VARIATION OF WHEEL ALIGNMENT UNDER DIFFERENT LOAD CONDITIONS WITH A COMPARISON TO KINEMATICS AND COMPLIANCE TEST DATA

by

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ABSTRACT

SAGAR PARADKAR. Variation of wheel alignment under different load conditions with a comparison to kinematics and compliance test data
(Under the direction of Dr. PETER TKACIK)

Passenger car suspension and wheel angles have a strong influence on ride, handling, and tire wear. These angles are affected by both static vehicle alignment (as done at a wheel alignment shop) and by changes due to vehicle loading while driving. This thesis work evaluates the variability of wheel alignment angles under different load conditions with a large (~500) set of measurements. In addition, this data is compared to Kinematics and Compliance test data as done on a professional K&C machine.

To get accurate variability information, large numbers of measurements are required and for these studies, nearly 500 were needed. However, wheel alignment measurements take a considerable amount of time so a study in which large numbers of measurements are needed, starts with a method for streamlining the measurement activities. The approach taken includes the construction of a rig to quickly and reliably raise a vehicle off the ground and place it safely on bearing plates. The system used allowed almost 500 complete wheel alignment measurements including caster sweeps. Unfortunately, the intense workload also wore out the pulley bearings on the modified four post lift and the lift nearly collapsed at around 490 measurements. Fortunately, the lift did not completely collapse and drop the Porsche 911 test vehicle to the ground. It did; however, require a large forklift to raise the car high enough to extract it from the lift.

In addition, a full barrage of Kinematics and Compliance (K&C) test data was gathered at a professional K&C machine at the business, “Morse Measurements”, in Salisbury NC.

Comparisons between the experimental measurements and K&C values of camber, caster, toe, cross-camber, total toe and thrust angle were then made at various load conditions. These revealed a good comparison between the K&C machine and average of experimental values measured statically under varying loads. That is, the various trends in camber and toe as a function of load or suspension displacement (i.e. camber and toe curves) matched between the experiments and K&C test results.

ACKNOWLEDGEMENTS

Firstly, I want to thank my master's thesis advisor Dr. Peter Tkacik for constant support, inspiration and showing confidence in me throughout my journey as a graduate research student under his guidance. I would like to express my gratitude especially for lending out his personal car (Porsche 911 Carrera) for the purpose of performing 500+ wheel alignment measurements.

I would like to thank the members of my defense committee Dr. Jun Xu and Dr. Jerry Dahlberg of spending their valuable time on judging my defense and giving me valuable inputs on my thesis. I also want to thank my colleague Juttenbir Tatla for his passionate contributions and inputs throughout my journey in this thesis.

I would also like to acknowledge Mason Marino who helped me get my frames welded for my measurements. Without the support and continuous encouragement of above-mentioned people my research would not have been possible.

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LIST OF ABBREVIATIONS

LF	Left Front
RF	Right Front
RR	Right Rear
LR	Left Rear
K&C	Kinematics and Compliance
lbs	Pounds
SPMM	Suspension Parameter Measurement Machine

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CHAPTER 1: INTRODUCTION

Vehicle wheel alignment refers to adjustment of vehicle wheel suspension angles to a required specification. These specifications are typically published by manufactures in case of commercially produced vehicles. For racing/motorsports applications, these specifications vary widely depending on application. There are various types of angles included in the suspension geometry that are a part of wheel alignments viz. camber, caster, toe, cross camber, thrust angle, total toe, etc. The proper selection of these angles helps to enhance vehicle handling and reduce tire wear. An optimal setting of the vehicle's alignment is very important for performance and the wear of tires. Amongst all the parameters of the alignments, camber and toe-in are the most important and influencing factors in the performance of the vehicle and tire wear.

Camber angle can be defined as the angle between the vertical axis of the wheel and the vertical axis of the car as viewed from the front. The unit of camber angle is degrees. A positive camber angle setting tilts the top of the tires away from the car as compared to the bottom, and a negative setting tilts the bottom of the tires further out as compared to the top. The toe-in angle gives the direction in which the tires are pointed, as seen from the top. There are two ways in which the toe angle can be set, toe-in and toe-out. Toe-in is the one in which the front of the tires is steered inwards as compared to the rear end of the tires as seen from the top (a pigeon-toed person would have toe-in). Toe out is the case where the front of the tires is tilted outwards as compared to the rear, as seen from the top. Typically, measurements are for toe-in and referred to as toe angle. Toe-out is typically referred to as negative toe. Toe angle setting is the most crucial for the tire wear.

There are various factors that can cause problems in the wheel alignment setting. When we drive the car, we want our steering wheel to align with the wheels for a good maneuverability. There are three common ways in which the wheels could get misaligned, they are, suspension damage, wearing of parts such as bushings and ball joints, and height change due to old and sagging springs. Impact is the most frequent way in which the wheel alignment goes bad. For example, going fast over a bump, meeting with an accident, hitting the sidewalk or driving over it, etc. Wheel alignments are also affected due to wearing of the parts such as suspension or king pin.

The kinematics or geometry of typical automobile suspensions have increasingly negative camber on jounce to help keep tires vertical while leaning on turns. One result is that if the suspension springs are worn out and sagging, the wheels will lean in with greater negative camber (or less positive). If adjustable, changing ride height will also influence camber. Some manufacturers such as Mazda Miata and Mini Cooper, specify camber angles as a function of ride height (or wheel center to fender lip dimension). Wheel alignment measurement and adjustment can be an extremely time-consuming process, but it is necessary in order to get optimal handling and wear performance out of the vehicle.

This research is done in three parts. Part one being, figuring out a way to significantly reduce the time required to measure multiple wheel alignment. There is a two-post setup in my lab on which wheel alignment measurements were being carried out. Since it was time consuming, the car was moved to a four-post for measurements with some modifications attached to the car and the four post. This significantly reduced the measurement time for multiple iterations. Part two of this research was collecting wheel alignment data. More than 500-wheel alignment measurements were made over summer

2018. This included various cases of loading the vehicle at different positions with various magnitudes of weight. A caster sweep was performed 30 times for a given weight and position. The third part of the research is the analysis of the data collected from the caster sweeps. In the analysis there are two things that were studied. Jutten Tatla analyzed the standard deviation of wheel alignment parameters as a function of loading of weight. I analyzed the variation in camber, caster and toe as a function of load magnitude and position. These results are compared to the Kinematics and Compliance Testing done in Morse Measurement with the experimental results and the comparison is used for validation.

CHAPTER 2: REVIEW OF IMPORTANT TOPICS

In this research I have compared my experimental data to the Kinematics and Compliance Test data obtained in the Morse Measurement, Salisbury, NC. K&C testing is the quasi-static simulation of on-road vehicle behavior by applying loads and displacements to a vehicle chassis and suspension, and simultaneously measuring suspension response through the wheel orientations and load variations. The K & C tests were performed on SPMM (Suspension Parameter Measurement Machine).

FIGURE 2. 1 SPMM Machine [4]

The Standard SPMM consist of four main parts. The central roll-pitch-bounce table, four wheel-stations, the measurement system and a data collection software. When the vehicle is loaded on to the machine, the wheel stations are automatically centered to the center of wheel and the vehicle is clamped to the chassis. The vehicle is then subjected to a variety of forces and displacements. It then measures kinematic, steering, suspension geometry and compliance due to springs, anti-roll bars and deformations. It is driven entirely by electric motors, it doesn't have any hydraulics, thus its less noisy and no leaking components.

In SPMM the car body is clamped to the central table of the machine that can move or simulate bounce, pitch and roll motion. A wide variety of measurements can be taken from the machine. There are precision digital encoders and load cells that always measure tire loads and wheel orientations, wheel deflections are also measured. For compliance testing the wheel pads can also be moved longitudinally or laterally. These wheel pads can maintain zero scrub force, or they can introduce ground level forces to simulate braking, acceleration and cornering loads at the tire contact patches. Steering system compliance can be measured by applying torque at the wheel pads. Alternatively, the steering can be driven using a motor drive that simulates driver inputs. Moment of inertia tests can also be performed at these machines. This is done by exciting the vehicle in roll, pitch and yaw motion. The software is used to analyze the measurements and produces matrix of moment of inertia and the position of the center of gravity. The machine has six degrees of freedom.

The Kinematics part in K & C is the suspension geometry and the compliance is suspension stiffness. Thus, a K&C testing analyzes a vehicle's suspension through the measurement of suspension geometry (kinematics) and suspension stiffness (compliance). The K&C testing is not 'dynamic' testing. It is quasi-static, which is very close to vehicle dynamics. All the forces and displacements are applied to the system very slowly to calculate the relationship between the suspension force-displacement system and friction. The measurements are very repeatable and thus using this test can reduce a lot of speculations and costs associated with the road tests.

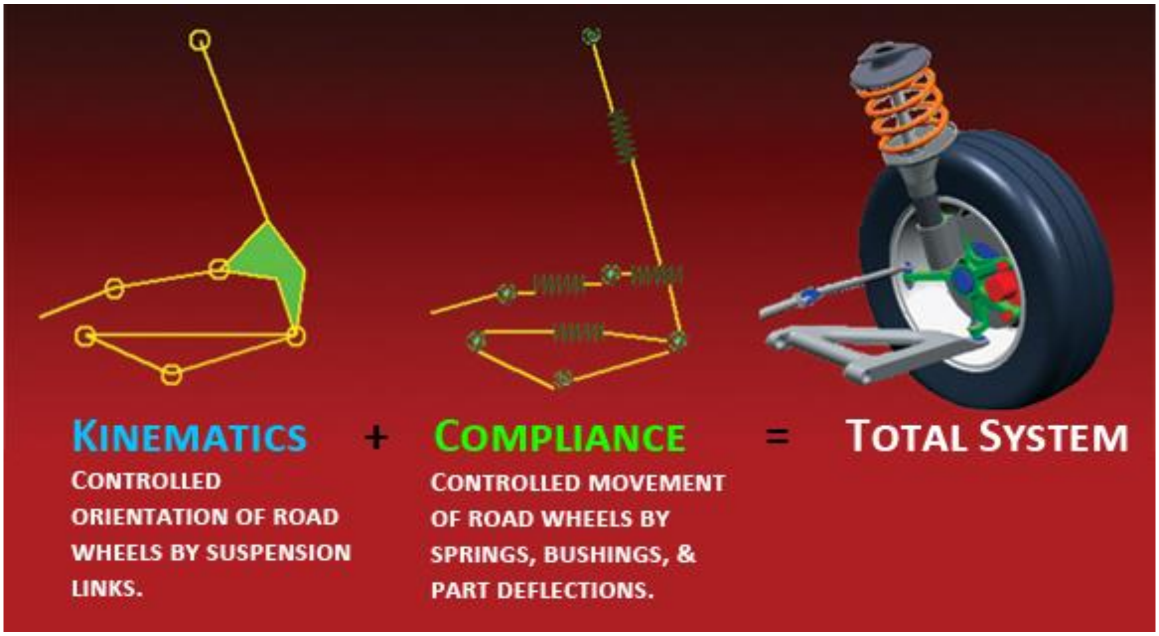


FIGURE 2. 2. K & C difference [4]

The tests that can be performed on the K&C test rig are

1. Kinematics Test
   a. Bounce and Pitch test
   b. Roll test
   c. Steering test
2. Compliance Test
   a. Lateral test
   b. Longitudinal test
   c. Aligning torque
3. Simulation Tests
   a. Cornering test
   b. Braking test
   c. Traction test

d. Track Simulation test

In the paper ‘Suspension Variable Influencing Static Vehicle Wheel Alignment Measurements’, Harsh Patel et al. talk about an effort that aims to study the influences of various factors on the accuracy and repeatability of the wheel alignments It also looks at the trends of the wheel alignment measurements due to the given factors. This includes the influences of suspension design, tire pressure, static wheel alignment settings, etc. They have used the same1 equipment as I have used in my project to measure wheel alignments. This data is collected on ten vehicles including, SUVs, sports cars, and racecars and analysis of 304 caster sweeps is done. Harsh Patel et al. found an interesting relation of wheel alignments and tire pressure. He carried out measurements with diagonal tires deflated and one tire deflated. He found that a single tire pressure error has a greater impact on the alignment measurements than two diagonal tires deflated.

He formed some measurements introducing wedge effects on one or more than one tires at a time. It was found that for accuracy of camber and toe measurements it’s important that the bearing plates are at the same level and coplanar. Some of the other important results that were mentioned in this paper are that wheel alignment measurements are quite repeatable as the measurements were carried out over a span of fourteen months and very little change was recorded in the readings. The repeatability of the measurements is not strongly affected by softness of the suspension. In repeated measurements, it is necessary to ensure that rear tires are not bound up on the bearing plate bumper. The takeaway from this paper was a list of warnings and tips that I used in my paper to take care of to get good result outputs.

Juttenbir Tatla, in his paper, 'Identifying Load Magnitude and Load Position Influences on Road Vehicle Wheel Alignment Variability' talks about whether the loading of weights on a vehicle affects the variability of the wheel alignment measurements. He has also tried to find some relationship of standard deviation with vehicle loading. Juttenbir and I worked on the same setup and same data to find different trends and results. As we moved from 2-post to 4-post he found that the 4 post is more accurate. He talked about a data manipulation technique in which he used quartiles and outliers. He divided the data into four quartiles and picked only those which falls between 1.5x the interquartile range in both the directions from the median. I found this technique very useful for data filtering, however, I haven't used this in my paper for my data filtration. I found my technique more effective because manual picking is faster. In the mathematical method, the size of the acceptable values changes significantly in each case. We get a small range if the data is close to zero and a big range if the data is far from zero. Furthermore, if we have stepped data use of quartiles do not detect the step. It gives us the results to accept the entire data.

With an initial analysis it seems that the standard deviation increases as the load increase for camber, toe and caster. The excel shows an upward trend for each of the cases when all the data is plotted on a same graph in increasing order of load. This data includes all the loading cases viz. left, right, front and rear load. But when each case is looked upon separately, no trend is found. Or in other words, there is no direct co-relation of the vehicle loads and standard deviation. One additional observation from this paper is that the rear wheels experience more loads due to rear engine placement. The rear suspension experiences more variability because of its suspension geometry. The front suspension has MacPherson Strut suspension and the rear is a multi-link suspension system.

CHAPTER 3: DEVELOPMENT

3.1: Pre-Development of the research

The Pre-Development phase of the research is in Spring 2018 when five cases of load positions were considered and 10 wheel alignment measurements were taken for each case. The main phase of the research included the data collection through the summer and fall of 2018. The entire data collection, test performance and analysis is carried out in the Motorsports Research Lab in UNC Charlotte. The main phase of the thesis included seventeen cases of loading weight at different positions and varying magnitudes. The results of the thesis are based on these seventeen cases.

3.1.a: Equipment used in the experimental procedure

a) Hunter's Pro Align 130 console

b) DSP 700 Alignment Heads

c) Alignment Stands

d) Bearing Plates

e) Porsche 911 Carrera

f) InterComp Wheel Scales

g) 4-post Support Stand

3.1.1: Construction of the 4-post Support Stand (referred as Stand)

This thesis aims at capturing the influence of load magnitude and load position on the wheel alignment parameters such as camber caster and toe. For this purpose, it was necessary to conduct many wheel alignment measurements and collect significant amount of data. My professor and I selected a 1999 Porsche 911 Carrera for data collection. We had a two post in our lab which is used to lower and raise the vehicle in order to perform a wheel alignment. A couple of wheel alignments were carried out and it was found that it's very time consuming to perform multiple measurements on two post. Between each measurement iteration, it is necessary for the vehicle wheels to be lifted off the bearing plate, and then put the vehicle back on the bearing plates to perform the next iteration. The problem with this is that every time the vehicle is put back on the bearing plates, the arms of the two post lose contact with the bottom of the vehicle and thus to lift the vehicle back again. It is necessary to be extra careful to put the arms back in the slots under the car and ensure that the car is not imbalanced on the two post when the vehicle is lifted.

FIGURE 3. 1 Two post

Bearing plates are used when measuring wheel alignments because these plates allow the tires to settle in the most natural positions. These avoid any chance of pre-loading of the wheels: it allows the contact patch to move wherever it needs to, without causing any stresses, twists or slide on the tires.

The alternative to a two post is a four post. On a four post, it's not necessary to worry about the arms resting on the exact place after every measurement since the entire car is on the post runway. This saves a lot of time to perform multiple alignment measurements. However, there's another problem with the four post. There is no way the wheels are lifted off the post during lowering and raising as all the wheels rest on the four post. It is necessary for the wheel to be off the ground between each iteration of the measurement.

FIGURE 3. 2 Four Post

Thus, it was necessary for us to build a structure that will hold the car to make its wheels off the runways. The structure is positioned at the center of the four post. As the car is being lowered the structure will come touch and hold the car while the four post still goes down to the point that the wheels are lifted off the post. To get the car back on the four post, the post is just lifted to the point when the car is lifted off the stand till it completely rested on the four post again. Now, there was another problem with this method. The car has a plastic under body for better aerodynamics and covering up small wiring and other lines. There are no solid contact points on the under body. As the vehicle is lowered to rest on the stand, the bottom of the vehicle could get damaged due to its own weight. Thus, we fixed two 2”x 4” support bars laterally at the bottom of the car. One near the front wheels and the other near the rear wheels. This served as resting structure for the car on the stand. It was easy to clamp these bars at the front as there was a slot for inserting a plate. We welded a nut to the plate and used a bolt to fix the bar to the car. The rear was a bit tricky. There was no slot for inserting any plate, however there was an oblong shaped hole. Thus, we welded an oblong shaped plate to a bolt and used wing nuts to fasten the bars to the bottom of the car. Due to the oblong shape of the hole, we could rotate the plate 90 degrees to fix it.

FIGURE 3. 3 Screw Arrangements for fixing 2”x4” bar

FIGURE 3. 4 Support Stand under the four post

This process is very easy and significantly reduced the time between each iteration. Where it took more than 1 hour to perform 10 measurements on a two post, it takes only 30-35 mins on a four post to perform 10 measurements. The stand used to rest the car is designed by my colleague Jutten Tatla and is made of steel 2”x4” elements for legs and top. Aluminum trusses are used as a support on the sides. Height adjustment screws are used at the bottom of the stand to ensure that all the four ground touch points are in the same plane when the care is rested on the stand. The stand was drawn in AutoCAD software.

Advantages of this this stand are that its length is 70 inches. This meant that the car had more room to shift as it has a very large potential contact area. Thus, we did not have to worry about a small contact area as in case of the 2-post lift. Secondly, as we attached adjustment screws at the bottom of the stand, we could ensure that the car is always levelled when resting on the support stand.

3.1.2: Initial Experimentation Cases

To generate large amounts of data for the analysis of the influence of load on wheel alignments, it's necessary to have a lot of cases of the positions of the weight acting on the car. These cases must include the weight acting on the front of the car, rear of the car, left of the car and right-hand side of the car. Thus, there could be five cases of loading under some constant conditions which initially were not thought of. The simple conditions are

i. Weight of the driver should be the same in each as it is the common factor (using same driver in each case).
ii. It should be ensured that the gas tank is filled to the same level. As the fuel tank of Porsche 911 is about seventeen gallons, it could mean a difference of as much as a difference of about hundred pounds
iii. It should be ensured that the tire pressure in all the wheels must be maintained through all the cases.
iv. It should be ensured that the top of Porsche is always down (it could be up or down, I selected down)

The five cases of load positions for readings in pre-development stage were as follows:

i. Baseline case (only driver- 180 lbs)
ii. Left load case (driver + 1 person at LR seat)
iii. Right load case (driver + 1 person at RF and 1 at RR seat)
iv. Rear load case (driver + 2 people at the back seat)
v. Front load case (driver + 1 person in the front trunk)

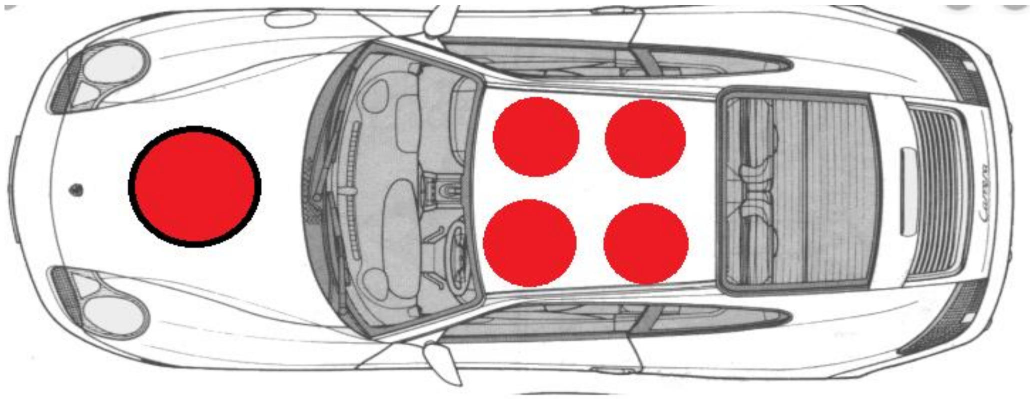


FIGURE 3. 5 Load positions in predevelopment stage

The figure above shows the positions of the loads for the corresponding locations given in the previous paragraph. For each of the load case ten measurements are taken. These measurements consisted of camber, caster and toe measurements for each of the five cases. To get the results, the mean of ten measurements were taken and graphs of camber for each iteration was plotted in the excel. Similar plots were obtained for caster and toe measurements. Standard deviation was also plotted against the load for camber caster and toe. Comparisons were made with K&C testing as well. The results only suggested that, with loading, the camber and toe changes. However, these preliminary tests did not give any trend on how the angles change, or by how much it changes. The K&C comparison results only showed that my data lies near the slop of the K&C data. It did not give any trends either. Greater efforts and research were necessary to come up with substantial conclusions about the variability of the wheel alignment parameters with the load magnitude and position in the Porsche. But through this short project I got an of what my thesis is supposed to be and in what direction should I be headed to get substantial results.

CHAPTER 4: DATA COLLECTION

4.1 Introduction to Data Collection

The project done in the previous stage was an attempt to find the relationship between the measurements and the load positioning. However, due to not keeping the required conditions the same and lack of enough data, the results obtained from the project were inconclusive. Thus, it was established that instead of using actual people as a substance for loading, sandbags should be used to load the vehicle at various positions. This would serve two purposes. 1st purpose was, the dependency on people would be reduced, the experimental procedure would thus require less rescheduling due to unavailability of the subjects. 2nd purpose was that it would be possible to load more weight at the same place, since sandbags can be stacked on top of each other. Thus, each of the five cases in the previous stage could again have multiple subcases. For example, consider the front case in the previous stage. Only one person could barely fit in the front trunk (180 lbs). With sandbags we can have multiple cases at the front position, and we can analyze the effect of the change of load magnitude at a given spot as well. Each sandbag was fifty pounds. Twenty such sandbags were ordered with a combined weight of one thousand pounds. The following are the cases and conditions on which the data was collected. There are 17 different cases in which the data on the wheel alignments is collected.

4.2 Cases and conditions

1. Conditions
    - i. Constant driver (180 lbs)
    - ii. ¾ Gas tank
    - iii. Constant tire pressure

iv. Car top down

v. 50 x 20 lbs sandbags

2. Cases: 3 sets of 10 measurements each in every sub case

i. Base Case

a. 1 person at the driver's seat

ii. Left Load Case

a. Driver + 150 lbs on left side of the car. Load evenly distributed along LF seat and LR seat

b. Driver + 300 lbs on the left side. Load evenly distributed along LF and LR seat

c. Driver + 450 lbs on the left side. Load evenly distributed along LF and LR seat

d. Driver + 600 lbs on the left side. Load evenly distributed along LF and LR seat

iii. Right Load case

a. Driver + 150 lbs on the right side. Load evenly distributed along RF and RR seat

b. Driver + 300 lbs on the right side. Load evenly distributed along RF and RR seat

c. Driver + 450 lbs on the right side. Load evenly distributed along RF and RR seat

d. Driver + 600 lbs on the right side. Load evenly distributed along RF and RR seat

iv. Front Load case

a. Driver + 150 lbs in the front trunk. Load evenly distributed along the length in the trunk.
b. Driver + 300 lbs in the front trunk. Load evenly distributed along the length in the trunk.
c. Driver + 400 lbs in the front trunk. Load evenly distributed along the length in the trunk.
d. Driver + 500 lbs in the front trunk. Load evenly distributed along the length in the trunk.

In the front case the loading increments are different from the other case. The load was applied in the front trunk. As we were conducting the 300 lbs front load case. The trunk ducked down significantly more than expected. We had to adjust the front wheel alignment sensors, so that the bumpers do not get in the way of the alignment sensors. Had we loaded the car with 600 lbs in the last subcase as all other, the sensor would have been blocked by the front bumpers. Thus, we altered the cases to 150 lbs, 300lbs, 400lbs and 500lbs instead of 150lbs, 300lbs, 450lbs, and 600lbs.

v. Rear Load case

a. Driver + 150 lbs on the rear seat. Load evenly distributed along the rear seat.
b. Driver + 300 lbs on the rear seat. Load evenly distributed along the rear seat

c. Driver + 450 lbs on the rear seat. Load evenly distributed along the rear seat
d. Driver + 600 lbs on the rear seat. Load evenly distributed along the rear seat.

4.3 Alignment Procedure

The first step towards our measurements is to fix the two 2”x4” support bars under the Porsche to help support the weight of the car when the car rests on the stand when the wheels are off the four post. There are bearing plates on the four post. The vehicle is then brought on the four post and the wedges are placed on the front of the wheels. Then the support stand is placed under the car on the four post by raising the car. A pallet jack is used to place the stand under the car. The wheel alignment sensor brackets are then mounted on the corresponding wheels. The instrument that is used for wheel alignment measurement is Hunter’s Pro Align 130 console, DSP 700 alignment head. The brackets need calibration each time when they are mounted on the wheels. For calibration of the sensors the wheels of the car need to be off ground. Each bracket has sensor height adjustment, so that it could be adjusted for different cars. Also, when the car is loaded the ground clearance is reduced. Thus, we need to adjust the sensor height suitably whenever the ground clearance is changed because the laser beams are obstructed by the lowering the car due to weight. Due to this reason we had to change our front-loading case to 400lbs and 500lbs of front trunk load instead of 450lbs and 600lbs of front load. As the front trunk was loaded with a lot of weight the bumper sagged down and the lasers were not able to reach from the LF to RF wheel. Thus, it was changed to lower weight as given earlier.

FIGURE 4. 1 Wheel Alignment Sensor (Top View)

After mounting the brackets, they need calibration. In order to calibrate first, assign an imaginary zero degree to any wheel position, press the only button on the device at the zero-degree position. There are 3 lights near the button, two of which are blinking. When we press the button, the lights become steady. Then turn the wheel 120 degrees, again press the button to make the blinking lights steady. Repeat this step one more time, this them all the three lights become steady which means the device is calibrated. Repeat this procedure for all the four wheels. We can use the knob given on the sensor to adjust the spirit level.

The vehicle information needs to be entered on in the system before calibration so that the system knows what the wheel alignments are required from the manufacturer and it can compare the measured alignments with the specified. Now, that the calibration is done and the vehicle information is entered, the machine is ready to measure the wheel alignment. For this machine it is required to have a driver in the car to turn the wheels as a required procedure.

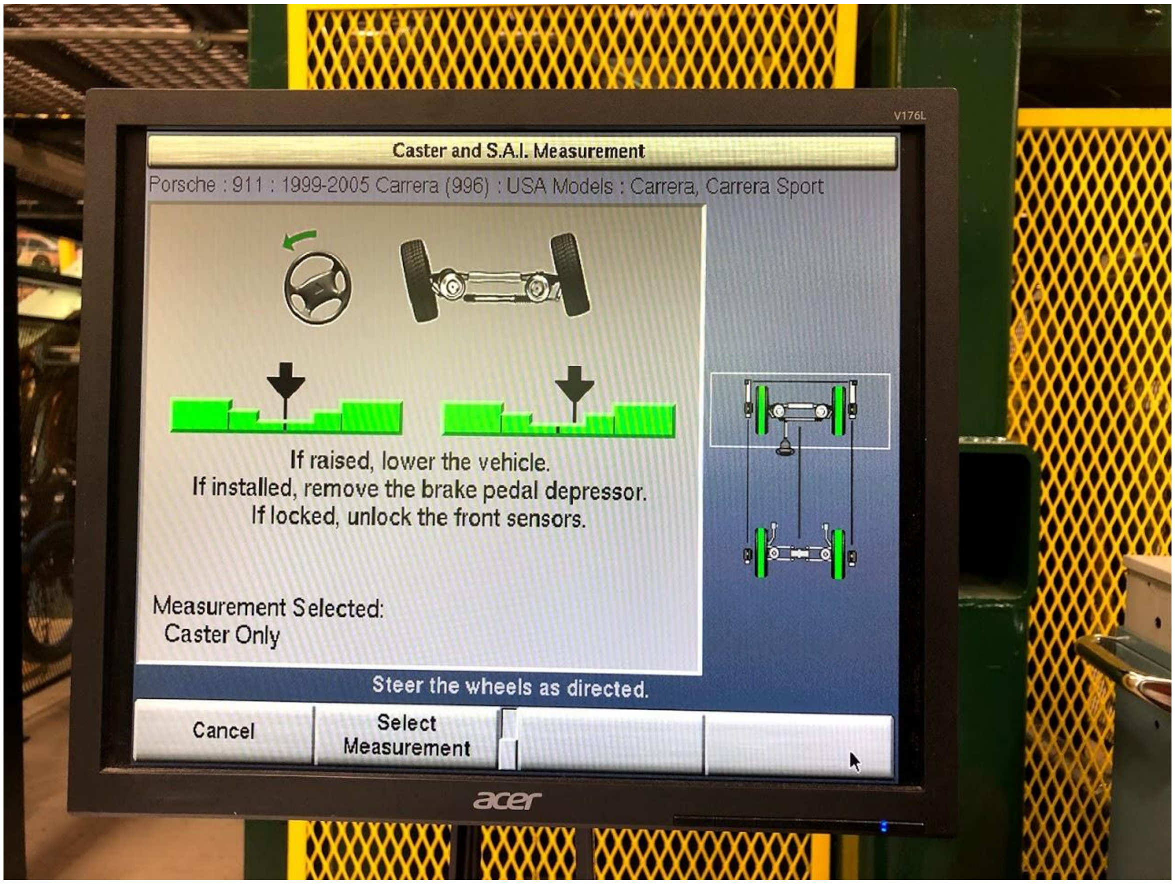


FIGURE 4. 2 Alignment Screen

To begin with the measurements, first the driver needs to make the wheels straight by following the arrow to the center as shown. Then the driver is required to steer the wheel approximately 180 degrees of steering wheel rotation to the required position shown by the pointer arrow on the screen.

There are two arrows on the screen. Due to Ackerman geometry it is required to have a different position for on screen arrows for each wheel to measure the alignment. Ackerman geometry means that the inner tire turns slightly more than the outer wheel. The reason we have Ackerman geometry in the steering system is that when the tires turn its necessary that they have a same center of turning. If they do not have a same center of turning, it will result in tire wear.

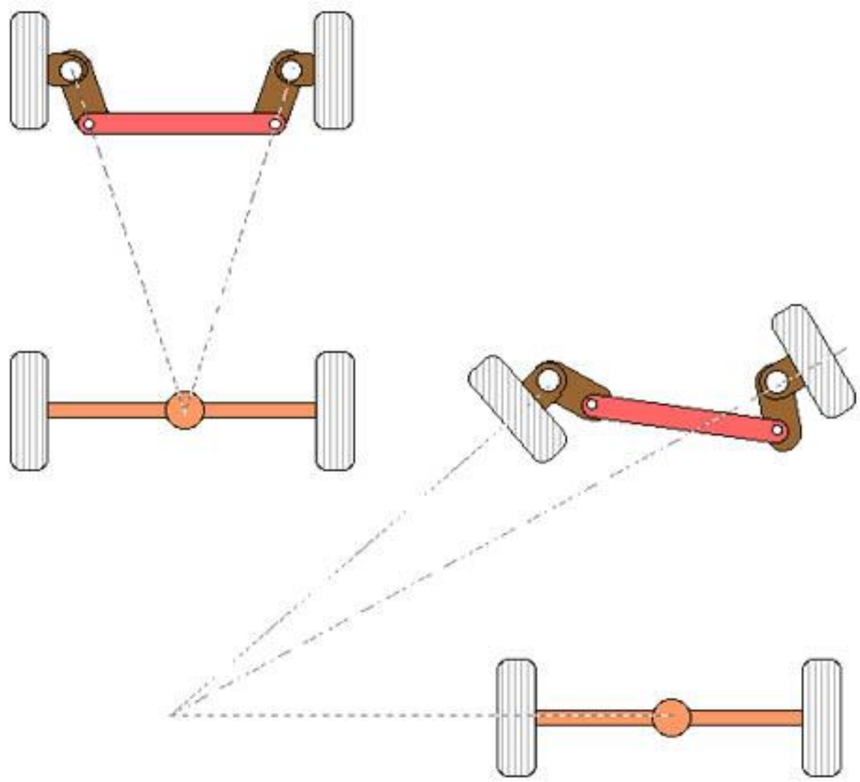
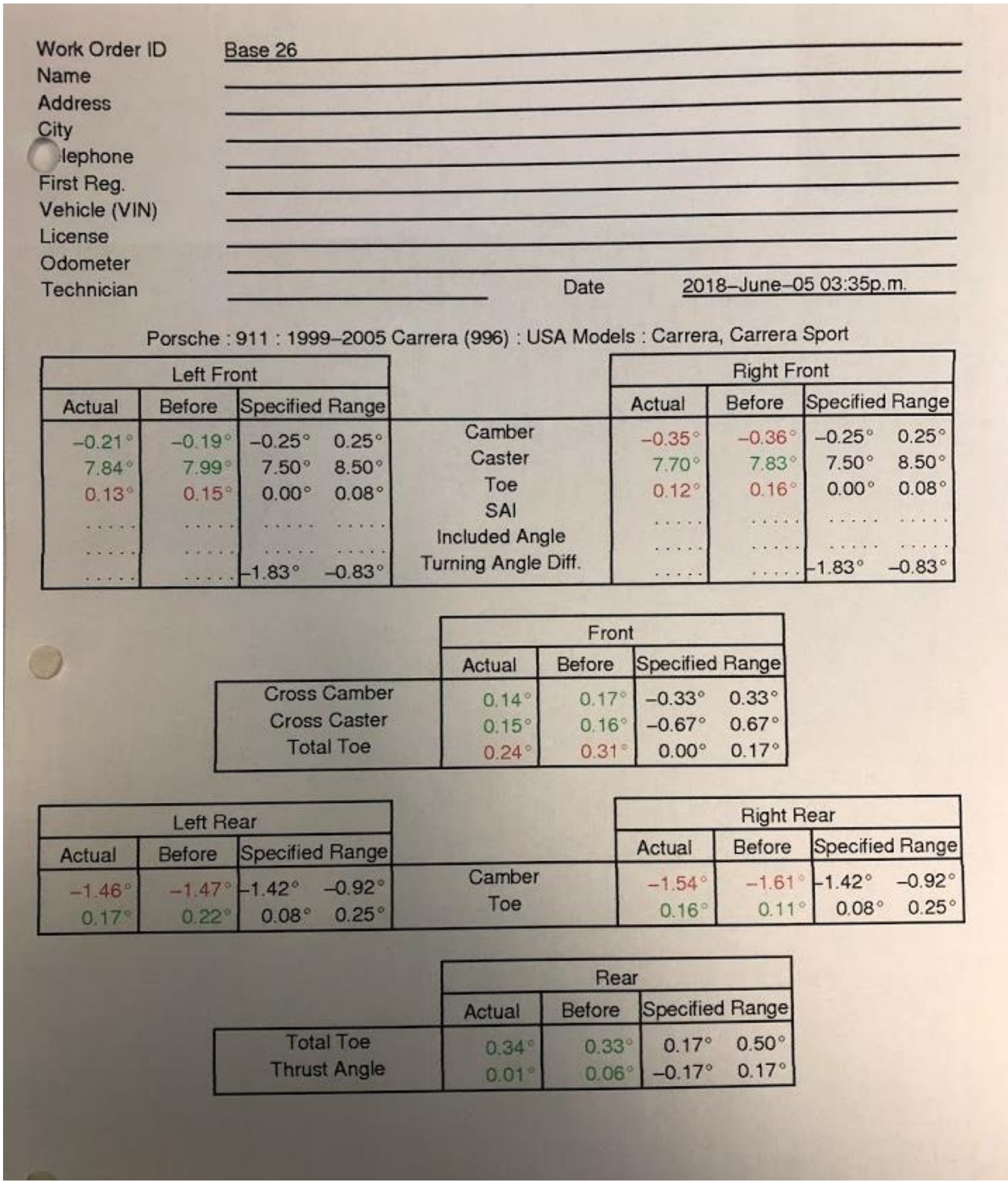


FIGURE 4. 3 Ackerman Geometry [14]

Repeat the same procedure for the right side. Then the screen will prompt you to get the wheels straight again. This is how one can get the wheel alignment sheet printed out.



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Porsche : 911 : 1999–2005 Carrera (996) : USA Models : Carrera, Carrera Sport

Left Front					Right Front			
Actual	Before	Specified Range			Actual	Before	Specified Range	
–0.21°	–0.19°	–0.25°	0.25°	Camber	–0.35°	–0.36°	–0.25°	0.25°
7.84°	7.99°	7.50°	8.50°	Caster	7.70°	7.83°	7.50°	8.50°
0.13°	0.15°	0.00°	0.08°	Toe	0.12°	0.16°	0.00°	0.08°
.....	.....	.....	.....	SAI	.....	.....	.....	.....
.....	.....	.....	.....	Included Angle	.....	.....	.....	.....
.....	.....	–1.83°	–0.83°	Turning Angle Diff.	.....	.....	–1.83°	–0.83°

	Front			
	Actual	Before	Specified Range	
Cross Camber	0.14°	0.17°	–0.33°	0.33°
Cross Caster	0.15°	0.16°	–0.67°	0.67°
Total Toe	0.24°	0.31°	0.00°	0.17°

Left Rear					Right Rear			
Actual	Before	Specified Range			Actual	Before	Specified Range	
–1.46°	–1.47°	–1.42°	–0.92°	Camber	–1.54°	–1.61°	–1.42°	–0.92°
0.17°	0.22°	0.08°	0.25°	Toe	0.16°	0.11°	0.08°	0.25°

	Rear			
	Actual	Before	Specified Range	
Total Toe	0.34°	0.33°	0.17°	0.50°
Thrust Angle	0.01°	0.06°	–0.17°	0.17°

FIGURE 4. 4 Alignment Sheet

This sheet will contain the information of your vehicle and wheel alignment parameters such as camber, caster, toe, cross camber, total toe and thrust angle. It will also show the previous alignment. This is helpful when you want to compare original alignment with the adjusted alignment. To take another measurement we need to take the wheels of the car off the ground (in this case, the four post). This can be done by lowering the four post to the point where the car rests on the central stand and keep lowering the four post until the wheels do not touch the bearing plates anymore. This is done to make sure that the suspension doesn't retain any stresses which would make the measurements readings not true. Again, raise the four post so that the car is lifted off the stand and now it's completely on the four post. It is a good idea to have the hand breaks on throughout the measurements so that the car doesn't accidently roll of the four post. Wedges can also be used for the same purpose. Before beginning with a new measurement, it is required to jounce the car from the front and the rear to settle the suspension. At the start of each set of 10 measurements. We also measured the weight of the car. The weight of the car is recorded 3 times of each of the seventeen subcases of wheel alignment variation.

4.4 List of problems faced during the measurement

To complete one set of wheel alignment measurement (10 measurement) it takes about 35 mins in best case scenario, if everything goes well. A lot of problems arise when these measurements are taken. The most common type of problem the was that the car would slip off on the bearing plate a little for each iteration, say about 1/3 in, within 10-15 iterations we would have to adjust the car back on the four post. This might affect the accuracy of the measurement.

There was another problem associated with taking the weights. As there were no wedges on the weight scale, the car would roll off the weighing scale when we tried to lift the car off on the weighing scale. So, we had to be extra careful or pull the hand brakes while the car is being loaded on the weighing scale to avoid the car being rolled off the weighing scales. The major problem that we faced and was noticed until the four post cables failed was lack of lubrication on pulleys of the four post. Here's a picture of a bolt that failed due to lack of lubrication.

FIGURE 4. 5 Bent Bolt

FIGURE 4. 6 Pulley Failure [4]

CHAPTER 5: RESULTS AND DISCUSSION

5.0 Comparing the accuracy of two post with four post.

In order to save time, we switch from two post lift to a four-post lift. But we also need to analyze whether the results obtained from the four-post lift are accurate enough to replace the traditional method. I obtained some values of two post measurement readings from Jutten's research paper which I am using to compare it to the measurement values from my data obtained from a four-post lift.

2015

	LF			RF			LR		RR	
Iteration	Camber	Caster	Toe	Camber	Caster	Toe	Camber	Toe	Camber	Toe
1	-0.18	7.96	0.01	-0.5	7.46	-0.07	-1.35	0.03	-1.36	0.19
2	-0.18	7.98	-0.03	-0.5	7.41	-0.03	-1.35	0.03	-1.36	0.18
3	-0.19	7.87	-0.03	-0.49	7.44	-0.04	-1.37	0.02	-1.35	0.16
4	-0.18	8.04	-0.04	-0.46	7.44	-0.02	-1.36	0.02	-1.36	0.16
5	-0.19	7.85	-0.04	-0.49	7.49	-0.02	-1.35	0.02	-1.36	0.16
6	-0.19	7.97	-0.02	-0.49	7.49	-0.04	-1.36	0.03	-1.37	-0.07
7	-0.19	7.84	-0.03	-0.49	7.53	-0.02	-1.36	0.02	-1.37	0.16
Std dev	0.00495	0.07091	0.01591	0.01245	0.03736	0.01678	0.007	0.00495	0.00639	0.08415

2018

	LF			RF			LR		RR	
Iteration	Camber	Caster	Toe	Camber	Caster	Toe	Camber	Toe	Camber	Toe
1	-0.19	7.86	0.13	-0.35	7.67	0.13	-1.45	0.23	-1.55	0.16
2	-0.2	7.89	0.15	-0.34	7.65	0.11	-1.44	0.22	-1.55	0.17
3	-0.2	7.87	0.13	-0.34	7.71	0.12	-1.45	0.23	-1.59	0.16
4	-0.19	7.93	0.13	-0.36	7.62	0.13	-1.46	0.23	-1.57	0.18
5	-0.2	7.85	0.13	-0.35	7.56	0.13	-1.47	0.22	-1.57	0.18
6	-0.2	7.83	0.17	-0.36	7.62	0.1	-1.49	0.2	-1.57	0.18
7	-0.22	7.84	0.13	-0.35	7.67	0.13	-1.54	0.22	-1.55	0.17
Std dev	0.00926	0.03149	0.01457	0.00756	0.04463	0.01125	0.03182	0.0099	0.014	0.00833

FIGURE 5. 1 Comparison of two post and four post standard deviations

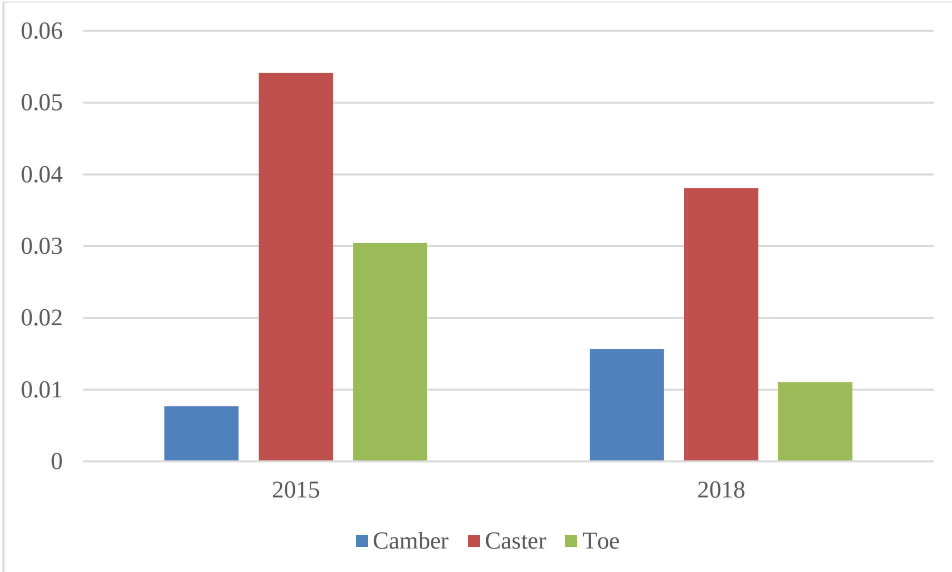

FIGURE 5. 2 STD. Deviation comparison Graph of Two post vs Four post

2015 data represent two post data and 2018 data represents the four-post data. The data available for this comparison is very small, so it is very difficult to generalize. But to my best possible interpretation, I can say that, on an average, four post gives a better accuracy in measurements. Thus, switching from the 2 post to the 4 post not only saved our time but also gave a better precision.

5.1 Data Organization

After the collection of huge data of almost 500 caster sweeps including 17 cases, it's very important to compile this data and organize it so that it makes sense to the reader. In a research, no doubt data collection is important, however, it's more important to analyze this data and interpret it. In order to analyze the collected data, I organized that raw data into the following steps. FIGURE 4.4. Alignment sheet shows the raw data. Initially the data was entered manually into excel sheet starting from the base case all the way up to Rear 600 case. (17 cases) A table that included LF, RF, LR, RR columns and Camber, Toe, and Caster in the sub columns. A sample table is given in the figure below. Then the data was segregated into tables in increasing load order for each of the type of measurement such as camber caster and toe. Then the data was plotted for a given wheel showing the measurement angle vs increasing wheel load.

Now with all the iterations of this data, each set is bound to have weird data points or spikes. In order to get rid of these weird data points I chose the method of manual picking. Initially I found the mean for all the cases, which is -1.73 degrees in this case, then plotted a graph of angle vs iteration number. From the graph I manually deleted the data points that were not within a tenth of a degree from mean. Thus, I went ahead and omitted the 7th data point to give the graph in figure 5.4.

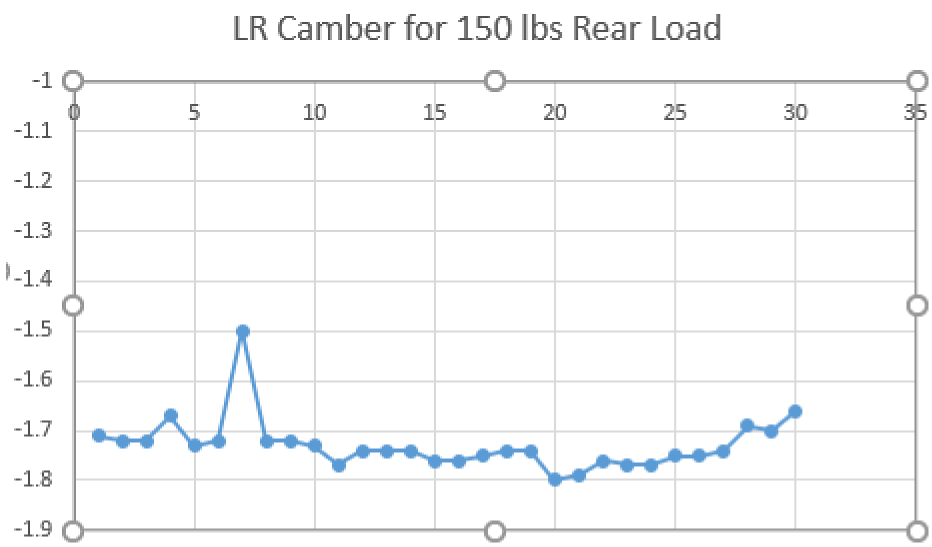

FIGURE 5. 3 Data Manipulation

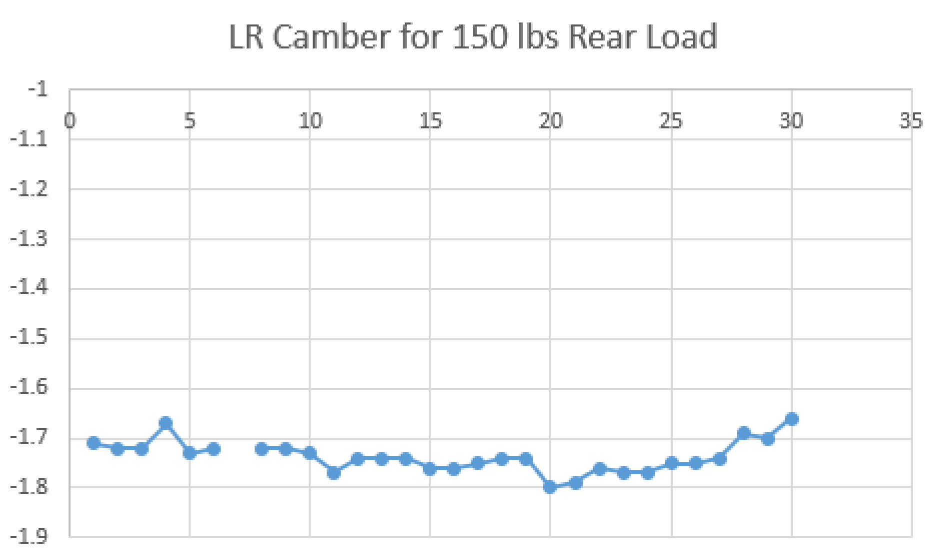

FIGURE 5. 4 Data Manipulation

Thus, we can see that we obtain a much smoother curve and the mean is only changed by less than 0.01 degree. I found this technique to be very effective and time saving. The only thing I had to do it is to plot all the graphs and pick the values which are not in the range of 0.1 degrees from the mean. A couple of cases had stepped data as in the example of Rear Loading 300 case of LR Camber.

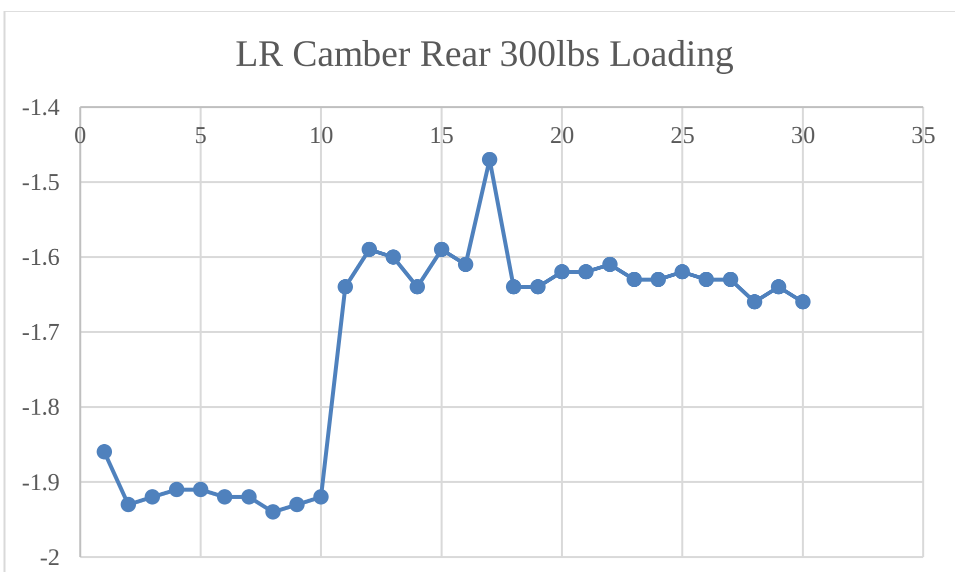

FIGURE 5. 5 Stepped Data

In this case we can see that the data suddenly jumps from the 11th iteration from an average of -1.92 to an average of -1.59. For this column I compared the values of the neighboring columns and judged which range of values made more sense. Turned out that when we plot the graph of camber angle vs wheel load -1.92 falls along the slope, not -1.62. The explanation that I can give for such a step the following. After every ten iterations we take a brake and start the next ten. During this time, we usually look for any adjustments necessary for the car. For example, check whether the car needs to be moved or the bearing plates need to be checked and adjusted. It could have so happened that as the car rests on the bearing plates the LR plate must have shifted to the end and no further movement is possible. So, the wheel did not have any room for any for assuming its natural movement. Thus, the reading got stuck 0.3 degrees off.

5.2 Results

The graphs given below are the plots of camber angle for individual wheels vs increasing load on the corresponding wheels. The graphs include error bars that give the standard deviation. These graphs are plotted to give a general trend of the change of camber angle with loading before its comparison with the K&C data.

5.2.1 Front Loading Camber Graphs

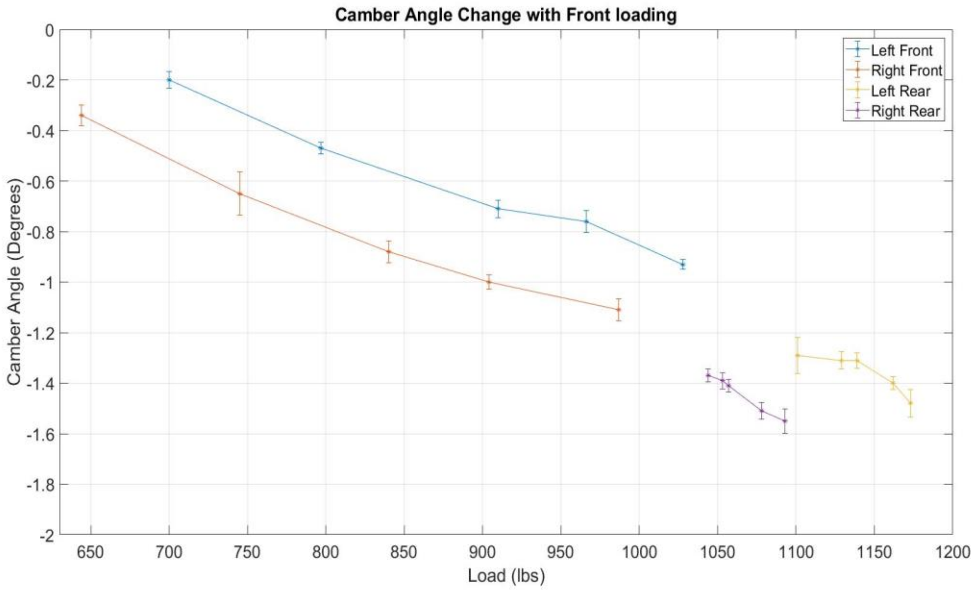

FIGURE 5. 6 Front Loading Camber for all wheels

5.2.2 Left Loading Camber Graphs

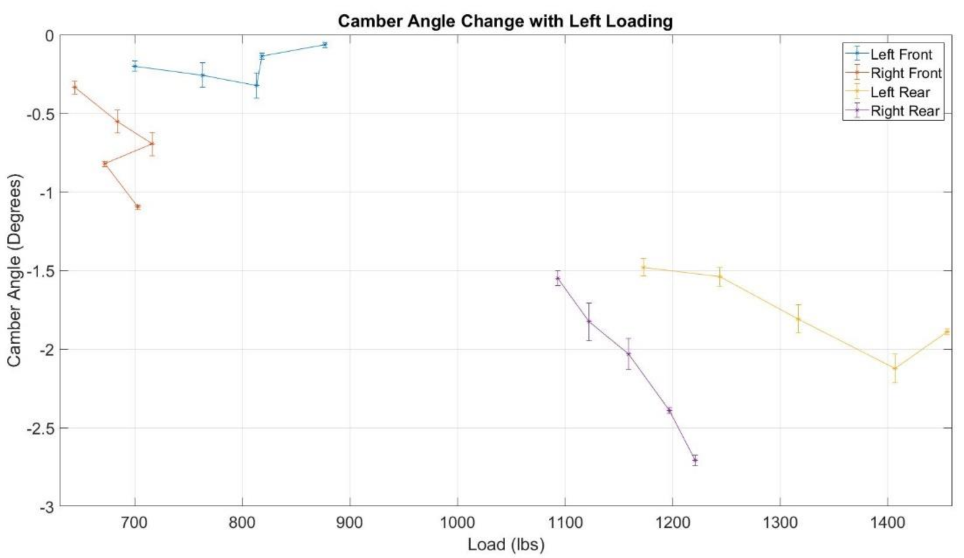

FIGURE 5. 7 Left Loading Camber for all Wheels

5.2.3 Right Loading Camber Graphs

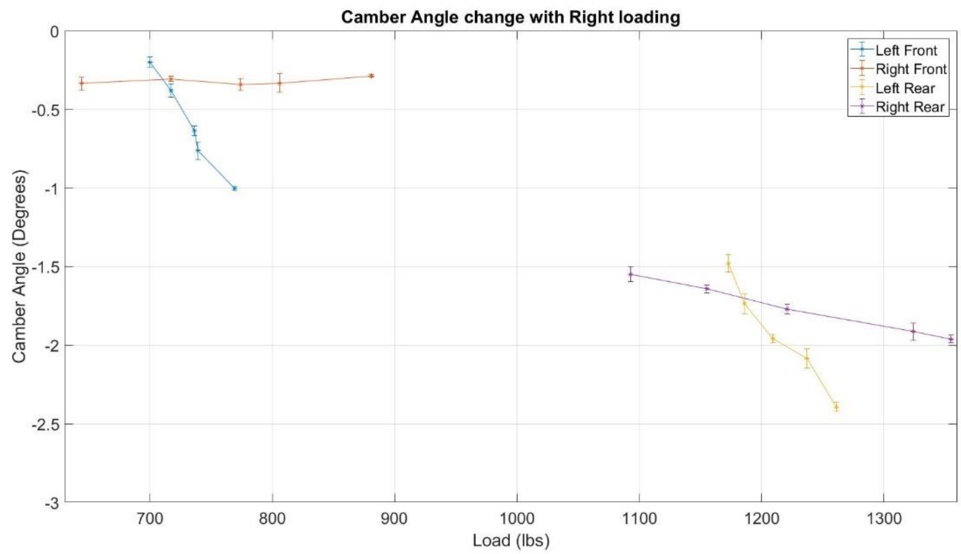

FIGURE 5. 8 Right Loading Camber for all Wheels

5.2.4 Rear Loading Camber Graphs

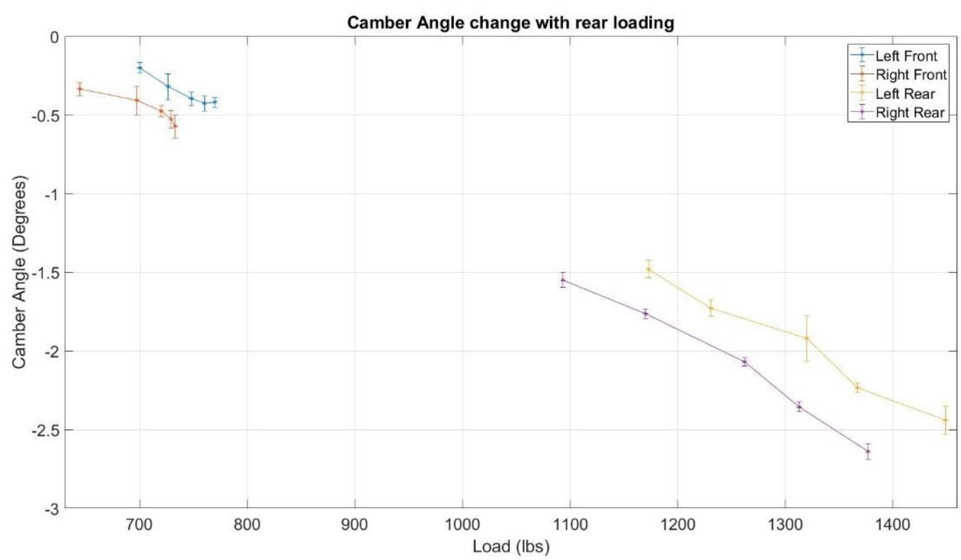

FIGURE 5. 9 Rear Loading Camber for all Wheels

5.2.5 Front Loading Toe Graphs

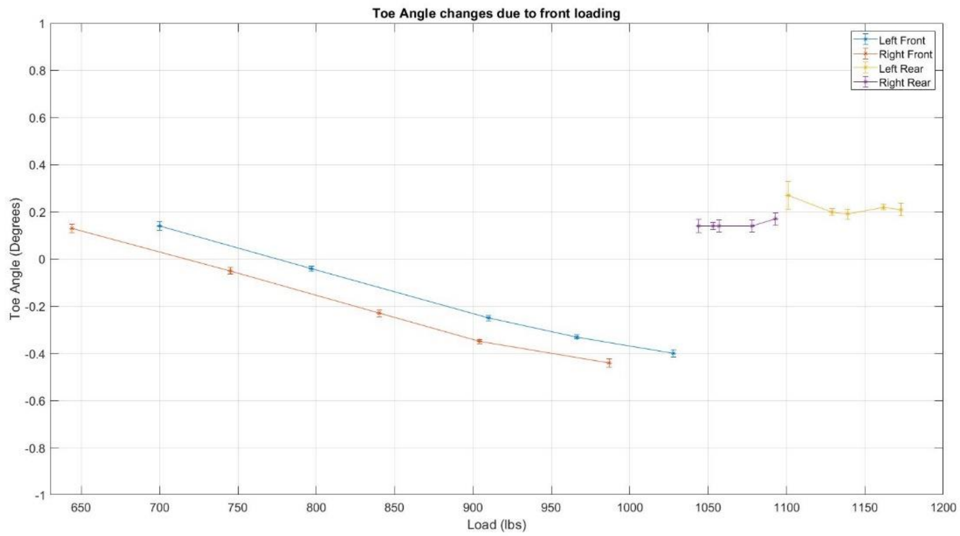

FIGURE 5. 10 Front Loading Toe for all Wheels

5.2.6 Left Loading Toe Graphs

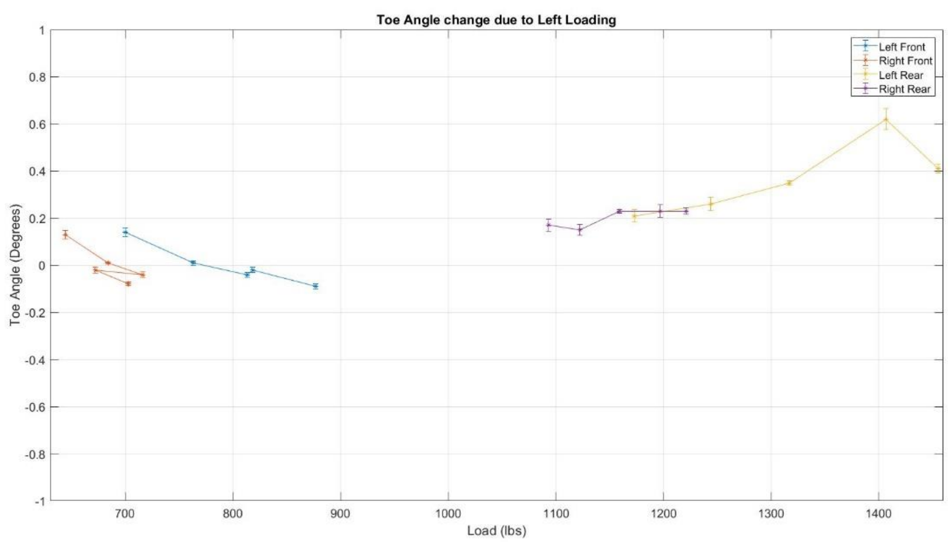

FIGURE 5. 11 Left Loading Toe Graph for all Wheels

5.2.7 Right Loading Toe Graphs

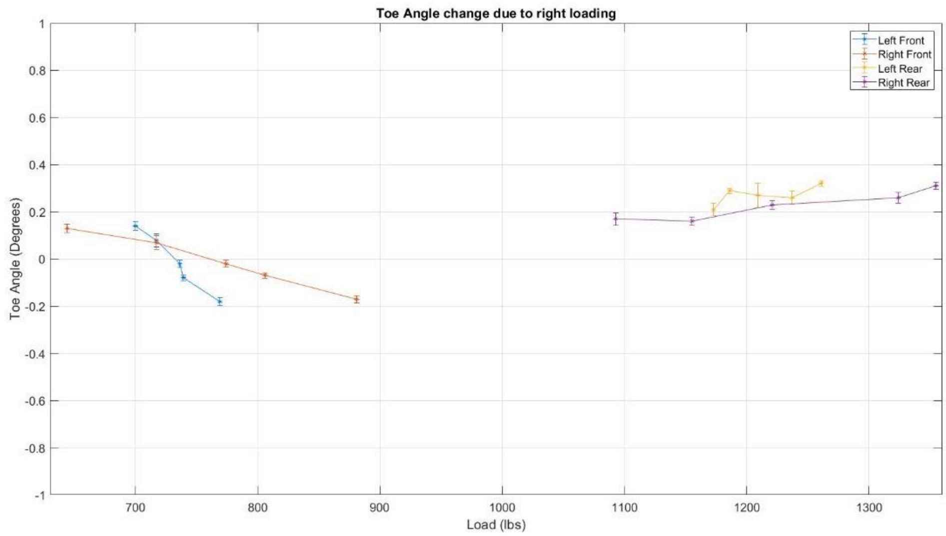

FIGURE 5. 12 Right Loading Toe for all Wheels

5.2.8 Rear Loading Toe Graphs

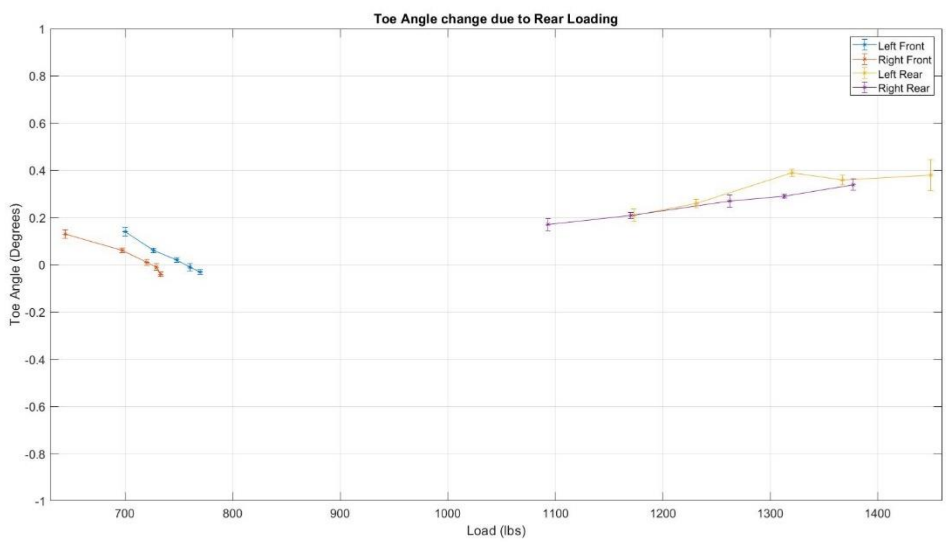

FIGURE 5. 13 Rear Loading Toe for all Wheels

5.2.9 Front Loading Caster Graphs

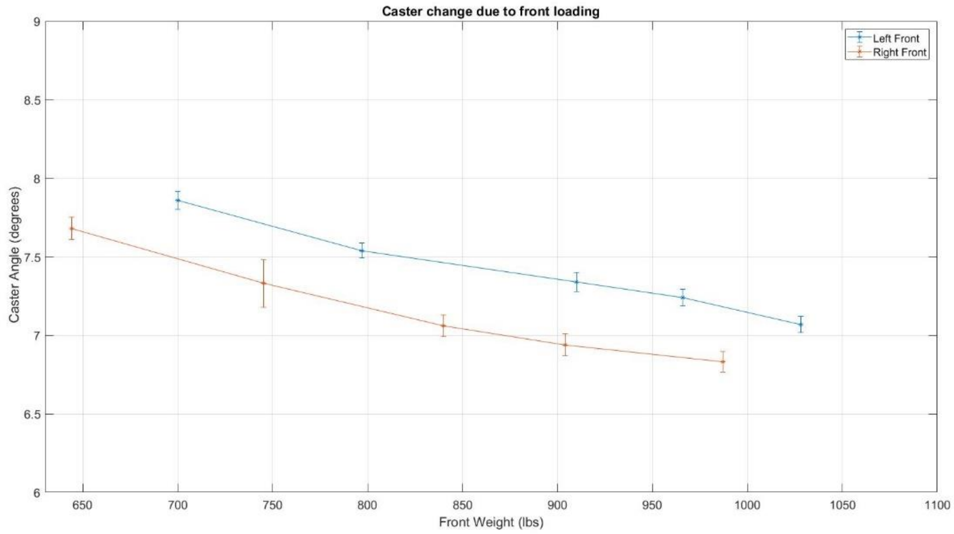

FIGURE 5. 14 Front Loading Caster for all Front Wheels

5.2.10 Left Loading Caster Graphs

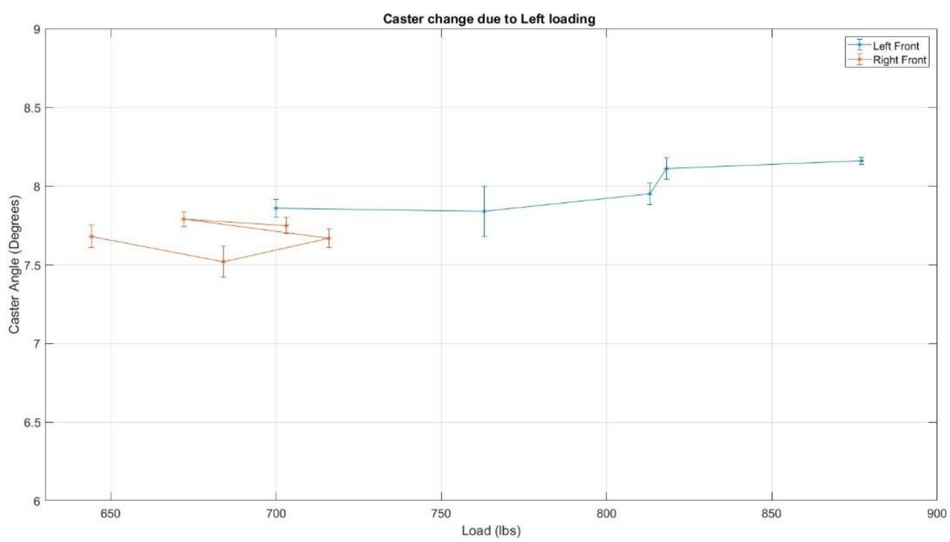

FIGURE 5. 15 Left Loading Caster for Front Wheels

5.2.11 Right Loading Caster Graphs

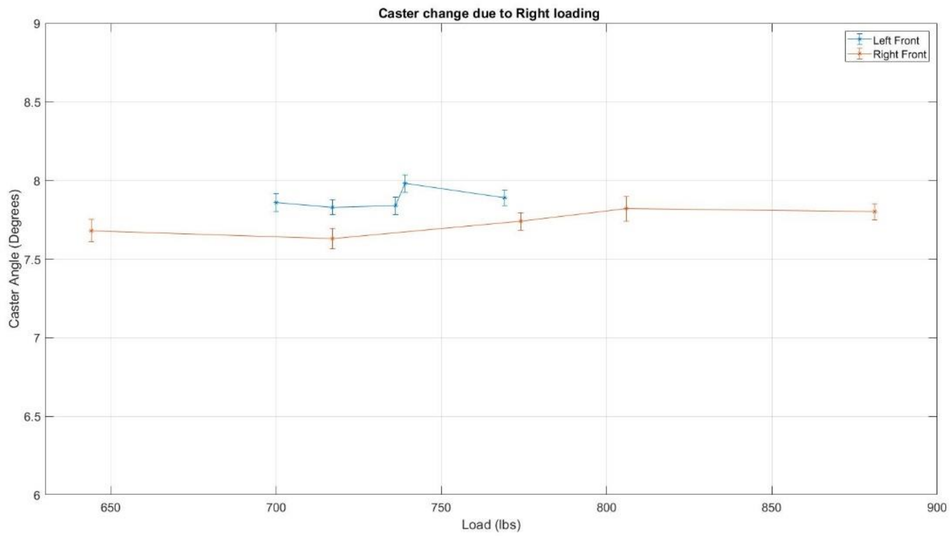

FIGURE 5. 16 Right Loading Caster for Front Wheels

5.2.12 Rear Loading Caster Graphs

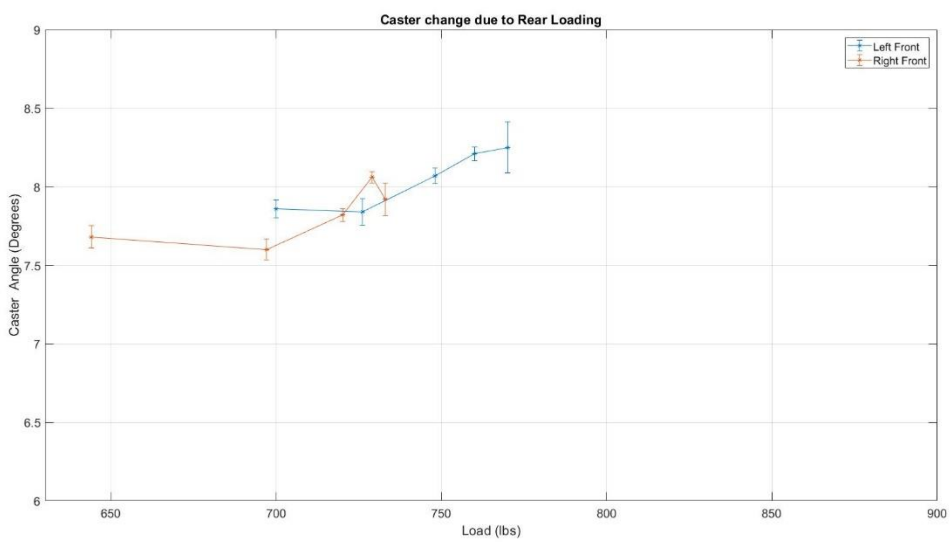

FIGURE 5. 17 Rear Loading Caster for Front Wheels

5.2.13: Discussion on Trends

In this section we will discuss the results obtained from figure 5.6 all the way up to FIGURE 5.17. The figures above show the graph of Load vs camber, caster and toe for all the wheel such as Left Front, Right Front, Left Rear and Right Rear for all the load cases. From the first glance, loading a vehicle has a significant impact on the wheel alignment variables. Let's look at the results of Camber, Caster and Toe separately and analyze them.

- Camber:
    - With the increase in load the camber angle decreases for front as well as the rear wheels.
    - For Front Loading, the decrease in camber angle is more in the front as compared to the rear wheels but the slope is almost the same. This is because front loading causes the front weight to change more.
    - For left loading case we see some anomalies. The LF wheel sees decrease in the camber angle as the load increases for initial loading, then sees an increase in camber angle. The RF wheel sees a very steep decrease in the camber angle as compared to LF. Similar is observed with LR and RR wheels.
    - For Right Loading case we see a steep decrease in camber with increased load on LF wheel. We see an increase in the camber angle with increasing in load. However, the slope is very less. For LR wheel, there is a steep decrease in camber angle, but RR wheel sees a relatively lesser steep decrease in the camber angle. The reason for this is the same as the left load case and it's discussed in the next section.

- For the rear loading case we observe that for all the four wheels, there is a decrease in the camber angle. The slope is more negative in case of the rear wheels as compared to the front wheels.

- Toe:
  - Toe shows different trends as compared to the camber trends. In toe angle, for the front-loading case, toe decreases by equal amounts on LF and RF tires. The effect of front loading on the rear wheels is not significant. But for an argument sake, toe angle increases for the r ear wheels.
  - Left loading case shows an anomaly in the RF tire, despite increase in the overall load, there is a steep decrease in the load for 450lbs left load. We can clearly see the effect of loading on the rear wheels here. There is an increase of toe angle for increasing load. The RR wheel toe angle remains almost the same.
  - We see a clearer trend in case of the right loading case. There is a sharp decrease of toe on the LF wheel. However, there is a steadier decrease of toe on the RF wheel. This is quite intuitive. We see a similar trend as in case of left loading except reversed. The RR wheels sees increase in the toe angle, the LR wheel remains almost the same.
  - The change of toe in the front is more as compared to the change of toe in the rear. This is an example of the bump steer. Bump steer is the tendency of the vehicle to move itself without the driver input. The front wheels are designed in a way that will cause them to toe out under compression. Which

is why we see a greater decrease (toe-out) in the front wheels. The opposite is designed for the rear wheels. Thus, we see toe angle increases in the rear.

  - By now we have established that the toe angle decreases on the front two wheels as a general argument and it increases on rear wheels with increasing load.

- Caster:
  - My research concern more about the camber and the toe angle. I have plotted caster angle vs loading because the data was available. The caster angle is the angle of steering axis with respect to the vertical as seen from the side. A positive caster is when the steering axis line meets ground ahead of the tire contact point.
  - With our graphs, front loading causes the caster angle to decrease, rear loading causes them to increase and lateral loading doesn't have a significant or a conclusive effect on caster angle.
  - A caster angle, when kept positive creates a torque that makes the tires straighten up when the tires are turned. Thus, this angle is responsible for the tires to straighten up when the steering is let go.

5.2.14 Exploring K & C data and Comparison

The tests performed above are compared to the K & C tests. The K & C data obtained from the Morse Measurements is huge. It contained data from 2016 tests performed on Dr. Tkacik' Porsche 911, 2017 Mercedes data and 2018 Mazda Miata data. The Porsche test data consisted of 5 sequences which included bounce test, roll test on fixed axis and natural axis, steering test, cornering test and braking test, etc. I went through all the test data and shortlisted few tests that I thought were comparable to my type of experimental data. After a thorough study of the K & C data. I found that the bounce test is closely aligned to what we have performed.

The braking simulation test was also close but, camber, caster and toe data were not there in this test. I tried to compare Roll test with Left and Right loading test. The figures below show graphical comparison of natural roll K & C Roll steer data with Left Loading Toe data for LF Wheel.

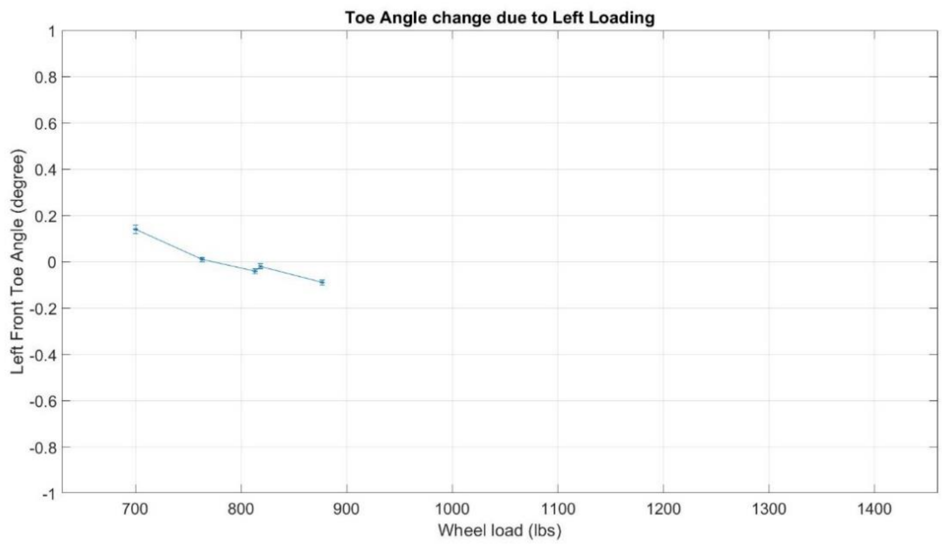

FIGURE 5. 18 Comparison graph of LF toe

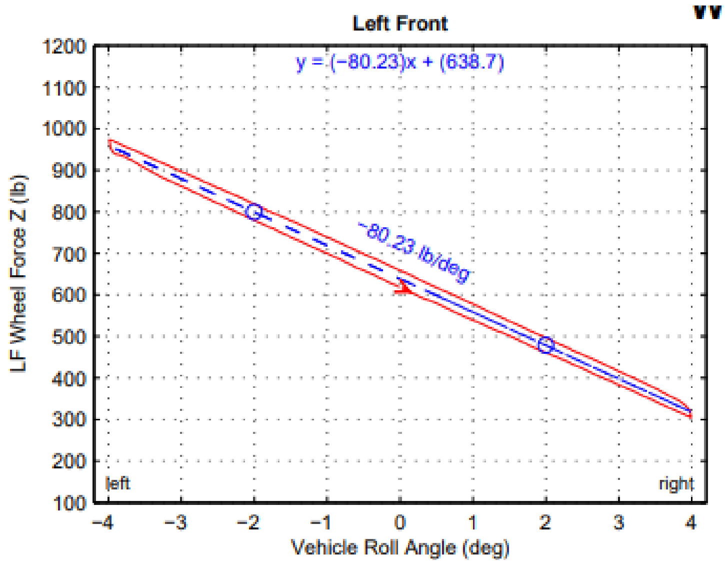

FIGURE 5. 19 K & C Roll Test Graphs [11]

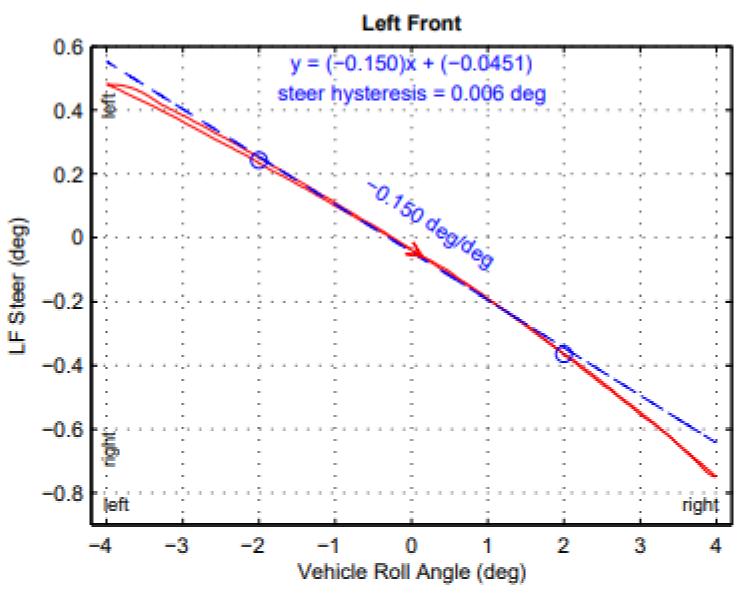

FIGURE 5. 20 K&C Roll Test Graphs [11]

If we compare the graphs 5.18, 5.19 and 5.20 we can observe a clear difference between the trends of change in the toe. In 5.18, the Toe decreases with an increase of loading on the LF wheel, however, if we look at the graphs in 5.19 and 5.20 we see that the LF steer increases as the load increases. This was rather surprising for me since I had expected that loading the vehicle on either side would result the vehicle in rolling. However, the graphical results suggested otherwise.

From which I concluded that adding weight on the car doesn't make the car roll, it just makes the car bounce more on one side as compared to the other. This is explained in the picture below.

FIGURE 5. 21 Porsche in Front View [15]

For the next picture, note that wheels stay on ground, only chassis is displaced. As we can see that in case of the Rolling Test one side of the suspension is in expansion state and other side of the suspension is in the compression state.

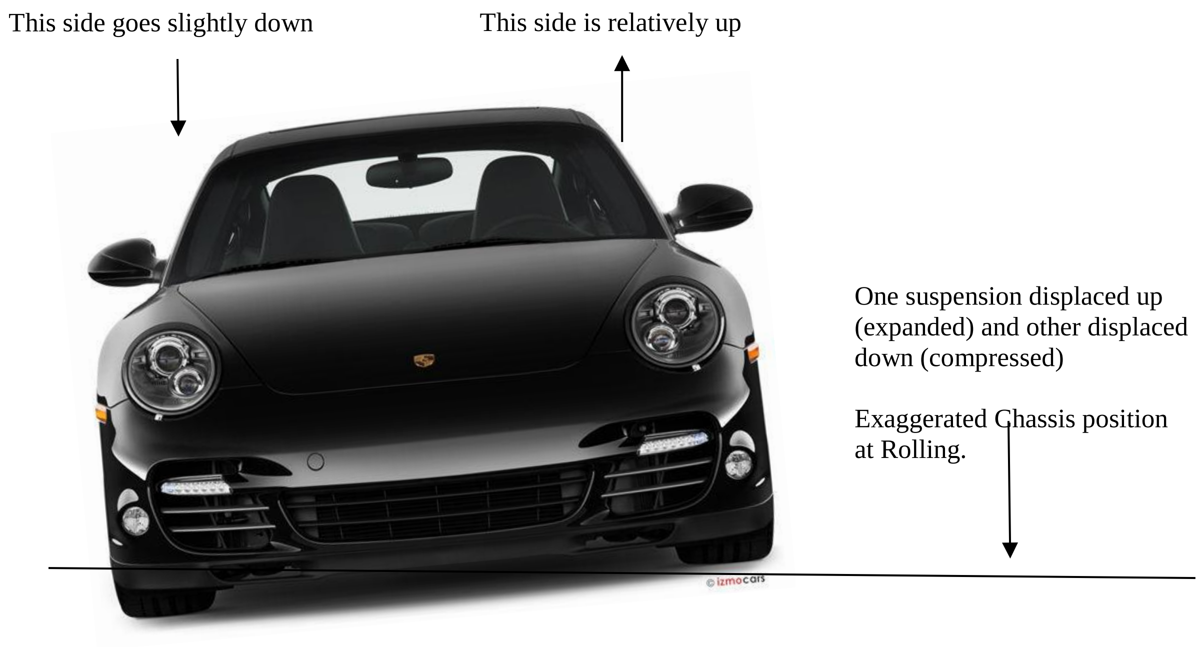

FIGURE 5. 22 Car in Pure Roll [15]

Now, let’s look at the bounce test K&C.

FIGURE 5. 23 Car in Pure Bounce [15]

We will now look at the position of the car when carrying out a right loading case.

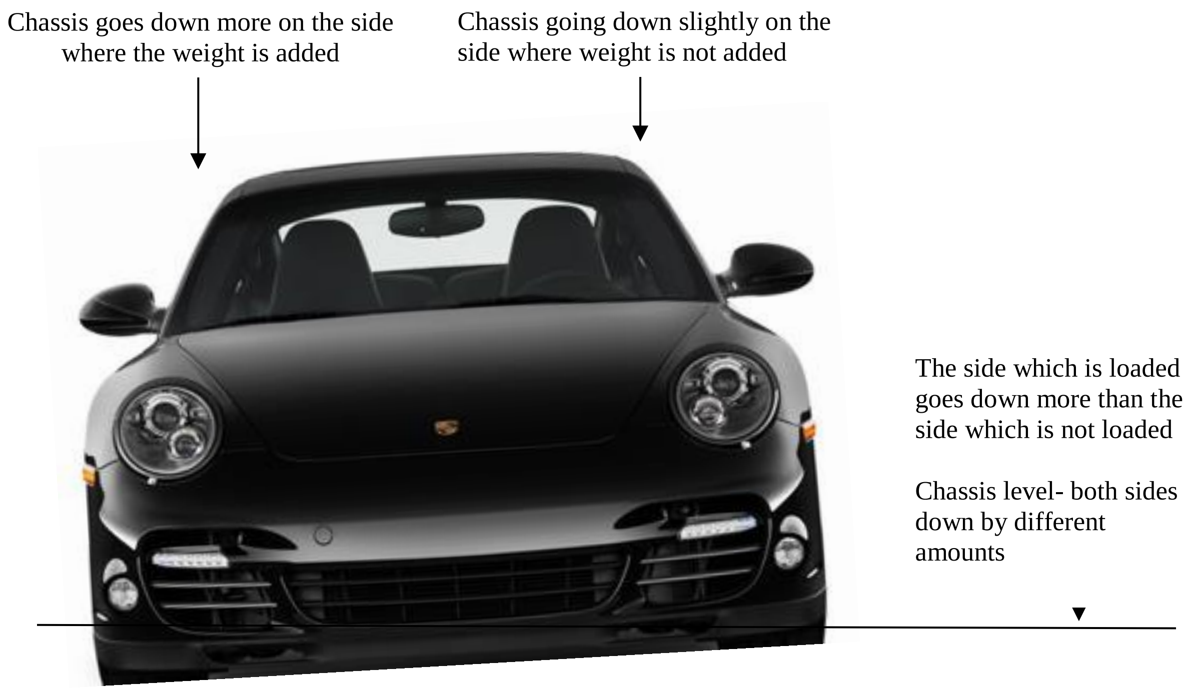

FIGURE 5. 24 Car in Right loading [15]

Comparing the FIGUREs 5.22, and 5.24 we can see that the experimental conditions of left and right rolling in K&C cannot be directly compared to my experimental data. In case of pure rolling of the car the side on which the car is being rolled goes down and the other side goes up relatively. However, in case of side loading of the vehicle both the sides go down with the side being loaded deflecting more than the other side. We can see this evidently using the wheel loads comparison. If our analysis is true, the weight on both the sides should go up. Let’s compare the wheel loads on Right Rear and Left Rear wheels for right loading case.

TABLE 5. 1: LR vs RR wheel loads for Right loading

Right Loading Weight (lbs)	LR wheel load (lbs)	RR wheel load (lbs)
0	1173	1093
150	1186	1155
300	1209	1221
450	1237	1324
600	1261	1355

Clearly this is not a case of pure rolling as in pure rolling, the load on the rolling side should increase and the load on the other side should decrease. But here load on both the sides is increasing.

5.2.14 K & C Bounce test comparison

In the K & C bounce test, the vehicle chassis is given a bounce motion. This is done by moving the K&C table straight up and down with a definite displacement, say +- 50mm. the vehicle chassis is clamped to the test center table to exercise the vertical motion. The lateral, longitudinal and aligning moments are maintained zero throughout the test. The three reasons why this test is comparable to our experimental data is that,

1. The lateral forces, longitudinal forces and alignments are maintained zero as in the case of our experiments.
2. The motion of the car is vertical in both the cases.
3. We are analyzing only wheel to wheel behavior, isolating three other wheels at a given comparison, of K&C and experimental data

The K & C bounce test doesn't directly show the wheel loads vs toe or wheel loads vs camber.

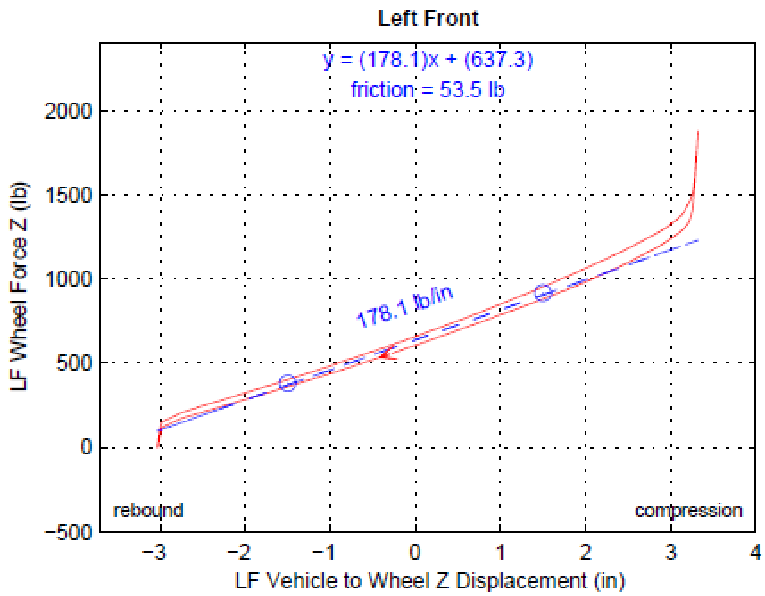

FIGURE 5. 25 Wheel Rate graph for LF wheel [10]

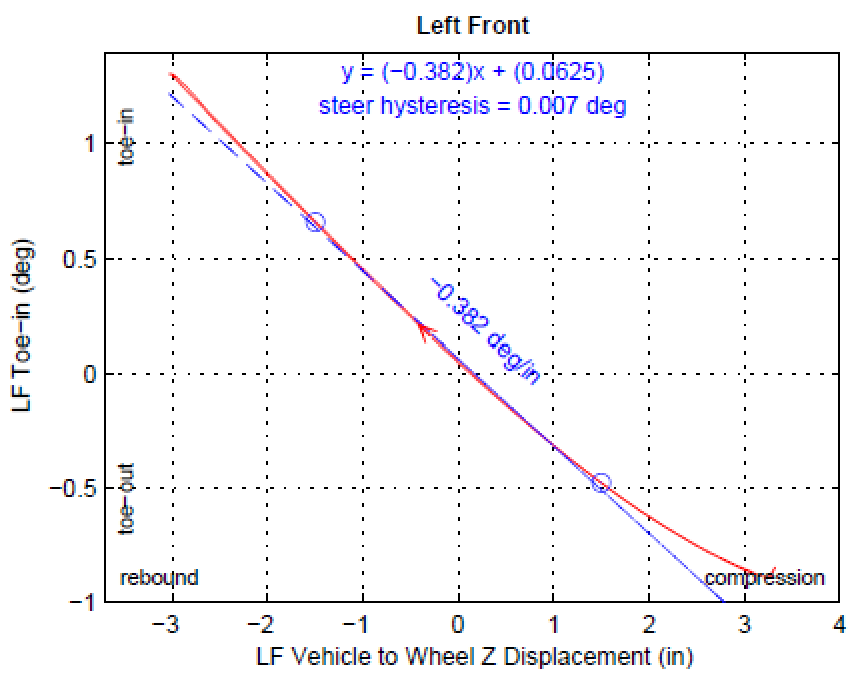

FIGURE 5. 26 Bump steer for LF wheel [10]

It has a graph of wheel rates which is wheel load vs vehicle to wheel displacement, and it has another graph of toe vs vehicle to wheel displacement known as bump steer for toe comparison and camber vs vehicle to wheel displacement known as bump camber for camber comparison. The figures given above show the required graphs for the LF wheel. There are graphs for RF, LR, and RR wheels for both toe and camber in K&C data.

With these two graphs I have constructed a graph for wheel loads vs toe using extrapolation technique in MATLAB. I found the vehicle to wheel displacement for the given load in experimental data from the figure 5.53and calculated the corresponding toe angle from FIGURE 5.54. I used the following formula twice, once for each graph

```
x = (((y-y1) *(x2-x1))/(y2-y1))+x1
```

where, x is the required displacement

x1, x2 are two reference points on the x axis

y1, y2 are two reference points on the y axis

y is the wheel load recorded in the experimental data

Using this formula once I could find the vehicle to wheel displacement for K&C Porsche at a given experimental load. Then I used the same formula to calculate the toe angle from the vehicle to wheel displacement. Then same procedure is repeated for rest of the three wheels using the corresponding graph. Then the whole process is again repeated to get the camber values. The tables given below will have all such values calculated using the formula given above.

TABLE 5. 2 LF Wheel Front Load

Weight (lbs)	Displacement (in)	Toe	Camber
700	0.3743	-0.0891	-0.11
797	0.8915	-0.2765	-0.3754
910	1.4629	-0.4670	-0.6119
966	1.7378	-0.5529	-0.7109
1028	2.02	-0.6305	-0.7885

Where,

Weight – Wheel Load measured on 911 in the lab

Displacement - Vehicle to Wheel displacement corresponding to Weight obtained from Wheel load vs Displacement K&C graph

Toe – Toe angle corresponding to the vehicle to wheel displacement from K&C graph

Camber – Camber angle corresponding to the vehicle to wheel displacement from K&C graph

TABLE 5. 3 RF Wheel Front Load

Weight (lbs)	Displacement (in)	Toe	Camber
645	0.3019	0.0139	-0.2965
745	0.8419	-0.1941	-0.5763
840	1.33	-0.3726	-0.7896
904	1.6487	-0.4832	-0.9092
987	2.0183	-0.6	-1.0186

TABLE 5. 4 LR Wheel Front Load

Weight (lbs)	Displacement (in)	Toe	Camber
1173	0.618	0.45	-1.7584
1162	0.5702	0.4419	-1.7167
1139	0.4708	0.4252	-1.6301
1129	0.4276	0.4179	-1.5925
1101	0.3067	0.3976	-1.4872

TABLE 5. 5 RR Wheel Front Load

Weight (lbs)	Displacement (in)	Toe	Camber
1093	0.3754	0.2113	-1.5870
1078	0.3099	0.2013	-1.53
1057	0.2182	0.1873	-1.4501
1053	0.2008	0.1847	-1.4349
1044	0.1615	0.1787	-1.4007

TABLE 5. 6 LF Wheel Rear Load

Weight (lbs)	Displacement (in)	Toe	Camber
700	0.3743	-0.0891	-0.11
726	0.5161	-0.1418	-0.1906
748	0.6362	-0.1864	-0.2557
760	0.7	-0.2095	-0.2877
770	0.7518	-0.2276	-0.3114

TABLE 5. 7 RF Wheel Rear Load

Weight (lbs)	Displacement (in)	Toe	Camber
645	0.3045	0.0139	-0.2965
697	0.5873	-0.0977	-0.4519
720	0.7109	-0.1453	-0.5159
729	0.7581	-0.1629	-0.5377
733	0.779	-0.1707	-0.5473

TABLE 5. 8 LR Wheel Rear Load

Weight (lbs)	Displacement (in)	Toe	Camber
1173	0.618	0.45	-1.7584
1231	0.8633	0.4925	-1.9752
1320	1.1845	0.5625	-2.2953
1367	1.3542	0.5995	-2.4645
1449	1.6455	0.6777	-2.7811

TABLE 5. 9 RR Wheel Rear Load

Weight (lbs)	Displacement (in)	Toe	Camber
1093	0.3754	0.2113	-1.5870
1170	0.7114	0.2627	-1.8797
1262	1.0613	0.3265	-2.2163
1313	1.2421	0.3625	-2.3996
1377	1.4701	0.4103	-2.6355

The tables above give the values of Toe and Camber for the specific wheel loads for K&C data. With this data I have constructed the graphs for Wheel loads vs Toe and Wheel loads vs Camber for front and rear loading for K&C. I have also plotted the same graph for experimental data on the same figure. A comparison is made. Here are the graphs of Wheel loads vs Toe.

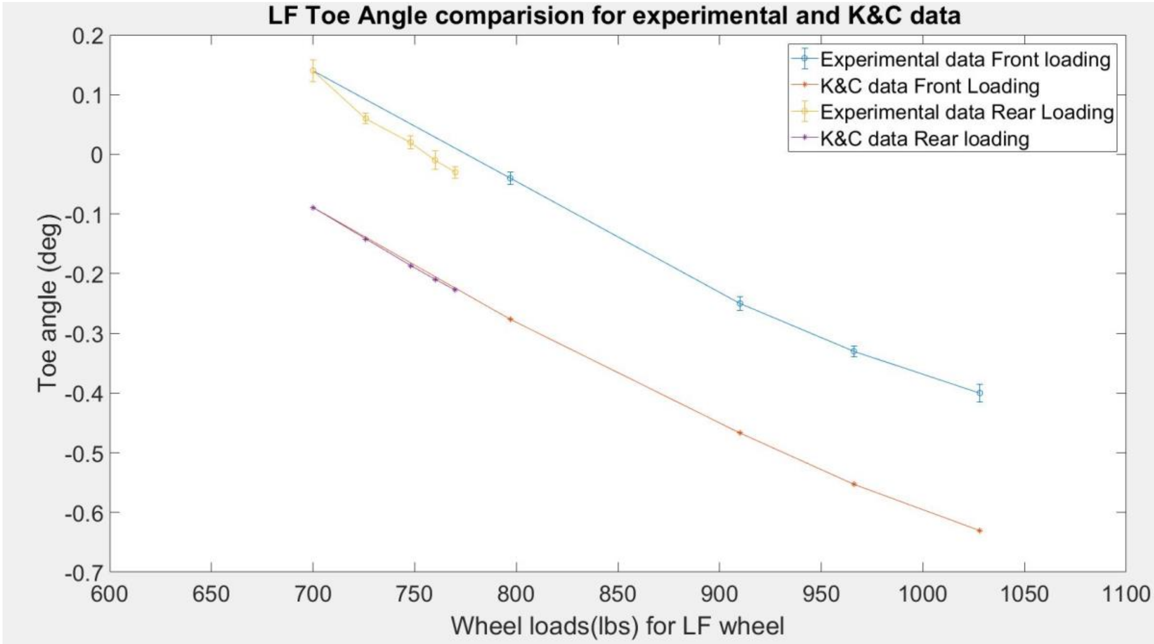

FIGURE 5. 27 K&C and experimental data comparison of LF Toe

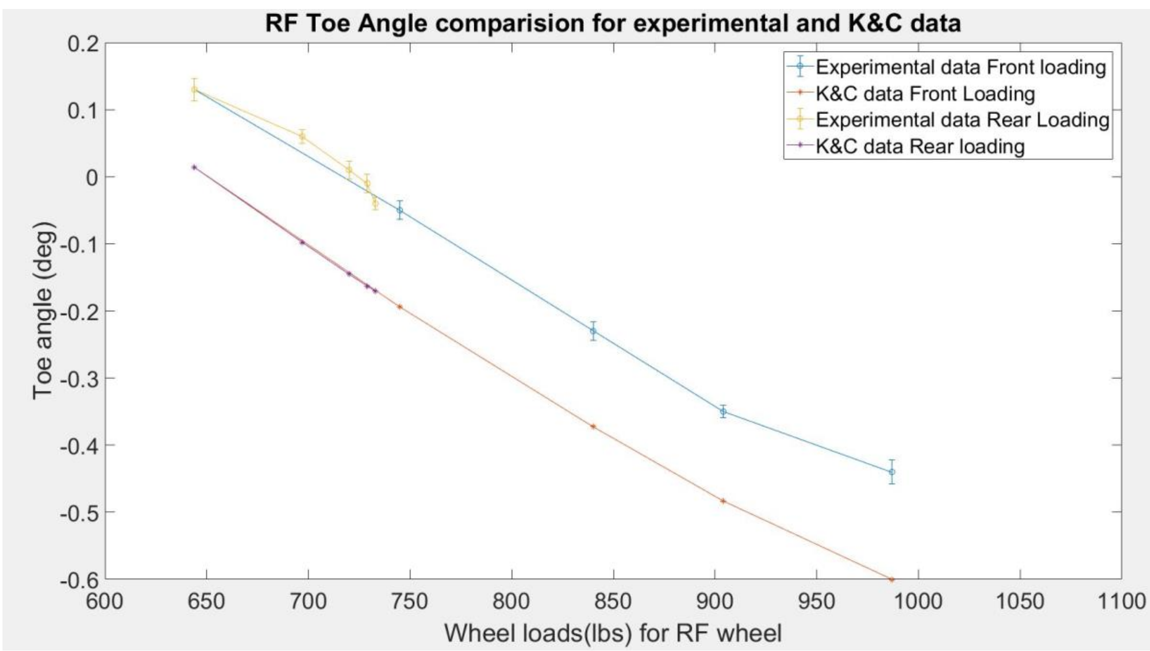

FIGURE 5. 28 K&C and experimental data comparison of RF Toe

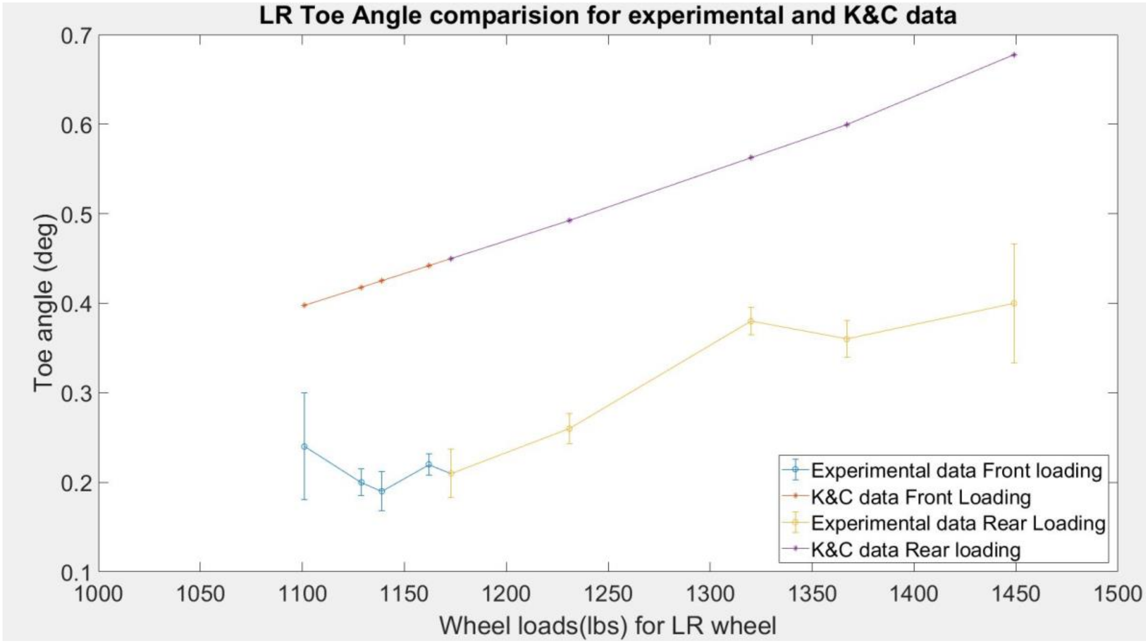

FIGURE 5. 29 K&C and experimental data comparison of LR Toe

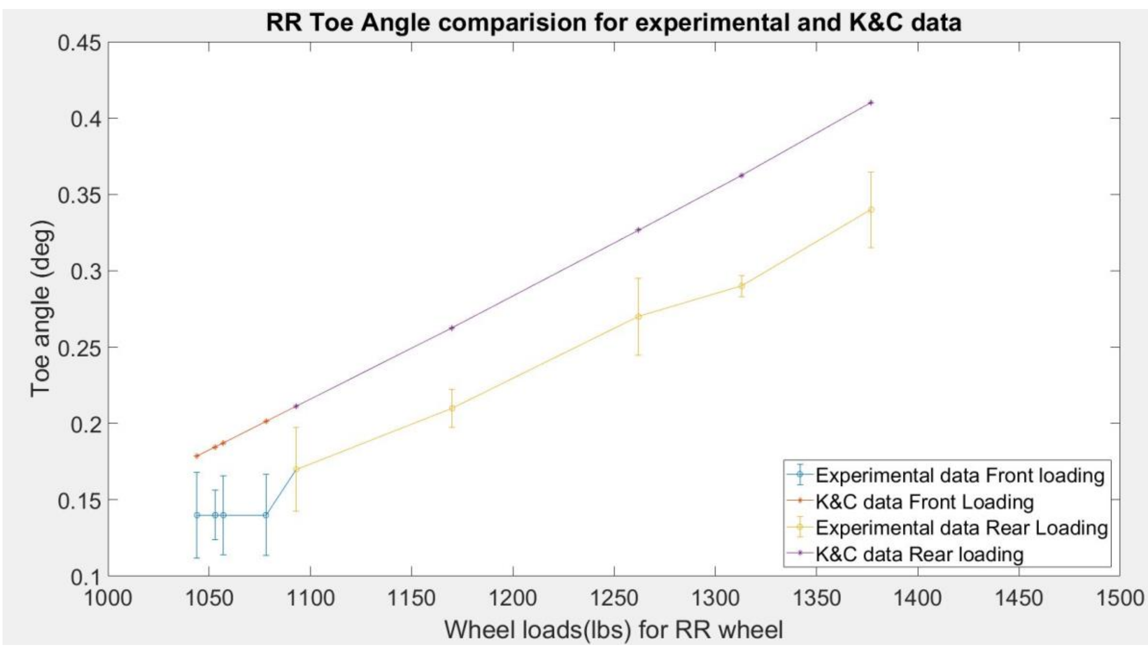

FIGURE 5. 30 K&C and experimental data comparison of RR Toe

From the graphs above we can see that the experimental data and K & C data follow the exact trend for LF, RF and RR Toe Comparison. However, we can see an average difference of 0.3 degrees of Toe for LF wheel, 0.15 degrees for RF wheel, 0.1 degrees for RR wheel. I checked the records from 2016 Wheel Alignment Caster sweeps which shows a toe adjustment of about the same. The K&C measurements were taken in early 2016 before the toe adjustment. So, I subtracted the average value of the adjustment from my experimental data collected in 2018 to match the data from early 2016 to get the following graphs for LF and RF. All the calculations were carried out in MATLAB.

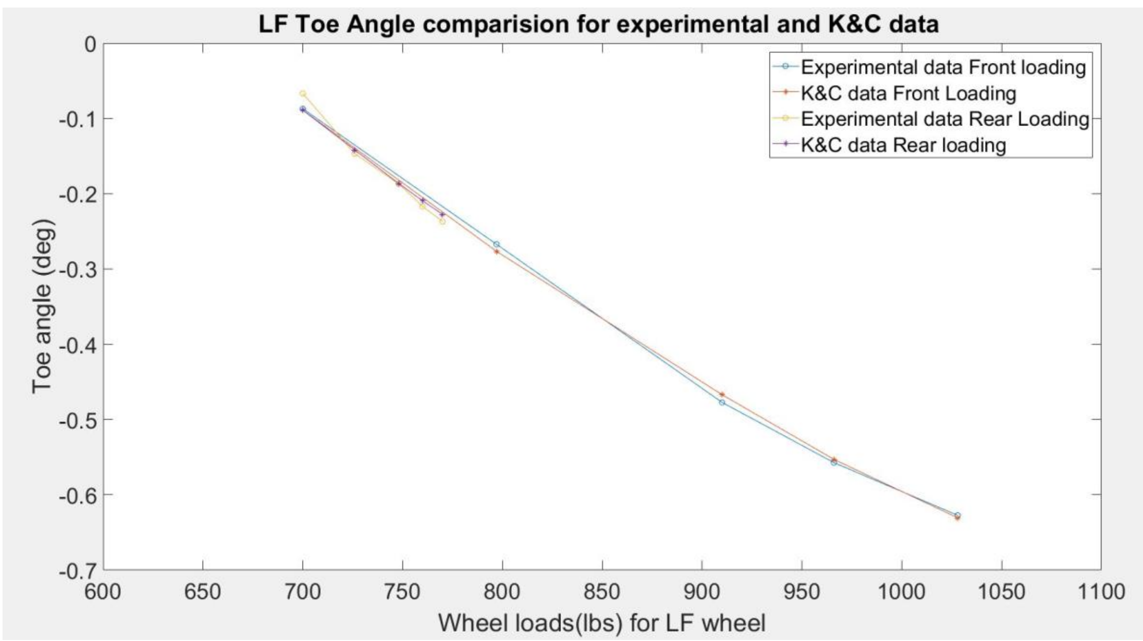

FIGURE 5. 31 Adjusted K&C and experimental data comparison of LF Toe

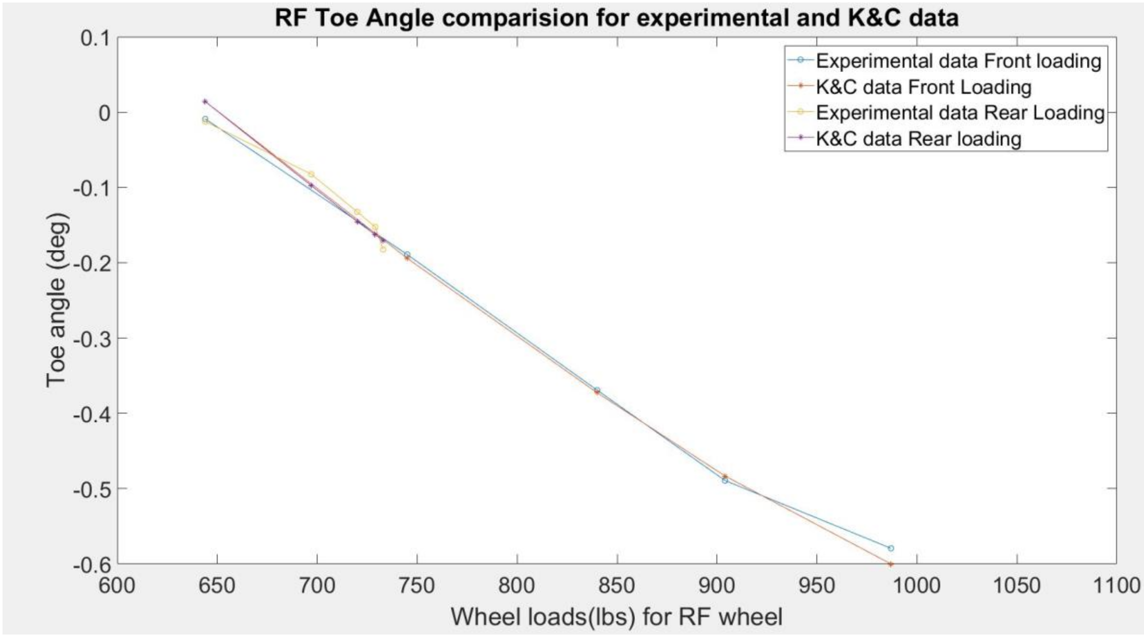

FIGURE 5. 32 Adjusted K&C and experimental data comparison of RF Toe.

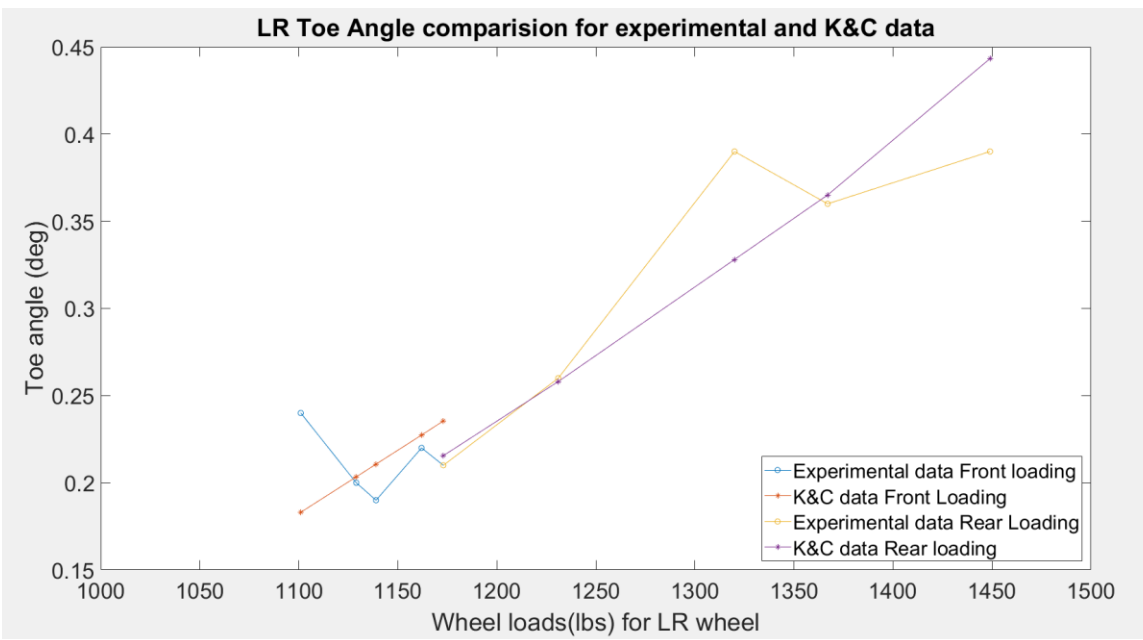

FIGURE 5. 33 Adjusted K&C experimental data comparison of LR Toe

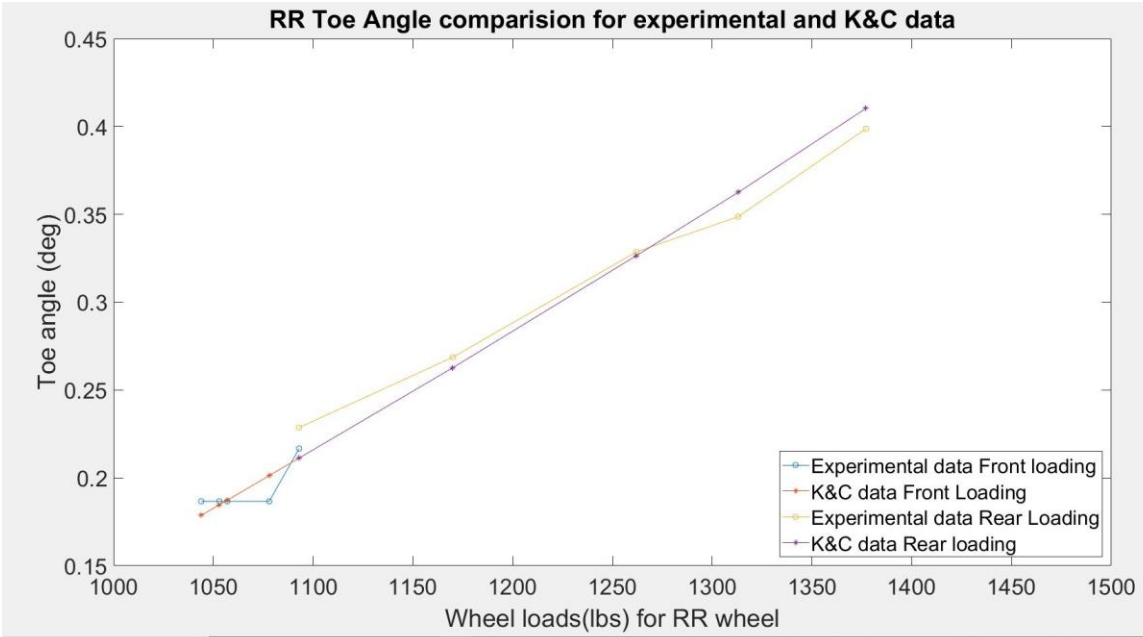

FIGURE 5. 34 Adjusted K&C and experimental data comparison of RR Toe

After the adjustment of the values to 2016 values, we can see that the K&C graphs and the experimental data graph exactly coincide. Thus, proving that we can recreate the data obtained from a 20 million dollar machine with a machine that is less than 20 thousand dollars. The trends are followed for both front loading case and the rear loading case for LF, RF and RR wheels as seen in the graph. LR graph (FIGURE 5.31) has a lot of anomalies. The K&C toe values for toe are different from 2016 caster sweep toe values from Dr. Tkacik’s data obtained from his lab. I will leave LR Toe case as inconclusive.

The camber values don’t seem to be adjusted in past three years. Let’s see if we get the same trends for the camber comparison. Each graph consists of camber angle vs wheel load at the given wheel for K&C and experimental data

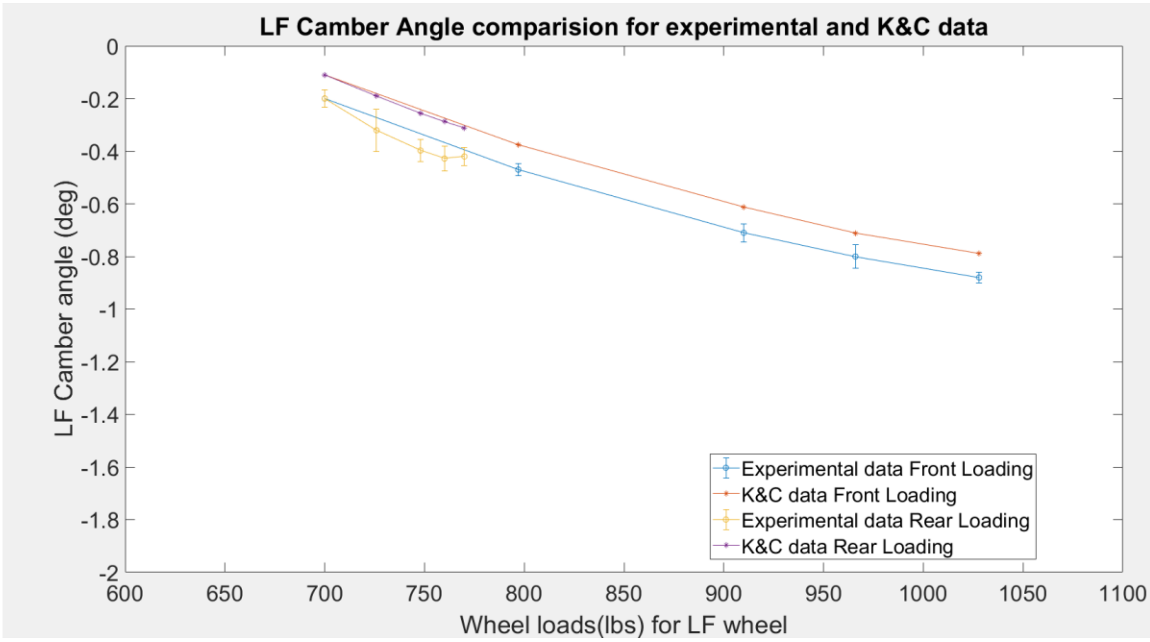

FIGURE 5. 35 K&C and experimental data comparison of LF Camber

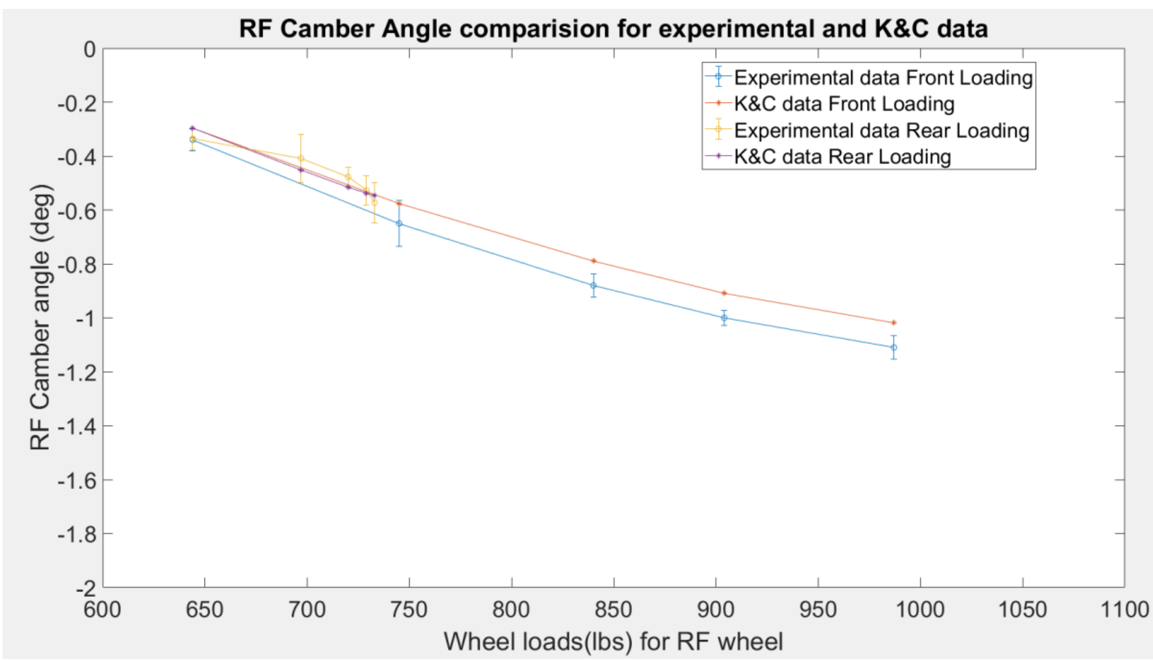

FIGURE 5. 36 K&C and experimental data comparison of RF Camber

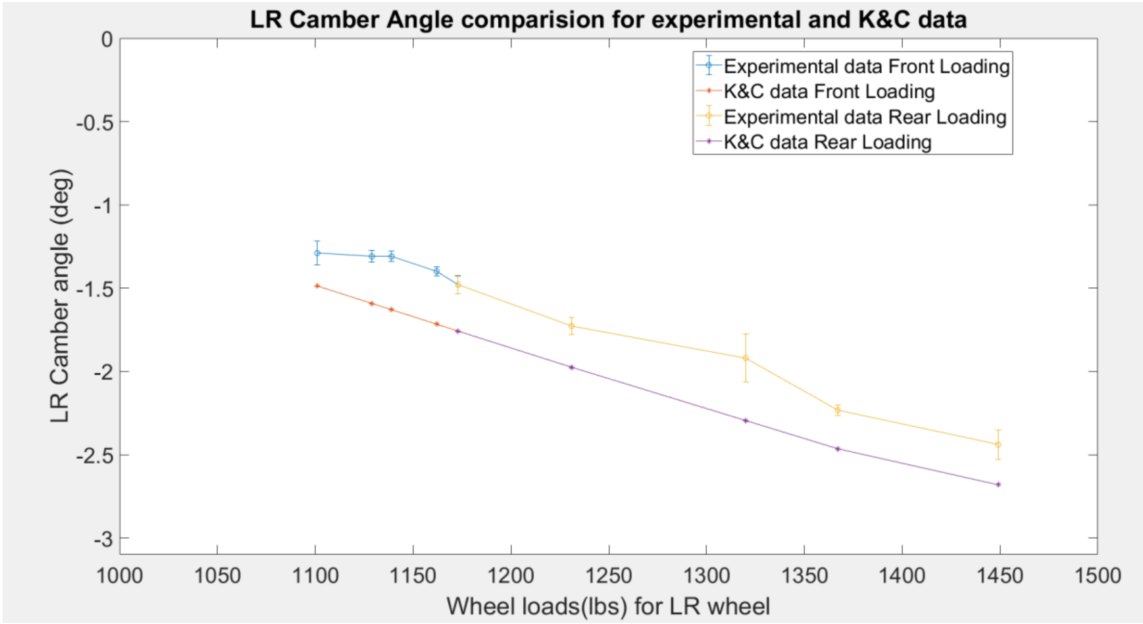

FIGURE 5. 37 K&C and experimental data comparison of LR Camber

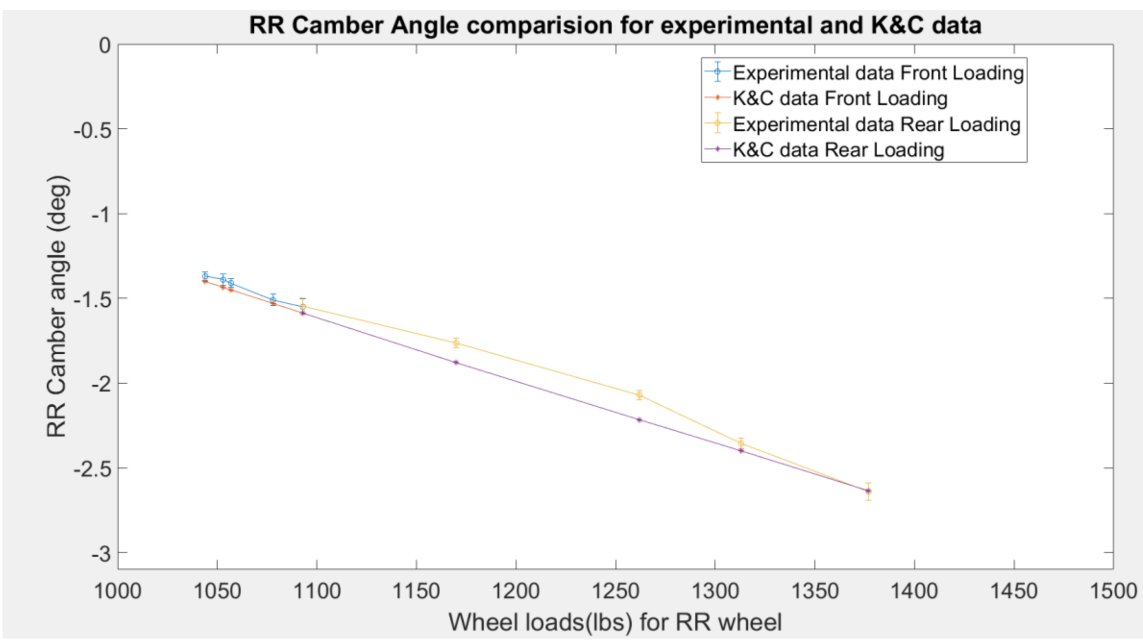

FIGURE 5. 38 K&C and experimental data comparison of RR Camber

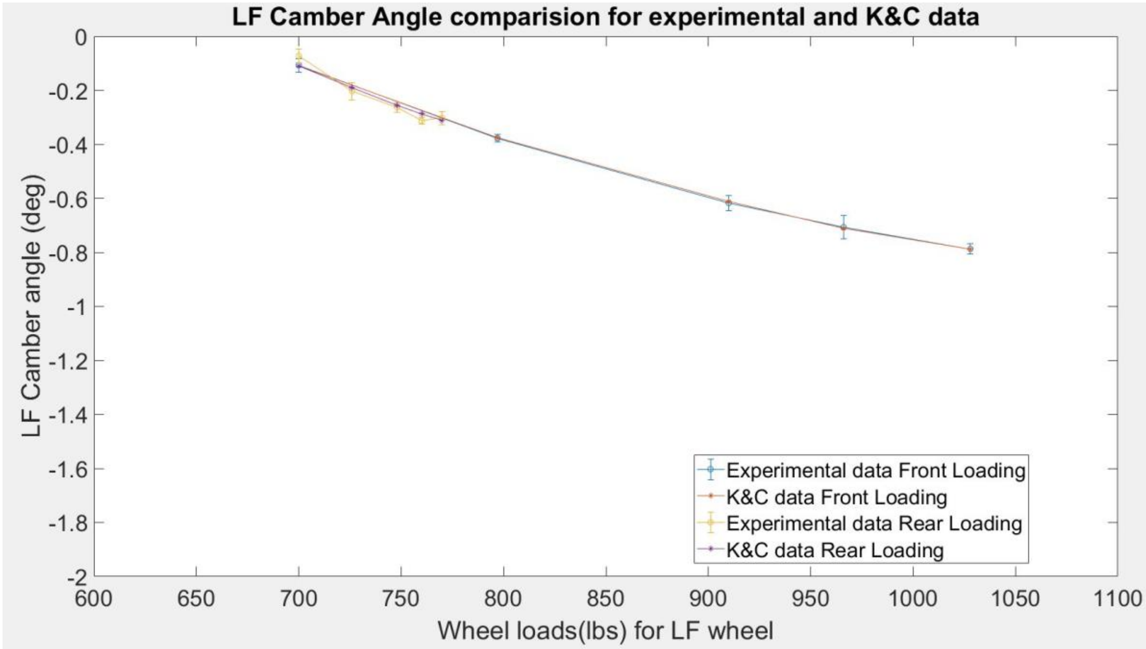

FIGURE 5. 39 K&C and experimental data comparison of LF Camber with no offset

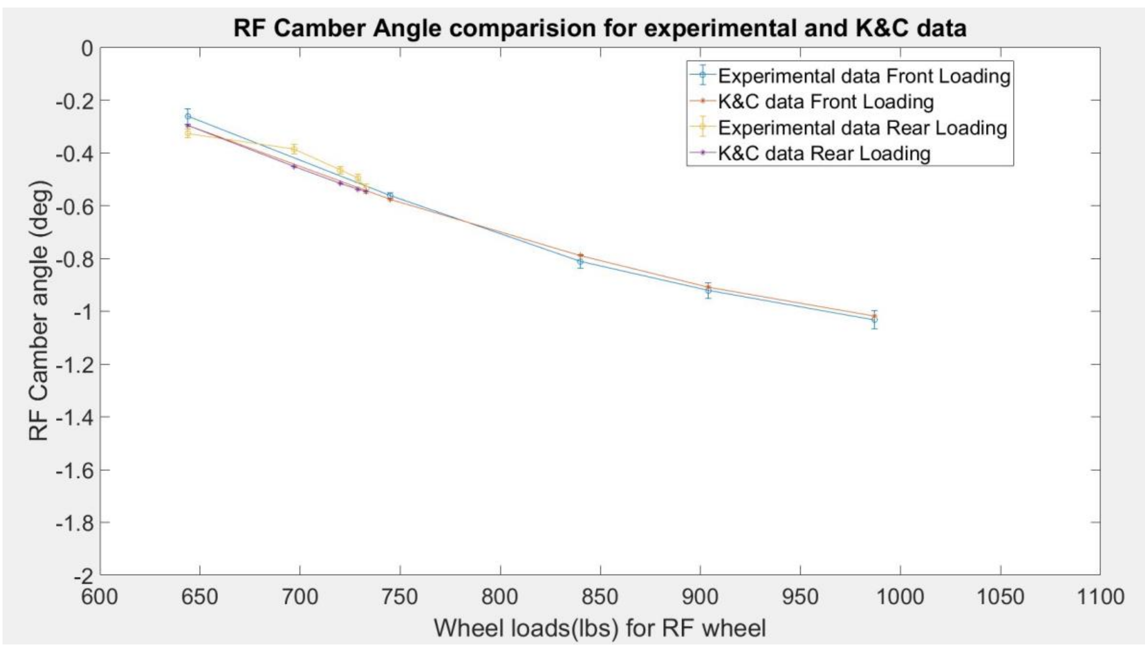

FIGURE 5. 40 K&C and experimental data comparison of RF Camber with no offset

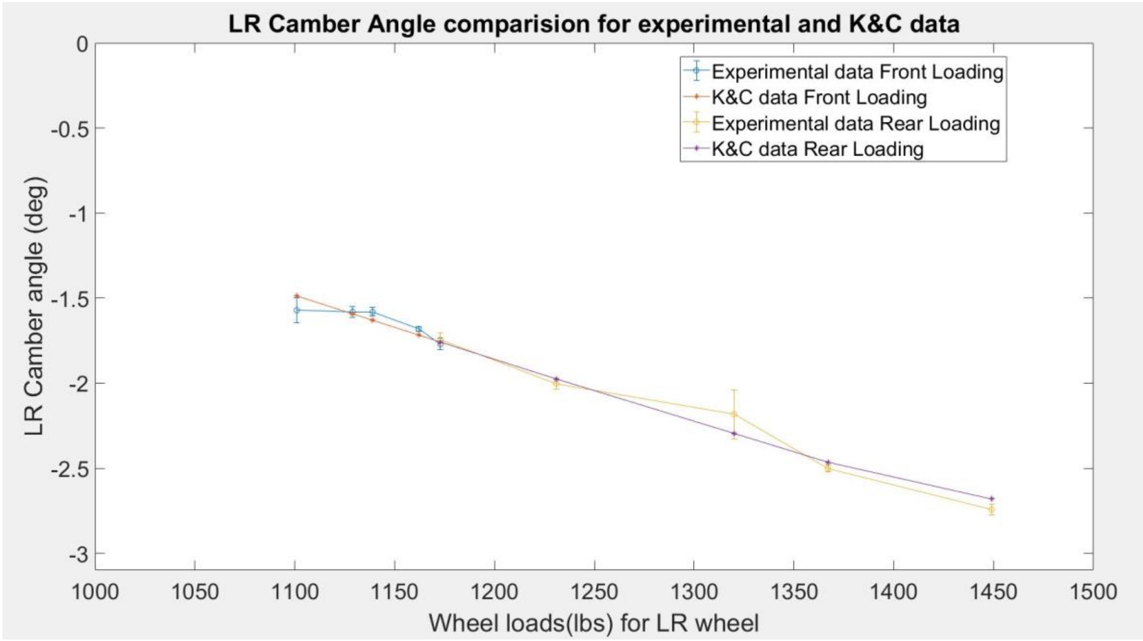

FIGURE 5. 41 K&C and experimental data comparison of LR Camber with no offset

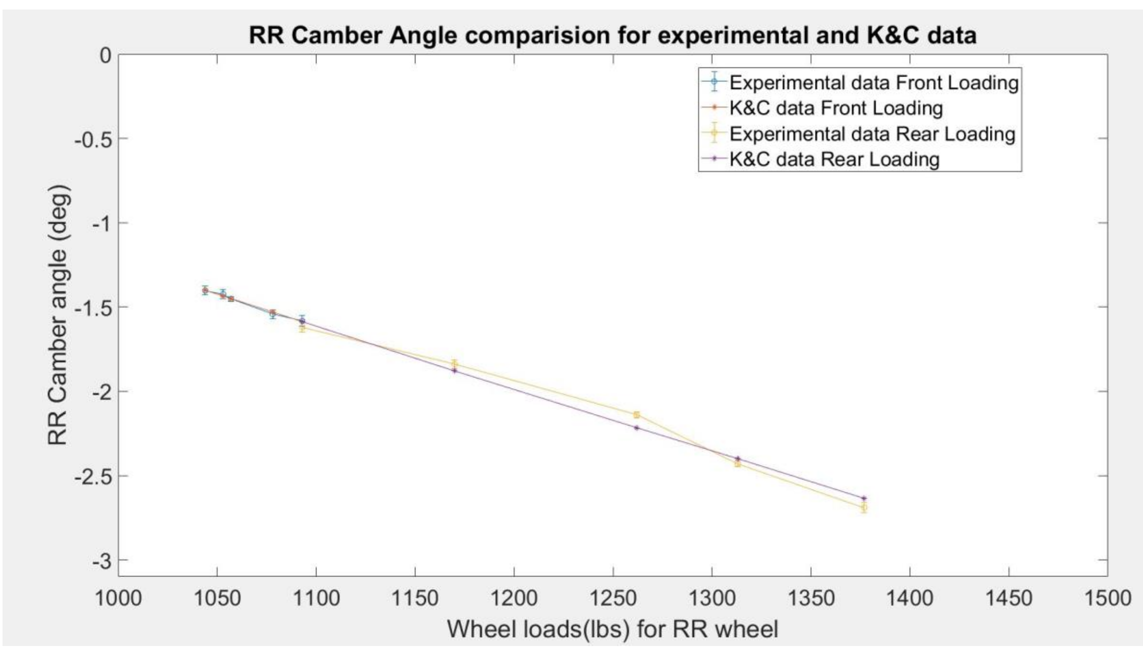

FIGURE 5. 42 K&C and experimental data comparison of RR Camber with no offset

Thus, we can see that my experimental data follows the same trend as that of the K&C data obtained from the Morse Measurements. There is a decrease of camber angle as with the increase in the load. From the toe and camber comparison with K&C data we can validate that there is a decrease in camber angle with increase in load on all the four wheels. There is a decrease in toe angle with the increase in load at the front two wheels, however, we can see an increment in the toe angle for an increase in the load. Thus, there is a direct relationship of rear wheel's toe and load. There is an inverse relation of the front toe and load. We can also see that the standard deviation is very less for front wheels in case of both front and rear loading. There are less anomalies in case of the front wheels. However, we can see greater anomalies and greater standard deviations in case of the rear wheels for, both, front and rear loading.

5.3 Suspension Analysis

In order to explain why the rear wheels behave differently, when we compare it to the front wheels, we need to look at the suspension system at the front and the rear wheels of the car. If we take a close look at the Front Loading Case LF and RF wheels for camber and compare it with Rear loading case LR and RR wheels for camber we see that the change in camber angle over 500lbs is 0.75° for LF, 0.8° for RF, 0.9° for RR and 0.83° for LR. At a glance these values look the same, but a closer analysis reveals otherwise. Use Figure 5.6, 5.7, 5.20, and 5.21. The position of the front loading is on or ahead of the front axle, Thus, entire loading on the front trunk affects the front suspension. However, the rear loading is done on the rear seat of the Porsche, which is very close to the rear axle but still between front and rear axle. Thus, not entire weight loaded in rear case is translated to the rear suspension, but some part of its loading is shared between front and the rear axle. Still we see a little more deflection on the rear suspension than the front suspension.

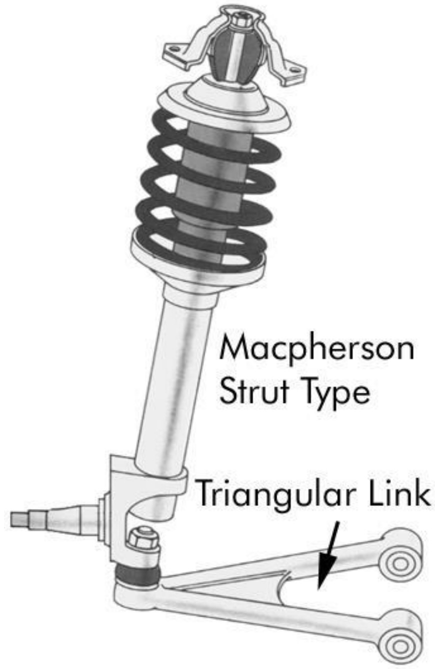

FIGURE 5. 43 MacPherson Strut Suspension [13]

The reason for this is the difference in the suspension types at the front and the rear wheels. The front wheels use MacPherson Strut Suspension and the rear wheels use multilink suspension. In Porsche it uses 5 link suspension. [4] A MacPherson Strut Suspension has a steering knuckle with two mounting points, one is mounted to the control arm and the other is attached to spring coil and the shock absorber. The control arm and the steering knuckle is attached to each other using a ball joint. The rear suspension is a multilink suspension for a purpose that facilitates better tuning of suspension according to the consumer needs. The suspension links are connected to each other using bushings rather than ball joints. The multilink suspension is a softer suspension is a softer of the two and this explains why the camber change is more in case of the rear wheels as compared to the front wheels. This also explains the behavior of rear wheels is anomalous. We can also see that the error bars are higher for rear wheels as compared to the front wheels. Thus, variability is higher in the rear wheels as compared to the front wheels.

5.4 Conclusion

In this thesis we have evaluated the variability of the wheel alignment measurements under different load conditions such as front loading, rear loading and side loading. We have looked at Camber, Caster and Toe as a function as these loads. In order to get the data for these trends, almost 500 measurements were performed on the four post. The four post was used instead of a two post in order to reduce the time required to carry out multiple wheel alignments. A support stand was used to rest the vehicle when the wheels are lifted off the ground which brought about a truncation in time by about 35% - 40% as compared to the use of two post lift.

Trends in the wheel alignment parameters were observed in the result section and we can conclude that camber angle decreases when the load increases. The slope of the curve increases with increase in the load. For loading on one side, the camber angle decreases faster on the opposite side. For Toe, it decreases on the front wheels as load increases on the front wheels. The toe increases as the load increases for the rear wheels. Bump steer effects are observed on the toe graphs. This prevents the oversteering of the car while negotiating the turn. The caster decreases as a function of loading. The behavior of LR and RR wheel is anomalous because of the use of softer suspension which is multilink suspension at the rear. The front suspension is MacPherson Strut suspension. Thus, we see that the variability in the rear suspension is more than the front suspension as the rear one is softer than the front suspension.

The comparison of K&C reveals surprisingly close results of toe and camber vs wheel loads as seen in the sections above. The front wheel alignment trends are identical to the K&C data point by point for camber and toe. Rear wheels also show a similar trend. Due to these results, I can say that there is a scope for experimentation and research to evaluate rolling test as well. We can improve the current setup by using load cells and wheel force sensors.

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