

University of Wales Trinity Saint David School of Engineering

The Use of Active Toe for Vehicle Dynamics

Research Proposal

Postgraduate Research Methods

Nicholas David Thomas

1702567

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1 Introduction

Suspension has been used in vehicles since the early 17th century initially using just strips of leather to absorb bumps in the road on horse drawn carriages (Landau, 1912). This then developed into metal springs which then naturally were then adapted for early motor cars (Daimler, 2009). This was then improved with the use of dampers to control the body of the vehicle and making sure that the tyre contact patch was being best used, initially with friction units and then fluid for better control (Monroe, n.d.). Especially in racing the steering geometry can make a large effect on the overall lap time of the vehicle. Poor steering geometry can cause unstable handling for the driver which can cause the driver to lose confidence in the car.

In recent years there has been an increase in active chassis control systems in road vehicles. These vary from rear wheel steering (RWS) to active dampers to change with the roll of the body (Sorniotti, et al., 2006). These have become possible with the improvement in technology which makes the system quick enough to change with the road conditions.

The author proposes to create a system that is able to control the toe during its travel to optimise the grip of the vehicle and therefore improve the handling. In doing this it is also possible to control the individual wheels to change the Ackerman steering angle. The toe of the vehicle is how much the wheels turn in or out of the car when viewed from above. The Ackerman steering angle is the difference in turning angle between the inner and outer wheel (Seward, 2014). The benefits of controlling the toe and Ackerman angle are that it can control how much the tyre is slipping and therefore the amount of lateral force the tyre is producing.

The aims of the project would be to create a control algorithm that when applied could control the toe of a car. To do this a number of objectives could be set such as:

- Create a vehicle model
- Create Test Scenarios
- Create control algorithm for the active adjustment of toe of front wheels
- Simulate model with and without systems to evaluate improvements.

2 Project Relevance

Active chassis control has been used in an automotive sense for almost 40 years since the mid 1980's. Since then, the technology has developed immensely and can come as an optional extra in many different car brands. This has become even more important in the current trend of big heavy SUV's (Voelk, 2020). From the high centre of gravity this can lead to the vehicles rolling over if performing quick manoeuvres. But with the increase of active chassis control this issue has decreased massively. With the relative death rate of SUV drivers decreasing fairly consistently since the higher prominence in technology such as electronic stability control (ESC) and active dynamics systems (Insurance Institute for Highway Safety, 2019). Not only do these systems improve the safety but in performance vehicles they can also improve the handling. This makes sure that the car is at its peak operating window in terms of slip angle of the tyres. Also gaining the correct yaw rate for a given hand wheel input (Aripin, et al., 2014).

The approach to active stability varies on brands and price points. From the cheapest cars since 2014 newly registered cars have to have ESC under EU law (Bowyer, 2009). In a higher price bracket, there is active antiroll devices which is an electromechanically controlled antiroll bar providing up to 1200Nm of torque on each axle (Visnic, 2020). With an even higher price there are a lot more different option. With examples of torque vectoring whether that is through brakes or an active differential (Driver Side, 2015) to active steering systems such as rear wheel steering (RWS) or variable gearing on the steering column (Koehn & Eckrich, 2004). There are also adaptable dampers to change the ride height and damping properties to the road conditions or setup option (Crosse, 2020). This has also been taken to the extreme in motorsports cases with the Williams FW14B that could change the ride height automatically going around the track so that it was in the optimal position for aerodynamics (Autosport, 2017). In more recent times there have been investigations into active toe systems to improve handling. The possibilities of this are that it cannot only improve handling but can decrease fuel usage and decrease tyre wear (Hatton, 2020). With people expecting more and more technology in their cars active systems like these can become the differentiator between models. It may also reduce CO2 emissions and make the vehicles safer.

3 Literature Review

3.1 Steering Geometry

There are a number of different steering geometries which can be put into two groups, either parallel or Ackerman steering. Parallel is simply when the two wheels move the same amount for a given input angle from the hand wheel. An Ackerman setup is when one wheel moves more than the other (Seward, 2014). A Pro-Ackerman system is when the inner wheel is steered at a greater angle than the outer wheel. This enables the inner wheel to go around the tighter radius of the inner part of the arc. This allows the tyres to roll purely without lateral slip when at low speeds when centrifugal forces are negligible (Wong, 2001). For a normal road car this is ideal as this prevents the tyres scrubbing when going around tight corners inducing early tyre wear. When in true Ackerman the steer angles of each wheel should satisfy the equations below:

$$\delta_o = \frac{L}{\left(R + \frac{t}{2}\right)}$$

Equation 1-Ackerman Steering Angle for Outside Wheel (College of Engineering, n.d.)

$$\delta_i = \frac{L}{\left(R - \frac{t}{2}\right)}$$

Equation 2-Ackerman Steering Angle for Inside Wheel (College of Engineering, n.d.)

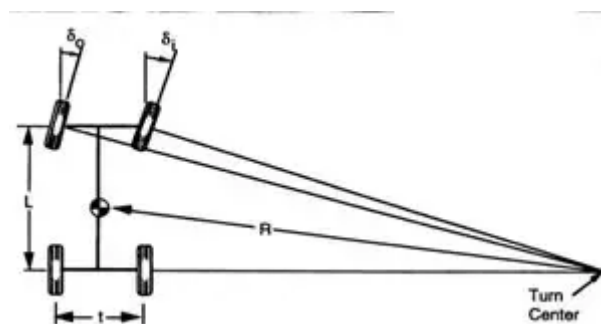


Figure 1-Ackerman Steering Angle Diagram (N.Jazer, 2007)

Where δ_i being the steer angle of the inner wheel, δ_o being the steer angle of the outer wheel, L being the wheelbase, t the vehicle track and R being the common turn centre. This is allowed by using a four-bar steering mechanism. This can also be known as kinematic steering condition. This does not have a huge effect on high-speed cornering but a large influence on self-centring torque during slow corners. Furthermore, the resistive steering torque grows consistently with the hand wheel angle (Gillespie, 1992).

It can also be beneficial to use an anti or reverse Ackerman geometry. This is when the inner wheels angle is less than that of the outer wheel. This is more of a benefit for higher speeds when the vehicle has weight transfer to the outer wheel. This cause the front outer wheel to be loaded more than the inner front so a normal Ackerman set up could cause the inside front wheel to skip across the road as it goes over its allowable slip angle. This has caused some race car designers to use an anti-Ackerman system. This does however make the vehicle very difficult to steer as the amount of force needed to go through the hand wheel is far greater (Smith, 1978). As this is a system proposed for a racing vehicle it is advised to have either a parallel system or a slight anti Ackerman (Milliken & Milliken, 1995).

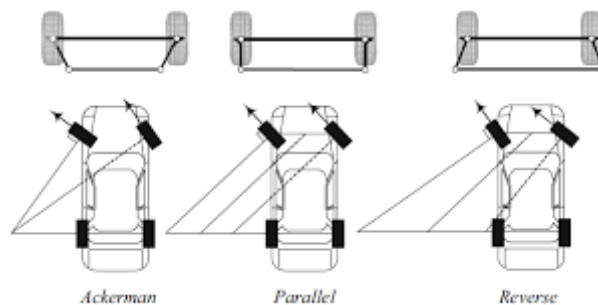


Figure 2-Different Types of Ackermann Steering Geometry (N.Jazer, 2007)

Another factor of steering which was mentioned previously is the toe. The toe of the vehicle is how much the wheels of the car are angles from the centre of the vehicle. Toe is generally described as toe in or toe out. Toe out is when the leading edge of the front wheels turn outwards (right) and toe in is when they are point inwards (left) (Smith, 2019).

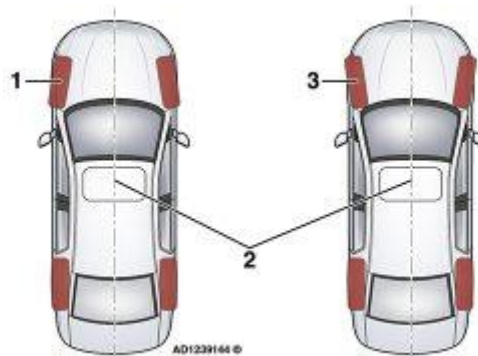


Figure 3-Toe of a Vehicle (Smith, 2019)

The effects of toe will vary from car to car but in general any toe will slow the vehicle down in a straight line as it causes the tyres to have extra drag from the slip angle being caused. As this occurs this will also increase the temperature of the tyres so for a vehicle that struggles to get the tyres to the correct operating conditions this can be a benefit. If the front wheels are toed out this will increase turn in response and help reduce understeer. This is good on tight technical circuits as the car can have a better initial turn in. However, in a faster pace

scenario this can cause the car to become unstable as any slight turn in the hand wheel will have a larger initial effect (Scott, 2018).

Bump steer will also have effect on the toe of the vehicle. This is the bumps in the road to cause the vehicle to steer slightly which can give an unwanted error and, in the extreme, can cause vehicle to be unstable with poor handling (Kulkarni, et al., 2016). This can also occur under braking as the force of the brakes applies a torque about the front axle. However, this only occurs in certain suspension layouts (Upadhyay, et al., 2008). These in turn have an effect on the toe of the vehicle at any given moment from the wheels going through its travel and changing the toe of the vehicle. By having active system this could be cancelled out so that there is limited bump steer, and the vehicles stability will be increased (Lee, et al., 2005).

3.2 Current Active Systems

There are currently a number of active steering systems available, mainly for road cars. These vary on the methods in which they actuate, and the wheels they act upon. One such example is the Nissan 4-wheel active steering system. This works by having actuators on the front and rear wheels which can control the amount the car is steering around a corner when at high speed. It also has the added benefit of reducing the driver's hand wheel torque needed at low speed. The system does this by steering the rear wheels by up to ± 0.5 degrees initially and then increasing over time (Nissan, n.d.). This is activated by actuators which adjust depending on the input from the steering wheel which can be seen below in figure 4. However, unless this is a system on a production car (such as the Nissan) it is not allowed to be added to race vehicle according to the (MSA, 2019) as no rear wheel steering is to be put on postproduction.

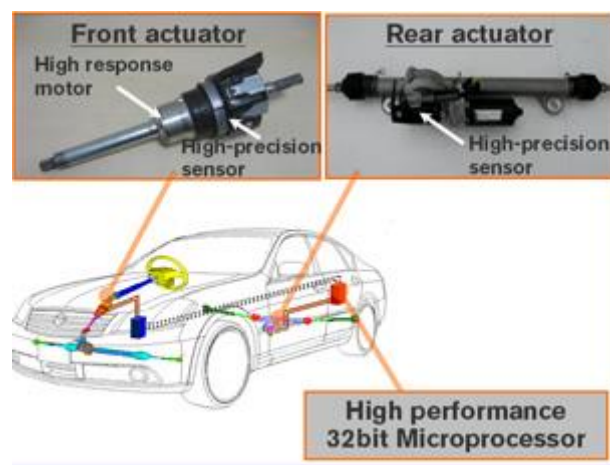


Figure 4-Nissan 4ws system (Nissan, n.d.)

There have also been attempts to apply a similar system to race vehicles such as (O'Kane & Timoney, 2004). They used an algorithm for a speed-dependent four-wheel steering system for a Formula Student SAE car. This was first started with a linear bicycle model in MATLAB/SIMULINK which was then developed using Dynamic Analysis and Design System (DADS) into a 3D model. The 3D model included weight transfer and the non-linearity of tyres. They found that the linear model was useful when developing the algorithm as it is much simpler and was effective in the non-linear region of vehicle dynamics.

Another system is a BMW approach which is essentially a power assisted steering rack with a double planetary system in the column. This is capable of effectively changing the steering ratio and sometimes steer independently of the driver. This allows the ECU to change the steering response to help the driver regain control in critical situations such as when breaking traction. This is a fairly safe system as if there were a failure in the actuators there is still the mechanical system in place just without the system working (Koehn & Eckrich, 2004). This will be a key part in designing a system as it needs to be safe, so if there is a systems failure the driver can still have some control over the steering of the vehicle.

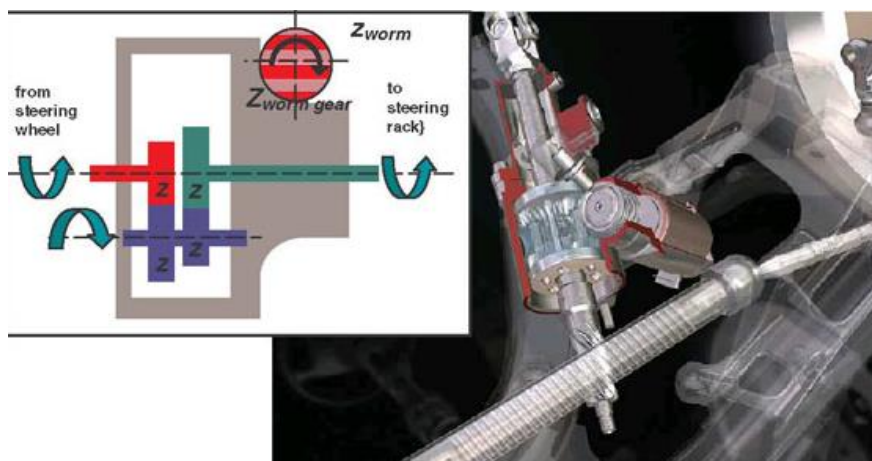


Figure 5-BMW Active Steering System (Koehn & Eckrich, 2004)

Furthermore, most recently there has been a system which has been proposed by (Doftek, 2018) where it can control camber, castor and toe whilst moving so that the correct setup is always being made. This uses electromechanical system which changes the location of the suspension strut for a given case. Doftek claims that this reduces fuel consumption, decreased tyre wear and improved handling. If the system is quick enough this is logical, as when in a straight line there can be zero toe so there is not the added drag of the tyres and then when in the corners the camber, toe and castor can be adapted to maximise the contact patch.

From what the author can find most systems are not speed dependent but more wheel travel dependent. (Kavitha, et al., 2018) suggests that using telescopic tie rods the system can

change the angle in real time using a proportional integral derivative (PID) controller which will change the length of the steering arm so that the toe angle will be at the correct angle for that loading case. This uses accelerometers to decide on the wheels travel at that point.

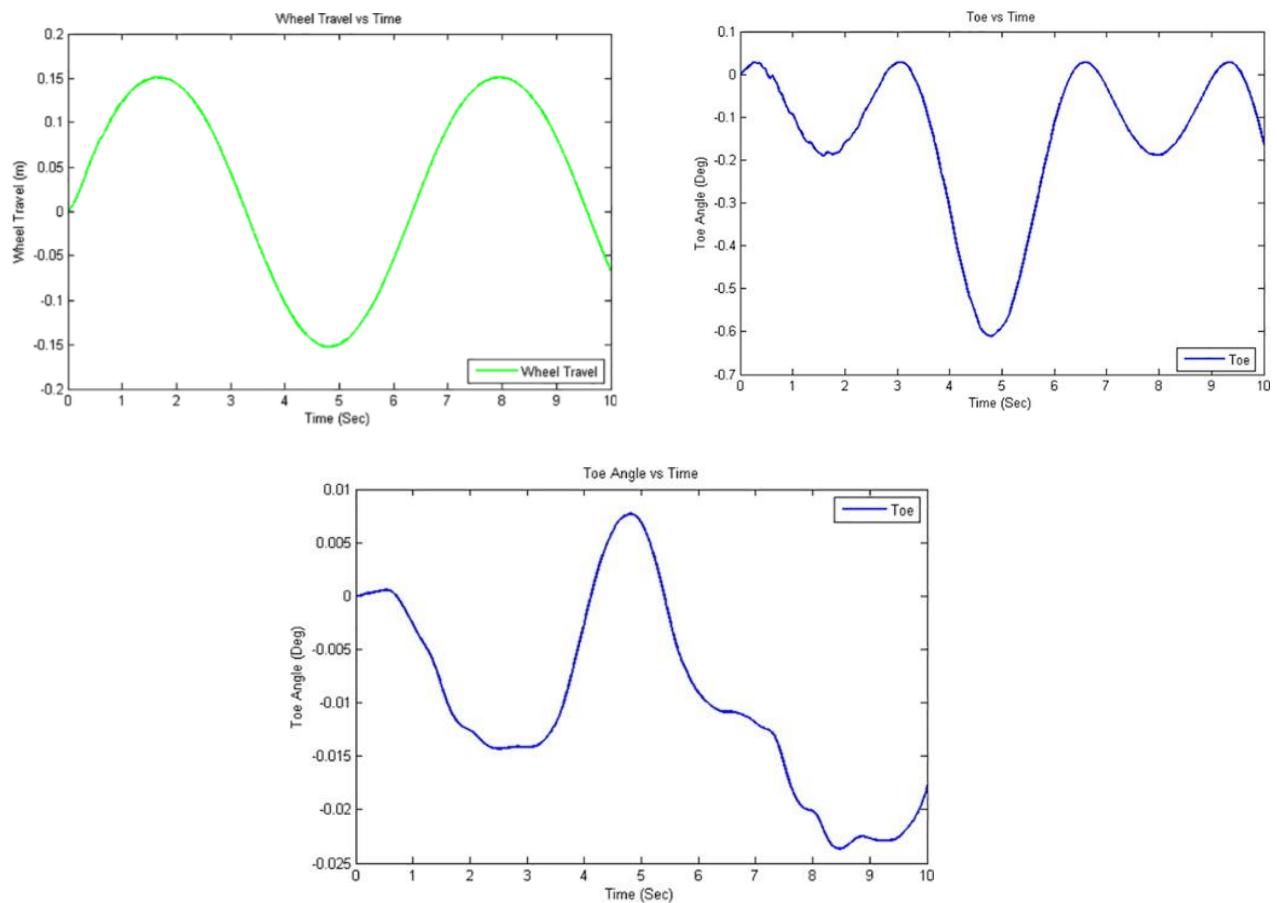


Figure 6-Effects on Toe Angle with an Active System Employed (Kavitha, et al., 2018)

3.3 Vehicle Simulation

Vehicle simulation can be split into two main categories of in and out the loop. In the loop means that a driver is in control of the vehicle and out is when the driver inputs are decided by the computer, each have their benefits. In the loop has the benefit of having real driver feedback so that the handling can be 'felt' by the driver. It is also a great training tool as the driver can get a real sense for a track without having to run a vehicle therefore saving money. However, the short comings of in the loop is where out the loop has its benefits in that out the loop has repeatability. This can make data gathering much easier as the inputs are the same every time so there are less variables to worry about. Out the loop has the option of running setup changes much quicker as it is instant rather than the driver having to go out and then feel the changes of the vehicle. Moreover, all simulation is better than real world as the time and money to perform a test day with setup changes are significantly reduced. But it does have inaccuracies which will skew the results from the actual car (Winter, et al., 2012).

3.3.1 Bicycle Model-2/3degree

A popular model to start with is the bicycle model. This is picturing the car with only one front and one rear wheel and considers longitudinal, lateral and yaw motion assuming no weight transfer (University of Buffalo, n.d.). There are two variations of this with 2 and 3 degrees of freedom. 2 degree only considers lateral and yaw motions where 3 included longitudinal motion also (Ramanata, 1998). This is a very simple method of simulation which is a good start to modelling steering systems.

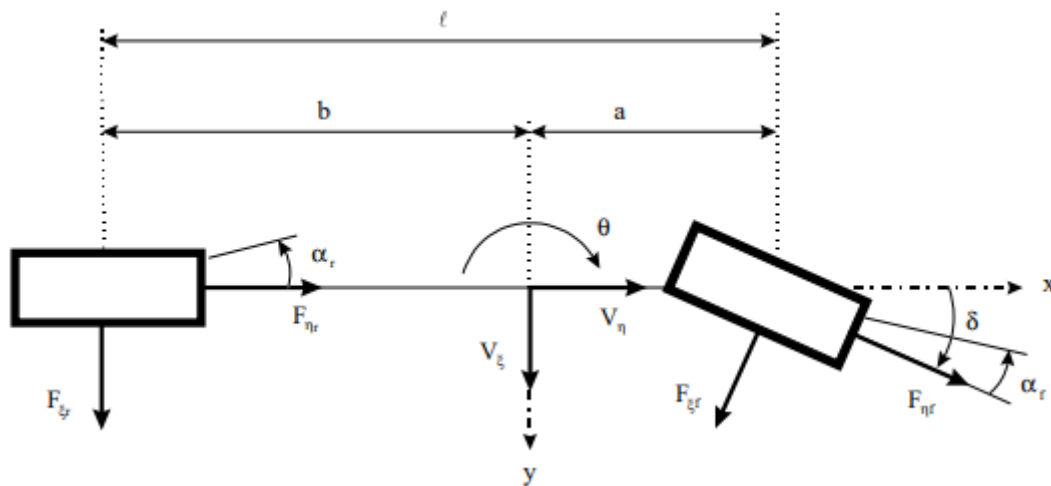


Figure 7-Bicycle Model (Ramanata, 1998)

3.3.2 SMD Model

Another model which is used within vehicle dynamics is Spring Mass Damper (SMD) model. This represents parts of the vehicle with point masses suspended on springs and dampers. This can be developed from 1 degree of freedom (Bereteu & Perescu, 2015) (1 mass and 1 spring and damper) all the way to 10 degrees of freedom to model a full vehicle (Sharma, et al., 2016). Although the author would argue that for the purposes of the project that 7 degrees would be ample. The springs and dampers closest to the ground represent the tyres then the mass above that the unsprung mass of the vehicle. Then above that the springs and dampers represent the physical springs and damper of the vehicle then the vehicles sprung mass (Blundell & Harty, 2015). This is good at representing basic vehicle handling but has its limits as it does not change through wheel travel as an actual car would. This issue can be combated with a changing damper rate depending on the velocity of the mass but will not change the wheelbase with the deflection of the suspension.

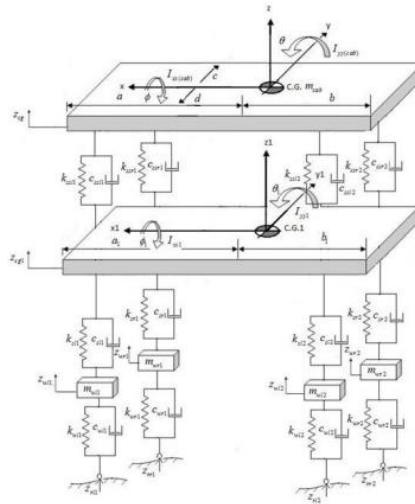


Figure 8-Example of Spring Mass Damper System of Car (Sharma, et al., 2016)

3.3.3 Multibody Simulation

A further detailed method is the multibody simulation. This is more complex than the others so computationally is much more taxing. This can be used to model individual parts and members as fine a detail as down to a door latch if necessary. This works by representing parts as solid bodies which are connected together by joints which restrict their motion. This can not only represent mechanical parts but also the electronic systems which interact with them. It can also have the solid parts with an amount of flex so that they can act as a spring or a damper (MSc Software, 2021). This will be most accurate, but it can be very complex to represent a whole car accurately. To get around this, whole bodies can be simplified so that if they are unnecessary to the simulation, they can be one mass rather than the individual intricacies (Forrister, 2018).

3.4 Control Systems

There are a number of different control systems which are suitable for certain situations. A controller is defined as a designed component that modifies a systems input-output response dynamic (A.Frank, 2018). Controllers can be split into two different structures, closed and open loops. Open loop is when an action of the system is independent of the output. A manual control system would be an example of an open loop system (Electrical4U, 2020). A closed loop will change its input depending on the output. This is often called a feedback system as it is getting information from the output to change the input (X-Engineer, 2021). This makes the closed loop much more complex as it needs more sensors and a more intricate algorithm to perform its task. However, these do have the added benefit of being able to reject disturbances so can get rid of noise. An example of a closed loop controller which is often used in the automotive industry is a PID controller (Dantas, et al., 2018). This is made up of proportional gain, integral gain, differential gain, and PD

controllers (Ellis, 2012). The proportional part improves speed but has a steady state error, integral improves the steady state error but has less stability so can overshoot and derivative improves the stability but is sensitive to noise. That is why they are all connected so that they work together to get the best results possible (Chin, 2009). This controller can be defined by the equation below with K_p , K_I and K_D are controller parameter to be selected. The aim is to have zero error with e being varying types of error and u being the control signal so e.g. steering wheel position (Christiansen, et al., 2005).

$$u = K_p e + K_I \int e + K_D \dot{e}$$

- e (current error)
- $\int e$ (accumulated error)
- $\dot{e}$ (error trend)

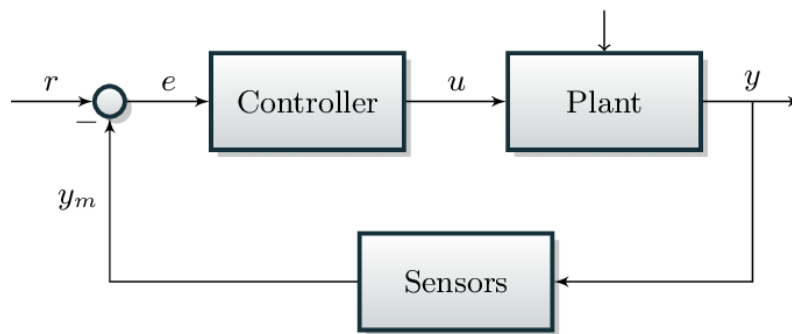


Figure 9-Example of Closed Loop Control System (Quesel, et al., 2016)

Another controller sometimes used is a sliding-mode controller (SMC). This is a non-linear control technique which has good accuracy, easy tuning and easy implementation as well as being robust (Universita' Degli Studi DI Cagliari, n.d.). This system fundamentally forces the system to 'slide' along a cross section of the normal behaviour.

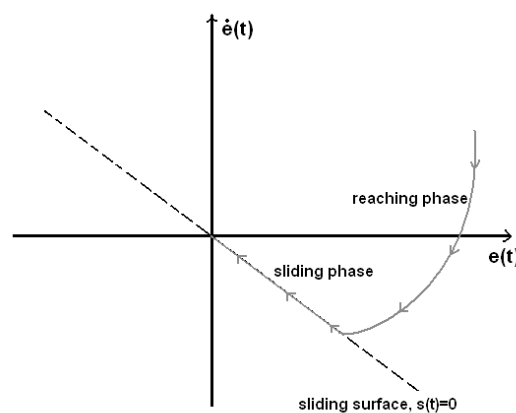


Figure 10-Example of Sliding-mode Control Logic (Ghazali, et al., 2001)

There is also fuzzy logic which is commonly used in some automotive systems (Emam, 2017). This is useful as it uses an analogue signal instead of digital so can have non discrete values. This could be of benefit to a steering system as it can mean that the system can output a steering angle across a map rather than just defined values (Naranjo, et al., 2007). So instead of turning x amount when a certain scenario is encountered it can change x amount depending on y and z input. Often these controllers can be used in conjunction with each other to solve a control a system in order to get the best control possible for a given scenario (Song, 2013).

3.5 Safety and legislation

Depending on which vehicle is finally chosen regulations will vary for safety concerns. For motorsport in the UK the regulations say that active systems are not disallowed but if it is rear wheel steering then it must be on the production car it is based off (MSA, 2019). If a road car is chosen there are few regulations governing active systems. EU law states that vehicles must be made to minimise injury to occupants and road users. Also, the car must be fitted with ABS, ESC and tyre pressure monitors (European Union, 2009). From looking at other manufactures solutions the author suggests a system which is fail safe so that if there was a parts failure then the car could stop without veering off the road (Koehn & Eckrich, 2004).

4 Methods

The author suggests an initial approach of using a multibody simulation. This has the added benefit of reduced cost and time than going straight into prototyping physical parts. The steps to this would first create a suitable vehicle model. Ideally this would then be validated by real data so that the model is known to be accurate. Furthermore, a test road needs to be created. This is so that there is a set of inputs into the model which are repeatable to see the improvements. This could be a generic track or an iso road test such as a double lane change manoeuvre which excites the suspension in a way typical to that of its normal use (Arefnezhad, et al., 2018). This is a good method as it is cheap to create and change. It also has time savings as the vehicle can be setup at a press of a button rather than having to setup a vehicle then run it around a test track.

Whilst that is going on the control system can be designed. But first the desired output to a set of inputs such as yaw response request and wheel travel must be decided upon. Then from this a base control algorithm can be written. In conjunction with this the actual physical parts need to be decided upon so that the type of output can be decided on whether that be an increase in rotation angle or an extension length for example.

Then the model needs to be tested and checked if the desired output is being produced. The previous steps of writing the code and then testing it can be repeated until the desired output has been achieved. Furthermore, a final test could be done to check say the lap time improvement around a track or through a certain section to evaluate the overall improvement from the system. If time and Covid-19 regulations allow perhaps the system could be put into a driver in the loop simulation so that the cars drivability could be investigated.

4.1 Alternative Methods

Instead of using a simulation approach a purely mathematical approach could be taken. (Du, et al., 2018) suggests making an active steering system using a bicycle model from base equations. The author would suggest this is a much more complicated method as there is space for human errors within the calculation. Furthermore, the equations will have a number of simplifications which will have an error associated with them.

Another alternative method could be using the SMD simulation technique mentioned in the literature review. This is a more simplified method but can increase error within the simulation from human calculation or an inaccurate representation of the vehicle. This would have the advantage of being quicker to calculate in the past. However, computing power has got to the point that the difference is between 10 seconds to calculate to 1 minute and for the added accuracy the author believes that the multibody simulation would be the better choice.

Furthermore, (Blundell & Harty, 2015) states that multibody simulation software has become so simple that the author would suggest it would be more complicated to calculate it using any of the other simulation techniques. This is because the simulation is pre-set equations rather than having to write the code from the base up.

5 Results

Most of the data will be qualitative from the output from the simulation results. Before the design process even take place the data from the base vehicle is needed to be compared with real life data and the simulation data. With variables including lap time, maximum lateral and longitudinal forces (Bianco, et al., 2018).

However, some data prior to the design process will be more subjective such as choosing which control strategy will be most suitable. But this could be made qualitative by perhaps modelling the system with a number of different controllers and then finalising the system with the controller which works best. After the design process has taken place variables such as lateral and longitudinal forces, desired and actual path trajectory as well as the error of the control system (Zhao, et al., 2012).

By gaining lateral and longitudinal accelerations a frictional ellipse or G-G diagram can be produced (Derbel & Landry, 2016). This shows force limiting behaviour of the tyres to road interaction. An ideal system should be on the edge of this ellipse so that the grip is being best used. However, (Brach & Brach, 2011) suggests this is a qualitative tool rather than quantitative as this does not represent the true nature of how the tyres react with a non-linearity to slip angle.

6 Timeline

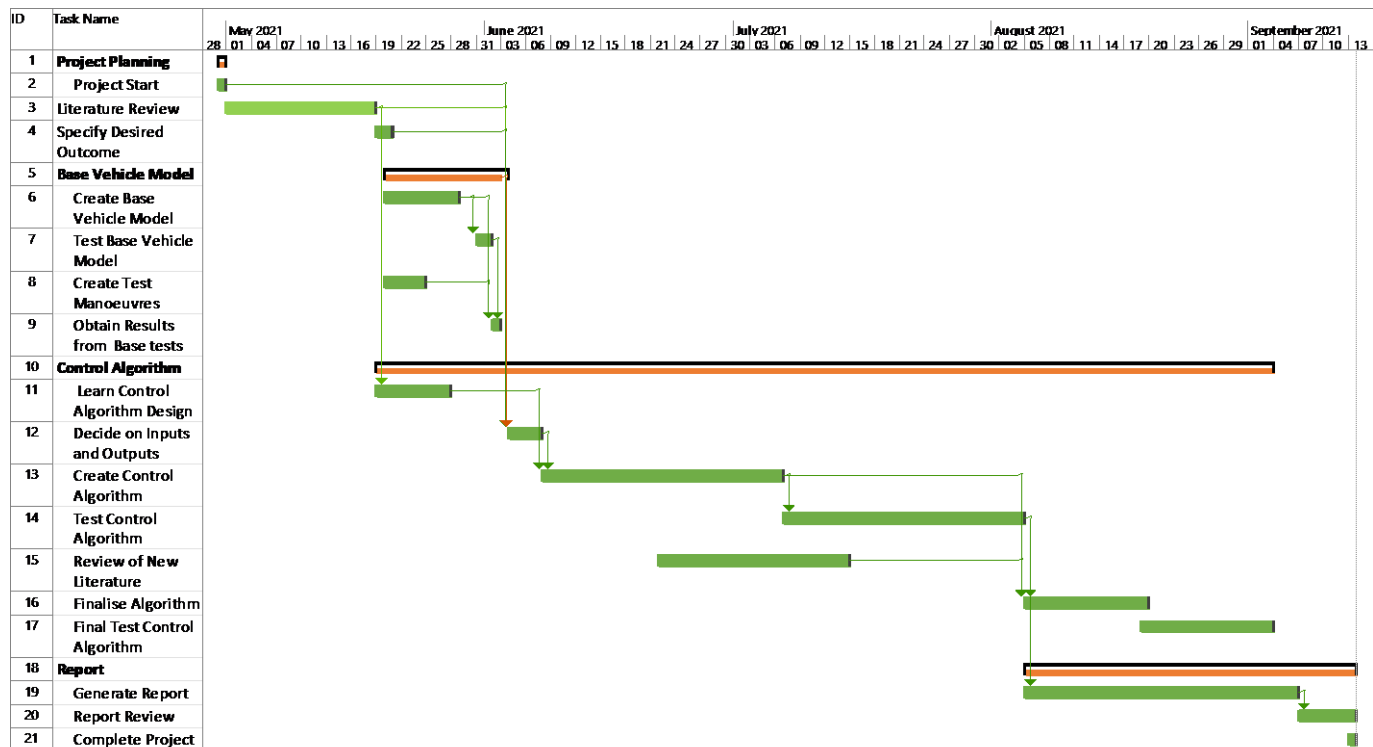


Figure 11-Predicted Timeline of Project

7 Evaluation

The author believes that the proposed research would be a benefit to the subject of automotive and potentially motorsport engineering. Although active steering systems are a relatively new technology the topic is well researched in production road vehicles. By investigating motorsport this adds a new dimension from the need of a quicker response time to the increased speed and loads acting on the system.

Using accurate simulation techniques, it is thought that the system response would be accurate enough to take into physical prototyping. However, without the access to a physical system it is unsure whether the system will be fully accurate. There are also the limitations of changing road conditions as a simulation can only go so far simulating real world conditions. Changing conditions will have an effect on how the system will perform so without that evaluation the quality of the project will be undermined. A further limitation is the accuracy of the simulation. There will always be a small amount of error from real world through the calculation, but it is the belief that these errors are small enough for this stage of the project.

8 References

A.Frank, S., 2018. *Control Theory Tutorial Basic Concepts Illustrated by Software Examples*. Irvine: Springer.

Arefnezhad, S., Ghaffari, A., Khodayari, A. & Nosoudi, S., 2018. Modeling of Double Lane Change Maneuver of Vehicles. *International Journal of Automotive Technology*, Volume 19, pp. 271-279.

Aripin, M. K. et al., 2014. A Review of Active Yaw Control System for Vehicle Handling. *International Journal of Vehicular Technology*, 14 June .

Autosport, 2017. *Patrick Head explains why the 1992 Williams FW14B was great*. [Online] Available at: <https://www.autosport.com/f1/news/patrick-head-explains-why-the-1992-williams-fw14b-was-great-4989593/4989593/?nrt=54> [Accessed 2021].

Bereteu, L. & Perescu, A., 2015. *Quarter Car Suspension System With One Degree Of Freedom Simulated Using Simulink*. Timisoara, DE Gruyter.

Bianco, N. D., Lot, R. & Gadola, M., 2018. Minimum time optimal control simulation of a GP2 race car. *Journal of Automobile Engineering*, 232(9), pp. 1180-1195.

Blundell, M. & Harty, D., 2015. *The Multibody Systems Approach to Vehicle Dynamics*. 2 ed. Coventry: Butterworth-Heinemann.

Bowyer, N., 2009. *New EC Regulation on General Safety..* [Online] Available at: <http://www.interregs.com/spotlight.php?id=84>

Brach, R. & Brach, M., 2011. The Tire-Force Ellipse (Friction Ellipse) and Tire Characteristics. *SAE International*.

Chin, D. H., 2009. *Feedback Control System Design*. Cambridge(Massachusetts): s.n.

Christiansen, D., Jurgen, R. & Fink, D., 2005. Control Systems. In: *The Electronics Engineers' Handbook*. s.l.:s.n.

College of Engineering, n.d. *Ackerman? Anti-Ackerman? Or Parallel Steering?*. [Online] Available at: www.racing-car-technology.com.au/Steering Ackerman4.doc

Crosse, J., 2020. *Under the skin: how air suspension helps more than ride qualit*. [Online] Available at: <https://www.autocar.co.uk/car-news/technology/under-skin-how-air-suspension-helps-more-ride-quality> [Accessed 2021].

Daimler, 2009. *History of suspension: from independent to active suspension*. [Online]
Available at:
<https://media.daimler.com/marsMediaSite/en/instance/ko.xhtml?oid=9361881&relId=1001&resultInfoTypeId=175#prevId=9244868>

Dantas, A. D. O. S. et al., 2018. PID Control for Electric Vehicles Subject to Control and Speed Signal Constraints. *Journal of Control Science and Engineering*, 01 August.

Derbel, O. & Landry, R. J., 2016. Driver behavior assessment based on the G-G diagram in the DVE system. *IFAC-PapersOnLine*, 49(11), pp. 89-94.

Doftek, 2018. *Electromechanical devices for controlling vehicle suspension settings*. Australia, Patent No. AU2018208842A.

Driver Side, 2015. *2015 Ferrari FF Base 2dr HB*. [Online]
Available at: <https://www.driverside.com/specs/ferrari-ff-2015-1121883-2966092-0>
[Accessed 17 May 2020].

Du, P.-P., Su, H. & Tang, G.-Y., 2018. Active Return-to-Center Control Based on Torque and. *MDPI*, 14 March.

Electrical4U, 2020. *Control Systems: What Are They? (Open-Loop & Closed-Loop Control System Examples)*. [Online]
Available at: <https://www.electrical4u.com/control-system-closed-loop-open-loop-control-system/>

Ellis, G., 2012. Chapter 6- Four Types of Controllers. In: *Control System Design Guide*. 4th ed. s.l.:Butterworth-Heinemann, pp. 97-119.

Emam, A. S., 2017. Active Vibration Control of Automotive Suspension System using Fuzzy Logic Algorithm. *International Journal of Vehicle Structures & Systems*, 09(2), pp. 77-82.

Escudier, M. & Atkins, T., 2019. *A Dictionary of Mechanical Engineering*. 2nd ed. s.l.:Oxford University Press.

European Union, 2009. REGULATION (EC) No 661/2009 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL. *Official Journal of the European Union*.

Forrister, T., 2018. *Analyzing Vehicle Suspension with Multibody Dynamics Modeling*. [Online]
Available at: <https://uk.comsol.com/blogs/analyzing-vehicle-suspension-with-multibody-dynamics-modeling/>

Ghazali, R., Rahmat, M. & Hashim, A., 2001. Performance Comparison between Sliding Mode Control with PID Sliding Surface and PID Controller for an Electro-hydraulic Positioning System. *International Journal on Advanced Science, Engineering and Information Technology*, 01 January. Volume 1.

Gillespie, T. D., 1992. *Fundamentals of Vehicle Dynamics*. s.l.:Society of Automotive Engineers, Inc.

Hatton, G., 2020. *How the Mercedes DAS system works*. [Online]
Available at: <https://www.racecar-engineering.com/articles/mercedes-w11-steering-wheel/>

Hillier, V. & Coombes, P., 2004. *Hillier's Fundamentals of Motor Vehicle Technology*. 5th ed. Cheltenham: Nelson Thornes Ltd.

Insurance Institute for Highway Safety, 2019. *SUVs no longer pose outside risk to car occupants, but pickup compatibility lags*, s.l.: s.n.

Kavitha, C. et al., 2018. *Active camber and toe control strategy for the double wishbone suspension system*, s.l.: s.n.

Koehn, P. & Eckrich, M., 2004. *Active Steering - The BMW Approach Towards Modern Steering Technology*, s.l.: s.n.

Kulkarni, U., Gowada, M. M. & Venna, H. K., 2016. *Effect of Tie Rod Length Variation on Bump Steer*, Bengaluru: SAE International.

Lamy, C. & Basset, M., 2010. A vision-based approach to wheel camber angle and tyre loaded. *Sensors and Actuators A: Physical*, 161(1-2), pp. 134-142.

Landau, D., 1912. *Leaf Springs Their Characteristics and Methods of Specification*. Wilkes-Barre(Pennsylvania): s.n.

Lee, S., Sung, H. & Lee, U., 2005. *The Development of Active Geometry Control Suspension (AGCS) System*, s.l.: SAE International.

Milliken, W. F. & Milliken, D. L., 1995. *Race Car Vehicle Dynamics*. s.l.:SAE International.

Monroe, n.d. *History of Shock Absorbers*. [Online]
Available at: <https://www.monroe.com.au/trade-corner/tech-info/suspension-systems/history-of-shock-absorbers.html>

MSA, 2019. *MSA Yearbook 2020*. s.l.:s.n.

MSc Software, 2021. *Multibody Dynamics*. [Online]
Available at: <https://www.mscsoftware.com/application/multibody-dynamics>

- N.Jazer, R., 2007. *Vehicle Dynamics Theory and Application*. s.l.:s.n.
- Naranjo, J., Gonzalez, C., Garcia, R. & Pedro, T. d., 2007. *Using Fuzzy Logic in Automated Vehicle Control*. s.l.:IEEE.
- Nissan, n.d. *4 Wheel Active Steer*. [Online]
Available at: <https://www.nissan-global.com/EN/TECHNOLOGY/OVERVIEW/4was.html>
- O'Kane, C. & Timoney, S., 2004. *Investigation of Four-wheel Steering Algorithms for a Formula SAE Car*, Dublin: SAE International.
- Park, S.-J. & Sohn, J.-H., 2012. Effects of camber angle control of front suspension on vehicle dynamic behaviors. *Journal of Mechanical Science and Technology*, 26(2), pp. 307-313.
- Quesel, J.-D., Mitsch, S., Loos, S. & Platzer, A., 2016. How to model and prove hybrid systems with KeYmaera: a tutorial on safety. *International Journal on Software Tools for Technology Transfer*, Volume 18.
- Ramanata, P., 1998. *Vehicle Dynamics Modeling*. [Online]
Available at: <https://vtechworks.lib.vt.edu/bitstream/handle/10919/36615/Chapter2a.pdf>
- Scott, W., 2018. *SUSPENSION SECRETS – HOW TO TUNE TOE SETTINGS*. [Online]
Available at: <https://brscc.co.uk/suspension-secrets-how-to-tune-toe-settings/>
- Seward, D., 2014. *Race Car Design*. 1st ed. Lancaster(Lancashire): CPI Group (UK).
- Sharma, S., Pare, V., Chouksey, M. & Rawal, B., 2016. *Numerical studies using full car model for combined primary and*. Indore, Elsevier.
- Smith, C., 1978. *Tune to Win*. s.l.:s.n.
- Smith, M., 2019. *The necessities of steering geometry*. [Online]
Available at: <https://autotechnician.co.uk/the-necessities-of-steering-geometry/>
- Song, J., 2013. Design and Comparison of AFS Controllers with PID,. *Advances in Mechanical Engineering*, Volume 2013, p. 13.
- Sorniotti, A., Morgando, A. & Velardocchia, M., 2006. *Active Roll Control (ARC): System Design and Hardware-Inthe-Loop Test Bench*, Turin: s.n.
- Universita' Degli Studi DI Cagliari, n.d. *A QUICK INTRODUCTION TO SLIDING MODE*. s.l.:s.n.

University of Buffalo, n.d. *Bicycle Model*. [Online]

Available at: <http://code.eng.buffalo.edu/dat/sites/model/bicycle.html>

Upadhyay, V. A., Gopalakrishma, K. & Kshirsagar, A. R., 2008. *A Simple, Cost Effective, Method of Evaluating Bump Steer and Brake Steer, and Achieving Correlation with ADAMS Analysis*, s.l.: SAE International.

Visnic, B., 2020. *Active roll stabilization introduced for Audi's large crossovers*. [Online]

Available at: <https://www.sae.org/news/2020/09/audi-active-roll-stabilization>

Voelk, T., 2020. Rise of S.U.V.s: Leaving Cars in Their Dust, With No Signs of Slowing. *The New York Times*, 21 May.

Winter, J. d., Leeuwen, P. v. & Happee, R., 2012. *Advantages and Disadvantages of Driving Simulators: A Discussion*, Delft: s.n.

Wong, J. Y., 2001. *Theory of Ground Vehicle*. 3rd ed. Ottawa: John Wiley & Sons.

X-Engineer, 2021. *Open loop vs. closed loop control systems (with Xcos simulations)*.

[Online]

Available at: <https://x-engineer.org/graduate-engineering/signals-systems/control-systems/open-loop-vs-closed-loop-control-systems-xcos/>

Zhao, P. et al., 2012. Design of a Control System. *International Journal of Advanced Robotic Systems*, 10 May.

9 Appendix

9.1 Camber

Camber is the angle of the wheels central plane and the roads perpendicular plane. Camber is seen as being negative when the top of the wheel leans inside of the body and positive when it leans away from the body of the car (Lamy & Basset, 2010). The reason for camber is to use the tyre to its potential, optimising the contact patch when going around the corner and the body leaning (Park & Sohn, 2012). Generally, this means the camber is negative to counteract the lean angle of the car at an angle if around -1° (Seward, 2014).

9.2 Castor Angle

Castor angle is kingpin inclination of the wheel hub when viewed along the axis of the steered wheels (Escudier & Atkins, 2019). This causes a self-aligning torque which gives the driver a 'feel' for the car going in a straight line. Too much castor can cause the steering to become difficult but too little and it can make the steering feel if its wandering. This angle is generally between 2° to 5° (Hillier & Coombes, 2004).