Adair, 2026]).

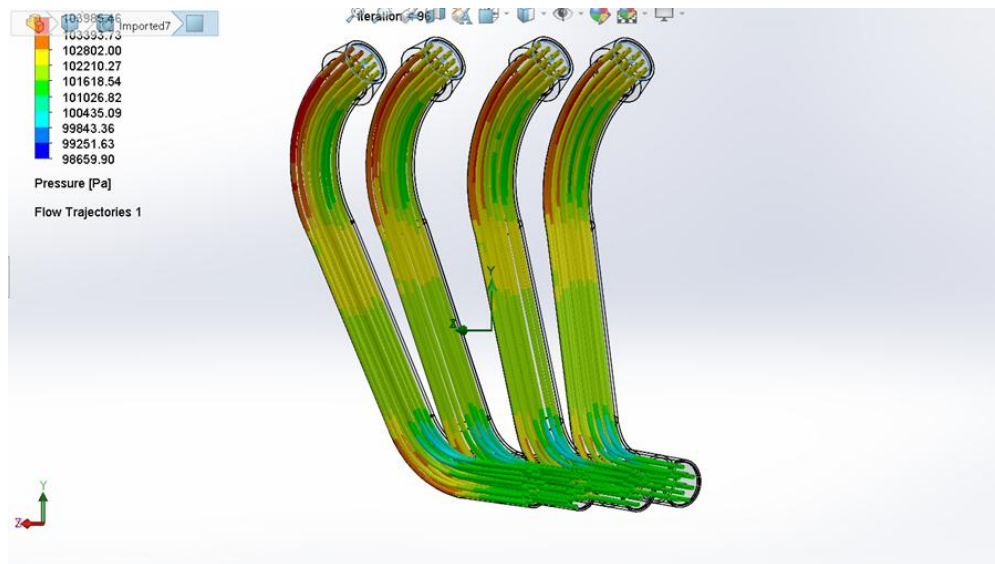


Figure 54 (original exhaust headers CAD model flow test (pressure) view 2 [Adair, 2026]).

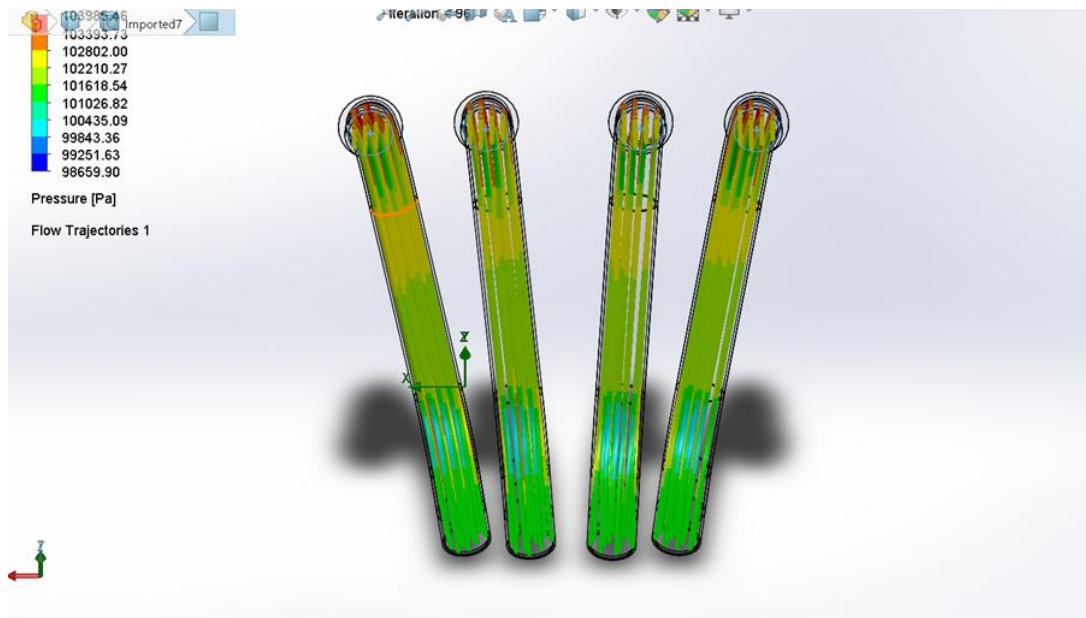


Figure 55 (original exhaust headers CAD model flow test (pressure) view 3 [Adair, 2026]).

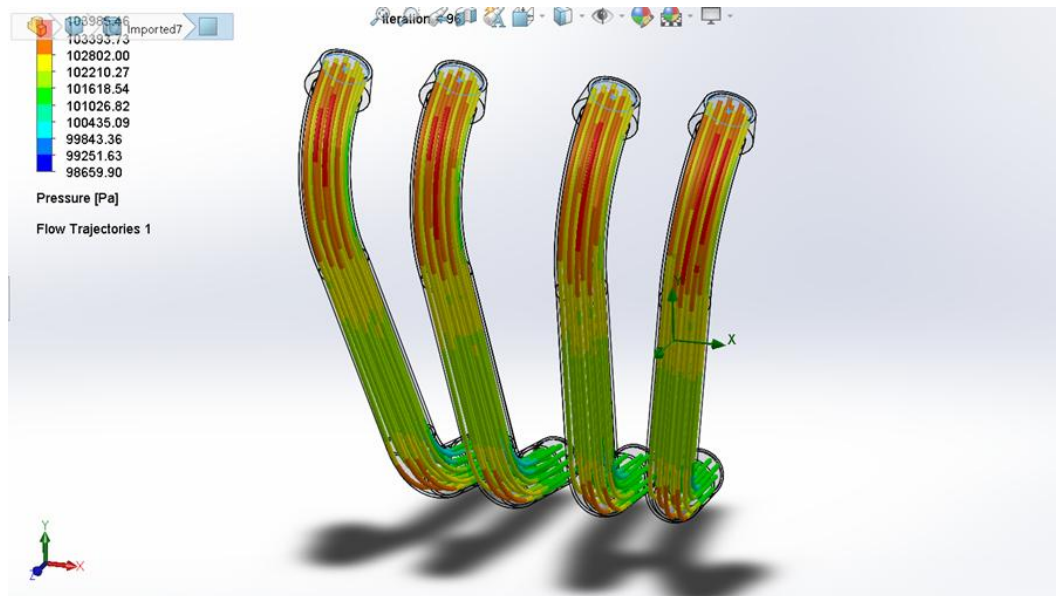


Figure 56 (original exhaust headers CAD model flow test (pressure) view 4 [Adair, 2026]).



Figure 57 (original exhaust headers CAD model view 4 [Adair, 2026]).

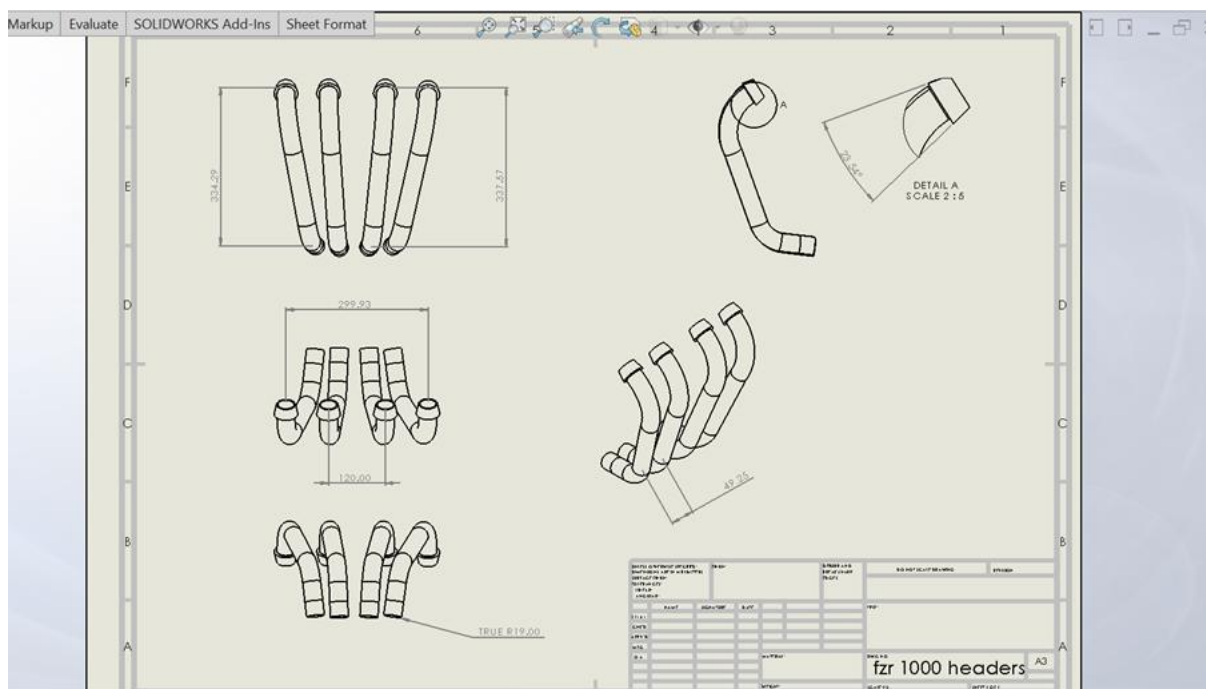


Figure 58 (original exhaust headers engineering drawing [Adair, 2026]).

The 4–1 collector design consistently demonstrated improved flow characteristics in simulation. The simplified geometry reduced turbulence and allowed for a smoother transition of gases from four primary pipes into a single outlet.

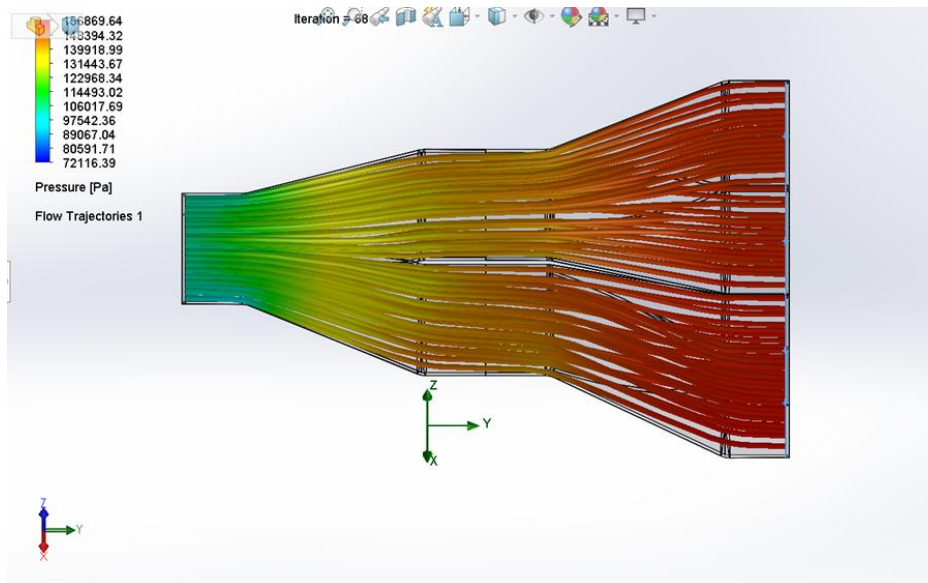


Figure 59 (4-2-1 collector CAD model flow sim (pressure) view 1 [Adair, 2026]).

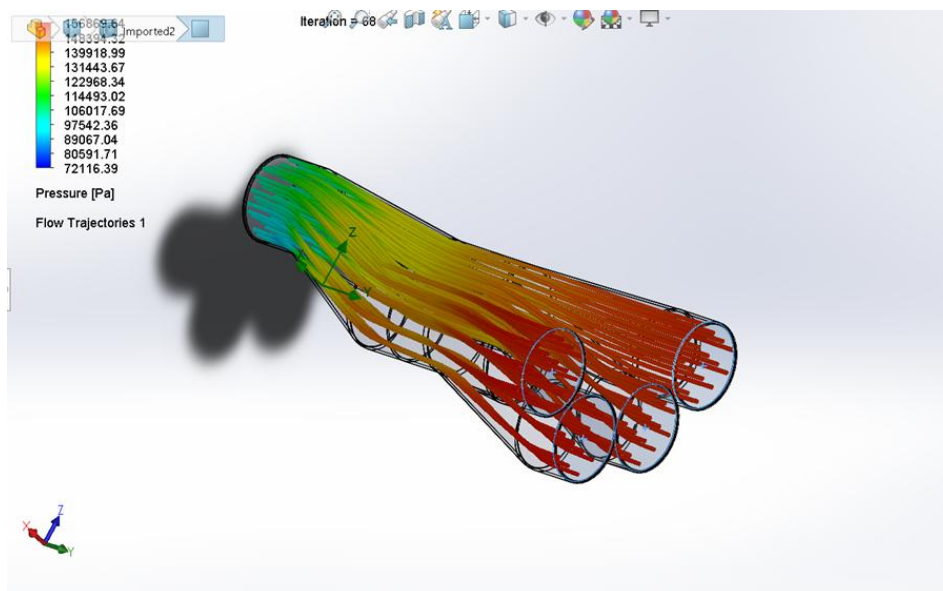


Figure 60 (4-2-1 collector CAD model flow sim (pressure) view 2 [Adair, 2026]).

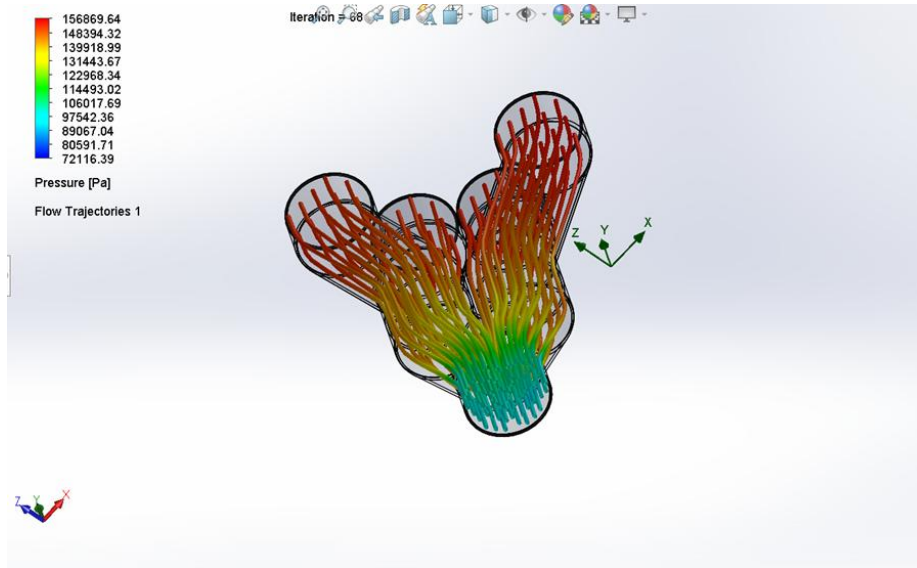


Figure 61 (4-2-1 collector CAD model flow sim (pressure) view 3 [Adair, 2026]).

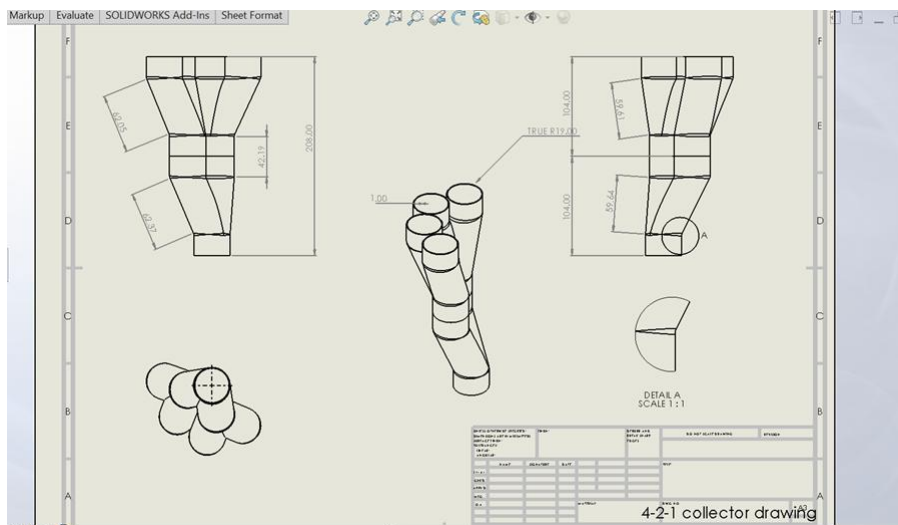


Figure 62 (4-2-1 collector engineering drawing [Adair, 2026]).

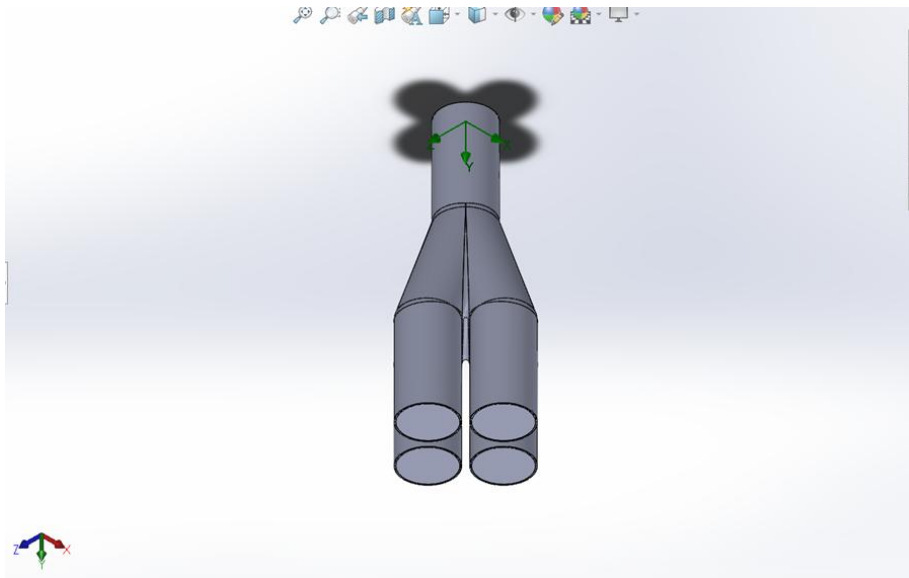


Figure 63 (4-1 collector CAD model view 3 [Adair, 2026]).

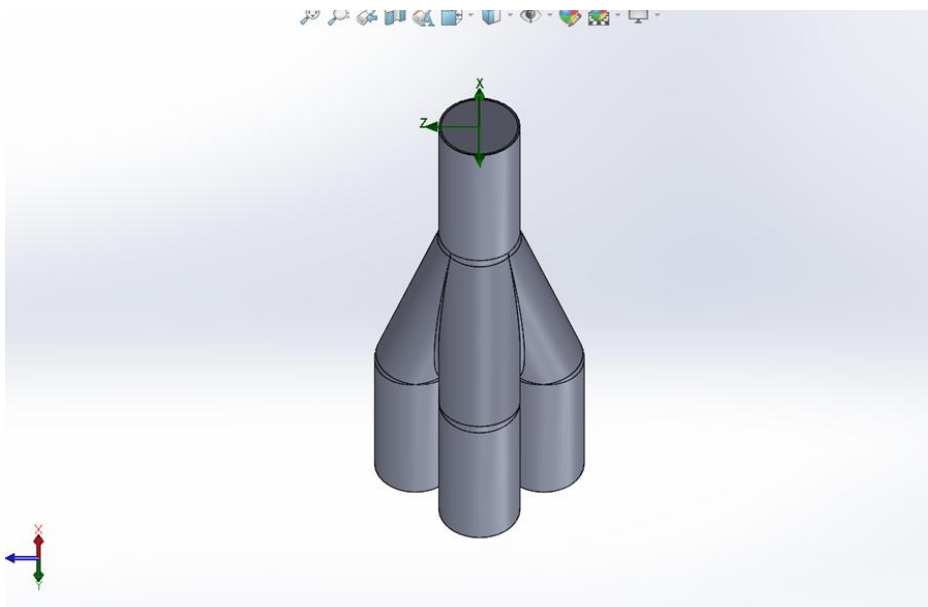


Figure 64 (4-1 collector CAD model view 4 [Adair, 2026]).

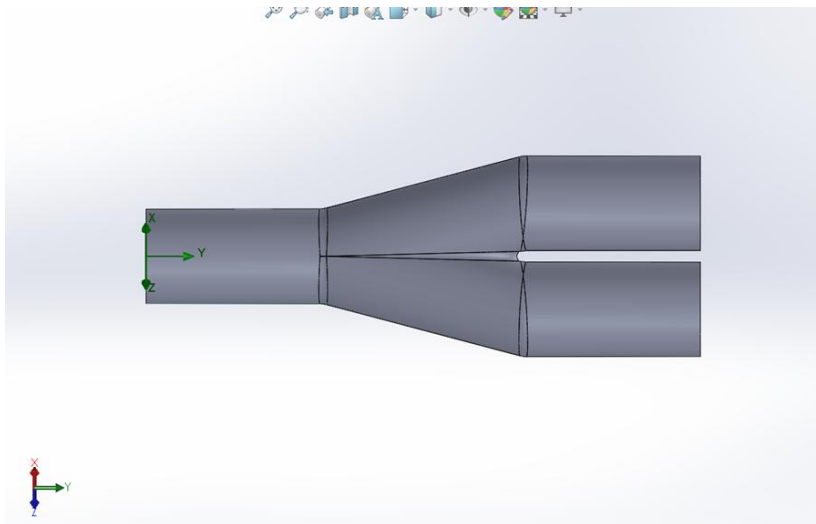


Figure 65 (4-1 collector CAD model view 5 [Adair, 2026]).

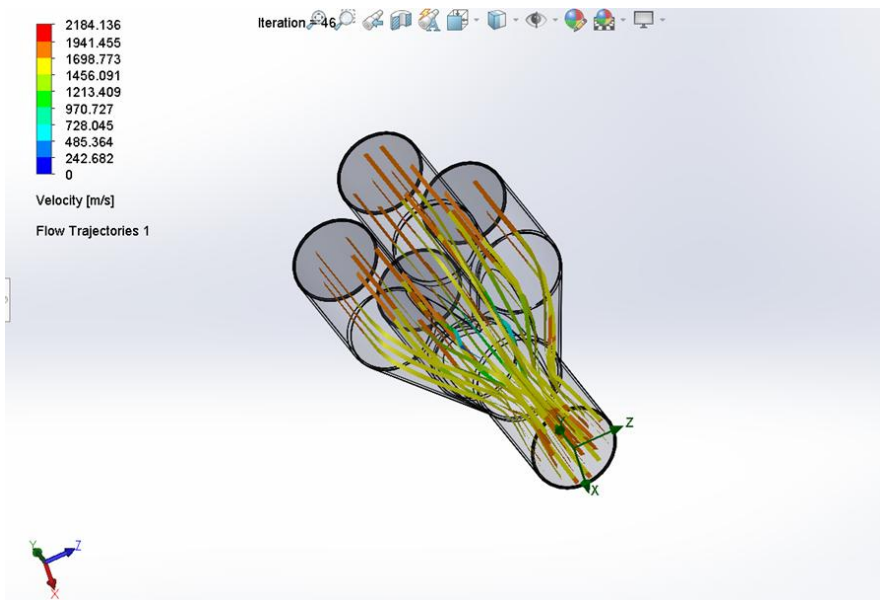


Figure 66 (4-1 collector CAD model flow sim (velocity) view 1 [Adair, 2026]).

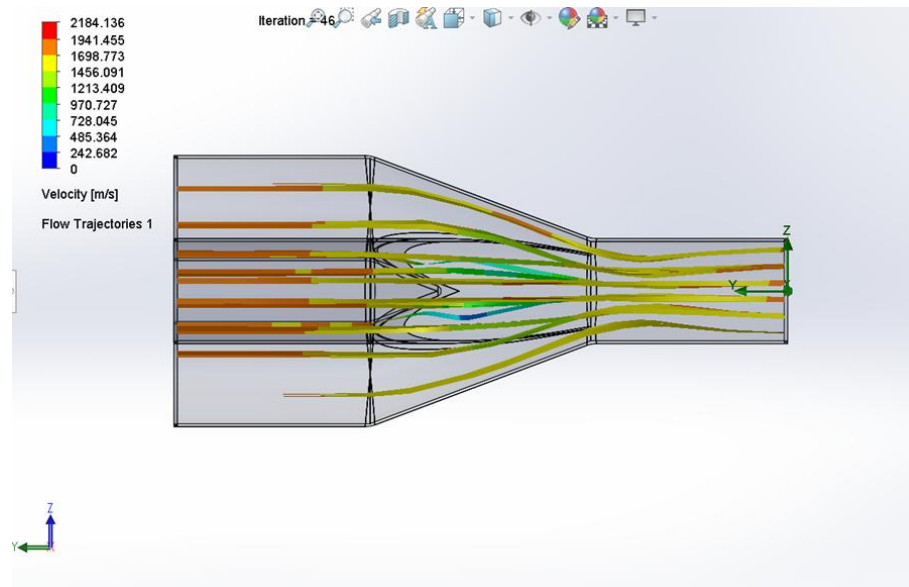


Figure 67 (4-1 collector CAD model flow sim (velocity) view 1 [Adair, 2026]).

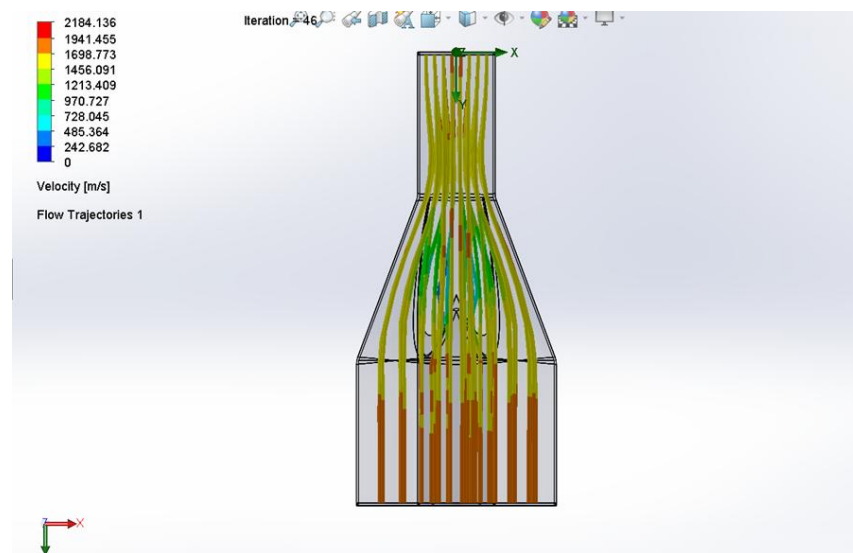


Figure 68 (4-1 collector CAD model flow sim (velocity) view 2 [Adair, 2026]).

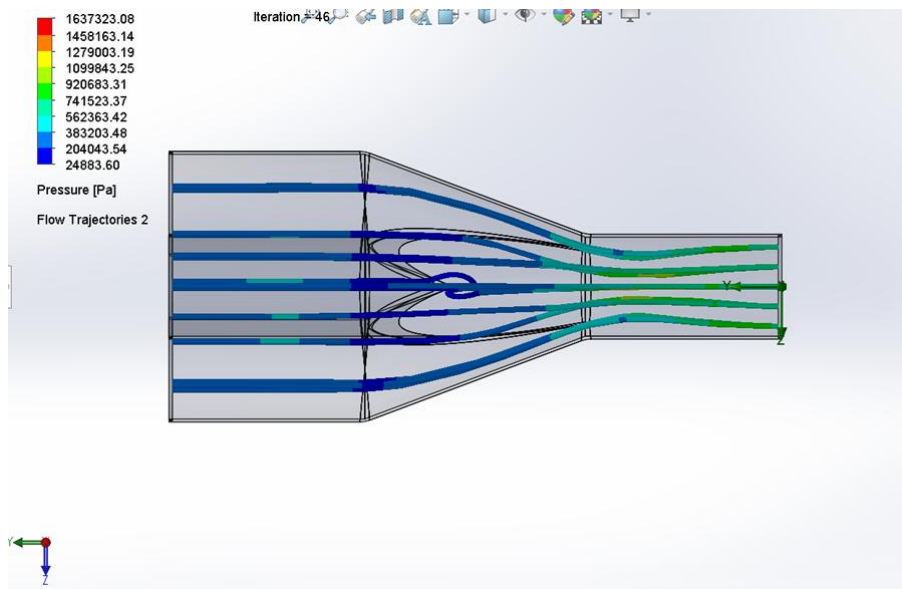


Figure 69 (4-1 collector CAD model flow sim (pressure) view 1 [Adair, 2026]).

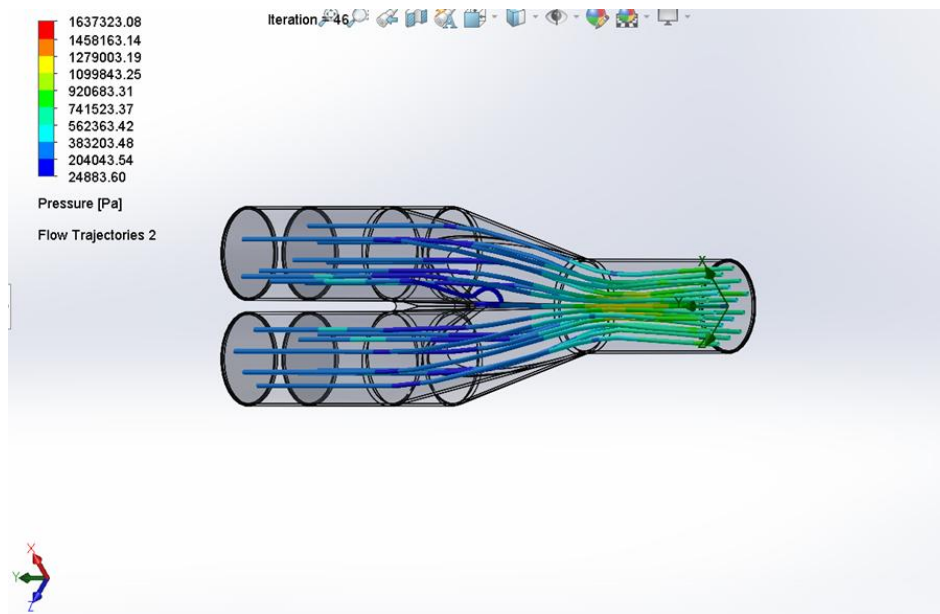


Figure 70 (4-1 collector CAD model flow sim (pressure) view 2 [Adair, 2026]).

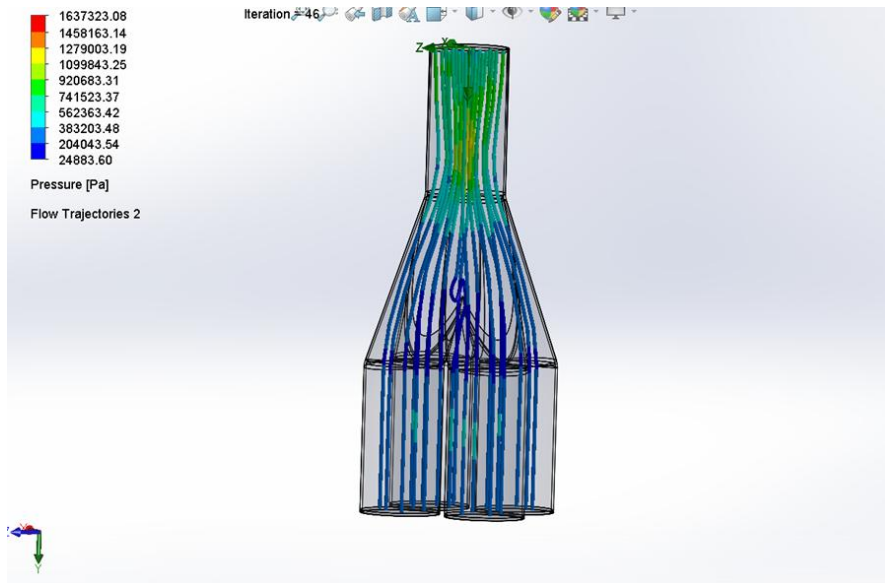


Figure 71 (4-1 collector CAD model flow sim (pressure) view 3 [Adair, 2026]).

9.4 Final Design Specification

The final exhaust design selected was a 4–1 collector system incorporating:

- Equal-length primary headers
- Primary pipe diameter of approximately 38 mm
- Collector outlet diameter of approximately 58 mm
- Gradual merge angles to minimise flow separation and turbulence

This configuration was chosen due to its balance of performance, simplicity, and packaging efficiency. The gradual merge angle is particularly important, as it reduces abrupt changes in flow direction, which would otherwise cause energy losses and turbulence.

The design is expected to significantly improve high-RPM performance by reducing flow restriction and enhancing scavenging effects. However, it is acknowledged that this configuration may result in a reduction in low-end torque due to decreased backpressure.

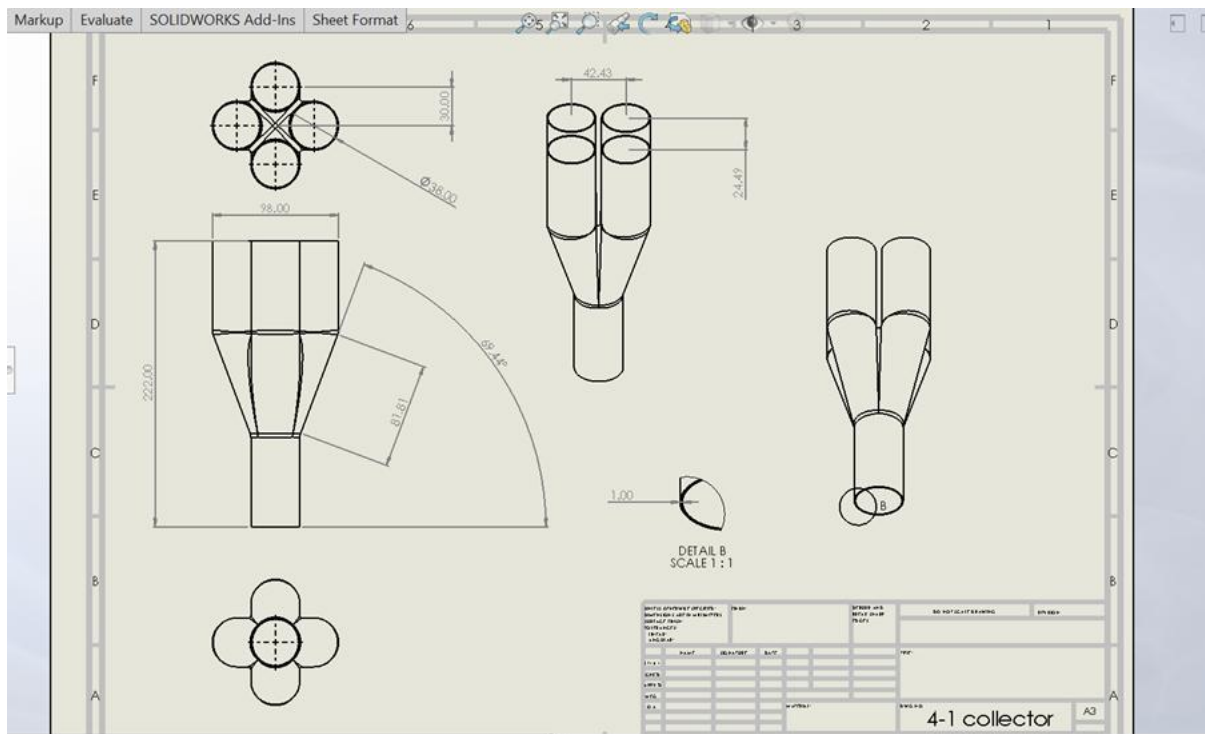


Figure 72 (4-1 collector engineering drawing [Adair, 2026]).

9.5 Material Selection and Manufacturing Strategy

Material selection was an important aspect of the design process. 304 stainless steel was chosen due to its favourable combination of properties, including (Gou et al., 2025):

- Good corrosion resistance
- Adequate strength at high temperatures
- Relatively low cost compared to advanced materials
- Ease of fabrication using TIG welding

According to Agapovichev et al. (2018), while materials such as titanium could offer further weight reduction, they were not considered viable due to cost constraints and limited manufacturing capability within the available facilities.

The manufacturing strategy involves modifying the existing headers where possible and fabricating a new collector section. This approach reduces complexity while still achieving the desired performance improvements. However, the tight geometry of the 4–1 collector presents fabrication challenges, particularly in achieving accurate alignment and high-quality welds.

9.6 Testing and Validation Strategy

At the current stage of the project, full physical validation has not yet been completed. However, a structured testing plan has been developed.

Initial validation will involve the use of 3D printed collector models. These models will allow for rapid prototyping, enabling fitment checks and preliminary flow testing using a flow bench. This approach reduces cost and allows multiple designs to be evaluated efficiently.

Following this, flow bench testing will be conducted to compare the airflow characteristics of the original and redesigned collectors. This will provide quantitative data to support the CFD findings.

Further validation is planned through dynamometer testing and track testing. It is expected that the redesigned exhaust will produce improved performance at mid-to-high engine speeds due to reduced restriction and improved gas flow.

10 Wiring Harness Redesign

10.1 Initial Assessment and Objectives

The original wiring harness was designed for a road-going motorcycle and therefore included numerous unnecessary circuits for a racing application. This resulted in increased weight, complexity, and reduced reliability.

The objective of the wiring harness redesign was to create a simplified, race-oriented system that integrates additional sensors and data acquisition equipment while improving reliability and serviceability.

10.2 Design Approach and System Integration

The redesign process began with the complete removal and documentation of the existing harness. Each circuit was analysed to determine its relevance to the new application.

The new design integrates a range of sensors and data acquisition systems, including:

- Wheel speed sensors
- Brake temperature sensors
- Suspension travel sensors
- Gyroscopic sensors
- GPS and data logging systems (2D Datarecording, MyLaps).

Table 3 (electrical wiring harness parts and component list [Adair, 2026]).

	A	B	C	D	E	F	G	H
	Component	Connects To	Wire Type	Wire Colour	Connector Type	Pin	Fuse	Notes
1								
2	Battery	Main Fuse	Power	Red	Ring	-	30A	Primary supply
3	Main Fuse	Ignition Switch/Kill	Power	Red	Spade	-	Yes	Master control
4	Ignition Switch	Ignitor Unit	Switched Power	Orange	DT	Pin 3	Yes	Ignition feed
5	Ignitor Unit	Ignition Coils	Signal	Yellow/Red	DT	-	No	Coil trigger
6	Ignition Coils	Spark Plugs	High Voltage	Black	HT Lead	-	No	Spark output
7	Pickup Coil	Ignitor Unit	Signal	Blue	Shielded	-	No	Timing signal
8	Alternator	Regulator/Rectifier	AC Power	White	Block	-	No	3-phase
9	Regulator/Rectifier	Battery	DC Power	Red/Black	Ring	-	No	Charging
10	Start Button	Starter Relay	Signal	Yellow/Green	DT	-	No	Start trigger
11	Starter Relay	Starter Motor	Power	Red	Ring	-	No	High current
12	Battery	Fuel Pump Relay	Power	Red	DT	-	Yes	Fuel system
13	Fuel Pump Relay	Fuel Pump	Power	Red	DT	-	Yes	Fuel delivery
14	Battery	Fan Relay	Power	Brown	DT	-	Yes	Cooling
15	Thermo Switch	Fan Relay	Signal	Black	DT	-	No	Ground trigger
16	Fan Relay	Fan Motor	Power	Red	DT	-	Yes	Cooling
17	Battery	Rain Light Switch	Power	Brown	DT	-	Yes	Lighting
18	Rain Light Switch	Rain Light	Power	Brown	DT	-	Yes	Rear safety
19	Battery	Data Logger	Power	Red	DT	-	5A	Logger supply
20	Ignition Coil (-)	Data Logger RPM	Signal	Blue	DT	-	No	RPM pickup
21	Wheel Speed Sensor F	Logger	Signal	Blue	DT-3	Pin 3	No	Shielded
22	Wheel Speed Sensor R	Logger	Signal	Blue	DT-3	Pin 3	No	Shielded
23	Brake Pressure F	Logger	Signal	Blue	DT-3	Pin 3	No	Analog
24	Brake Pressure R	Logger	Signal	Blue	DT-3	Pin 3	No	Analog
25	Suspension F	Logger	Signal	Blue	DT-3	Pin 3	No	Analog
26	Suspension R	Logger	Signal	Blue	DT-3	Pin 3	No	Analog
27	Tyre Temp F	Logger	Signal	Blue	DT-3	Pin 3	No	IR sensor
28	Tyre Temp R	Logger	Signal	Blue	DT-3	Pin 3	No	IR sensor
29	Air Temp Sensor	Logger	Signal	Blue	DT-3	Pin 3	No	Airbox
30	Air Pressure Sensor	Logger	Signal	Blue	DT-3	Pin 3	No	Airbox
31	IMU	Logger (CAN)	CAN	Green/Yellow	DT-4	-	No	Twisted pair
32								

The system retains a standard 12V system/design and continues to utilise the stock ECU alongside an external data logger.

10.3 Manufacturing Techniques and Improvements

A key feature of the redesigned harness is the implementation of concentric twisting techniques. This involves twisting individual wires and groups of wires in a structured manner, improving electromagnetic compatibility and mechanical durability (YourSpec, 2024).

The harness is constructed progressively, with inner wire pairs twisted first, followed by larger groupings. This results in a compact, flexible loom that is well-suited to the dynamic environment of a racing motorcycle (Mancino Innovations LLC, 2024).

High-quality, waterproof connectors are also used to improve reliability. As written by Lee (2025), these connectors allow for controlled disconnection in the event of a crash, preventing damage to critical components.

Routing has been carefully considered to minimise the risk of damage from heat, vibration, or mechanical interference.

10.4 Electrical Performance and Signal Integrity Considerations

In addition to physical packaging and reliability, the redesign of the wiring harness also considered electrical performance, particularly in relation to signal integrity. Modern data acquisition systems rely on accurate sensor readings, which can be affected by electromagnetic interference (EMI) generated by other electrical components on the motorcycle (Jia et al., 2024).

The use of concentric twisting plays a key role in mitigating these effects. By twisting wires together, electromagnetic fields generated by current flow are effectively cancelled out, reducing noise in the system (Xu et al., 1997). This is particularly important for low-voltage sensor signals, such as those from wheel speed or temperature sensors, which are more susceptible to EMI interference (Richelli, 2026).

Shielded wiring further enhances this protection by preventing external electromagnetic fields from affecting the signal. This is especially relevant in a motorcycle environment, where components such as the ignition system and alternator can generate significant electrical noise.

According to Wahl et al. (2025), the combination of twisted pairs, shielding, and improved connector quality contributes to a more stable and reliable electrical system, which is essential for accurate data logging and overall system performance.

10.5 Evaluation of Design Trade-offs

The redesigned harness introduces several trade-offs. While unnecessary circuits have been removed, the addition of new sensors increases system complexity. Similarly, the use of high-quality connectors improves reliability but increases cost.

Balancing these factors required careful consideration of performance benefits versus practical constraints.

11 Progress, Challenges, and Limitations

Progress in the design and analysis stages has been strong, particularly for the exhaust system. However, several challenges have limited overall progress.

Time constraints have been a significant factor, with competing academic commitments affecting the ability to complete physical testing and fabrication. Access to manufacturing resources, such as 3D printing facilities, has also been limited.

Group coordination challenges further impacted progress, particularly in relation to wiring harness design, where decisions regarding component placement were required before finalising the layout.

12 Critical Evaluation and Reflection

The exhaust redesign represents a successful application of engineering principles, with clear improvements identified through simulation. However, the lack of physical validation limits the ability to fully confirm these improvements.

The wiring harness redesign is more difficult to evaluate, as its benefits are less immediately measurable. While improvements in reliability and integration have been achieved, further testing is required to fully assess performance.

From a personal perspective, time management and organisation were areas of weakness. Improved planning and earlier engagement with available resources would have allowed for greater project completion.

13 Future Work and Recommendations

Due to time and resource constraints, several aspects of the project remain incomplete and require further development. Future work should prioritise the physical validation of the exhaust system through flow bench testing and dynamometer analysis. This would provide quantitative data to confirm the performance improvements predicted by CFD simulations.

Further refinement of the exhaust design could also be undertaken, including optimisation of header lengths for specific engine speeds and exploration of alternative materials such as titanium for additional weight reduction.

For the wiring harness, future work should focus on final fabrication and full system testing. This includes verifying the functionality of all sensors, ensuring reliable data acquisition, and assessing the durability of the harness under real-world conditions.

Additionally, further optimisation of wiring routes could be explored to balance weight reduction with accessibility and ease of maintenance.

14 Critical Reflection

From a technical perspective, the exhaust redesign represents a strong outcome in terms of analysis and design development. The identification of the collector as the primary restriction and the selection of a 4–1 configuration demonstrates a clear understanding of exhaust flow dynamics. However, the absence of physical validation remains a significant limitation, as real-world testing is essential to fully confirm the effectiveness of the design.

The wiring harness redesign presents a more complex evaluation. While improvements in reliability, organisation, and system capability have been achieved, the benefits are less immediately measurable. The value of these improvements will only be fully realised once the system is implemented and tested under operating conditions.

A key area for improvement in my own performance is time management and project planning. While significant progress was made in design and analysis, delays in fabrication and testing limited the overall completeness of the work. Earlier engagement with manufacturing resources and more structured planning would have enabled greater progress.

Additionally, group coordination challenges affected the progression of certain tasks, particularly where interdependent decisions were required. Improving communication and establishing clearer timelines within the group would have enhanced overall efficiency.

Despite these challenges, the project has provided valuable experience in both technical design and project management, highlighting the importance of balancing theoretical work with practical implementation.

15 Oska Robertson

15.1 Introduction

The primary objective of my role within this project is to ensure that the motorcycle is properly prepared for competitive circuit racing and complies with all relevant technical regulations.

Preparing a motorcycle for racing requires a systematic process that involves understanding the governing rules of the competition, evaluating the current condition and configuration of the motorcycle, and implementing any necessary modifications to ensure compliance with those rules.

In motorsport, regulatory compliance is critical because failure to meet the specified technical standards can result in a motorcycle failing scrutineering, preventing it from competing in an event.

To achieve this objective, I will undertake a variety of tasks including researching the appropriate rule set for the racing series we intend to enter, analysing the technical requirements within those regulations, and implementing the modifications necessary to ensure the motorcycle complies with those requirements. In addition to completing these modifications myself, I will also be responsible for monitoring the work completed by other members of the team to ensure that all aspects of the project remain within the permitted regulations. This ensures that the motorcycle will pass scrutineering inspection before competing in a race event.

The racing series selected for this project is the No Limits Racing Team Power Trophy. This championship provides endurance-style racing events designed for production-based motorcycles and offers an accessible platform for amateur and semi-professional racing teams. One advantage of preparing the motorcycle to meet the requirements of this series is that the same regulations are also used by the ACU National Endurance 1000. As a result, ensuring compliance with these rules allows the motorcycle to compete in both competitions without requiring additional modifications.

15.2 Regulations

At the beginning of the project, locating the correct and most up-to-date technical regulations proved challenging. The only publicly accessible document that I initially located was the 2011 version of the regulations, which was clearly outdated. In motorsport, regulations are frequently updated to reflect improvements in safety standards, changes in technology, and evolving competitive structures (Auto Cycle Union, 2024). Therefore, relying on outdated documentation could lead to the motorcycle being prepared incorrectly and potentially failing the scrutineering process.

To resolve this issue, I contacted a representative from No Limits Racing who directed me to the No Limits Racing Riders Information Board, which contains the 2026 Technical Regulations² for the championship. This resource also includes event-specific regulations and rider registration details; however, the technical regulations are the most relevant document at the current stage of the project because they define the mechanical and safety requirements for the motorcycle.

While reviewing the No Limits Racing regulations, it became clear that motorcycles competing in this championship must also comply with the rules defined by the Auto Cycle Union (ACU)¹. The ACU is responsible for regulating motorcycle racing within the United Kingdom and establishes baseline safety and technical standards for all sanctioned racing events.

The ACU Handbook outlines a comprehensive set of rules governing motorcycle construction, safety features, and operational procedures. These rules are intended to ensure a consistent level of safety across all events and minimise the risk of injury to riders, officials, and spectators (Auto Cycle Union, 2024).

During the initial review of these regulations, it became clear that many of the requirements are already satisfied by the motorcycle in its factory configuration. The project motorcycle, a Yamaha FZR1000, was originally designed as a high-performance sport motorcycle and therefore already includes several safety features that align with racing regulations.

For example, the ACU regulations specify that brake and clutch levers must have rounded ends to minimise the risk of injury during a crash. The original levers fitted to the motorcycle already meet this requirement. Similarly, the footpegs installed on the motorcycle comply with the regulations regarding construction and shape, meaning that no modification is required in this area.

Although many of the requirements were already satisfied, it was still necessary to conduct a detailed review of the entire regulatory framework. The ACU handbook and the No Limits Racing technical regulations together consist of over 100 pages of technical documentation. Expecting every member of the team to regularly consult these documents would be inefficient and could lead to misunderstandings.

To address this issue, I compiled a simplified regulatory summary document for the team. This involved reviewing each section of the regulations and extracting the information that directly applies to our motorcycle and racing category. Duplicate rules were removed, and sections that were irrelevant to the project were excluded.

The resulting document condensed more than 100 pages of regulatory information into an 11-page summary that highlights the key technical requirements relevant to the team. This simplified

reference enables team members to quickly verify whether their modifications comply with the regulations while reducing the risk of accidental rule violations.

15.3 Rain Light Design

One of the first physical modifications undertaken as part of this project was the replacement of the rear brake light with a rear safety light, commonly referred to as a rain light. Rain lights are commonly used in motorsports to improve visibility in wet weather conditions. When motorcycles are racing in heavy rain, spray generated by the tyres can significantly reduce visibility for following riders. A bright rear light helps riders identify the position of the motorcycle ahead and reduces the risk of collisions.

The technical requirements for this component are specified in Section 15.10 of the ACU Handbook and Section 6 of the No Limits Racing Technical Regulations. According to these rules, the rain light must meet several conditions.

First, the light must be controllable from the handlebars while the motorcycle is in motion. This ensures that the rider can activate the light quickly when track conditions require it. Secondly, the light must emit a continuous red signal while the motorcycle is on track during wet conditions. Flashing operation is only permitted when the motorcycle is in the pit lane.

The regulations also specify the acceptable power output of the bulb used in the rain light. LED bulbs must operate between 0.6 W and 1.8 W, while incandescent bulbs must operate between 10 W and 15 W. In addition, the light must be visible from 15 degrees above and below the centreline of the motorcycle, ensuring that it remains visible to riders approaching from slightly different angles.

Instead of purchasing a commercially available rain light, I decided to design a custom housing using computer-aided design (CAD) software. Designing the component myself allows the housing to be tailored to the exact dimensions of the motorcycle while also providing an opportunity to apply engineering design principles within the project.

The starting point for the design process was measuring the original brake light housing on the motorcycle. Because the brake light will be removed during the racing conversion, the rain light can be installed in the same location. This simplifies installation and ensures that the light remains positioned in a location that is clearly visible to other riders.

The base of this has a measurement of 145 x 80 mm³, which I used as the foundation of my own casing. I then extruded this shape by 60mm, which is also the size of the original piece. I also decided to include a draft element into this design, with an angle of 15 degrees to make sure the light will be visible at the required range. I also included a chamfer on the external edges to avoid any sharp 90-

degree angles. Finally, I used the shell function to create a hollow box with the front side open and a thickness of 3mm.

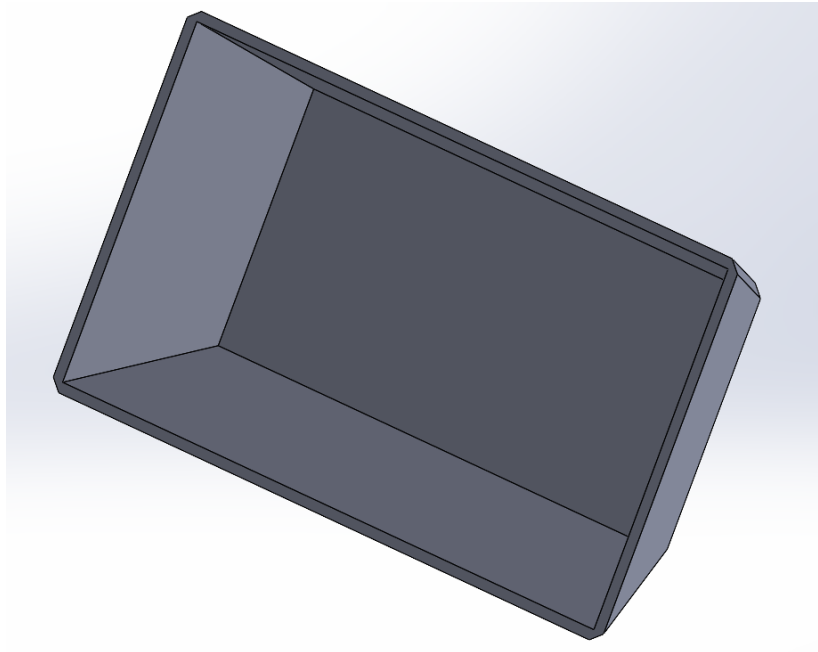


Figure 29 Rain Light Housing (O. Robertson, 2026)

After the basics of the housing were in place, I moved on to implementing the LED bulb into the design. As I knew it already had to be a 0.6-1.8 W LED bulb, I started by finding a bulb that will fit this definition. I opted to use an 1157 LED, which is commonly used in brake lights, and has an output of 1.2W, and a total length of 40mm. This will fit perfectly within my design. These bulbs use a BAY15D dual contact base, which I will have to factor into my design. I could not find a 3D model to represent the 1157 LED, but I did find a model for a General Electric 1157 bulb. This bulb has similar dimensions and uses the same BAY15D base, so the design should work with either bulb. I also downloaded a BAY15D base, which I can incorporate into my housing design.

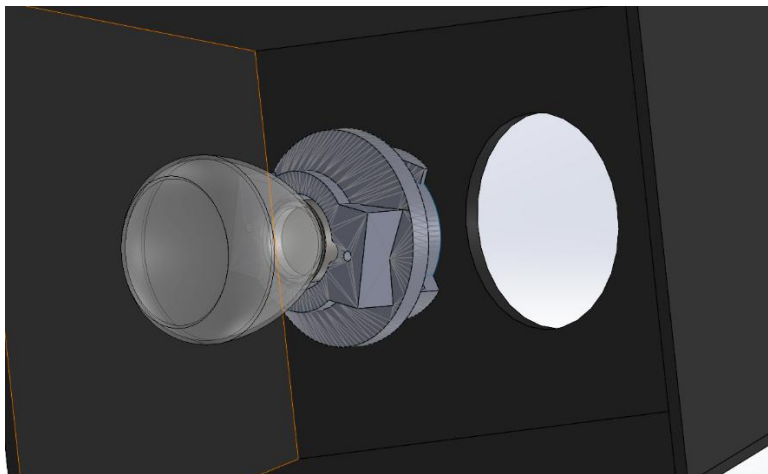


Figure 29 Bulb Assembly (O. Robertson, 2026)

I also added a red tinted glass piece to the housing, which is attached by 4 M4 Screws, which are attached in the corners of the open side of the housing. These screws require a 3.3mm hole which I incorporated into my design. The glass piece also features the same 15-degree draft that I used for the housing, so the piece should fit snugly.

This part can be 3D printed and installed onto the bike, as I plan to build this component out of plastic.

I also need to design mounting brackets and the wiring for the rain light, ensuring that the new light can safely attach to the old bracket. I will need to inspect the current light on the bike to do this, but we are currently lacking these components. I will also have to install a switch on the handlebars to activate the rain light.

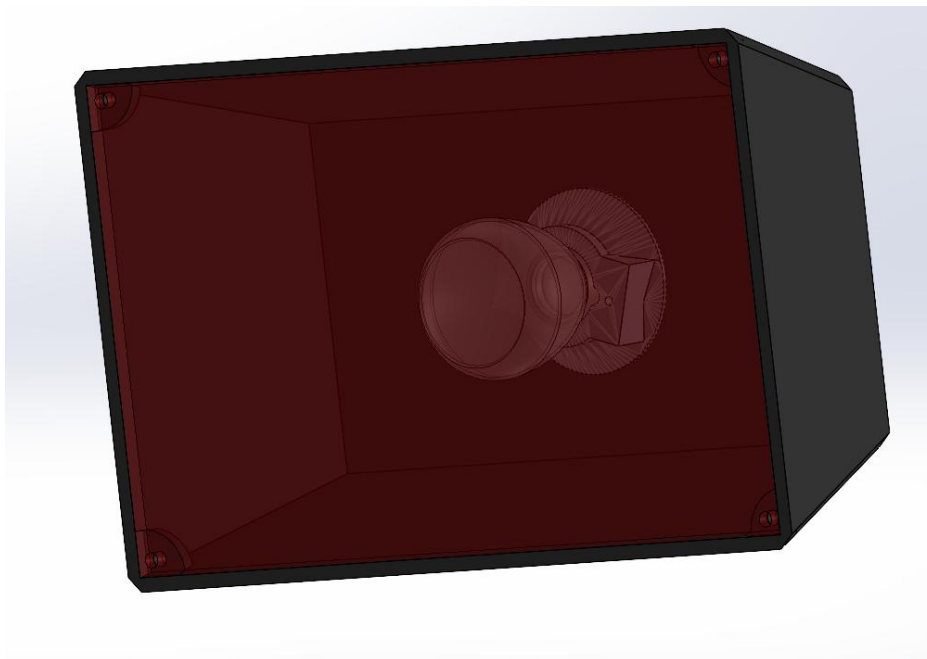


Figure 30 Rain Light Assembly (O. Robertson, 2026)

15.4 Electrical Safety Systems

Because modifications to the motorcycle's electrical system are already required for the rain light installation, it is efficient to integrate several additional safety systems at the same time.

One of the most important systems is the oil pressure warning light. Maintaining sufficient oil pressure is critical for engine lubrication, particularly during racing conditions where the engine operates at high speeds and elevated temperatures.

The warning system will function by installing a pressure switch into the engine's oil gallery, typically located near the oil filter. The pressure switch will be connected to a 12-volt warning light located on

the dashboard. If oil pressure falls below the required threshold, the pressure switch will complete the electrical circuit and illuminate the warning light. This provides the rider with immediate visual feedback, allowing them to shut down the engine before serious mechanical damage occurs.

Another important safety feature is the ignition kill switch, which allows the engine to be shut down quickly in an emergency. The switch will be mounted on the handlebars so that it is easily accessible to the rider.

The kill switch operates by interrupting the electrical circuit that supplies power to the ignition system. When the switch is activated, the circuit is broken and the ignition coils no longer receive electrical power. Without this power, the engine cannot continue operating and shut down immediately.

In addition to installing new safety systems, several road-legal components must be removed before the motorcycle can be used for racing. These components include indicators, mirrors, the horn, the number plate and mounting bracket, and passenger footrests. Removing these components reduces unnecessary weight and simplifies the motorcycle's configuration for track use.

15.5 Fairing Modifications and Oil Containment

Another important regulation relates to oil containment, which is described in Section 15.9 of the ACU Handbook. This rule requires that the lower fairing of the motorcycle must be capable of containing at least half of the engine's total oil and coolant capacity in the event of an engine failure.

The Yamaha FZR1000 used in this project has an oil capacity of 3 litres and a coolant capacity of 2.4 litres, resulting in a combined capacity of 5.4 litres. According to the ACU regulations, the lower fairing must therefore be capable of containing at least 2.7 litres of fluid.

Manufacturing a suitable fairing within the university workshop would be difficult because racing fairings are typically produced from fibreglass or composite materials using moulding processes that require specialised equipment.

For this reason, the most practical solution is to purchase a purpose-built racing fairing designed specifically for the Yamaha FZR1000. A suitable component can be purchased for approximately £165,⁴ which is significantly more cost-effective than manufacturing one from scratch.



Figure 31 Potential Fairing (eBay, 2025)

While replacing the fairings, there is also an opportunity to modify the rear section of the motorcycle. Because the motorcycle will only be used for racing, the passenger seat is unnecessary. Removing the passenger seat allows the rear subframe to be shortened, reducing overall weight and improving the aerodynamic profile of the motorcycle.

15.6 Conclusion

Preparing a motorcycle for competitive racing requires a structured approach that combines regulatory analysis, engineering design, and mechanical modification. Throughout this project, my primary responsibility has been to ensure that the motorcycle complies with the regulations of the No Limits Racing Team Power Trophy and the ACU National Endurance 1000.

This process began with identifying and analysing the correct technical regulations and compiling a simplified reference document for the team. This document enables team members to work efficiently while ensuring that all modifications remain within the permitted guidelines.

Several modifications have been planned or designed as part of this preparation process. These include the design and integration of a rain light system, installation of additional electrical safety systems such as an oil pressure warning light and ignition kills switch, removal of unnecessary road-legal components, and replacement of the lower fairing to meet oil containment regulations.

By implementing these modifications, the motorcycle will not only meet the safety and technical requirements of the regulations but will also be better optimised for competitive racing performance. Ensuring regulatory compliance at every stage of the project will allow the motorcycle to successfully pass scrutineering and compete safely in endurance racing events.

16 Project Achievements

One of the group initial successes was collaboratively disassembling of the motorcycle down to the frame while preserving all the internal parts.



Figure 73 Initial Achievement of Bike Disassembly (F. Flye, 2025)

Figure 28 presents the dismantled motorcycle with the engine placed on the trolley and ready for the installation in the engine bay room. This setup marked the critical transition towards the team's second major achievement.

The second major achievement was successfully reassembling the engine after team collaboration regarding the engine valving through thorough inspection and adjustments ensuring they were within the specified tolerances. The engines Camshaft is shown in figure 29 below, illustrating the open cover where the measurements were taken.

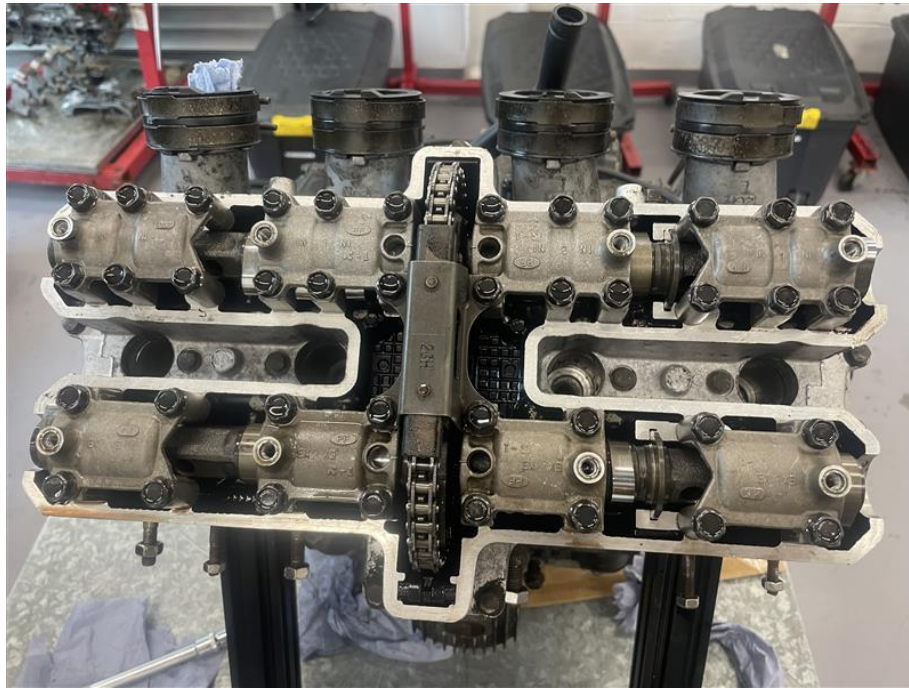


Figure 74 Engine Cams and valves (F. Flye, 2025)

The Third major achievement was the reinstalment of the engine back into the frame, enabling the team members to advance their individual areas.

17 Timeline and Gantt Chart

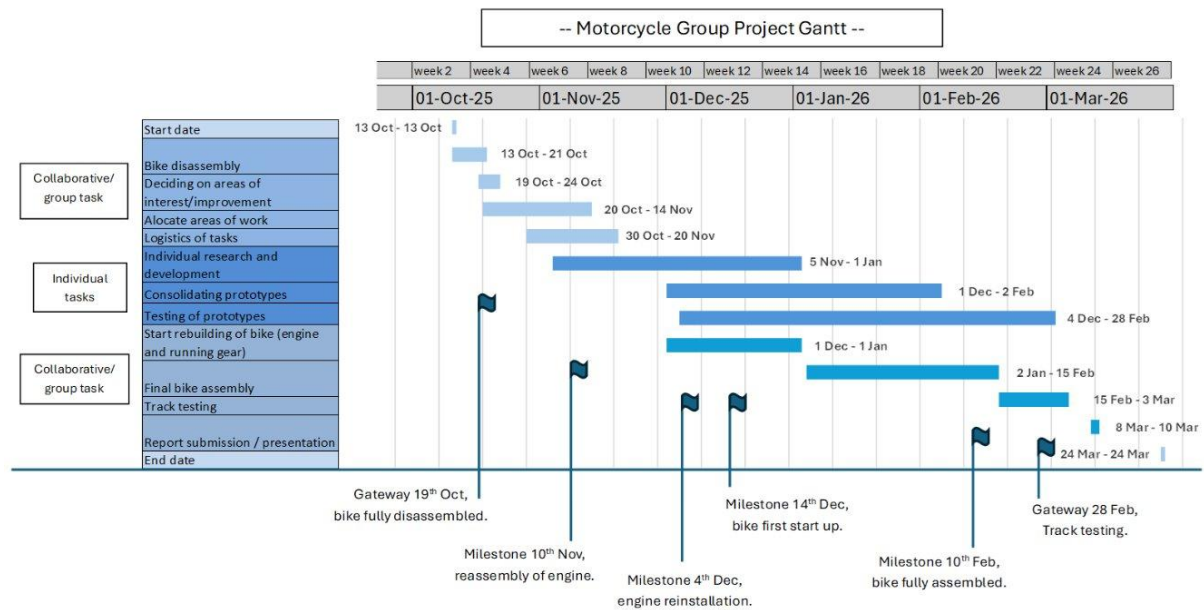


Figure 75 Team Gantt Chart showing the timeline of Tasks and milestones (M. Adair, 2025)

18 Conclusion

18.1 Project Successes

In conclusion the team has made solid progress across mechanical design work; These endeavours include the successful reinstalment of the motorcycles engine back into the frame with initial inspections of proper alignment and mounting stability. Secondly, the team conducted thorough research into our respective areas that, ended up locating the regulations for the no limits endurance racing scene and ensuring our build aligns with the safety, technical and competitive guidelines.

Furthermore, Detailed CAD models have been created of the top and bottom yokes alongside the creation of the rear suspension, linkage and exhaust model. These models consider the kinematics and mounting for the respective areas, with being easily adjustable to equate for changes made to the motorcycle.

Finally, a compliant model of the rear rain light assembly has been constructed which is mandatory for any scene of racing, this model ensures we meet the regulations visibility and mounting specifications while integrating into the rear smoothly.

18.2 Project Improvements

To ensure the motorcycle is completely rebuilt on schedule while delivering a competitive and complaint machine to the regulations. The team will commit to the following improvements: prioritizing the full motorcycle assembly, with a reestablished non-negotiable deadline that incorporates the CAD models, ensuring regular checkpoint updates to negate early signs of delays. Following this the team will shift focus to full collaborative work rather than individual to always ensure adequate focus on the motorcycle to reach this deadline. To further on this note the team will foster a more positive team culture by conversing and celebrating over personal goals that have been reached which in turn will boost team moral to continue work on the machine itself.

In addition, the team will implement mandatory focused meetings at consistent times with a clear agenda addressed prior. As in previous endeavours the meetings would fall through or be partially attended. These faster paced meetings will ensure the information will be relayed across quickly and effectively without burdening members.

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20 Appendix

20.1 Finn Flye

20.1.1 MATLAB Code

```
clc
clear
close all

vel = [0.00, 0.02, 0.04, 0.06, 0.08, 0.10, 0.12, 0.14, 0.16, 0.18, 0.20, 0.22,
0.24]';

force_comp_base = [0, 6, 11, 16, 21, 26, 30, 33.5, 37, 40, 43, 46.5, 50]';
force_reb_base = [0, -40, -80, -120, -160, -190, -215, -235, -250, -265, -275, -
285, -290]';

overall_scale = 1.8;
reb_scale_factor = 0.35;
force_comp = force_comp_base * overall_scale;
force_reb = force_reb_base * reb_scale_factor * overall_scale;

v_comp = vel; f_comp = force_comp;
v_reb = -vel; f_reb = force_reb;
```

```

f_comp_N = f_comp * 9.81;
f_reb_N = f_reb * 9.81;

vel_key = [0.025, 0.05, 0.075, 0.10, 0.125, 0.15, 0.20, 0.25]';
f_comp_key = interp1(v_comp, f_comp, vel_key, 'linear', 'extrap');
f_reb_key = interp1(v_reb, f_reb, -vel_key, 'linear', 'extrap');
ratio_key = abs(f_reb_key ./ f_comp_key);

low_mask = vel >= 0.01 & vel <= 0.08;
high_mask = vel >= 0.12;
C_comp_low_orig = polyfit(vel(low_mask), f_comp_N(low_mask), 1);
C_reb_low_orig = polyfit(vel(low_mask), abs(f_reb_N(low_mask)), 1);

C_comp_high = polyfit(vel(high_mask), f_comp_N(high_mask), 1);
C_reb_high = polyfit(vel(high_mask), abs(f_reb_N(high_mask)), 1);

slope_local_comp = gradient(f_comp_N, v_comp);
slope_local_reb = gradient(f_reb_N, v_reb);

knee_comp_idx = find(slope_local_comp < 0.6 * C_comp_low_orig(1), 1, 'first');
knee_reb_idx = find(abs(slope_local_reb) < 0.6 * C_reb_low_orig(1), 1, 'first');

knee_comp = NaN; if ~isempty(knee_comp_idx), knee_comp = v_comp(knee_comp_idx);
end
knee_reb = NaN; if ~isempty(knee_reb_idx), knee_reb = v_reb(knee_reb_idx); end

motion_ratio = 2.6;
sprung_mass_rear_kg = 114;
wheel_spring_rate_Nm = 30000;

C_crit_wheel = 2 * sqrt(wheel_spring_rate_Nm * sprung_mass_rear_kg);

C_comp_low_wheel_orig = C_comp_low_orig(1) / (motion_ratio^2);
C_reb_low_wheel_orig = C_reb_low_orig(1) / (motion_ratio^2);
C_comp_high_wheel = C_comp_high(1) / (motion_ratio^2);
C_reb_high_wheel = C_reb_high(1) / (motion_ratio^2);

zeta_comp_low_orig = C_comp_low_wheel_orig / C_crit_wheel;
zeta_reb_low_orig = C_reb_low_wheel_orig / C_crit_wheel;
zeta_comp_high = C_comp_high_wheel / C_crit_wheel;
zeta_reb_high = C_reb_high_wheel / C_crit_wheel;

omega_n = sqrt(wheel_spring_rate_Nm / sprung_mass_rear_kg);
f_natural_Hz = omega_n / (2 * pi);

fprintf('FZR1000 Rear Damper Analysis - Scaled & Optimized\n');
fprintf('=====\n\n');
fprintf('Motion Ratio: %.1f | Rear Sprung: %.0f kg | Wheel Rate: %.0f N/m\n', ...
    motion_ratio, sprung_mass_rear_kg, wheel_spring_rate_Nm);
fprintf('Critical Damping: %.0f N·s/m | Natural Freq: %.2f Hz\n\n', C_crit_wheel,
    f_natural_Hz);

fprintf('Original Low-speed Shaft Damping (0.01-0.08 m/s):\n');
fprintf(' Comp: %.6f N·s/m | Reb: %.6f N·s/m\n', C_comp_low_orig(1),
    C_reb_low_orig(1));
fprintf('Wheel-rate: Comp %.0f | Reb %.0f N·s/m\n\n', C_comp_low_wheel_orig,
    C_reb_low_wheel_orig);

fprintf('Original Damping Ratios ζ (Rear Wheel):\n');

```

```
fprintf(' Low-speed Comp: %.3f | Reb: %.3f\n', zeta_comp_low_orig,
zeta_reb_low_orig);
fprintf(' High-speed Comp: %.3f | Reb: %.3f\n\n', zeta_comp_high, zeta_reb_high);
```

```
target_zeta_reb_low = 0.70;
target_zeta_comp_low = 0.30;
target_ratio_low = 4.0;
```

```
C_comp_range = linspace(0.5 * C_comp_low_orig(1), 1.8 * C_comp_low_orig(1), 30);
C_reb_range = linspace(0.5 * C_reb_low_orig(1), 2.5 * C_reb_low_orig(1), 30);
```

```
cost_grid = zeros(length(C_comp_range), length(C_reb_range));
best_cost = inf; best_C_comp = NaN; best_C_reb = NaN;
```

```
for i = 1:length(C_comp_range)
    for j = 1:length(C_reb_range)
        Cc = C_comp_range(i);
        Cr = C_reb_range(j);
        Cc_wheel = Cc / (motion_ratio^2);
        Cr_wheel = Cr / (motion_ratio^2);
        zc = Cc_wheel / C_crit_wheel;
        zr = Cr_wheel / C_crit_wheel;
        ratio_approx = Cr / Cc;
        cost = (zc - target_zeta_comp_low)^2 + (zr - target_zeta_reb_low)^2 + ...
            4 * (ratio_approx - target_ratio_low)^2;
        cost_grid(i,j) = cost;
        if cost < best_cost
            best_cost = cost;
            best_C_comp = Cc;
            best_C_reb = Cr;
        end
    end
end
```

```
C_comp_low_opt = best_C_comp;
C_reb_low_opt = best_C_reb;
C_comp_low_opt_wheel = C_comp_low_opt / (motion_ratio^2);
C_reb_low_opt_wheel = C_reb_low_opt / (motion_ratio^2);
zeta_comp_low_opt = C_comp_low_opt_wheel / C_crit_wheel;
zeta_reb_low_opt = C_reb_low_opt_wheel / C_crit_wheel;
```

```
fprintf('\n=== Low-Speed Optimization Results ===\n');
fprintf('Best Comp: %6.0f N.s/m (wheel: %.0f)  $\zeta$  = %.3f\n', C_comp_low_opt,
C_comp_low_opt_wheel, zeta_comp_low_opt);
fprintf('Best Reb : %6.0f N.s/m (wheel: %.0f)  $\zeta$  = %.3f\n', C_reb_low_opt,
C_reb_low_opt_wheel, zeta_reb_low_opt);
fprintf('Achieved rebound:comp ratio  $\approx$  %.2f:1\n\n', C_reb_low_opt /
C_comp_low_opt);
```

```
figure('Color','w','Position',[100 100 1400 900]);
sgtitle('FZR1000 Rear Damper - Scaled vs Low-Speed Optimized','FontSize',16);
```

```
subplot(2,2,1);
plot(vcl, force_comp,'b.-','LineWidth',2); hold on;
plot(vcl, force_reb,'r.-','LineWidth',2);
plot(vcl, polyval(C_comp_low_opt*[1 0],vcl)/9.81,'b.-','LineWidth',1.8);
```

```

plot(vel, -polyval(C_reb_low_opt*[1 0],vel)/9.81,'r--','LineWidth',1.8);
grid on; legend('Scaled Comp','Scaled Reb','Opt Comp','Opt Reb');
xlabel('Shaft Velocity (m/s)'); ylabel('Force (kg)'); title('Force-Velocity');

subplot(2,2,2);
semilogy(vel_key, ratio_key,'k.-','LineWidth',2.5,'MarkerSize',12); hold on;
plot(vel_key, ratio_key,'ko','MarkerFaceColor','k');
grid on; ylim([1 10]);
xlabel('Velocity (m/s)'); ylabel('Reb/Comp Ratio'); title('Rebound Dominance');

subplot(2,2,[3,4]);
categories = categorical({'Comp Low', 'Reb Low', 'Comp High', 'Reb High'});
orig_zeta = [zeta_comp_low_orig; zeta_reb_low_orig; zeta_comp_high;
zeta_reb_high];
opt_zeta = [zeta_comp_low_opt; zeta_reb_low_opt; zeta_comp_high;
zeta_reb_high];
bar(categories, [orig_zeta opt_zeta]);
ylabel('Damping Ratio  $\zeta$ '); grid on;
legend('Scaled Original','Low-Speed Optimized');
title('Damping Ratio Comparison (Wheel Rate)');

fprintf('Rear Natural Frequency: %.2f Hz → ', f_natural_Hz);
if f_natural_Hz < 1.8
    fprintf('Quite soft/plush (good street comfort, may wallow on track).\n');
elseif f_natural_Hz < 2.3
    fprintf('Balanced street/track (typical FZR setup).\n');
elseif f_natural_Hz < 2.8
    fprintf('Firm/track-oriented (quick response).\n');
else
    fprintf('Very stiff/race-like (harsh on street).\n');
end

```

20.1.2 Optimised MATLAB Code

```

clc
clear
close all

vel = [0.00, 0.02, 0.04, 0.06, 0.08, 0.10, 0.12, 0.14, 0.16, 0.18, 0.20, 0.22,
0.24]';
force_comp = [0, 12, 22, 32, 42, 52, 60, 67, 74, 80, 86, 93, 100]';
force_reb = [0, -40, -80, -120, -160, -190, -215, -235, -250, -265, -275, -285, -
290]';
v_comp = vel;
f_comp = force_comp;
v_reb = -vel;
f_reb = force_reb;
f_comp_N = f_comp * 9.81;
f_reb_N = f_reb * 9.81;

vel_key = [0.025, 0.05, 0.075, 0.10, 0.125, 0.15, 0.20, 0.25]';
f_comp_key = interp1(v_comp, f_comp, vel_key, 'linear', 'extrap');
f_reb_key = interp1(v_reb, f_reb, -vel_key, 'linear', 'extrap');
ratio_key = abs(f_reb_key ./ f_comp_key);

low_mask = vel >= 0.01 & vel <= 0.08;
high_mask = vel >= 0.12;

```

```

C_comp_low_orig = polyfit(vel(low_mask), f_comp_N(low_mask), 1);
C_reb_low_orig = polyfit(vel(low_mask), abs(f_reb_N(low_mask)), 1);
C_comp_high = polyfit(vel(high_mask), f_comp_N(high_mask), 1);
C_reb_high = polyfit(vel(high_mask), abs(f_reb_N(high_mask)), 1);

slope_local_comp = gradient(f_comp_N, v_comp);
slope_local_reb = gradient(f_reb_N, v_reb);
knee_comp_idx = find(slope_local_comp < 0.6 * C_comp_low_orig(1), 1, 'first');
knee_reb_idx = find(abs(slope_local_reb) < 0.6 * C_reb_low_orig(1), 1, 'first');

knee_comp = NaN; if ~isempty(knee_comp_idx), knee_comp = v_comp(knee_comp_idx);
end
knee_reb = NaN; if ~isempty(knee_reb_idx), knee_reb = v_reb(knee_reb_idx); end

motion_ratio = 2.0;
sprung_mass_rear_kg = 150;
wheel_spring_rate_Nm = 50000;
C_crit_wheel = 2 * sqrt(wheel_spring_rate_Nm * sprung_mass_rear_kg);

C_comp_low_wheel_orig = C_comp_low_orig(1) / (motion_ratio^2);
C_reb_low_wheel_orig = C_reb_low_orig(1) / (motion_ratio^2);
C_comp_high_wheel = C_comp_high(1) / (motion_ratio^2);
C_reb_high_wheel = C_reb_high(1) / (motion_ratio^2);

zeta_comp_low_orig = C_comp_low_wheel_orig / C_crit_wheel;
zeta_reb_low_orig = C_reb_low_wheel_orig / C_crit_wheel;
zeta_comp_high = C_comp_high_wheel / C_crit_wheel;
zeta_reb_high = C_reb_high_wheel / C_crit_wheel;

omega_n = sqrt(wheel_spring_rate_Nm / sprung_mass_rear_kg);
f_natural_Hz = omega_n / (2 * pi);
fprintf('FZR1000 Rear Damper Analysis - Original\n');
fprintf('=====\n\n');

fprintf('Motion Ratio: %.2f | Rear Sprung: %.0f kg | Wheel Rate: %.0f N/m | Crit
Damping: %.0f N·s/m\n\n', ...
    motion_ratio, sprung_mass_rear_kg, wheel_spring_rate_Nm, C_crit_wheel);

fprintf('Low-speed Shaft Damping (0.01-0.08 m/s):\n');
fprintf('  Comp: %.0f N·s/m   Reb: %.0f N·s/m\n', C_comp_low_orig(1),
C_reb_low_orig(1));
fprintf('Wheel-rate: Comp %.0f   Reb %.0f N·s/m\n\n', C_comp_low_wheel_orig,
C_reb_low_wheel_orig);

fprintf('Damping Ratios ζ (Rear Wheel):\n');
fprintf('  Low-speed Comp: %.3f   Reb: %.3f\n', zeta_comp_low_orig,
zeta_reb_low_orig);
fprintf('  High-speed Comp: %.3f   Reb: %.3f\n\n', zeta_comp_high, zeta_reb_high);

fprintf('Natural Frequency: %.2f Hz → %s\n\n', f_natural_Hz, ...
    ifelse(f_natural_Hz < 1.8, 'Soft/street', ...
    ifelse(f_natural_Hz < 2.3, 'Balanced street/track', ...
    ifelse(f_natural_Hz < 2.8, 'Firm/track', 'Very stiff/race')));

target_zeta_reb_low = 0.60;
target_zeta_comp_low = 0.35;
target_ratio_low = 4.0;

```

```

C_comp_range = linspace(0.4 * C_comp_low_orig(1), 1.6 * C_comp_low_orig(1), 25);
C_reb_range = linspace(0.4 * C_reb_low_orig(1), 1.6 * C_reb_low_orig(1), 25);

cost_grid = zeros(length(C_comp_range), length(C_reb_range));
best_cost = inf;
best_C_comp = NaN;
best_C_reb = NaN;

for i = 1:length(C_comp_range)
    for j = 1:length(C_reb_range)
        Cc = C_comp_range(i);
        Cr = C_reb_range(j);

        Cc_wheel = Cc / (motion_ratio^2);
        Cr_wheel = Cr / (motion_ratio^2);

        zc = Cc_wheel / C_crit_wheel;
        zr = Cr_wheel / C_crit_wheel;

        ratio_approx = Cr / Cc;

        cost = (zc - target_zeta_comp_low)^2 + (zr - target_zeta_reb_low)^2 + ...
            5 * (ratio_approx - target_ratio_low)^2;

        cost_grid(i,j) = cost;

        if cost < best_cost
            best_cost = cost;
            best_C_comp = Cc;
            best_C_reb = Cr;
        end
    end
end

C_comp_low_opt = best_C_comp;
C_reb_low_opt = best_C_reb;

C_comp_low_opt_wheel = C_comp_low_opt / (motion_ratio^2);
C_reb_low_opt_wheel = C_reb_low_opt / (motion_ratio^2);

zeta_comp_low_opt = C_comp_low_opt_wheel / C_crit_wheel;
zeta_reb_low_opt = C_reb_low_opt_wheel / C_crit_wheel;

fprintf('\n=== Grid-Search Optimized Low-Speed Damping ===\n');
fprintf('Best Comp: %6.0f N·s/m (wheel: %.0f)  ζ = %.3f\n', C_comp_low_opt,
    C_comp_low_opt_wheel, zeta_comp_low_opt);
fprintf('Best Reb : %6.0f N·s/m (wheel: %.0f)  ζ = %.3f\n', C_reb_low_opt,
    C_reb_low_opt_wheel, zeta_reb_low_opt);
fprintf('Achieved rebound:comp ratio ≈ %.2f:1\n\n', C_reb_low_opt /
    C_comp_low_opt);

figure('Color','w','Position',[100 100 1400 900]);
sgtitle('FZR1000 Damper - Original vs Grid-Optimized (Low-Speed)','FontSize',16);

subplot(2,2,1);
plot(vel, force_comp,'b.-','LineWidth',2); hold on;
plot(vel, force_reb, 'r.-','LineWidth',2);
plot(vel, polyval(C_comp_low_opt*[1 0],vel)/9.81,'b.-','LineWidth',1.8);
plot(vel, -polyval(C_reb_low_opt*[1 0],vel)/9.81,'r.-','LineWidth',1.8);

```

```

grid on; legend('Orig Comp','Orig Reb','Opt Comp (low)','Opt Reb (low)');
xlabel('Shaft Velocity (m/s)'); ylabel('Force (kg)'); title('Force-Velocity');

subplot(2,2,2);
semilogy(vel_key, ratio_key,'k.-','LineWidth',2.5,'MarkerSize',12); hold on;
plot(vel_key, ratio_key,'ko','MarkerFaceColor','k');
grid on; ylim([1 10]);
xlabel('Velocity (m/s)'); ylabel('Reb/Comp Force Ratio'); title('Rebound
Dominance');

subplot(2,2,[3,4]);
categories = categorical({'Comp Low', 'Reb Low', 'Comp High', 'Reb High'});
orig_zeta = [zeta_comp_low_orig; zeta_reb_low_orig; zeta_comp_high;
zeta_reb_high];
opt_zeta = [zeta_comp_low_opt; zeta_reb_low_opt; zeta_comp_high; zeta_reb_high];
bar(categories, [orig_zeta opt_zeta]);
ylabel('Damping Ratio  $\zeta$ '); grid on;
legend('Original','Optimized (low-speed)');
title('Damping Ratio Comparison - Wheel Rate');

function str = ifelse(cond, a, b)
    if cond, str = a; else, str = b; end
end

```

20.2 Lars Millner