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Parametric Study for Vehicle Response and Stability

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Abstract

Vehicle response and stability plays important role in ensuring superior handling characteristics, especially on diverse and challenging Indian road conditions. This paper focuses on parametric benchmarking of vehicle response and stability, giving a systematic approach to analyze these parameters as well as to set performance target during initial stages of vehicle development. In this paper, key parameter like front and rear roll steer coefficient, front and rear compliance steer, tire cornering stiffness, vehicle characteristic speed and yaw rate gain are analyzed using data measured from vehicle dynamics test bench. By analyzing the relation between these parameters, this paper aims to provide insights that will be helpful in decision making for vehicle development. The findings from this study will assist readers how to use data from vehicle dynamics test bench for benchmarking as well as to analyze the vehicle handling performance.

Keywords: Vehicle dynamics, response and stability, yaw rate gain, slip angle gradient, understeer gradient, compliance steer, roll steer, tire cornering stiffness, vehicle characteristics speed, benchmarking, target setting, handling performance, twist beam, multi-link suspension.

1. INTRODUCTION

Vehicle dynamics is an important area of focus in automotive industry, as it influences the customer buying decision based on how good vehicle ride and handling qualities are. Among various aspects of vehicle dynamics, vehicle response and stability are crucial aspect that defines how vehicle handles in different driving conditions. This performance influence driver's confidence, passenger comfort and safety making it essential to consider during vehicle development. In region like India, where there are diverse driving road conditions, vehicle response and stability play crucial role as a buying factor.

This paper focus on parametric approach for benchmarking vehicle response and stability, including setting performance target during initial stage of vehicle development. A structured framework for evaluating vehicle performance against other vehicle is demonstrated in this paper, thereby enabling manufacturers how they can identify key areas of improvement and align with customer expectation and market requirements using this framework.

Parameters used in this study includes front and rear roll steer coefficients, front and rear compliance steer, tire cornering stiffness, vehicle characteristic speed and yaw rate gain. For this study we have chosen 6 vehicles which are hatchback and of same segment, but with different rear axle, for better analysis of influence of different suspension on handling. Parameters data are measured on vehicle dynamics test

bench and this data is than analyzed using charts.
This analysis helps to study the performance as well as compare the performance of vehicle with respect to other vehicle and helps in decision making for setting initial level targets during initial stages of vehicle development. In subsequent section, parameters, methodology and analysis of this study have been discussed.

2. Vehicle Response and Stability Parameters

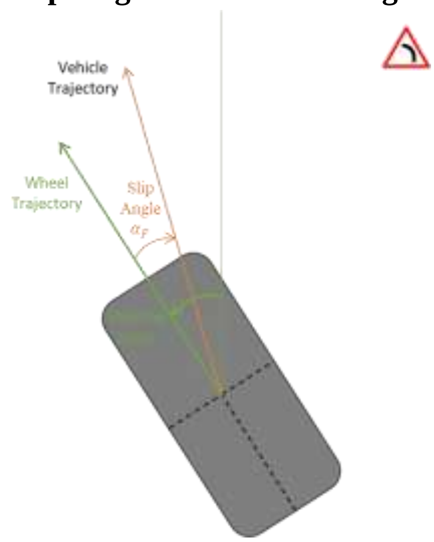
2.1 Axle Lateral Stiffness

Lateral stiffness is an important parameter for vehicle response and stability. Axle lateral stiffness is the resistance of suspension system to the lateral forces acting on front and rear axle. Higher axle lateral stiffness is preferred because, it improves steering response due to less compliance related delays, helps in reducing understeer, improves cornering stability, provides better agility and provides better overall vehicle balance during lateral transitions [1].

2.2 Slip Angle Gradient

Slip angle is the angle formed between tire's direction of travel and the direction in which it is pointing as shown in figure 1. Slip angle is generated due to lateral force, causing it to deviate from intended path. This occurs due to elastic deformation of tire under load.

Figure 1. Slip Angle of Vehicle during Turning.

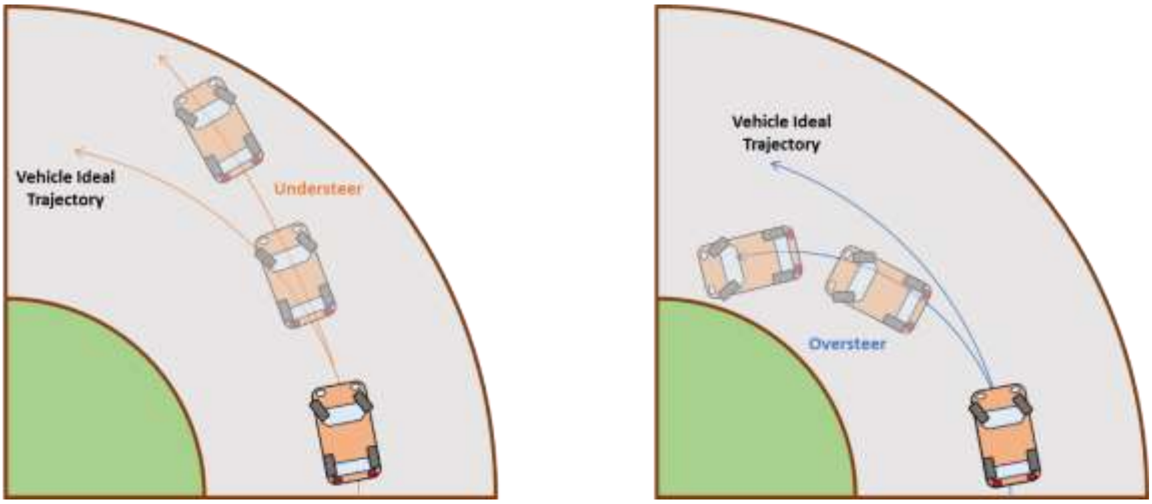


Slip angle is critical in determining how vehicle responds to steering inputs. A high slip angle can show delay in response or loss of lateral grip, which affects the handling characteristics [2]. Similarly, a well optimized slip angle shows better control and stability, ensuring a confident driving experience.
Slip angle gradient refers to rate of change of slip angle with respect to lateral force, where:
$\Delta\alpha^{s}$, Slip angle gradient.
$\Delta\alpha_{F}$, Change in front slip angle.
ΔF_{y}, Change in lateral force.
Therefore, Slip angle gradient in front, $\Delta\alpha_{F}^{s} = \frac{\Delta\alpha_{F}}{\Delta F_{y}}$ (1)

2.3 Understeer Gradient

Understeer and oversteer are key handling characteristics that represents how a vehicle responds to steering inputs during cornering. Understeer occurs when front tires of vehicle lose grips before the rear tires, causing vehicle to turn less than intended [3]. Opposite to that, oversteer occurs when rear tires of vehicle lose grip first, making vehicle to turn more than intended. Both understeer and oversteer are important for optimizing vehicle handling balance.

Figure 2. Vehicle Trajectory during Understeer and Oversteer.



The understeer gradient quantifies degree of understeer or oversteer in a vehicle and it's an important parameter for analyzing the ease of control during cornering [4]. Understeer gradient is calculated as product of difference of front and rear slip angle gradient and the overall steering ratio.
Mathematically:
n, Overall steering ratio.
$\Delta\alpha_F^s$, Front slip angle gradient.
$\Delta\alpha_R^s$, Rear slip angle gradient.
Therefore, Understeer gradient, $u_s = n.(\Delta\alpha_F^s - \Delta\alpha_R^s)$ (2)
For stable vehicle $\Delta\alpha_F^s > \Delta\alpha_R^s$, if $\Delta\alpha_F^s \gg \Delta\alpha_R^s$, vehicle will have deep understeer behavior.
If a vehicle has low understeer gradient, it may offer a more agile and responsive driving experience, but it may make vehicle harder to control. Similarly, if vehicle have high understeer gradient, it may make vehicle control safer and more predictable, but it can lead to dull or boring driving experience thereby reducing engaging driving experience.

2.4 Compliance Steer

Compliance steer refers to the unintended steering effect caused due to suspension and bushing compliance under external load like lateral and longitudinal loads. Apart from steering input provided by driver, compliance steer occurs due to elastic deformation of suspension components, leading to minor but significant changes in vehicle direction.
Compliance steer that occurs due to lateral forces, for e.g. during cornering, the suspension compliance causes a steering effect as shown in Figure 3. Similarly, compliance steer occurs due to longitudinal forces, known as longitudinal compliance which can result in unwanted steering corrections [5].
Generally, most of vehicles don't have rear wheel steering, so during cornering rear axle doesn't assist the vehicle to corner, but due to compliance in suspension system and different suspension system are used by OEMs for their vehicle, there will be different rear compliance steer for different suspension system

due to their suspension geometry.

Figure 3 Steering Effect due to Compliance in Bush.

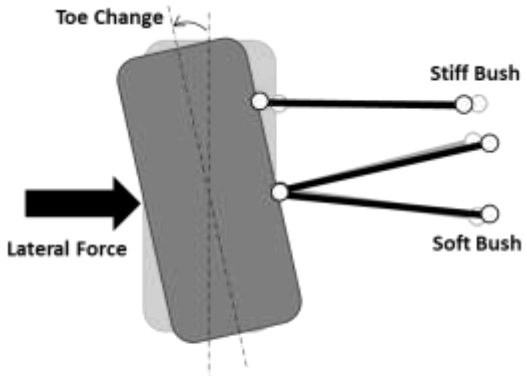
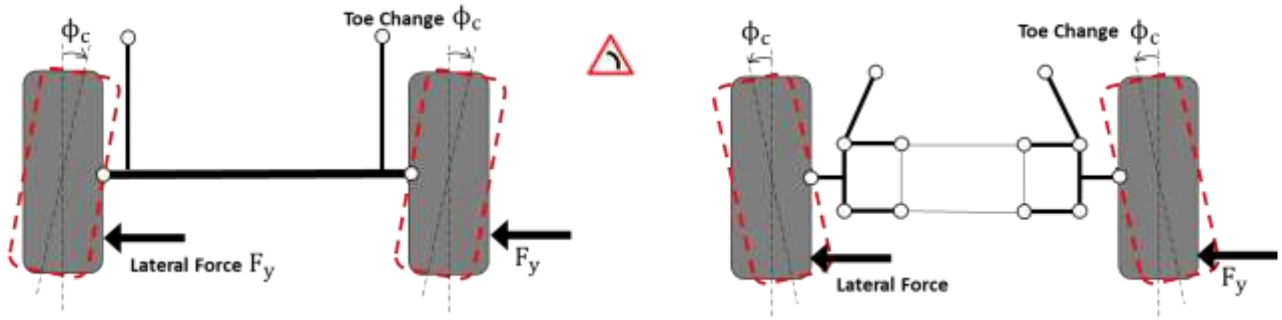


Figure 4. Compliance Steer in Twist Beam and Multi-link Rear Suspension during Cornering.



Torsion beam: Oversteer compliance steer.

Compliance steer; $C_c = \frac{\phi_c}{F_y} < 0$ (3)

Multi-link: Understeer compliance steer.

Compliance steer; $C_c = \frac{\phi_c}{F_y} > 0$ (4)

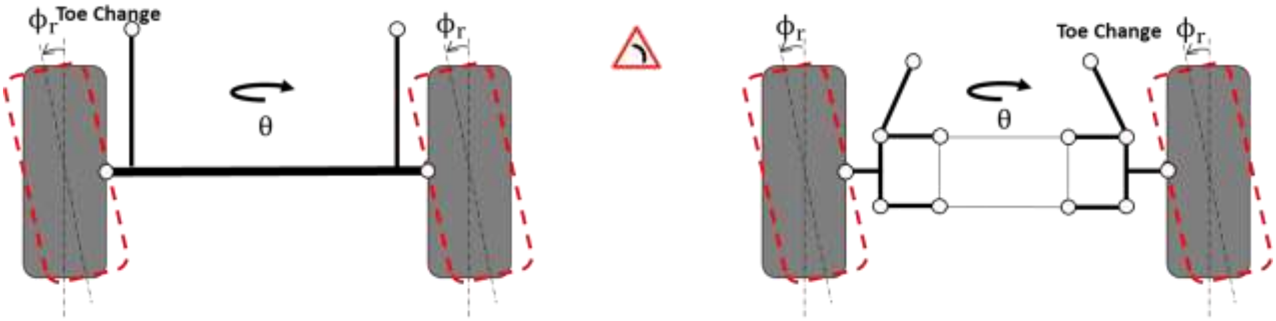
As shown in Figure 4, if vehicle have torsion / twist beam suspension setup, the rear of vehicle tends to oversteer due to compliance steer, similarly if vehicle have multi-link suspension system, then rear of vehicle tends to understeer. This compliance steer at rear can make vehicle stable or unstable during cornering.

2.5 Roll Steer

Roll steer is the steering effect induced on front and rear axle due to vehicle body roll. During cornering, lateral load causes the vehicle body to roll outer side of the turn. Due to this roll motion the outer suspension compress, and the inner suspension extends, leading to variation in wheel toe angles due to suspension geometry. These toe changes result in steering effect without any direct input from driver.

This roll steer influences vehicle understeer and oversteer behavior, if the rear wheel toe in on the compression during roll, it causes understeer effect and reduces oversteer [6]. Similarly, if rear wheel toe out on the compression side, it causes oversteer making vehicle more responsive and may lead to reduced stability at high speeds.

Figure 5. Roll Steer in Twist Beam and Multi-link Rear Suspension during Cornering.



Where, θ is vehicle roll angle.
Torsion beam / Twist beam: very understeer roll steer.

Roll Steer Coefficient; $C_r = \frac{\phi_r}{\theta} \gg 0$ (5)

Multi-link: slightly understeer roll steer.

Roll Steer Coefficient; $C_r = \frac{\phi_r}{\theta} > 0$ (6)

As we have seen in compliance steer, the effect of suspension geometry at rear can change the vehicle stability and response characteristics, similarly in roll steer, if vehicle is having twist beam suspension setup at rear, vehicle can have high understeer due to roll steer as shown in Figure 5. Similarly, if vehicle have multilink suspension at rear it is having slight understeer roll steer characteristics [7].

2.6 Yaw Rate Gain

Yaw rate gain is vehicles yaw rate to steering wheel input. Yaw rate gain shows how much a vehicle responds to given steering commands, and it is important for defining vehicle agility, stability. And handling precision. A high yaw rate gain shows that with a small steering input there will be a high yaw response, which shows vehicle having high agility. Similarly, if yaw rate gain is low, it shows vehicle is bit unresponsive or less agile to steering inputs. If yaw rate gain is too high in a vehicle, vehicle may become over sensitive and will make it difficult to control at high speeds [8].

2.7 Vehicle Characteristics Speed

Vehicle characteristics speed is the speed at which vehicle gains its maximum yaw rate gain [9] as shown in Figure 6. Vehicle characteristics speed shows the speed at which a vehicle gains peak responsiveness and plays a key role in determining its handling characteristics.

A vehicle must have good medium vehicle characteristics speed as it will make vehicle easy to control as well as agile for the driver. If a vehicle has lower vehicle characteristics speed, than vehicle will be very hard to control for a driver, and if vehicle is having higher vehicle characteristics speed, than at slow speed vehicle will be very sluggish and less responsive to steering inputs.

Figure 6. Vehicle Speed vs Yaw Rate Gain Graph.

3. Methodology

For this study, we are taking 6 vehicles for better understanding of vehicle response and stability for different rear axle like twist beam and multi-link. In this vehicle A is having multi-link suspension at rear, Vehicle B and C are same vehicle but with different rear suspension – vehicle B is having multi-link, and vehicle C is having torsion / twist beam suspension., similarly Vehicle D and E are same vehicle but again with different rear suspension – vehicle D is having torsion / twist beam, and vehicle E is having multi-link suspension and lastly Vehicle F which is having twist beam rear suspension system. We have tries to keep different types of vehicles with different vehicle to gain better insight thru this study for vehicle response and stability. Parametric data of these vehicles are taken from vehicle dynamics test bench and are organized in excel sheet or table as shown in the chart, further these data of different vehicles are compared using charts which is presented in analysis section of this paper.

Table 1: Vehicle Response and Stability data of measured vehicle.

Vehicle Name	Vehicle A	Vehicle B	Vehicle C	Vehicle D	Vehicle E	Vehicle F
Front track	1591 mm	1529 mm	1537 mm	1565 mm	1570 mm	1518 mm
Rear track	1586 mm	1495 mm	1510 mm	1548 mm	1560 mm	1499 mm
Wheelbase (l)	2669 mm	2630 mm	2635 mm	2705 mm	2700 mm	2650 mm
Vehicle Mass	1280 kg	1383 kg	1262 kg	1315 kg	1394 kg	1253 kg
Overall steering ratio (n)	16.1	14.9	14.9	14.4	14.4	15.2
Front axle lateral stiffness	703 N/mm	1035 N/mm	1075 N/mm	1554 N/mm	1496 N/mm	813 N/mm
Front roll steer coefficient (C_r^F)	-10.0%	-7.0%	-5.6%	-8.3%	-8.3%	-4.0%
Front compliance steer (C_c^F)	-0.91 mrad/kN	-2.98 mrad/kN	-2.64 mrad/kN	-0.75 mrad/kN	-0.60 mrad/kN	-0.93 mrad/kN
Rear axle lateral stiffness	555 N/mm	664 N/mm	569 N/mm	386 N/mm	765 N/mm	523 N/mm
Rear roll steer coefficient (C_r^R)	12.0%	1.3%	16.6%	5.3%	4.6%	15.4%
Rear compliance steer (C_c^R)	-0.50 mrad/kN	0.40 mrad/kN	-0.94 mrad/kN	-0.16 mrad/kN	-0.01 mrad/kN	-0.95 mrad/kN
Understeer gradient	3.6 ° s²/m	3.1 ° s²/m	3.4 ° s²/m	2.9 ° s²/m	3.1 ° s²/m	3.7 ° s²/m
Vehicle characteristic speed (Vch)	26.3 m/s	27.1 m/s	25.6 m/s	27.7 m/s	26.9 m/s	25.0 m/s
Max yaw rate gain @ Vch	0.30 s⁻¹	0.35 s⁻¹	0.33 s⁻¹	0.36 s⁻¹	0.34 s⁻¹	0.31 s⁻¹
Axles contribution to understeer gradient	0.114 ° s²/m	0.207 ° s²/m	0.186 ° s²/m	0.081 ° s²/m	0.081 ° s²/m	0.086 ° s²/m

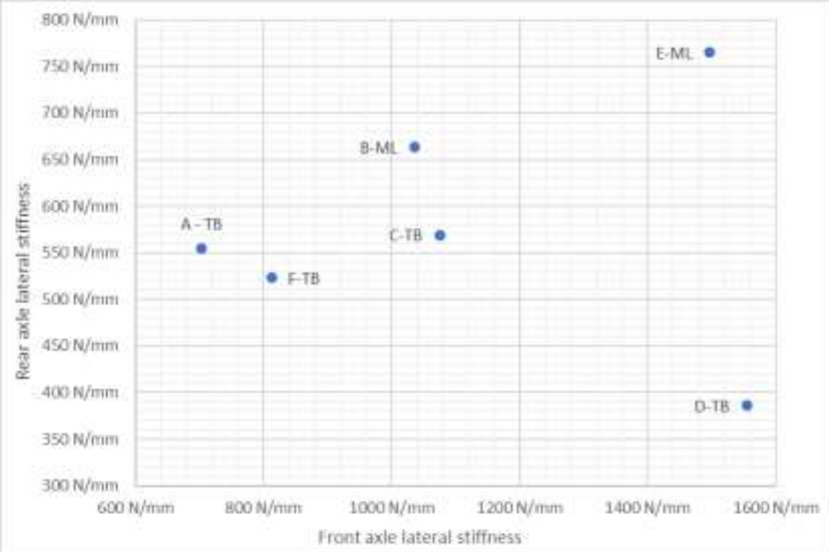
Axle contribution to slip angle gradient	-0.029 ° s²/m	-0.022 ° s²/m	-0.035 ° s²/m	-0.013 ° s²/m	-0.017 ° s²/m	-0.025 ° s²/m

4. Analysis

4.1 Axle Lateral Stiffness:

In this paper we are comparing front and rear axle lateral stiffness for the selected vehicle. The result are shown in Figure 7 as form of chart. From the chart, Vehicle E is having highest front and rear axle lateral stiffness, indicating superior responsiveness and better chassis balance. Vehicle D shows huge difference in front and rear axle lateral stiffness, this difference may lead to oversteer behavior, especially at higher speeds or during sudden lane changes. (TB: Twist Beam, ML -Multi-link)

Figure 7. Front Axle vs Rear Axle Lateral Stiffness Chart.

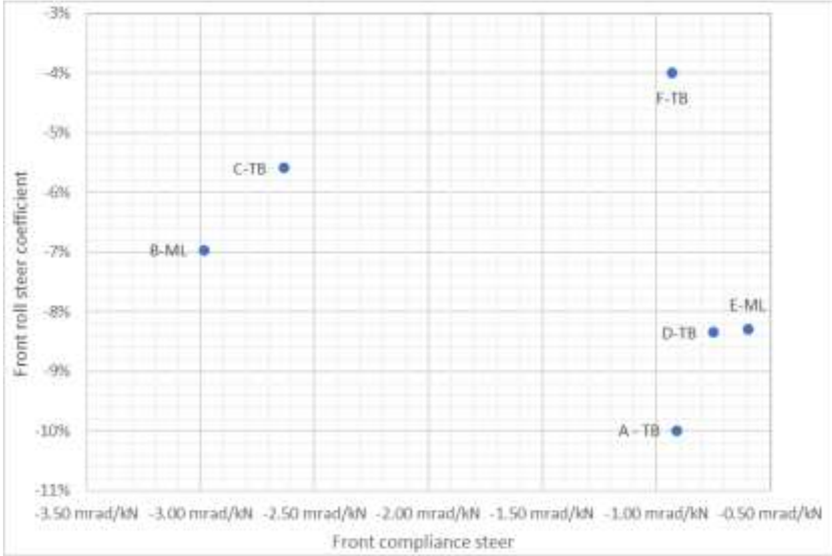


Vehicles B and C are having moderate front and rear lateral stiffness, showing a more balanced handling characteristic with a gradual understeer tendency. Such type of setup is generally preferred for regular driving, as it provides good balance between handling performance and ride comfort. Vehicles A and F are having lower front and rear axle lateral stiffness among other vehicles. Low lateral stiffness can result in delayed steering response, making the vehicle feel less agile and predictable during dynamic maneuvers. By this type of comparison and analysis we define the initial level performance target during initial vehicle development phase.

4.2 Front Roll Steer Coefficient and Compliance Steer:

In this analysis, the front compliance steer and roll steer coefficient are evaluated to understand the understeer characteristics of each vehicle. From Figure 8, Vehicles D and E shows a well-balanced understeer behavior, as they have optimal roll steer coefficient and compliance steer values, which shows these vehicles are having predictable handling, and good stability during cornering. Vehicle A is having a high negative roll steer coefficient, which indicates higher understeer characteristics during roll motion, this can lead to delay in response as well as reduced agility.

Figure 8. Front Compliance Steer vs Front Roll Steer Coefficient Chart.

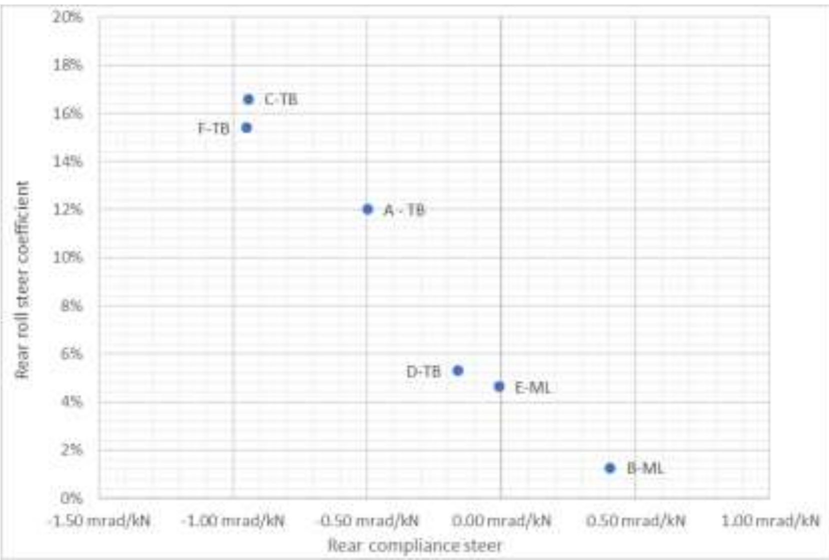


Vehicles F shows relatively higher responsiveness due to less negative roll steer coefficient values, precise handling to steering inputs while maintaining stability. On the other hand, Vehicle B and C have high compliance steer value, indicating delay in handling. This may increase deep understeer to steering inputs may lead to instability, making the vehicle difficult to control, especially in high-speed or sudden maneuvering conditions. By this analysis we can decide the amount of understeer performance to be kept for vehicle during initial vehicle development stage.

4.3 Rear Roll Steer Coefficient and Compliance Steer:

From Figure 9, Vehicles E and B shows strong rear support, with Vehicle E demonstrating a high roll steer coefficient along with good rear compliance steer. Similarly, Vehicle B also has a high rear compliance steer value combined with a favorable rear roll steer coefficient, contributing to improved rear-end stability. Multi-link suspension systems provide good cornering support compared to torsion beam or twist beam suspension setups from above analysis.

Figure 9. Rear Compliance Steer vs Rear Roll Steer Coefficient Chart.

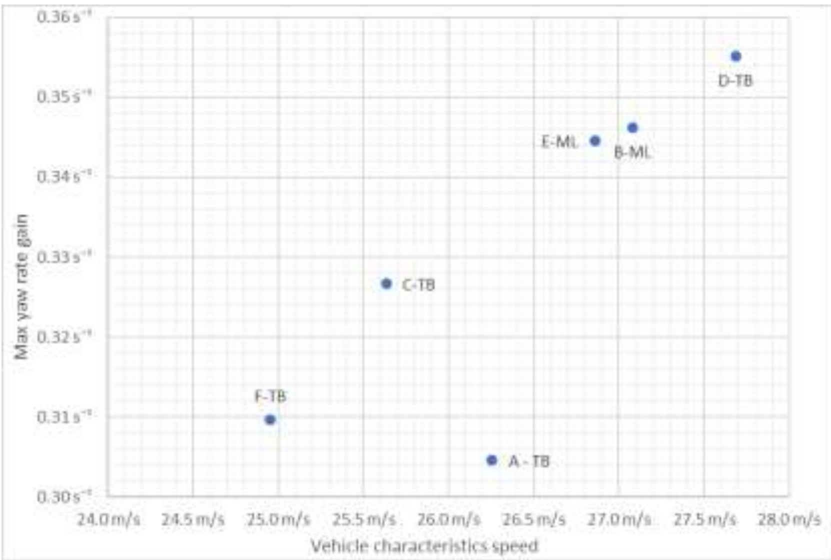


Due to the inherent oversteer tendency of torsion or twist beam suspensions in compliance steer, a higher roll steer coefficient is desirable to counteract oversteer by inducing understeer through roll motion. Vehicles C and F indicates good rear support with balanced understeer behavior in comparison to other twist beam / torsion beam suspension vehicle of this study. Vehicle A indicates moderate support and response, but Vehicle D indicates least understeer characteristics in comparison to other vehicles. Due to weak rear support in Vehicle D, it leads to increased instability during cornering, which compromises handling performance. By comparing rear roll steer coefficient and compliance steer value of different vehicles, it helps to understand the balance of vehicle and helps in setting the performance of vehicle during initial development stage of vehicle.

4.4 Max Yaw Rate Gain and Vehicle Characteristics Speed:

This analysis studies the relationship between vehicle characteristic speed and maximum yaw rate gain, which shows performance of vehicle's responsiveness. Generally, a higher yaw rate gain indicates better responsiveness, adding to improved agility and handling.

Figure 10. Vehicle Characteristics Speed vs Max Yaw Rate Gain Chart.



From Figure 10, Vehicle F shows the highest agility in this study, due to low vehicle characteristics speed. Similarly, Vehicles C and A, also show good response characteristics, making them well-suited for predictable handling. Vehicles E and B shows slightly higher responsiveness, indicating improvement in agility compared to Vehicle A, C and F. Vehicle D, however, have the highest responsiveness among all the vehicles analyzed, making it more responsive but less agile in comparison due to high vehicle characteristics speed. Optimizing yaw rate gain and vehicle characteristic speed is important in achieving balanced handling, ensuring a vehicle remains predictable and responsive to driver inputs. From this analysis we can decide or compare vehicles responsive performance parameter.

4.5 Slip Angle Gradient and Understeer Gradient:

This analysis studies the relationship between slip angle gradient and understeer gradient to understand vehicle stability and responsiveness. In Figure 11, Vehicle C indicates good stability, due to good understeer gradient and a low slip angle gradient, showing good response characteristics of vehicle. Vehicles A, B, and F are having moderate understeer gradient values, which indicates stability of vehicle with good predictability due to average slip angle gradient values.

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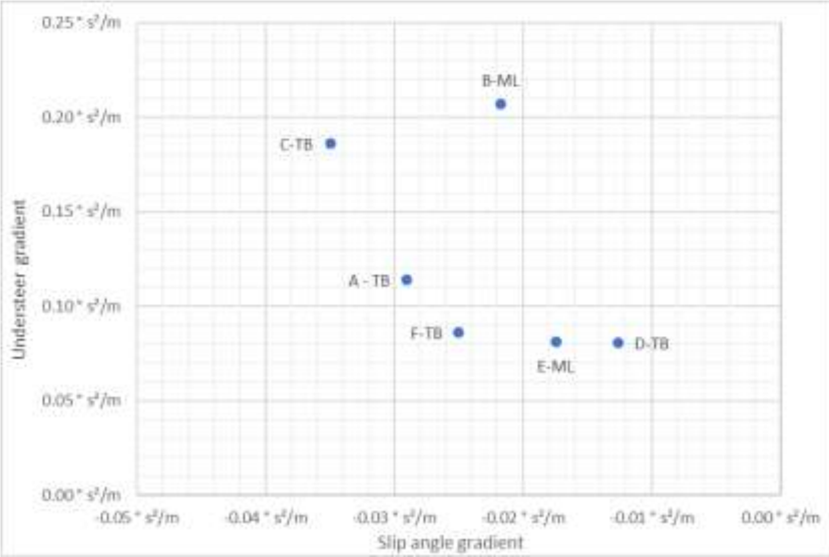
Figure 11. Slip Angle vs Understeer Gradient Chart.



Vehicles E and D also have good stability due to good understeer gradient values. But, due to higher slip angle gradient in comparison to other vehicles indicates delay in response, which makes them slightly less agile in dynamic driving conditions. By this type of analysis, it helps to understand vehicle performance based on slip angel gradient and understeer gradient and helps in defining the targets.

From the above analysis, it shows that vehicle stability and responsiveness cannot be defined by a single parameter. Instead, multiple parameters influence a vehicle's performance under various conditions. The findings from the analysis shows that Vehicle E is having superior response and stability in comparison to the other vehicle, also it shows that multi-link suspension provide good stability and handling in comparison to twist beam / torsion beam suspension. By this structured analysis helps in benchmarking of vehicle performance and gives valuable insight for setting initial targets during the early stages of vehicle development as shown in Table 2.

Table 2. Summary of Analysis.

Vehicle Response and Stability Parameter	**Best**	**Average**	**Below Average**
Axle Lateral Stiffness	Front: 1500 N/mm Rear:800 N/mm	Front: 1000 N/mm Rear: 500 N/mm	Front: 800 N/mm Rear: 400 N/mm
Front Compliance Steer	-0.5 mrad/kN	-1.0 mrad/kN	-1.5 mrad/kN
Rear Compliance Steer	TB: -0.1 mrad/kN ML: 0.5 mrad/kN	TB: -0.5 mrad/kN ML: 0.3 mrad/kN	TB: -1.0 mrad/kN ML: 0 mrad/kN
Front Roll Steer Coefficient	Between -4 % to -10 %		
Rear Roll Steer Coefficient	TB: 20 % ML: 7 %	TB: 14 % ML: 5 %	TB: 5 % ML: 0 %
Max Yaw Rate Gain	0.36 s^{-1}	0.33 s^{-1}	0.30 s^{-1}
Vehicle Characteristics Speed	24.5 m/s	26.5 m/s	28 m/s
Understeer Gradient	Between 0.05 ° s^2/m and 0.3 ° s^2/m		

Slip Angle Gradient	-0.04 ° s²/m	-0.02 ° s²/m	0 ° s²/m

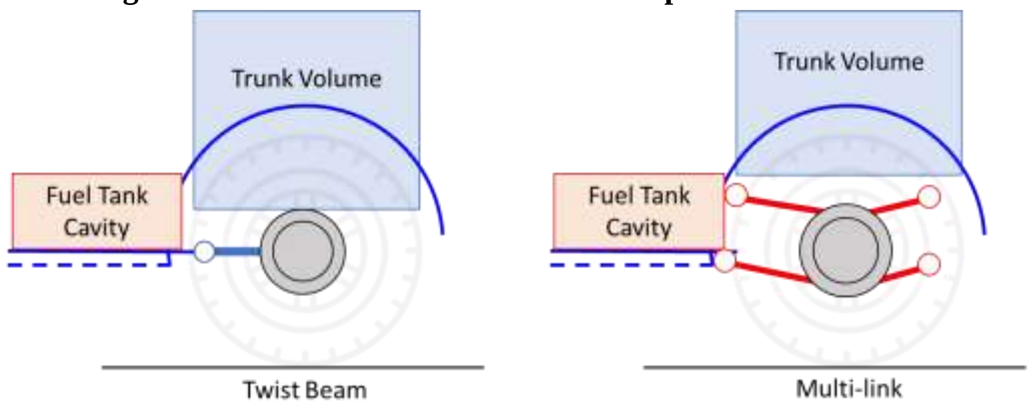
5. Multi-Link Suspension Integration :

As we have seen multi-link suspension is better in terms of providing good rear support during cornering and offers superior chassis balance compared to twist beam or torsion beam suspension, this is due to their ability to independently control wheel kinematics (camber, toe, and caster) across a range of driving conditions. By employing multiple lateral and longitudinal control arms, multi-link systems decouple vertical, lateral, and longitudinal forces, enabling precise tuning of the suspension's kinematic and compliance characteristics. This results in, reduced wheel alignment errors under cornering, braking, and uneven surfaces, enhancing tire contact and grip. Better management of body roll and lateral load transfer, improving cornering stability. Still lot of vehicles are not adopted with multi-link rear suspension, or it is offered in premium vehicles, as multi-link suspension system comes with certain constraints.

Constraints of Multi-Link suspension:

Despite their performance advantages, multi-link systems face several adoption challenges like cost and complexity due to more components (links, bushings, subframes), increasing material and assembly costs. Another factor is precise calibration of link geometries and elastokinematic properties for bushes which demands advanced simulation tools and testing, raising R&D expenses.

Figure 12. Twist Beam Vs Multi-Link Suspension Illustration.



Compared to twist beam suspension multi-link system face huge packaging constraints like multi-arm layout occupies significant underbody space, conflicting with trunk volume, fuel tank placement, or aerodynamic underbody panels, integrating multilink systems in compact or front-wheel-drive (FWD) vehicles often necessitates a rear subframe, complicating weight distribution, and in electric vehicles, battery packaging constraints may limit the feasibility of multilink rear suspensions. Also, in multi-link suspension due to increase in components, it increases the complexity to package and route the flexible parts like brake hose, sensors wires, etc., there by increasing the complexity as well as vehicle development time.

Other factors like, higher component count increases susceptibility to bushing wear and joint fatigue, potentially raising long-term maintenance costs. Exposure to road debris and corrosion in harsh environments can compromise durability compared to the robust, sealed twist beam design.

Why Twist Beam Remains Competitive:

Twist beam suspensions, while less sophisticated, offer distinct advantages in cost-sensitive and space-constrained applications. A single torsion beam and trailing arms simplify packaging, freeing space for cargo or electrification components. Fewer parts and simpler manufacturing make twist beams ideal for economy vehicles. Robust welded construction ensures reliability in low-maintenance use cases.

Drawback of Twist Beam:

As we have seen, twist beam suspension do not provide good rear support during cornering, which limits the handling as well as stability of the vehicle. Also due to dependent nature of twist beam suspension overall ride comfort and body motion of a vehicle performance is poor compared to multi-link suspension system and its limitation to only front wheel drive vehicle is also another drawback.

While multi-link systems excel in delivering refined stability and dynamic balance, their adoption is constrained by cost, packaging complexity, and maintenance trade-offs. Twist beam suspensions remain a pragmatic choice for manufacturers prioritizing affordability and space efficiency over high-performance handling. Advances in multilink modular designs and lightweight materials may narrow these gaps, but current market segmentation ensures both systems coexist to serve diverse vehicle requirements.

6. Conclusion

This technical paper presents a detailed analysis of the key parameters influencing vehicle response and stability. The study focuses on critical aspects such as front and rear axle lateral stiffness, compliance steer, roll steer coefficients, maximum yaw rate gain, vehicle characteristic speed, understeer gradient, and slip angle gradient. Through a systematic evaluation of these factors, we analyzed various vehicle configurations to assess their impact on handling dynamics.

Our findings indicate that multi-link suspension systems provide superior stability and chassis balance during cornering compared to twist beam or torsion beam suspension setups. Specifically, Vehicle E, equipped with a multi-link suspension, demonstrated enhanced response and stability characteristics compared to Vehicle D, which features a twist beam suspension. However, the constraints of implementing a multi-link suspension, such as increased complexity, packaging challenges, and cost implications, were also discussed in contrast to simpler torsion beam designs.

Furthermore, the study reinforces that vehicle response and stability cannot be defined by a single parameter; instead, multiple factors collectively determine dynamic behavior under various conditions. By systematically analyzing these parameters, engineers can effectively benchmark vehicle performance and establish objective targets during the early stages of vehicle development. This structured approach aids in optimizing suspension tuning, improving chassis dynamics, and enhancing overall vehicle handling characteristics to meet performance and safety requirements.

In conclusion, the insights gained from this paper will guide to refine the vehicle response and stability and overall vehicle dynamics for the vehicle during initial development stage, ensuring it meets the high standards of performance and response and stability in its segment.

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