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***Development of a Chassis Simulation &
Optimisation Programme Specialised for
Motorcycles with Hub-Centre Steering with The
Aim of Designing a Race-Spec Suspension
System***

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List of Abbreviations

HCS→Hub-Centre Steering

CAD→Computer Aided Design

ECU→Electronic Control Unit

IMU→Inertial Measurement Unit

GPS→Global Positioning System

R&D→Research and Development

1 Introduction

Chassis evaluation and optimisation tools for motorcycles are predominantly crafted around the conventional telescopic fork front end, reducing their ability to represent alternative configurations such as hub-centre steering (HCS). The current approaches to simulation are insufficient in accurately modelling and optimisation of a HCS configuration due to the fundamental differences in kinematic behaviours compared to telescopic forks, with a reduction of the coupling between the suspensions motion and steering, transformed load paths, and the non-linear variation of geometry when experiencing dynamic conditions, calling for a dedicated analysis tool.

The purpose of this project is to address the aforementioned gap by developing a HCS specific chassis program tailored to the unique kinematic characteristics present. This program will use derived geometric inputs from both CAD model and physical measurements taken and integrate these with data gathered from track testing to validate the model's accuracy, ensuring relevance to the real-world. The framework created will then be used to investigate and test alternative front and rear linkage configurations to attain kinematic characteristics desirable for a race-spec bike.

The expected outcome of the project is a functional tool for simulation that has been validated as well as a refined configuration for the suspension system that supports the development of a race-spec variant of the Arc Vector bike.

1.1 Aims

- ❖ Identify and compare the relationship between Fork and HCS set-up changes and associated effects on kinematics continuing on to develop an updated, race-spec suspension system for the Arc Vector based on the desired kinematic values.

1.2 Objectives

- ❖ Research and develop linkage systems for front and rear suspension if desirable kinematics can be met or adjustability is required
- ❖ Develop a system in a suitable programming language to compare and analyse characteristics and associated kinematics of a HCS bike

- ❖ Detail relationships of mechanical configurations to kinematic characteristics of the HCS bike and compare with that of standard front fork configuration relationships
- ❖ Collect dynamic behaviour data of key characteristics from the baseline bike during track testing sessions for comparison with model data during the program development phase
- ❖ Adjust/redesign the current mechanical configuration of the HCS bike to achieve the desired kinematic characteristics decided on by

1.3 Justification of Research

1.3.1 Development of Mechanical Simulation Programme

Current commercially available motorcycle dynamics simulation programs are designed and focused predominantly around conventional telescopic fork systems. As a result, they do not include the required coding needed to simulate a bike with a hub-centre steering system such as the Arc Vector. This leaves a significant gap in access to the modelling and analysis of the load paths, geometric behaviour, and decoupled suspension-steering characteristics unique to HCS configured motorcycles.

1.3.2 Arc Vector Project Goals

Due to other ongoing projects, there is an established collaborative relationship between the university and Arc, supporting a direct industry linked context for this research. The current development plan at Arc includes a transitional re-design aimed at creating a race-specification variant, with the goal of attaining handling characteristics which are compatible to those of a conventional high-performance race bike. These objectives are directly supported by this project's outcomes with the development of a modelling program bespoke to HCS motorcycles enabling analysis and optimisation of the chief kinematic parameters.

2 Literature Review

2.1 Motorcycle Suspension Configurations

2.1.1 Front Suspension

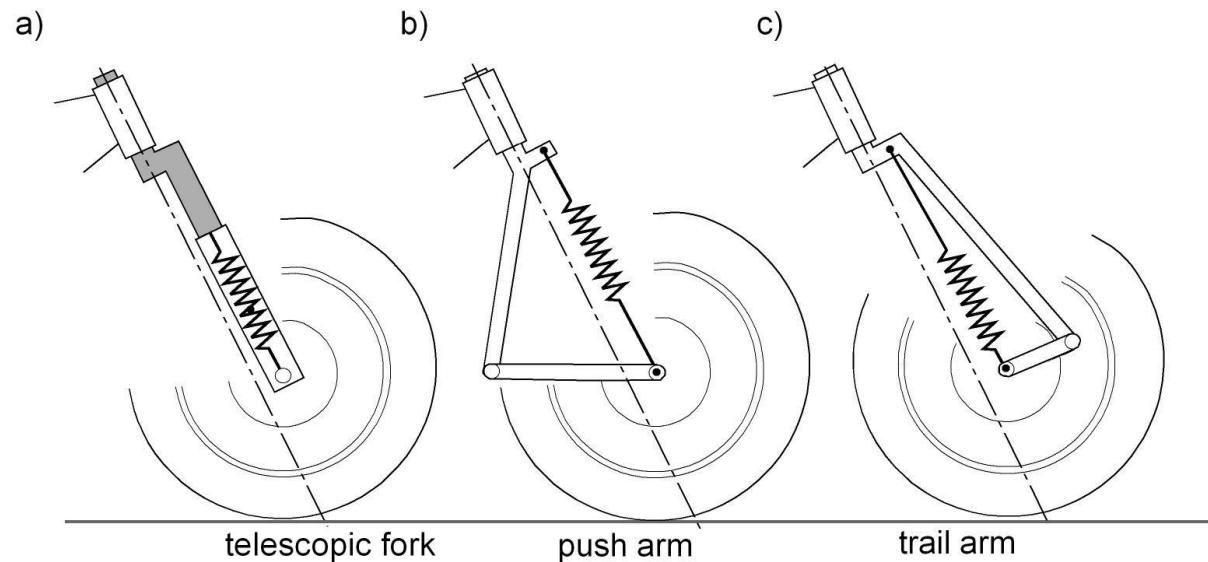


Figure 2.1: Most Common Systems (Cossalter, 2014)

Telescopic forks (figure 2.1a) are the most common and conventional system used for front geometry, as the name suggests, they utilise telescopic sliders which travel along the inside of fork tubes, this set up contains the spring and damper system within itself as a closed system that deals with steering, braking, and suspension forces, and as motion under braking is linear, high levels of “dive” can be an issue (Mavroudakakis and Eberhard, 2015). While this is the typical system used in most bikes there are many alternative types including: the push arm or “Earles fork” (figure 2.1b) found on some vintage bikes like the 60s BMW models have the spring/damper assembly separated from a swing arm with the wheel mounted in front of the pivot, this system eliminates dive under braking and can even introduce lift depending on the location of the arms pivot point relative to the wheel centre. The system separates the braking load from the damper assembly which often smoothens operation, and as the system is made from a swing arm assembly, the lateral stiffness is greatly increased; the trail arm (figure 2.1c) found on Vespa scooters is much like the push arm except reversed with the wheel mounted behind the pivot, this system provides the opposite dive to the push arm,

promoting dive under braking but also increases stability as due to the wheel lagging behind the pivot, small bumps can't be felt as much, and as the suspension compresses the trail increases, increasing the self-centring force. Another configuration is hub-centre steering which will be discussed in a dedicated section.

2.1.2 Rear Suspension

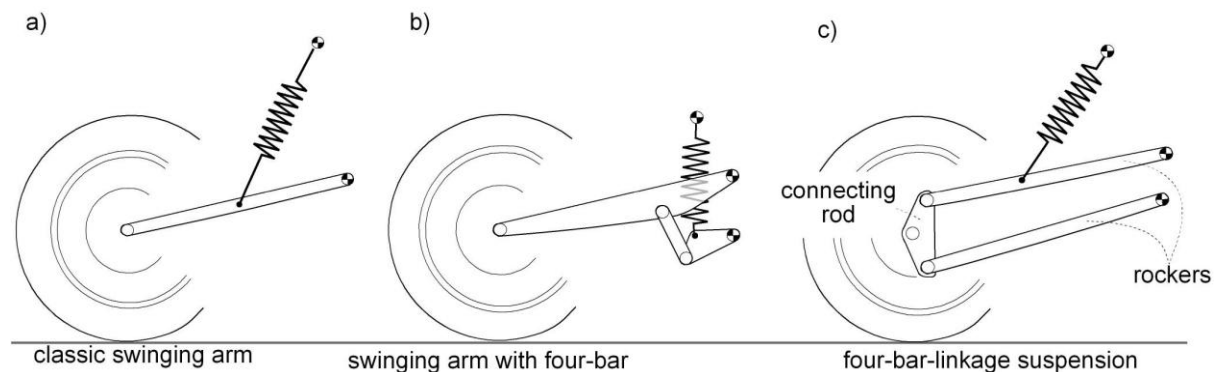


Figure 2.2: Rear Suspension Types (Cossalter, 2014)

The classic swing arm (figure 2.2a) is a swing arm system made from 2 arms with the wheel mounted in between, usually has 2 damper assemblies (one either side) with a common problem arising from the separate damper assemblies producing different forces and so introducing torsional stress to the system with an alternative mono-shock system that eliminates this torsional issue, but due to its packaging close to the engine, can overheat causing issues, this system like the classic also cannot achieve a progressive force curve over the suspensions travel. Moving to four-bar linkages (figures 2.2a&b), these allow for a design that can achieve adjustable-rate suspension to obtain the desired stiffness curve from the damper assembly, with mounting points often being adjustable.

2.2 Linkage Systems

2.2.1 Direct Shock

Like discussed with the classic swing arm variant, direct shock is where the damper assembly is connected between the swing arm and chassis, this is simple design lowers mass, complexity and reduces the number of potential failure points, however, possesses a fixed motion ratio and as such the relationship between the dampers motion and the wheel travel is linear

2.2.2 Linear Rate

These also produce only linear motion ratios however, due to the added linkage system, the leverage can be adjusted through moving pivot points and the linkage system also provides smoothing meaning that behaviour is more predictable, with a constant response being better suited for performance applications, even with added complexity of the system.

2.2.3 Rising Rate

Rising rate linkages enable the tuning of force response of the damper assembly over its displacement, allowing for a system that displays lower stiffness initially which is good for smaller bumps and keeping maximum contact with the road surface, but then ramps up to be stiffer as the travel increases, providing resistance to bottoming out from high loads. These systems are well suited to performance applications (Foale, 2006) but do increase complexity significantly and can prove difficult to tune with sensitivity to geometric parameters.

2.3 Hub-Centre Steering

2.3.1 Background

Hub-centre steering (HCS) is another front end alternative to conventional telescopic forks that utilises a swing arm setup like that of a rear system, but places the steering pivot at the wheels hub instead of at the top of the forks, this separates steering forces and responses from wheel travel and braking forces allowing for increased control over load paths. Due to the use of a linkage system being used to control steering, this systems complexity is significantly high (Davis, 2012), with added cost and rider feel from separated forces being a large barrier to wider acceptance and implementation.

2.3.2 Considerations

This systems platform stability is notably improved via the separation or “decoupling” of the 3 forces mentioned above reducing the movement of geometry under braking (Cossalter, 2014). These benefits are often seen to be offset by the cost of development, increased complexity, and loss of rider feel as forces are no longer directly transferred to the rider but are instead transferred through multiple parts of the linkage system, with any tolerances of individual parts adding up over the forces travel and meaning riders can

feel muted and detached from the forces (Foale, 2006). Other factors limiting adoption include industry path dependence, with conventional forks being highly developed, a switch in system being seen as too much effort and hard to justify (Mavrouidakis and Eberhard, 2015) with increased financial and time resources needed for R&D of these systems.

3 Methodology

3.1 Data Collection

3.1.1 Metrology

Measurements of the bike will be derived from the detailed CAD models provided by Arc, providing values for mount/pivot locations, swing-arm lengths, and current damper placements along with other key geometric parameters. This data will establish the basis for the kinematic model's construction within the chosen coding environment.

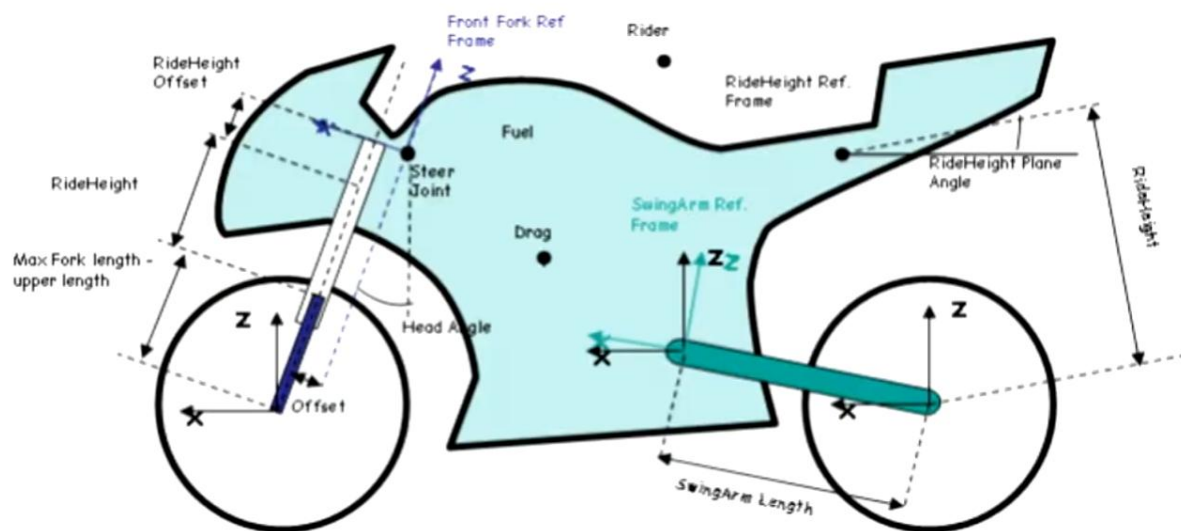


Figure 3.1: Key Geometry (VI-Grade Software)

Measurements of key parameters such as swing arm lengths and pivot locations seen in figure 3.1 will be conducted physically to ensure the CAD attained data's reliability. These values will be compared with that of the CAD measurements to identify possible discrepancies and verify critical dimensions. If found, any discrepancies will be checked and the values will be corrected, improving the fidelity of the constructed model.

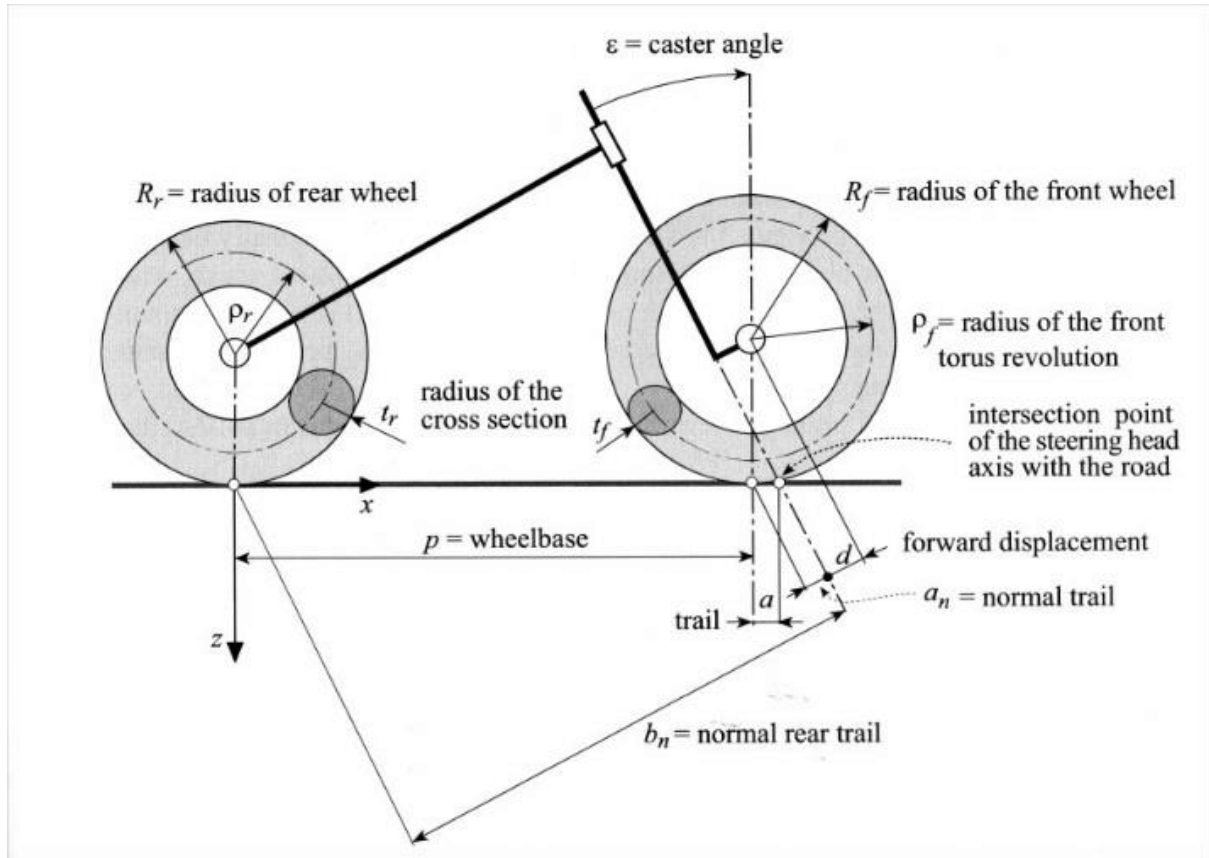


Figure 3.2: Motorcycle Front-End Geometry (Cossalter, 2014)

The final validated dataset of geometric values will then be implemented into the tailored program, allowing accurate simulation of the chassis kinematics, including the front and rear suspension before the addition of linkages. This progression will provide a consistent base for the evaluation and subsequent optimisation of the bikes suspension system by ensuring the model will be grounded in real-world data along with its theoretical design focus.

3.1.2 Track Testing

Further validation of the simulation model under real-world operating conditions will be carried out by running the base bike around the Pembrey circuit (figure 3.3),

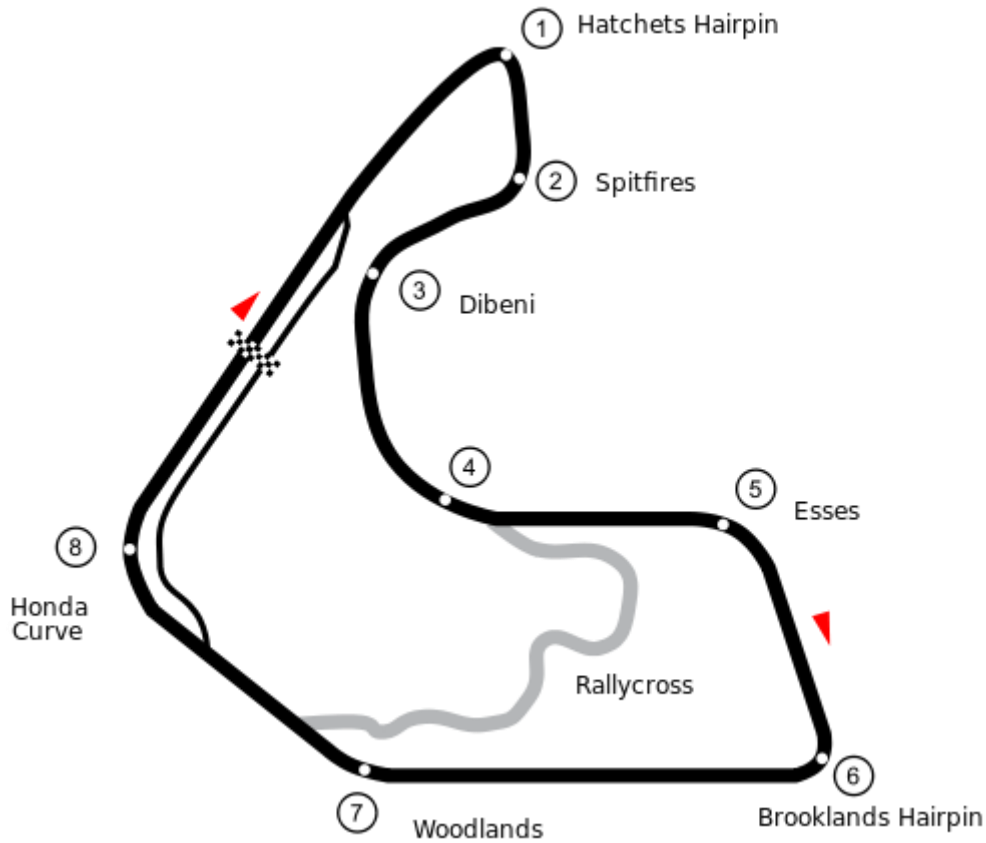


Figure 3.3: Pembrey Circuit Layout

with a suite of sensors and data loggers fitted to measure and log a variety of dynamic values (figure 3.4), these include steering angle, brake pressures, and damper displacements as well as measurements logged by the bike's ECU and fitted IMU such as GPS speed, 3-axis acceleration/gyro, and motor speed. These will enable direct identification of braking/acceleration responses, suspension behaviour under loads, and mid-manoeuve steering inputs. There are also channels derivable from directly logged ones including wheel travel from damper travel and rear wheel speed from motor speed, although dedicated wheel speed sensors will likely be fitted during the project which will give more accurate measurements, enabling for thorough evaluation of slip behaviour.

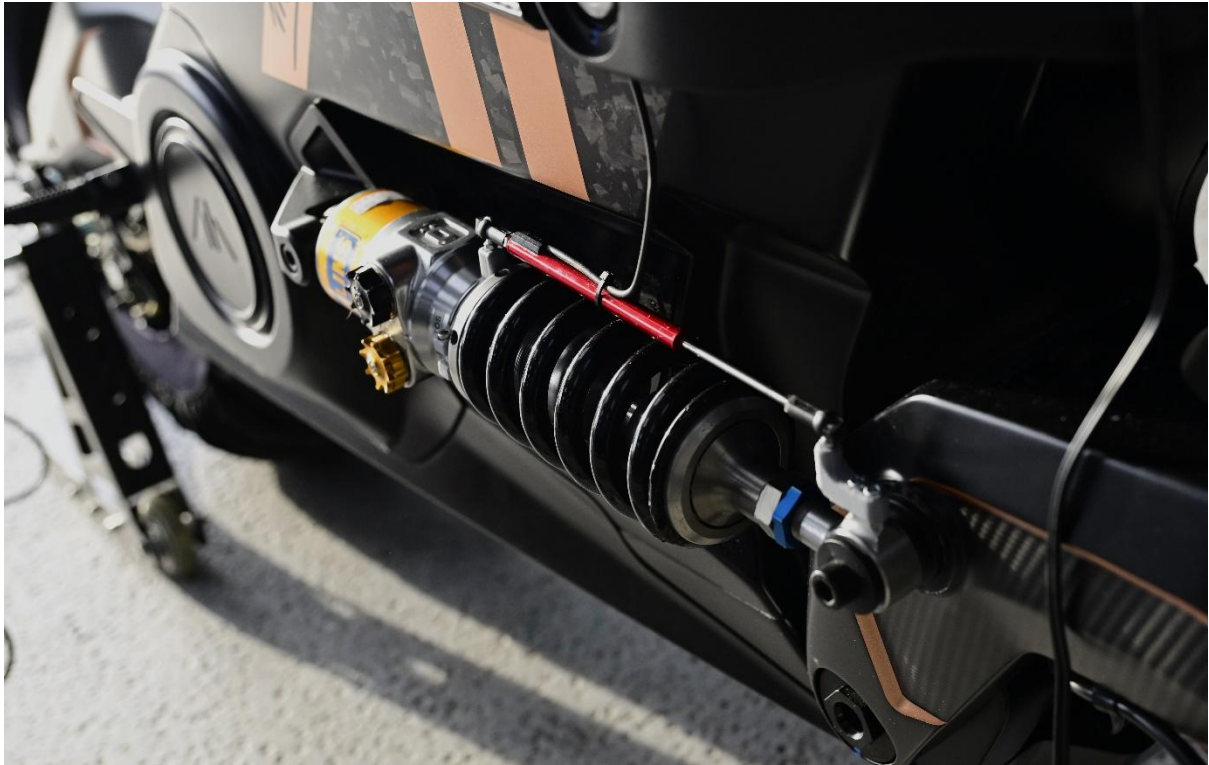


Figure 3.4: Arc Vector Front Damper & Potentiometer

The selected channels of data will be chosen based upon their capability in analysing the relationships between key kinematics vital to the HCS system performance and may change throughout the project as the required data changes.

All collected data from the circuit will be analysed to enable the assessment of model precision via comparison against the simulated datasets. This will be achieved through the correlation of the simulation's predicted suspension motion and the measured real-world motion with any inconsistencies identified being used to further refine the model, guaranteeing a representative simulation tool that can reliably approximate real-world system behaviours.

3.2 2D Data Analysis

The 2D data analysis software will be used to conduct an evaluation of the data gathered from track testing by visualising and interpreting channels measured directly via sensors/loggers, as well as channels derived from these. Directly recorded channels will include steering angle, brake pressures, and damper displacement values for the front and rear in addition to motor speed from the ECU along with GPS speed and 3-axis gyroscopic and accelerometer data recorded by the IMU. The directly measured data will

supply a representation of the bikes response with rider inputs while experiencing dynamic conditions.

Secondary, derived channels will be calculated from the former to provide a more intuitive illustration of the bike's physical behaviours. These will include but are not limited to wheel displacement, calculated from the established geometry with damper displacement values; rear wheel speed, calculated using the motor speed value along with the sprocket ratios, this may become more accurate as dedicated ABS rings are likely to be added; and dive/squat behaviour, calculated from the relationship correlation between the longitudinal acceleration values from the IMU and the displacement of the suspension.

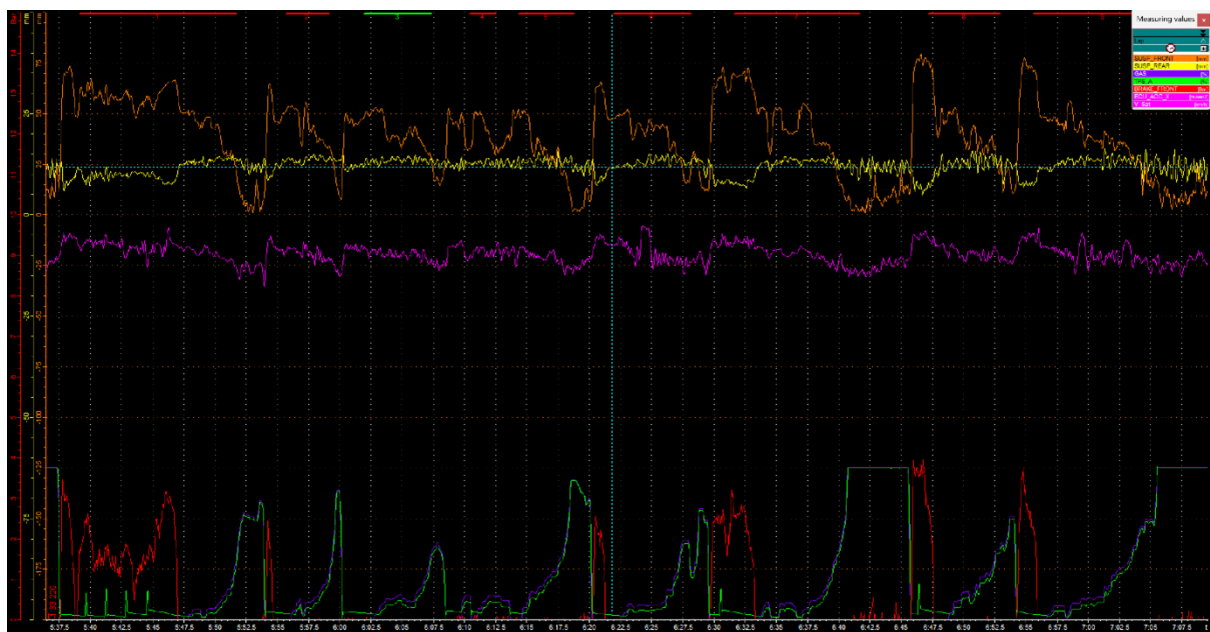


Figure 3.5: Example 2D Data Plot

Tailored displays will be created based upon a specific focus such as front and rear wheel speed, which will help visualise slip behaviours. Furthermore, trends, relationships, and distributions within the data will be identified using histogram/scatter plot tools, an approach allowing for qualitative evaluation of performance in addition to quantitative.

3.3 Virtual Modelling

Before beginning development of a custom program specified for HCS motorcycles, a detailed evaluation of available software will be carried out, the purpose of which is to

determine if any alternative software has the capability to accurately represent and simulate a HCS system as well as offer adjustable configuration parameters.

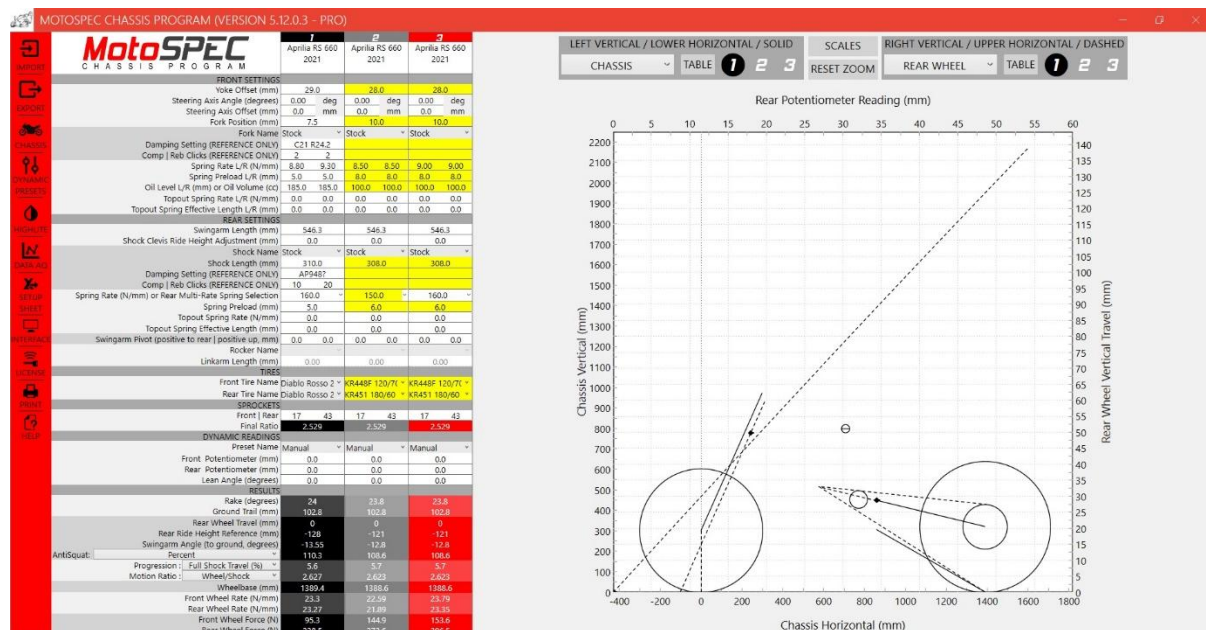


Figure 3.6: Moto SPEC Chassis Program

One software being investigated is MotoSPEC seen in figure 3.6, which builds a virtual bike from a collection of geometric values such as swing arm length and pivot locations. This program is tailored for comparing geometry changes on a conventional telescopic fork systems and does not note any options for alternative front-end configurations, so requires an in-depth analysis and contact with the company to determine viability.

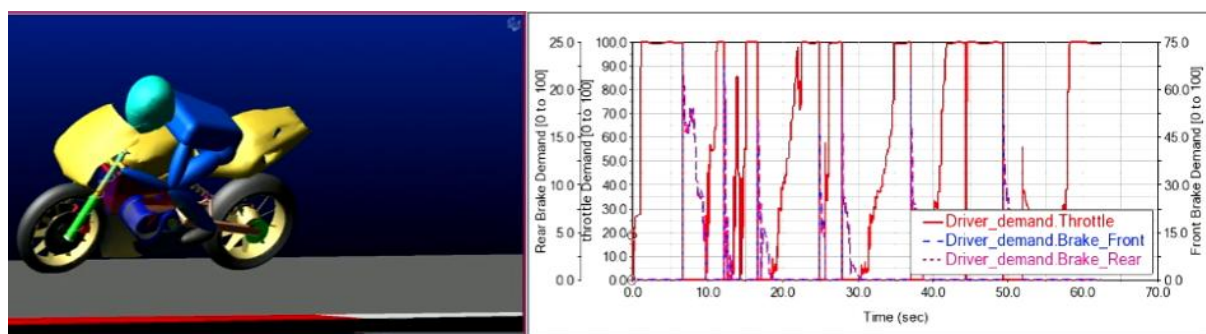


Figure 3.7: VI-BikeRealTime Simulation Program

Another software to be investigated is VI-BikeRealTime seen in figure 3.7, this is a simulation package designed to evaluate changes in geometry of a bike through running lap-time simulations with an array of tuneable values such as rake angle and swing arm lengths. Like MotoSPEC, this has been developed around the telescopic fork system and

contains rear suspension configurations including direct shock and progressive linkages, however, there is also a *conceptual* bike variant that states “any type of suspension can be modelled” (VI-Grade, 2024). This could possibly make the software viable for use in this project although its main goals do not inherently include lap simulation, for this reason, further investigation is required to ascertain if any meaningful outcomes could be produced via this method.

3.4 Design Optimisation

This section covers the development and testing of multiple interchangeable linkage types on both the front and rear suspension systems in addition to general chassis/suspension geometry optimisation. Before this phase is started, a formal meeting will be planned with the project lead(s) at Arc as well as the research project supervisor to discuss goals, limitations, and overall direction the company wishes to take. This meeting will include the definition and tolerance of any desired characteristics and an agreement on those initial targets. Also included will be the discussion of any limitations that may arise, this may be physical packaging bounds, time constraints, and acceptable compromises. From this stage onwards, regular contact with Arc will be maintained to ensure any alterations required are communicated effectively and in good time.

The development of the chassis program will then start, with the measurements took in chapter 3.1.1 being implemented as a base bike set-up that will produce initial kinematic values that will be validated against those found during track testing

chapter 3.1.2. Once validation of the base bike is finalised, linkage configurations for the front and rear suspension will be developed and tested against the metrics set out in the target phase, with any chassis, swing arm, or steering system alterations also being carried out.

3.5 Preliminary Project Plan

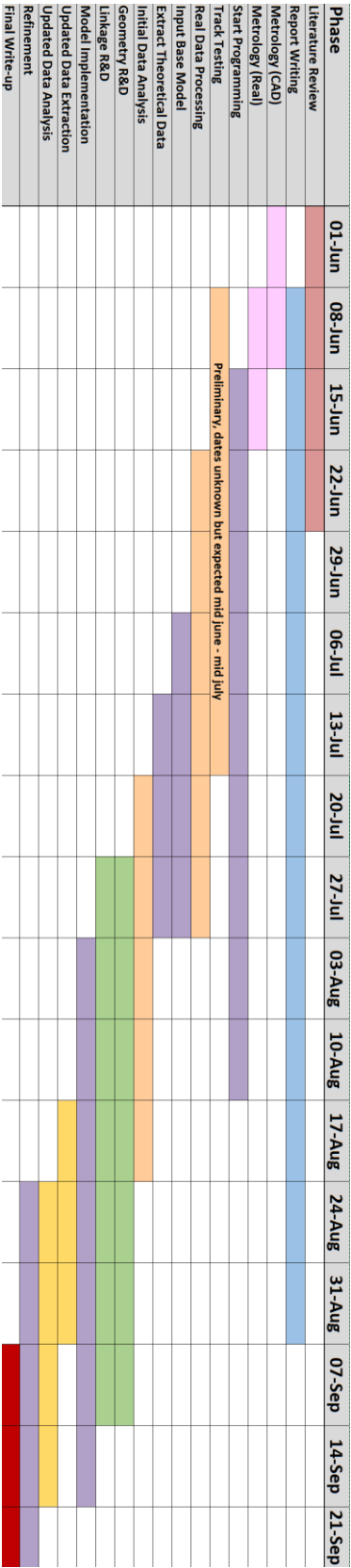


Figure 3.8: Project Gantt Chart

4 Expected Results

4.1 Real World Data

4.1.1 Direct Data

The directly gathered data are the channels logged by each sensor/logger, these come straight from testing and can be seen in real-time, however they do not always provide the required/preferred data, and often need to be manipulated to provide analytical datasets used to express complex relationships. Examples include but are not limited to:

- Front damper travel
- Rear damper travel
- Front brake pressure
- Rear brake pressure
- Steering angle
- GPS speed
- ECU data (e.g. Motor Speed)
- IMU data (e.g. lean/pitch angle)

4.1.2 Inferred/Calculated Data

Often understanding is improved when data can be analysed in respect to a specific and preferred reference point, or visualisation of combined system relationships can be achieved with new channels. Through the manipulation of the direct datasets and predetermined values, inferred channels of data can be calculated. These include:

- Squat/dive characteristics
- Front suspension travel (i.e. wheel travel opposed to damper travel)
- Rear suspension travel
- Rear wheel speed (using motor speed and gearing ratio)

4.2 2D Data Analysis

The data gathered from the loggers will be imported into a data analysis software such as the logger proprietary software, 2D. The imported data will then be processed to

provide both understanding and visualisation of selected channels as well as creating math derived channels and producing graphs and visuals for further evaluation.

Examples of this include:

- Dive & Squat characteristics
- Lean/roll relationship

Also,

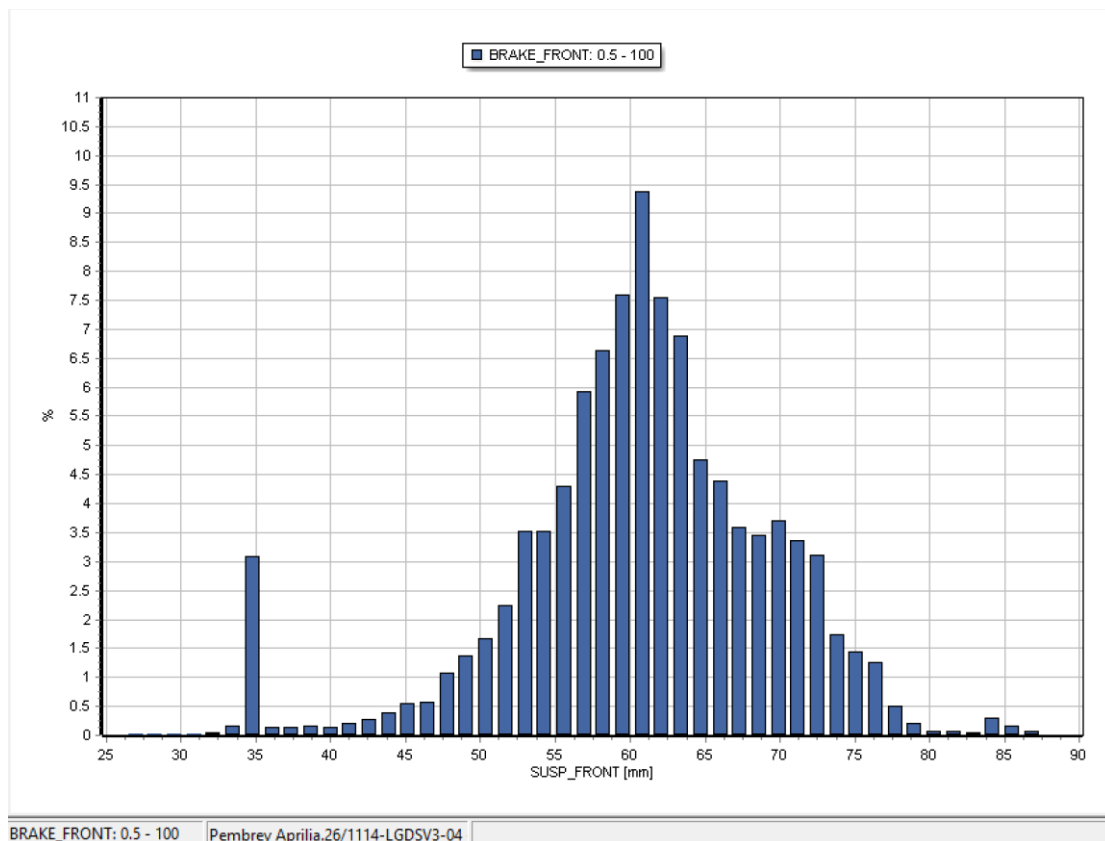


Figure 4.1: Example Histogram of Front Suspension Displacement Under Braking

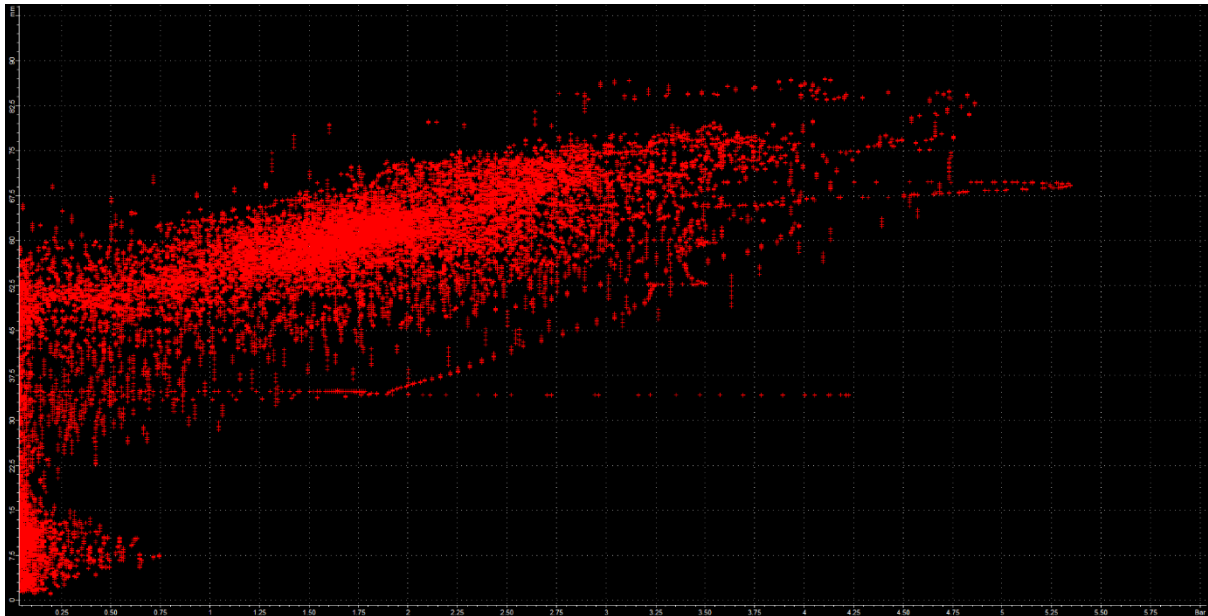


*Figure 4.2: Example Scatter Plot of
Front Suspension Travel vs Brake Pressure*

These graphs and visual aids will enable identification of trends, extremes, and relationships.

4.3 MATLAB Calculations

4.3.1 Baseline Bike

This section will include all notable values produced by the program for the base bike, and will be compared with track test data as validation of system accuracy.

- Theoretical Kinematics (e.g. CofG, camber thrust, trail, etc.)
- Anti-geometry percentages/rates
- Platform stability

4.3.2 Updated Bike

This section will include all final designs with their individual characteristics, as well as a full system analysis which will return key values in a dataset like that taken from the baseline bike but with all updated values.

- Front linkage design
- Rear linkage design

- Joint system design
- Theoretical Kinematics (e.g. CofG, camber thrust, trail, etc.)
- Anti-geometry percentages/rates
- Platform stability

If validation of the model with real-world data exhibits low error and high precision, then the simulated data values for the updated system will be more reliable and provide an accurate system representation that can be used for evaluation.

5 Evaluation

5.1 Excepted Outcomes & Impact

The primary outcome of this research report is to produce a working, validated tool for accurately simulating the kinematics of a HCS configured motorcycle. A simulation tool like this would allow for the methodical analysis of both linkage and chassis geometry variations, currently a non-supported area by the available platforms.

This report aims to expand the narrow knowledge base around alternate front-end systems, specifically within the linking of dynamic behaviours in real-world scenarios with theoretical based kinematic design.

Within an industrial context, the planned outcomes of this research would have a direct impact on the continued development of Arc's next, "race-spec" bike. The potential reduction in R&D time by enabling the analysis and realisation of design modification effects, before any physical component/system is implemented, would vastly increase development efficiency.

5.2 Success Criteria & Validation

The research's successfulness will be determined on the precision of correlation between the track gathered datasets and that of the program's simulated values. Brake-pitch behaviours, suspension travel and other critical parameters will be observed and evaluated to ascertain the accuracy of the program.

Further validation will be accomplished through the analysis of the model's reliability in reproducing linkage-driven motion metrics, under-load geometry variance, and other kinematic relationships with the expected results. The project will be deemed successful after demonstrating its ability to consistently produce real-world reflective metrics and behaviours.

5.3 Constraints & Limitations

A possible limitation of this project is the reliance on the logged sensor data from track testing, which might cause issues if not all the required data is logged or is able to be

logged such as the current wheel speed being measured only from the motor speed on the rear. A plan is in place to update this by fitting speed rings to accurately measure directly at the wheel; however, this highlights the inherent limitation of practical testing as it is not always possible to fit more sensors, and current ones can have errors. Where incomplete or inaccurate data can greatly affect the reliability of the validation it provides, extra testing may not be feasible due to time and cost restraints, however, due to other ongoing projects based around the bike, expenditure for track outings is theoretically split over them all making justification less problematic.

This research will take place over the span of approximately 4 months, and as such time constraints could affect the end outcomes as delays and unforeseeable problems arise and subtract from the allotted time. As this research requires the conduction of track testing, scheduling can play a large role in when and how often this can be done, meaning the data gathering, analysis, and implementation stages may all be delayed, depleting remaining time planned for sequential stages. This can be mitigated by ensuring there is always several simultaneous branches of research being conducted allowing for resources to divert and divide amongst paths instead of a complete halt in progression occurring.

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