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Kinematic Analysis of a Novel Four-Wheel Independent Drive and Steering Electric Vehicles Suspension Module Design

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Abstract. Recent developments in electric vehicle (EV) technology present substantial potential for reducing carbon emissions and advancing sustainable transportation systems. In this context, the integration of four-wheel independent drive (4WID) and four-wheel independent steering (4WIS) configurations has gained attention due to their ability to enhance vehicle manoeuvrability, control, and spatial efficiency. This study proposes a novel design and conducts a comprehensive kinematic analysis of a 4WID-4WIS suspension module. The analysis, which includes a detailed chassis model and simulations involving 120 mm wheel travel, assesses the effects on key kinematic parameters, including roll center height, toe angle variation, and camber gain. Additionally, variations in hardpoint positions were analyzed to determine their influence on suspension behavior. The findings demonstrate that the optimized suspension geometry effectively minimizes undesirable kinematic responses while enabling a 90° steering capability. These outcomes offer valuable insights for developing agile, stable, and compact EV platforms, contributing to realizing space-efficient urban mobility solutions and sustainable city infrastructures.

1 Introduction

Electric vehicles offer several advantages over conventional vehicles due to their environmental benefits and the growing consumer demand for sustainable transportation solutions. As EVs continue to gain popularity, there is an increasing need to refine their design to ensure optimal performance. One of the emerging EV technologies is the Four-Wheel Independent Drive and Four-Wheel Independent Steering (4WID–4WIS) system, which allows independent

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control of the steering angle and drive/braking torque of each wheel [1]. This results in a higher degree of freedom (DOF) in control than conventional vehicles, enabling more versatile steering modes. Such advancements are particularly beneficial for improving mobility in confined urban spaces, thereby supporting the development of sustainable cities and communities [2].

The suspension system, a fundamental component in vehicle dynamics, plays a critical role in stability, ride comfort, and structural integrity. In the context of 4WID–4WIS electric vehicles, the suspension design becomes even more crucial due to the integration of in-wheel electric vehicles. This architectural shift significantly increases the unsprung mass and alters the distribution of dynamic forces between the sprung and unsprung components compared to traditional internal combustion engine (ICE) vehicles with off-wheel drive motors. These modifications influence the force transmission characteristics, directly affecting the vehicle's overall balance, stability, and safety under dynamic driving conditions.

When navigating uneven terrain or road irregularities, the increased unsprung mass reacts more abruptly to vertical excitations, transmitting amplified forces to the suspension system and chassis. This behavior alters the suspension's kinematic response, which may degrade the vehicle's handling performance if not adequately addressed. Therefore, an optimized suspension architecture capable of mitigating these effects is imperative in the design of 4WID–4WIS platforms.

Moreover, the geometric configuration of the suspension system strongly influences critical parameters such as roll center height, camber angle, caster angle, and toe variation—each of which directly impacts vehicle controllability, tire-road contact behavior, and occupant comfort. Accurately modeling these geometric factors is essential for comprehensive vehicle dynamics simulations. In particular, positioning suspension hardpoints—defined as the spatial coordinates of joints and bushing centers—directly determines the suspension's kinematic and compliance (K&C) behavior. These K&C parameters are indispensable in evaluating suspension performance under static and dynamic loading conditions, providing insights into vehicle stability and handling quality [3].

In 2023, Sadegh Yarmohammadisatri studied how suspension geometry design influences vehicle stability [4]. This study used suspension parameters as inputs in a suspension geometry model to evaluate their impact on vehicle behavior. The proposed model was simulated using Adams software and validated through experimental testing. The results showed that the determination of suspension geometry significantly affects vehicle stability. Moreover, Schmitz's research in individually steerable five-link suspension design shows that the hardpoint location optimization of the 4WID–4WIS suspension concept can improve the vehicle stability parameter [5]. Therefore, it is crucial to analyze suspension kinematics based on the hardpoint locations of a 4WID–4WIS suspension system to obtain the optimal geometry design for vehicle stability.

In this research, the parameters and dimensions of the vehicle are based on the Multi-Purpose Electric Vehicle ITS (MEVITS). MEVITS is a multi-purpose battery-powered electric vehicle developed by the Mechanical Engineering Department of ITS. Several 4WID–4WIS suspension designs were created by adopting a double wishbone (DW) suspension model with variations in hardpoint locations. These designs were then analyzed to determine the K&C parameters of the suspension under road excitation on straight and dry road conditions. The K&C parameters from each design variation will be used to evaluate and select the 4WID–4WIS suspension geometry that offers the best stability.

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2 Methods

2.1 Suspension geometry parameters

The geometry of the suspension system in a Double Wishbone (DW) configuration significantly impacts vehicle handling and ride comfort compared to other systems, such as the MacPherson strut. Therefore, this study investigates the effect of the DW suspension geometry parameters on vehicle stability. Several tire geometry parameters must be considered, as illustrated in Figure 1. One of the key kinematic factors influencing vehicle control is the camber angle, which is defined as the angle between the wheel's vertical axis and the vehicle's vertical axis when viewed from the front or rear. This angle is an important consideration in the design of steering and suspension systems.

The camber angle plays a crucial role in the performance of a suspension system, particularly in how it handles during cornering. Specifically, a negative camber improves traction by ensuring a more optimal contact angle between the tire and the road. This adjustment allows forces to be transmitted vertically through the tire rather than being exerted as shear across its surface.

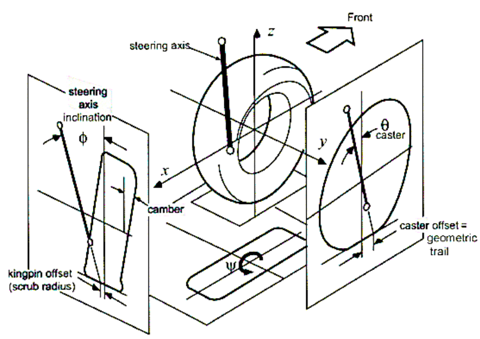

Fig. 1. Geometric parameters of a pneumatic tire, illustrating key dimensions used in suspension design [6].

Toe angle refers to the orientation of the wheels in relation to the vehicle's longitudinal axis and plays a crucial role in determining vehicle dynamics. Proper toe alignment directly influences three key performance aspects, i.e., wear, straight-line stability, and cornering behavior [7]. Excessive toe-in angles cause the tires to scrub against their outer edges, leading to increased and uneven tire wear. In contrast, excessive toe-out results in accelerated wear on the inner edges, thus reducing overall tire lifespan. Variations in camber angle due to vertical wheel travel or steering input are quantified by camber gain, as illustrated in Figure 2.

Similar with toe gain, camber gain is highly influenced by the orientation of the steering axis and the geometric asymmetry between the upper and lower suspension arms. The camber compliance, defined as the change in camber angle per unit of lateral force applied to the tire, reflects the suspension system's ability to accommodate lateral loads. This parameter encompasses the combined elastic deformation of suspension arms, bushings, subframes, and tire structures, which serves as an important indicator of the system's lateral flexibility and dynamic response.

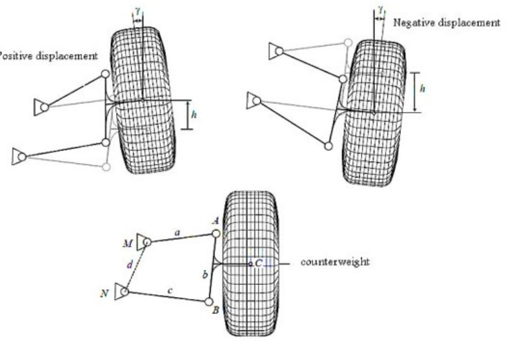

Fig. 2. Variation of camber gain during vertical wheel movement during suspension jounce and rebound [6].

The caster angle is defined as the inclination between the steering axis and the vertical axis in the longitudinal (x–z) plane, as illustrated in Figure 1. When combined with the kingpin inclination, a positive caster angle generates a self-aligning torque on the steered wheels, enhancing steering feedback, directional stability, and straight-line tracking. Additionally, positive caster contributes to camber angle variation during steering maneuvers, significantly influencing vehicle cornering behavior.

Specifically, the combination of positive caster and positive kingpin inclination induces negative camber gain on the outer wheel and positive camber gain on the inner wheel during steering, which helps maintain optimal tire contact and lateral grip. Therefore, the caster angle is commonly adjusted with kingpin inclination to optimize camber gain characteristics under both steering and vertical suspension motions.

2.2 CAD modelling

For the initial design of the 4WID-4WIS suspension system, a 3D model was created using SolidWorks software to achieve a steering angle of up to ±90°, while considering the constraints of the existing vehicle frame. The result preliminary design is shown in Figure 3.

a

b c

Fig. 3. Initial suspension design of the novel 4WID-4WIS system with various mode positions, straight driving (a), pivot steering for on-the-spot rotation or zero-turning mode (b), and crab parking mode (c).

Figure 3 illustrates the initial structure of the DW suspension system capable of achieving a ±90° steering angle, enabling multiple driving modes for the 4WID-4WIS configuration: straight driving mode in Fig.1a, pivot steering for on-the-spot rotation or zero-turning mode showed in Fig.1b, and crab parking mode as shown in Fig.1c, which is used when the vehicle needs to move sideways for parking. These modes allow the vehicle to manoeuvre effectively even in confined spaces.

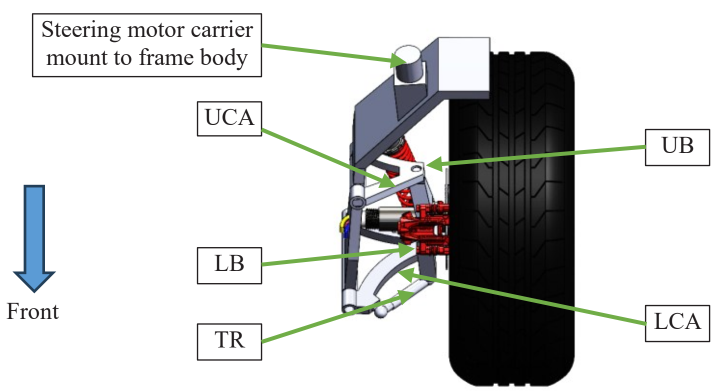

Fig. 4. Quarter vehicle model of the proposed 4WID-4WIS suspension system, highlighting the modular design concept.

A quarter-car representation of the proposed suspension module is presented in Figure 4 for a more comprehensive evaluation. This suspension design uses the DW concept because the layout of DW offers excellent control of all important suspension parameters [8]. This schematic captures the precise geometric dimensions and spatial coordinates of all suspension hardpoints, the computed locations of joints and bushing centers, which serve as the primary inputs for constructing a validated multi-body system (MBS) model.

By translating hardpoint definitions of the proposed design into the MBS environment, dynamic simulations can be performed to examine suspension kinematics under specified loading and wheel-travel conditions. This approach enables detailed analysis of roll-center migration, camber and toe variations, and overall K&C behavior, providing critical insights for optimizing the 4WID–4WIS suspension geometry.

Table 1. Geometric parameters in 4WID-4WIS suspension system.

Parameter	**Unit**	**LA**	**SA**	**SLA1**	**SLA2**	**SLA3**
Front Upper arm length	mm	177	92	133	92	290
Rear Upper arm length	mm	179	116	135	94	292
Front Lower arm length	mm	240	199	218	240	366
Rear Lower arm length	mm	175	134	153	175	301
Tie rod	mm	138	97	116	138	264

By modifying the hardpoint positions of the Lower Control Arm (LCA), Upper Control Arm (UCA), Upper Ball joint (UB), Lower Ball joint (LB), and Tie Rod (TR) in the DW suspension model as can be seen in Fig.4, several variations of the 4WID-4WIS suspension parameters were obtained, as shown in Table 1. Five design variations were developed: Long Arm (LA), Short Arm (SA), and Short Long Arm (SLA) 1, 2, and 3. To analyze how geometric parameters influence vehicle ride comfort, the study as illustrated in Fig. 5 was conducted to assess the chamber angle changes influenced by vehicle roll and vertical tire deflection (bump).

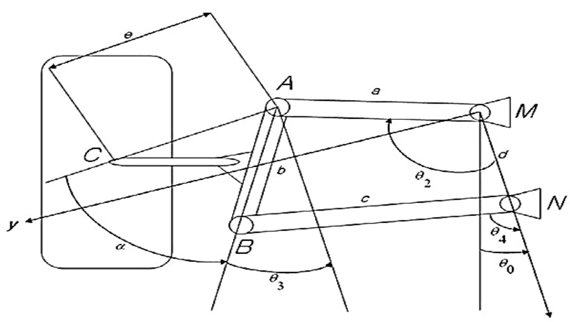

Fig. 5. Double wishbone suspension layout and associated geometric parameters relevant to kinematic analysis [6].

Based on Fig. 5, the suspension system reaches a dynamic equilibrium when the arms of the double wishbone (DW) suspension are positioned at their initial angles of θ_{40}, θ_{30}, θ_{20}. From the equation in the research that conducted by Afkar [6] we can find the geometric relation of the camber angle, caster angle**,** steering deviation**,** and scrub radius as below.

The camber angle (γ) is the difference between initial and bump or rebound condition of upright axis angle related to wheel center position, defined as:

$$\gamma = \theta_{30} - \theta_3 \quad (1)$$

The angle θ_3 can be derived as function of the vertical displacement of the wheel using the quadratic function, as shown below:

$$\theta_3 = 2tan^{-1}\frac{-\mathrm{E} \pm \sqrt{E^2 - 4\mathrm{DF}}}{2\mathrm{D}} \quad (2)$$

When the variable D represent a geometric parameter that incorporates the arm lengths and relatives pivot positions. It is defined as:

$$\mathrm{D} = \frac{c^2 - d^2 - a^2 - b^2}{2ab} - \frac{d}{a} + \left(1 + \frac{d}{a}\right)\cos\theta \tag{3}$$

The variable a and c are the lengths of the upper and lower control arms, respectively; b represent of the upright length, and d is the vertical separation between the inner pivots of the upper and lower arms, which plays a crucial role in determining the suspension geometry and roll center behaviour. The term E is derived from the sine component of the delta length between outer upper arm pivot and wheel center. of the suspension arm's angular motion and is expressed as:

$$E = -2\sin\theta \tag{4}$$

$$F = \frac{c^2 - d^2 - a^2 - b^2}{2ab} + \frac{d}{a} - \left(1 - \frac{d}{a}\right)\cos\theta \tag{5}$$

By combining Eqs. (1) to (5), variations of camber angle based on wheel geometry and suspension system are acquired. The relationship between camber and steering angles under various wheel movements is illustrated in Figure 6, which presents the interaction behaviour of the DW suspension system during cornering and vertical displacement.

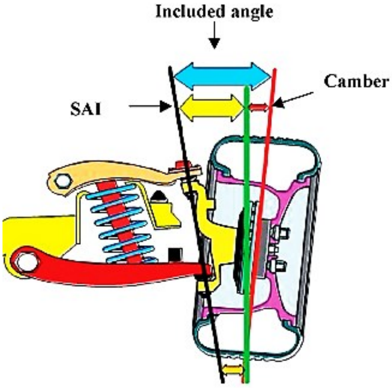

Fig. 6. Camber and steering angle relation in a double wishbone suspension system [9].

As shown in Figure 5, the steering axis intersects the wheel-ground contact surface at a point defined by coordinates (s_a, s_b, $-R_w$). These coordinates can be expressed as follows:

$$\mathrm{S}_a = \frac{\cos\theta\sin\theta}{\sqrt{\cos^2\varphi + \cos^2\theta\sin^2\varphi}} \tag{6}$$

$$\mathrm{S}_b = \frac{\cos\theta\sin\theta}{\sqrt{\cos^2\varphi + \cos^2\theta\sin^2\varphi}} \tag{7}$$

$$R_w = \frac{\cos\theta\sin\theta}{\sqrt{\cos^2\varphi + \cos^2\theta\sin^2\varphi}} \tag{8}$$

These geometric relationships allow for the determination of other important suspension parameters, such as the caster angle**,** steering deviation**,** and scrub radius, all of which are influenced by changes in camber and suspension configuration. Therefore, accurate modelling of these variables is essential in analysing and optimizing the kinematic performance of the 4WID–4WIS suspension system.

2.3 MBS modelling

Based on the hardpoints of the 4WID-4WIS suspension design shown in Figure 4 and the variable variations listed in Table 1, an MBS (Multibody Simulation) model of the suspension can be developed, as illustrated in Figure 7.

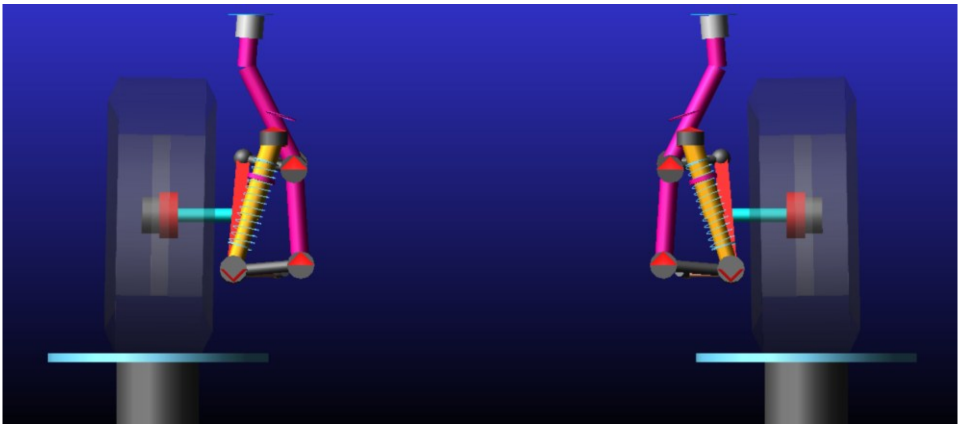

Fig. 7. Front view multibody simulations (MBS) model developed for the 4WID-WIS suspension system

Subsequently, a kinematic and compliance (K&C) analysis was conducted using the developed multibody system (MBS) model of the suspension. The simulation uses the parallel wheel travel method, in which a total vertical wheel travel of 120 mm consisting of +60 mm bump and -60 mm rebound was applied to replicate the suspension jounce motion.

This test scenario was designed to investigate the influence of vertical wheel displacement on critical suspension characteristics, particularly the vertical migration of the roll center, as well as the corresponding variations in toe gain and camber gain. The results offer valuable insights into the suspension's ability to maintain stability and tire alignment under dynamic loading conditions.

3 Results and Discussion

This study evaluated the kinematic performance of five suspension geometries SA, SLA1_1, SLA2_1, SLA3, and LA_1 through parallel wheel travel simulation involving ±60 mm of vertical displacement. Seven K&C key parameters were analyzed: toe angle, camber angle, caster angle, kingpin inclination (KPI), scrub radius, camber compliance under lateral load, and roll center vertical movement. These metrics collectively influence vehicle agility, stability, and ride comfort, especially under extreme steering angles, which are essential for 4WID–4WIS electric vehicles operating in urban environments.

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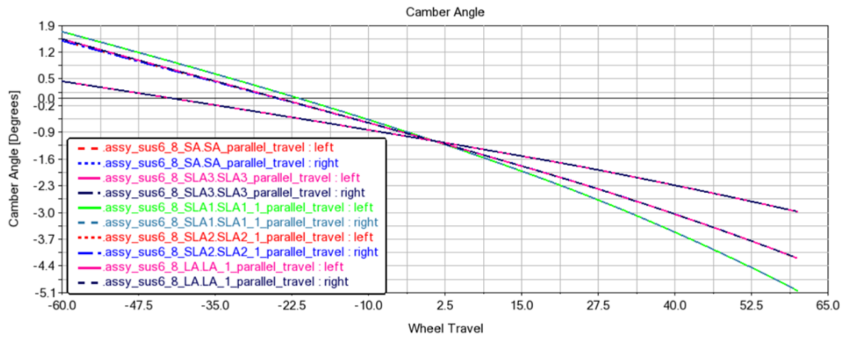

Fig. 8. Simulation result showing the camber angle response under suspension travel

Camber angle determines how well the tire maintains contact with the road surface, especially during cornering. According to the figure 8, the SLA1 geometry demonstrated the highest positive camber gain, reaching up almost +1.9° at full rebound, which reduce grip during lateral manoeuvres, furthermore at full bump the camber reaching -5.1, this will increase inner tire wear and reduces braking efficiency in straight-line travel.

The SLA3 configurations again stood out with their more linear and moderate camber profiles. These geometries ensure a consistent tire footprint on the road, supporting traction and vehicle control while minimizing wear. LA_1, SLA1_1 and SLA2_1 offered balanced camber changes less extreme than SA, but slightly more variable than SLA3. These results highlight SLA3 as the most appropriate choices for urban EVs requiring both agility and tire longevity.

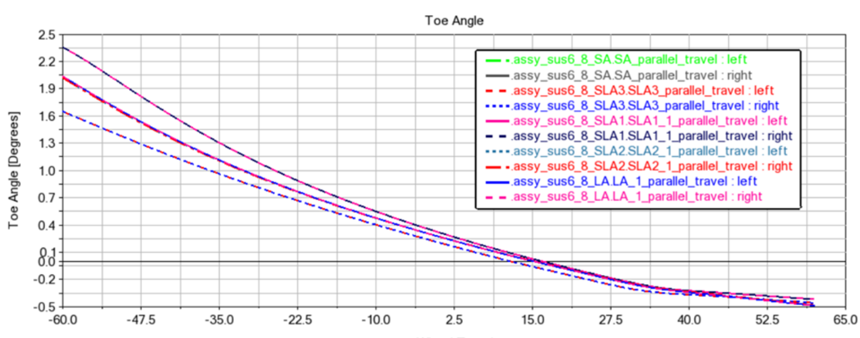

Fig. 9. Toe angle variation with respect to suspension displacement

The SA and SLA1_1 suspension design shows the most pronounced toe angle change, starting with a significant toe-in during bump and decreasing steadily toward zero or slight toe-out as the wheel travels upward as seen in figure 9, such characteristics may lead to increased tire wear and unpredictable behaviour in low-speed tight manoeuvres. In contrast, the LA, SLA2_1 and SLA3 configurations offer better toe characteristics.

These designs reduce undesirable toe changes under suspension movement, resulting in more consistent handling and improved predictability during manoeuvres. Among them, SLA3 stands out with the lowest toe variation, suggesting it could deliver the most stable ride with minimal alignment deviations during wheel travel.

The LA_1 and SLA2_1 setup also performs similarly to SLA3 in terms of toe behaviour. SLA3 offered the most linear and stable toe and camber behaviour throughout suspension travel, enhancing steering precision and tire-road contact consistency crucial for frequent urban cornering and low-speed manoeuvring.

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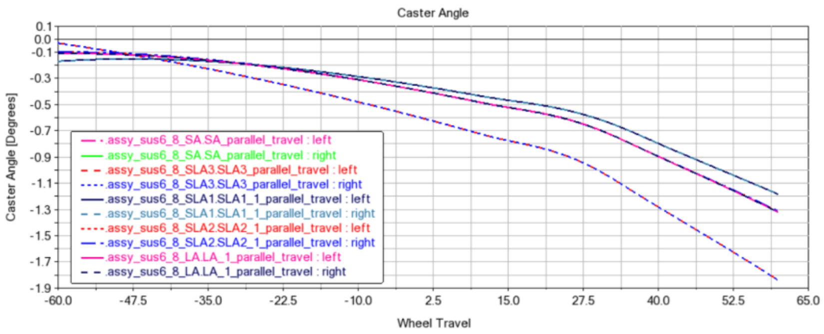

Fig. 10. Caster angle configuration and its change during vertical wheel motion.

Caster angle affects steering feel, returnability, and directional stability. SLA3 geometry in figure 10 showed significant variation in caster as the wheel moved through its travel, which may compromise steering self-alignment. LA_1, SA and SLA2_1 showed more stable caster behaviour but still fluctuated under extreme jounce/rebound. LA_1, SA and SLA2_1 maintained relatively flat caster curves, ensuring consistent steering effort and smooth response throughout suspension movement critical for manoeuvrability in tight urban environments.

Kingpin inclination (KPI) contributes to scrub radius and steering torque characteristics, KPI result trends showed in Figure 11 mirrored the caster results from figure 10. SLA_1 had the highest and most variable KPI, possibly leading to increased steering effort and torque steer at full lock. SLA3 and SLA2_1 maintained moderate KPI values with gentle gradients, enhancing steering controllability. LA and SA were slightly more variable but still offered reasonable KPI management.

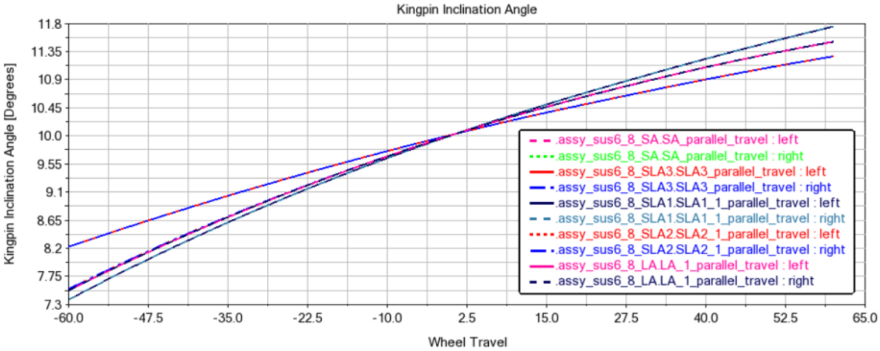

Fig. 11. Kingpin inclination angle visualization, critical for steering geometry optimization.

The simulation result of scrub radius in figure 12 show that scrub radius was most stable in SA and SLA1_1, which helps isolate road feedback. However, this came with trade-offs in KPI and caster instability. LA and SLA2_1 offered less scrub radius than SLA3, but slightly more variable than SLA1_1. SLA3 showed higher variability but still in controlled with the increase of scrub radius approx. 0.5° compared with the LA.

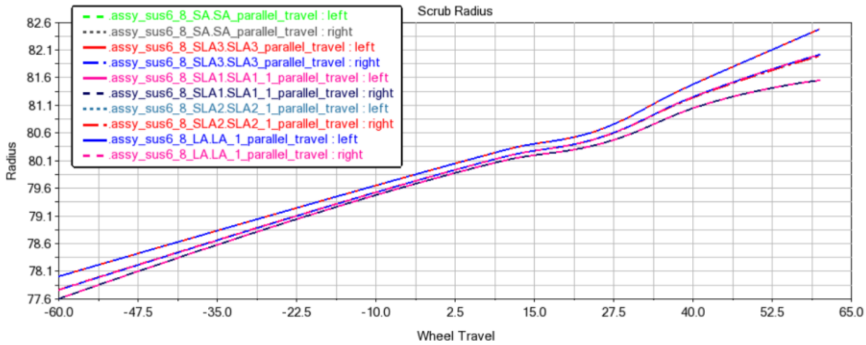

Fig. 12. Scrub radius measurement derived from the front view geometry of the suspension system.

Camber compliance under lateral force is critical in preserving tire alignment under cornering. The result of simulation in figure 13 show that LA and SLA2_1 had higher compliance, which may benefit high-speed grip but reduces steering accuracy under varying loads. SLA3 demonstrated low and consistent compliance, maintaining tire orientation and promoting neutral handling—important for comfort and control during urban stop-and-go traffic.

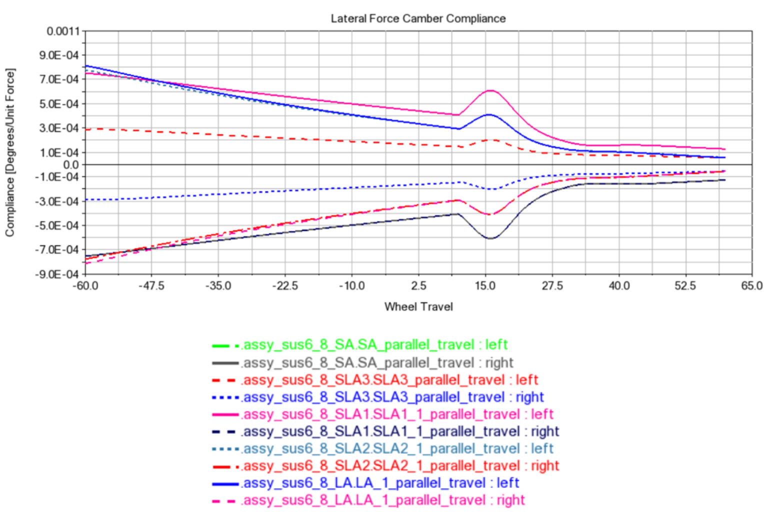

Fig. 13. Camber compliance characteristics under vertical loading conditions.

Roll center vertical location simulation result in figure 14 show that the parameter more stable in SLA3 and LA_1 compared to other designs. SA's roll center vertical location dropped significantly during bump travel, introducing potential for excessive body roll and lateral jacking forces. LA, SLA1_1 and SLA2_1 had moderate change of roll center, while SLA3 exhibited the most consistent vertical roll center movement, translating into reduced body motion and better passenger comfort on uneven city streets.

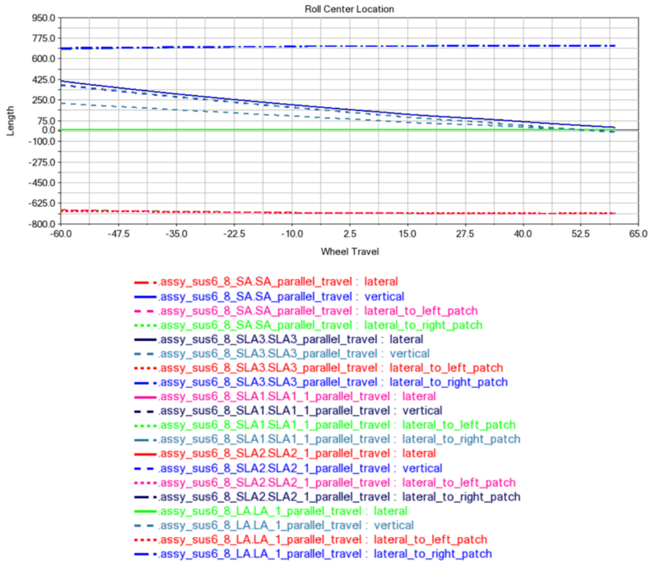

Fig. 14. Vertical position of the roll center as function of wheel travel, indicating chassis roll behaviour.

Based on the result from the simulation, the maximum value of all kinematic parameter was compiled in the Table 2. From the result we can notice that SLA3 exhibited superior roll center stability and minimized toe and camber variations, indicating enhanced consistency in vehicle behaviour during suspension travel.

Table 2. Kinematic simulation result of 4WID-4WIS suspension system.

Parameter	Unit	LA	SA	SLA1	SLA2	SLA3
Camber angle	deg	1.53	1.55	1.725	1.54	0.45
Toe angle	deg	2.05	2.35	2.35	2.05	1.675
Caster angle	deg	-1.31	-1.31	-1.2	-1.31	-1.82
KPI angle	deg	11.56	11.56	11.8	11.33	11.33
Scrub radius	mm	82	81.5	81.5	82	82.5
Camber compliance	deg/kN	0.00077	0.00075	0.00074	0.00077	0.0003
Roll center vertical location	mm	381	687	425	425	207

Based on Table 2, LA_1 delivered better performance compared with SLA3, particularly in terms of kingpin inclination (KPI) and caster angle control. SLA3 and LA_1 configuration demonstrated the most suitable suspension geometries for urban electric vehicle applications. Both setups achieved an optimal balance among manoeuvrability, and dynamic stability.

4. Conclusion

This research examined the kinematic behaviour of a novel 4WID–4WIS suspension module designed for electric urban vehicles, capable of supporting extreme steering angles of up to 90°. Parallel wheel travel simulations (±60 mm) were conducted to analyzed seven key parameters related to kinematics and compliance (K&C)—including toe angle, camber angle, caster angle, kingpin inclination angle, scrub radius, camber compliance under lateral force, and roll center location—across five different suspension geometries named SA, LA, SLA1, SLA2, and SLA3.

Among the setups tested, the SLA3 and LA_1 geometries consistently exhibited superior performance. They showed minimal variation in toe and camber angles, stable caster and kingpin inclination (KPI) angle, controlled scrub radius, low camber compliance under lateral loads, and consistent roll center movement. These characteristics contribute to improved steering accuracy, predictable vehicle dynamics, and reduced tire wear, making them ideal for complex, low-speed urban driving that involves frequent direction changes.

The SA and SLA1_1 geometry, while offering aggressive handling, exhibited undesirable fluctuations in camber, toe, KPI, roll center, and compliance, making it less appropriate for comfort- and control-oriented applications. SLA2_1 offered better results than SA but lacked the refinement shown by SLA3 and LA_1.

In conclusion, LA and SLA3 emerges as the most appropriate suspension design for 4WID–4WIS urban electric vehicles, providing an ideal balance of agility, kinematic precision, and ride comfort. Furthermore, the proposed design of 4WID-4WIS capable to operate with a ±90° steering angle, enabling multiple driving modes configuration as shown in Fig.1. These modes allow the vehicle to manoeuvre effectively even in confined spaces.

These result insights for the development of steer-by-wire, space-efficient chassis technologies that are essential for the future of smart city mobility platforms. Further research in the steering modes of 4WID-4WIS EV can advancing the vehicle manoeuvrability remarkably [10-11]. In addition to the manoeuvrability advancement at low-speed conditions, active 4WS can improve vehicles' handling stability at high-speed conditions [11-13]. This advancement will support the sustainable cities and communities.

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