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OPTIMIZATION OF SUSPENSION PARAMETERS FOR BATTERY ELECTRIC VEHICLE

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Abstract

The persistent challenge of global warming and environmental pollution necessitates the adoption of sustainable and alternative mobility technologies. A significant contributor to these issues is the exhaust emissions from conventional internal combustion engine vehicles. Plug-in and hybrid electric vehicles (EVs) offer promising solutions to mitigate these concerns. This research focuses on the development of a student-designed electric car: the Battery Electric Vehicle (BEV). This urban concept car leverages compact geographical area, ideal for adopting electric cars. EVs provide advantages such as lower operating and maintenance costs and higher efficiency. By centralizing pollution to power stations, EVs offer a cleaner alternative. Despite range limitations, continuous advancements are enhancing EV capabilities. This paper details the selection and optimization of suspension parameters for the BEV's suspension system, ensuring good handling, stability, and performance while balancing optimum values with practical implementation constraints.

Keywords: BEV, EV, Suspension system, Wishbone, SLA. C.G., SAT

I. INTRODUCTION

The world continues to grapple with the persistent challenge of global warming, compounded by environmental pollution which poses a significant threat to human health. A key contributor to this problem is the exhaust gases emitted by conventional internal combustion engine vehicles. Over the years, the global vehicle count is projected to reach approximately 1.8 billion, and the continuous rise in oil prices underscores the urgency of adopting sustainable and alternative mobility technologies. Plug-in and hybrid vehicles are promising alternatives that hold substantial potential for mitigating these issues. This project focuses on the research and development of a student-designed electric car. Electric vehicles (EVs) are gaining traction worldwide due to their eco-friendly nature and zero emissions. Battery Electric Vehicle (BEV) is an urban concept car that leverages compact geographical area, making it an ideal location for the adoption of electric cars. The continuous escalation of oil prices and the intensifying impact of global warming have necessitated the adoption of alternative mobility technologies. Electric vehicles (EVs) present a compelling alternative to conventional internal combustion engine vehicles [1].

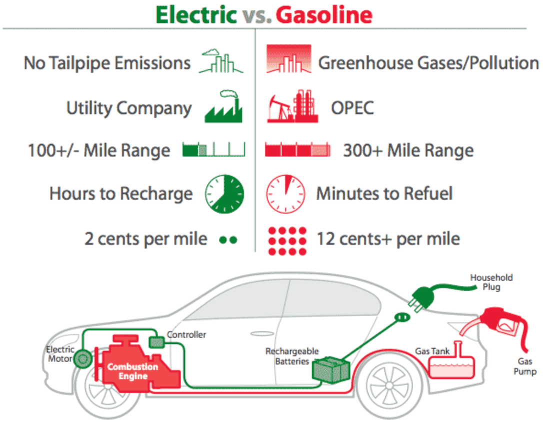


Figure 1: Electric v/s Gasoline [2]

Atmospheric pollution from exhaust gases emitted by internal combustion engines, coupled with the constant rise in oil prices, has paved the way for the adoption of electric cars globally. Electric vehicles offer significant advantages over conventional internal combustion engine vehicles, including lower operating and maintenance costs, as well as higher efficiency as shown in figure 1. Electric cars centralize pollution sources to power stations that generate electricity, whereas conventional cars distribute pollution, making them less efficient. Although the limited range of electric cars has been a discouraging factor, continuous advancements are being made to enhance their range. Numerous automakers, such as Honda, Toyota, Mercedes-Benz, BMW, and Tesla, have already commenced manufacturing electric street and sports cars as shown in figure 2 [3].

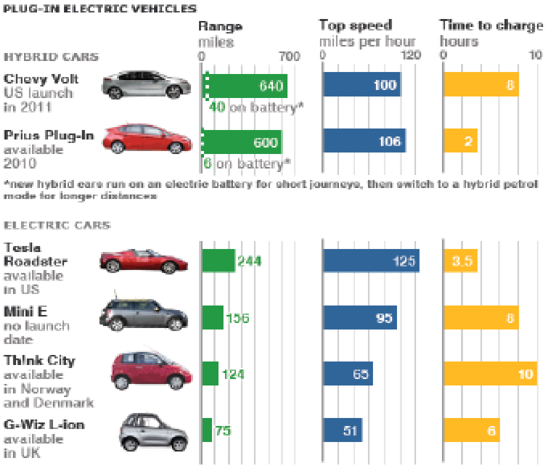


Figure 2: Different plug-in electric cars [3]

An electric car is a vehicle powered by an electric motor, utilizing electrical energy stored in devices such as batteries or capacitors. A plug-in electric car is recharged using an external electricity source. Electric vehicles, including hybrid and plug-in electric cars, are poised to play a crucial role in the future mobility landscape [5]. This project aims to challenge students to design and stimulate their creativity, fostering innovative ideas and solutions to bring first plug-in electric car to life. The concept of the Battery Electric Vehicle (BEV) revolves around generating clean energy from lithium-ion battery packs. The electrical power is directed to the motor through a controller, which in turn drives the rear differential. This paper includes detailed explanations on design, engineering, manufacturing and testing of the braking system for Battery Electric Vehicle.

II. SUSPENSION SYSTEM OVERVIEW

The suspension system is a three-dimensional four-bar linkage that includes shock absorbers, springs, and linkages, which connect the vehicle chassis to its wheels, allowing for relative motion between the two [4]. The suspension system fulfils three primary roles:

- **Comfort:** It provides vertical compliance, enabling the wheels to follow the road surface, while isolating the chassis from road roughness to enhance passenger comfort.
- **Safety**: It responds to control forces produced by the tires, including longitudinal and lateral forces, as well as braking and driving torques. This ensures the protection of passengers, luggage, other mechanical and electrical systems, and the vehicle itself.
- **Handling:** It maintains tire contact with the road with minimal load variations and resists chassis roll. Keeping the wheels in contact with the road surface is crucial, as all road or ground forces acting on the vehicle are transmitted through the tire contact patches.

Battery Electric Vehicle (BEV) features a double wishbone or short-long arm (SLA) suspension system at both the front and rear wheels. This system includes two unequal-length "A" or "wishbone" shaped control arms that are not parallel. These arms connect to the chassis and sub-frame at one end and the steering knuckle at the other. The upper arms are shorter than the lower ones and are mounted on the chassis, which helps maintain a constant wheel track [6][7]. Shock absorbers are attached to the lower wishbone and chassis to manage the vehicle's vertical movement. The double wishbone suspension is an independent design that allows for the independent movement of all four wheels, thereby eliminating wheel wobbling as illustrated in figure 3.

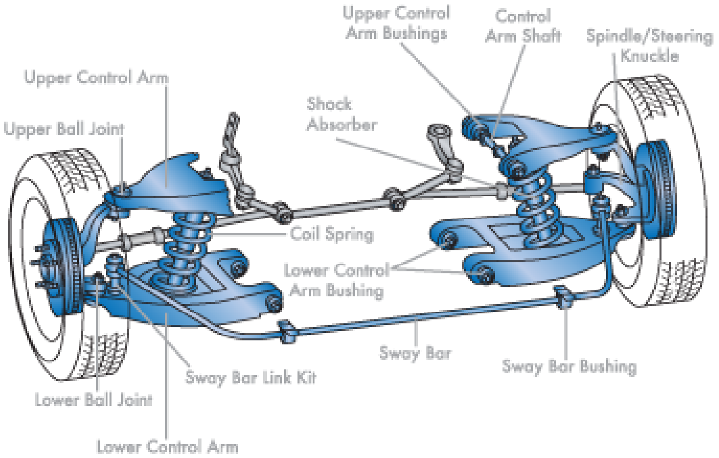


Figure 3: Double wish-bone suspension system [7]

Advantages of SLA Suspension System:

- Versatility: Allows engineers to precisely control wheel motion throughout suspension travel, managing parameters such as camber angle, caster angle, toe pattern, roll center height, scrub radius, and scuff

- Reduced Camber Angle Gain: Minimizes changes in track width
- Enhanced Handling and Safety: Improves handling, driving safety, and ride characteristics
- Lateral Stiffness: Provides good lateral stiffness to the vehicle

Disadvantages of SLA Suspension System:

- Complexity and Cost: Requires more components, increasing manufacturing costs and space requirements
- Installation Requirements: Necessitates a front and rear sub-frame, raising assembly costs, complexity, and vehicle weight [8]

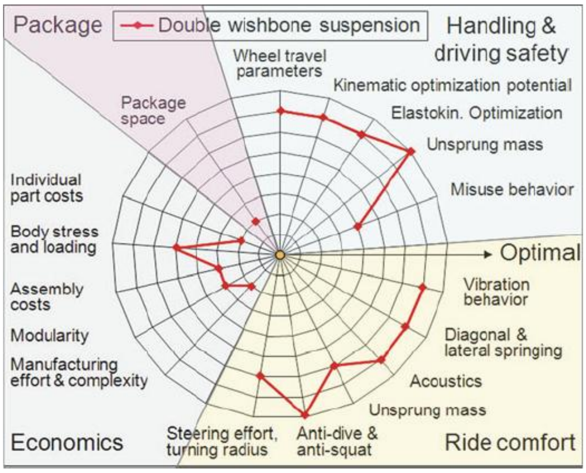


Figure 4: Performance profile-double wishbone suspension system [4]

The different components of a double wishbone suspension and their roles are as follows:

- **Spring & Shock Absorber:** Together, they support the weight of the vehicle and enable the control arms and wheels to move up and down. The primary function of the shock absorber is to dampen the body and wheel vibrations caused by uneven roads, while the coil spring cushions these vibrations to provide a comfortable ride. Without the shock absorber, the vehicle would continue to bounce after encountering an uneven road surface.
- **Anti-Roll or Stabilizer Bar:** This component limits the vehicle's body roll during cornering, maintaining constant wheel contact with the road. It connects the lower control arms on both sides of the vehicle through bar links and bushings, reducing excessive body lean or roll by resisting the centrifugal forces experienced during cornering [9].
- **Mechanism**: This specifies the kinematics of pivot points during lateral and vertical movement, controlling the suspension geometry. The mechanism includes various other components such as:

A. **Control Arms**: These define the wheel kinematics relative to the chassis. The outer end of the control arm contains a ball joint linked to the steering knuckle, while the inner end consists of a rubber bushing as shown in figure 5.

Figure 5: Upper & lower control arms.

B. **Steering Knuckle:** As shown in figure 6, this component accommodates the installation of wheels, braking, and steering elements. It features three pivot points that connect to the upper and lower control arms and the steering rod. When the steering is turned, it rotates the knuckle, which subsequently turns the wheel assembly.

Figure 6: Upper & lower control arms.

C. **Ball Joints:** These components link the steering knuckle with the control arms, allowing freedom of movement in two translational directions and one rotational direction as illustrated in figure 7. The ball joints in the control arms have a spring mounted on them, making them load carriers.

Figure 7: Ball joint [31]

D. **Bushings:** These supplementary units absorb and isolate vibrations and noise, enhancing the wear resistance of components. Control arm bushings comprise rubber sandwiched between a metal inner sleeve and a metal outer sleeve. The inner sleeve remains stationary, while the outer sleeve moves with the control arm as displayed in figure 8. Bushings are also used in anti-roll bars, shock absorbers, and strut rods.

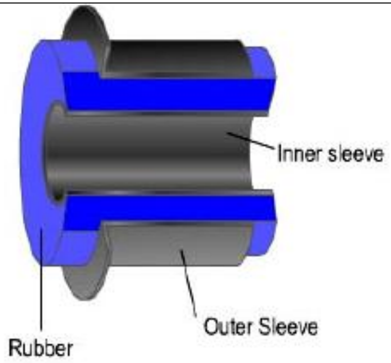


Figure 8: Bushing [31]

E. **Strut Rods:** Strut rods prevent the lower control arm from moving fore and aft, providing stability. They are connected to the frame and bolted to the outer end of the lower control arms. The installation of strut rods typically depends on the drive configuration of the vehicle, whether it is front-wheel drive (FWD) or rear-wheel drive (RWD). In Battery Electric Vehicle (BEV), strut rods are installed at the rear since it is a RWD car [10].

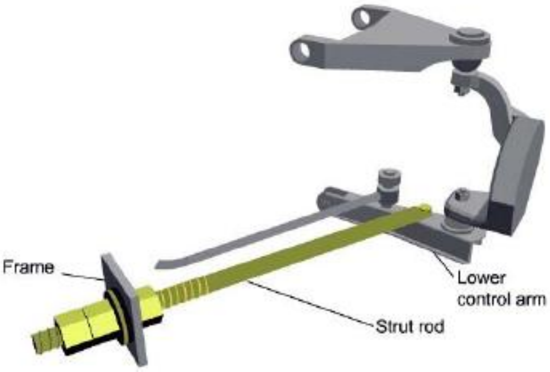


Figure 9: Strut rod [31]

III. SUSPENSION PARAMETER OPTIMIZATION)

Suspension kinematics is the study of the motion of tires relative to suspension components. The type of suspension system determines the orientation of the tires and the functions of various suspension components. Determining the suspension parameters of a car is based on making useful approximations; it is not an exact science. The suspension system is one of the most complex and underappreciated aspects of automotive engineering, and this section aims to elucidate its intricacies.

A. Track width

As illustrated in figure 10, track width is the distance between the centers of the left and right tire contact patches. It plays a significant role in influencing a vehicle's cornering ability.

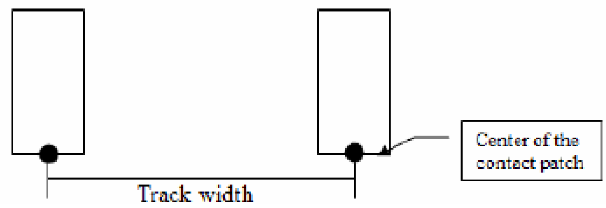


Figure 10: Track width of a car [22]

A larger track width allows the car to navigate curves at higher speeds. The double wishbone suspension enables changes in track width during deflections, providing better road grip [13]. BEV features front and rear track widths of approximately 1.49 meters and 1.55 meters, respectively. These values differ slightly from the Honda S2000's front and rear track widths of 1.47 meters and 1.51 meters, respectively, due to an increase in the rim offset value of the front and rear rims by 0.01 meters and 0.02 meters, respectively as shown in figure 11. This increase in track width enhances the BEV's cornering ability at high speeds.

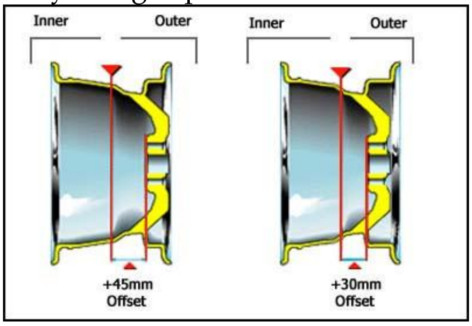


Figure 11: Rim offset [13]

B. Instantaneous center

The instantaneous center is an imaginary point about which the wheel rotates under the constraints provided by the control arms [16]. It is located at the intersection of lines passing through the upper and lower control arms. The instantaneous centers of the front and rear axles were determined using a 2D CAD drawing of the Honda S2000's suspension. SolidWorks sketch entities were employed to locate the intersecting points of the lines passing through the upper and lower control arms. For the instantaneous centers of the front and rear axles of the BEV, refer to the roll center section.

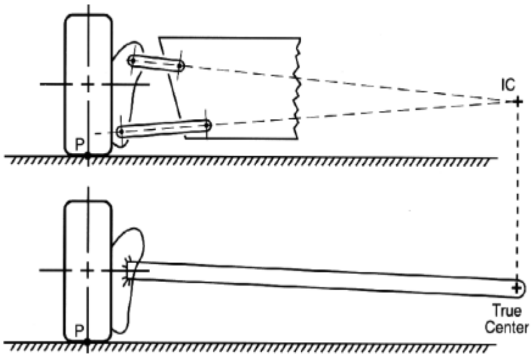
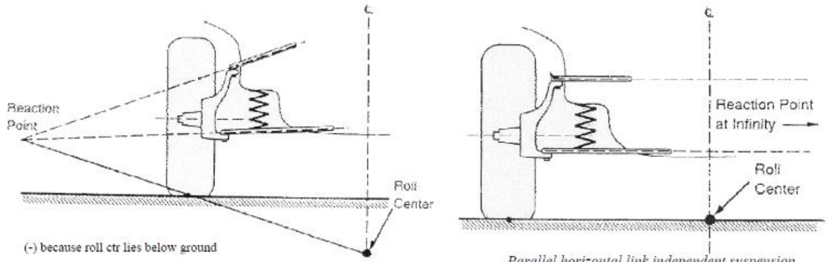


Figure 12: Instantaneous center [14]

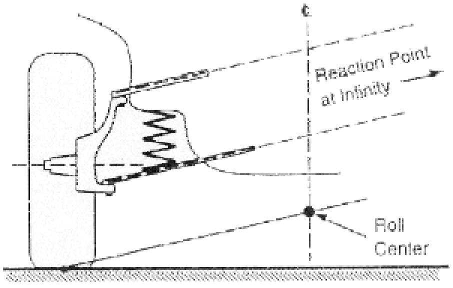
C. Roll Center

The roll center is a precisely defined imaginary point on the centerline of the car around which the vehicle rolls on its suspensions [22][28]. Both the front and rear suspensions have their respective roll centers. The roll center is laterally positioned at the car's centerline when the suspensions on the left and right sides are mirror images of each other. The roll centers along the vehicle's centerline can be high, low, at, or below ground level, depending on the suspension geometry.



Negative swing arm independent suspension.

Parallel horizontal link independent suspension.



Inclined parallel link independent suspension.

Figure 13: Negative roll center (top left), zero roll center (top right), and Positive roll center (bottom) [28]

The distance between the roll center and the center of gravity (C.G) significantly influences vehicle dynamics and handling. A larger distance results in a higher roll moment, increasing the likelihood of the car flipping over when cornering at high speeds. Conversely, if the roll center is too high and close to the C.G, it can induce jacking forces. To counteract high roll moments and jacking forces, the most effective technique is to maintain a low C.G for the car.

The roll centers of the front and rear axles were determined using a 2D CAD drawing of the Honda S2000's suspension as shown in figure 14. After identifying the instantaneous centers, SolidWorks sketch entities were employed to locate the car's centerline and the line connecting the wheel centerline to the instantaneous center.

The BEV's center of gravity (C.G) is located approximately 370 mm above ground, with front and rear roll centers at about 93 mm and 196.84 mm above the ground, respectively. The BEV has a weight distribution ratio of 45:55, indicating that a greater portion of its weight rests on the rear axle, making the rear roll center more significant than the front. The distance between the rear roll center and the C.G is approximately 170 mm, which is considered ideal as it prevents high roll moments and large jacking forces. The suspension system and sub-frames were originally designed for the Honda S2000, limiting the changes to the suspension geometry and, consequently, the front and rear roll centers.

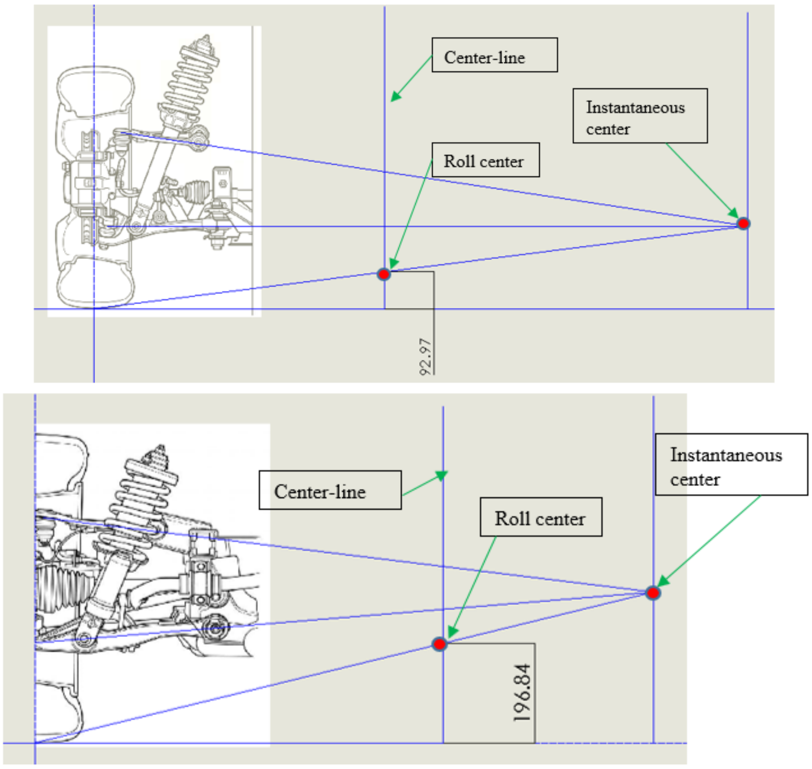


Figure 14: Front (top) and rear (bottom) suspension roll and instantaneous centers.

D. Camber Angle

The camber angle is the angle between the tire's centerline and the vertical axis of the car when viewed from the front or rear as displayed in figure 15.

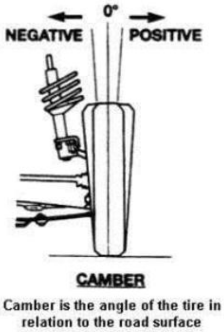


Figure 15: Camber angle [28]

Positive camber occurs when the tire is tilted away from the chassis, while negative camber is achieved when the tire is tilted towards or inside the chassis [28]. Drastic camber angles lead to uneven tire abrasion. A slight positive camber angle improves steering and handling, but an extreme positive camber angle will cause uneven pressure distribution, abrading the outside of the tire. Negative camber enhances road grip and improves cornering ability by increasing the car's lateral stiffness. Optimal camber angle values for performance and minimal wear are -1° for the front tires and -2° for the rear tires.

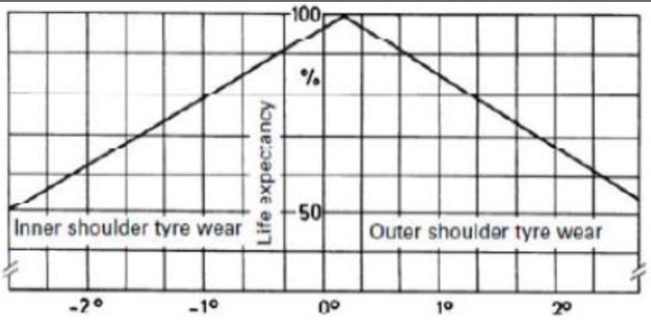


Figure 16: Graph of tire wear v/s chamber angle [28]

The front tires of the BEV have a camber angle of approximately -0.67°, while the rear tires have a camber angle of about -1.67°. BEV features negative camber angles at both the front and rear tires. This increases the BEV's lateral stiffness, providing a firm grip on the road and enabling high-speed cornering. The camber angle could not be optimized to the desired values due to limitations imposed by the adjusting bolt of the lower control arms, which were originally designed for the Honda S2000.

E. Toe Angle

The toe angle is the symmetrical angle between the direction in which the tire points and the longitudinal axis of the car, as viewed from above (shown in figure 16). Toe-in angle refers to the condition where the front sides of the tires are closer together than the rear sides. Conversely, the toe-out angle refers to the condition where the rear sides of the tires are closer together than the front sides [28].

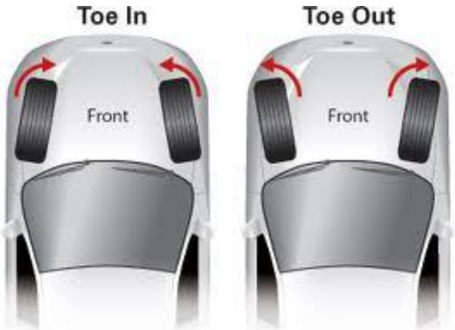


Figure 16: Toe-in and Toe-out [28]

The toe angle is a measure of the initial steering response of a vehicle. This tuning characteristic is often overlooked, but different toe angle configurations are crucial for various types of vehicles. The effects of different toe angle variations are detailed in Tables 1 and 2.

Table 1: Front Toe-in v/s Toe-out [6][7]

	Front toe-in	**Front toe-out**
Comments	(1) Adopted by most of the production cars. (2) Applicable for day-to-day driving.	(1) Very rarely seen in production cars.
Effects	(1) During the initial portion of the turn it induces understeer. (2) Good straight-line stability.	(1) It reduces the effect of understeer during the initial portion of the turn. (2) FWD/AWD vehicles have tendency to counter toe out. (3) Very good steering response.
At the limit	(1) Takes time for steering to respond. (2) Unstable during sudden & heavy braking.	(1) It degrades the stability during sudden & heavy braking. (2) Very poor straight-line stability & may lead to catastrophic understeer.

Table 2: Rear Toe-in v/s Toe-out [6][7]

	Rear toe-in	**Rear toe-out**
Comments	(1) Popular setting with drift cars as it stabilizes the back. (2) Not advisable for normal drivers.	(1) Mostly used in rally sport cars
Effect	(1) Provides rear stability. (2) Provides the manageable feeling of over steering.	(1) Helps the car to maneuver in mid-turn and prevents understeer from the front tires by taking some of the load
At the limit	(1) Could lead to catastrophic understeer in AWD and FWD vehicles. (2) Very instable and uncontrollable while negotiating a corner & might lead to sudden rollover.	(1) Poor steering response & has tendency to understeer. (2) Initial understeer can lead to uncontrollable over-steer.

The optimal toe-in angle values for balanced stability and steering control are 0° for the front tires and 0.33° for the rear tires. For the BEV, the front tires have a toe-in angle of 0° and the rear tires have a toe-in angle of 0.33°. This configuration provides greater in-line and rear stability to the car, albeit with some sluggishness in turning response. The optimal toe-in angle values were successfully achieved by adjusting the length of the steering tie rods and strut bars at the front and rear axles, respectively.

F. Caster Angle

The caster angle is the angle between the imaginary pivot line that joins the upper and lower ball joints and the vertical axis, as viewed from the side, around which the tire turns (illustrated in figure 17). Essentially, it is the angle at which the steering axis is tilted. When the steering axis is inclined backward, it results in a positive caster angle. Conversely, when the steering axis is inclined forward, it produces a negative caster angle. A zero caster angle occurs when the steering axis coincides with the vertical axis. The caster angle affects the caster trail, which determines the self-aligning torque (SAT) characteristics of the steering. Most street vehicles today have a positive caster angle [28][33].

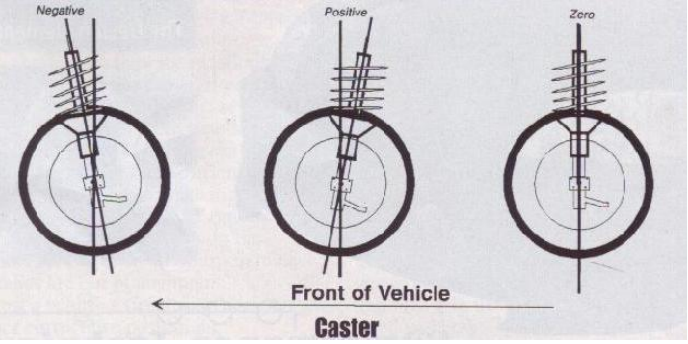


Figure 17: Caster angle conditions [33]

The differences between positive and negative caster angle are explained in table 3 below.

Table 3: Positive v/s Negative Caster [6][7]

Positive caster angle	Negative caster angle
(1) Require more steering torque to counter SAT, which gives the driver good feel of the road.	(1) Needs much less steering torque due to absence of SAT and provides no feedback to the driver.
(2) Provides improved handling characteristics while cornering and excellent directional stability to the vehicle.	(2) Induces wobbling of tires at high speeds and makes the vehicle highly unstable.
(3) Usually found in normal street cars and race cars.	(3) It is used in heavy vehicles like trucks, buses etc. to reduce the required steering torque.

BEV has a positive caster angle of approximately 6.25° on both sides. This angle enhances the BEV's in-line stability, handling characteristics, and self-aligning torque, thereby reducing driving effort. The optimal positive caster angle is suggested to be 6.5°. The slight difference in the caster angle values is due to the original geometry of the control arms designed for the Honda S2000. The caster angle value must be determined during the design phase of the control arms' geometry, as it is a non-adjustable parameter.

G. Caster Trail

The caster trail is the distance between the point directly below the axle on the ground and the point where the line drawn through the steering axis intersects the ground, known as the Dave point, as viewed from the side and shown in figure 18 below.

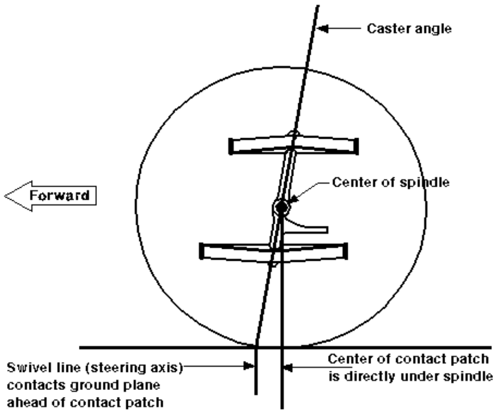


Figure 18: Positive Caster trial [28]

A positive caster angle creates a positive mechanical trail, and vice versa. With a positive caster angle, the line drawn through the steering axis intersects the road surface slightly ahead of the tire's contact patch. This positive mechanical trail enhances directional stability and makes driving easier. The primary purpose of the positive caster trail is to provide the crucial self-centering characteristic for the steering [28][33].

The distance between the Dave point and the tire's contact patch generates a moment arm, which produces self-aligning torque (SAT) whenever the driver turns the vehicle. This SAT tends to straighten the tires whenever the driver releases the steering wheel. A greater caster angle results in higher self-aligning torque, improving straight-line stability. However, excessive positive caster can make the steering heavy and difficult for the driver. If the caster angle differs on either side, the vehicle will be pulled towards the side with less positive caster. Although caster angle does not affect tire wear, it is a non-adjustable parameter and must be determined during the design phase. BEV has a positive caster trail of 3.2 cm due to the positive caster angle created by the steering axis. This positive caster trail provides self-aligning torque, straightening the steering after each turn. It also enhances the driver's feel of the road surface and improves lateral stability.

H. King-pin inclination

The kingpin angle is the angle between the vertical line and the line joining the upper and lower ball joints, as viewed from the front of the vehicle and illustrated in figure 19. A positive kingpin angle is defined when the upper ball joint is closer to the chassis than the lower one, and vice versa for a negative kingpin angle.

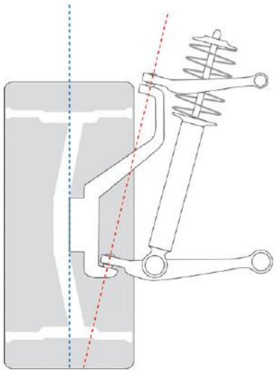


Figure 19: King-pin inclination [16]

Kingpin inclination affects the straight-line stability of the vehicle and the self-aligning torque of the steering. Due to kingpin inclination, the axle path follows an inverted U-shaped motion as viewed from the side. The axle is at the highest point of this inverted U-shaped path when the steering wheel is kept straight. When the steering wheel is turned left or right, the axle reaches the lowest points of the inverted U-shaped path, causing the entire front of the car to be lifted. The point of equilibrium or lowest energy is at the highest point of this inverted U-shaped path. This alignment generates the self-aligning torque, centering the steering. Additionally, kingpin inclination affects the scrub radius [16][33].

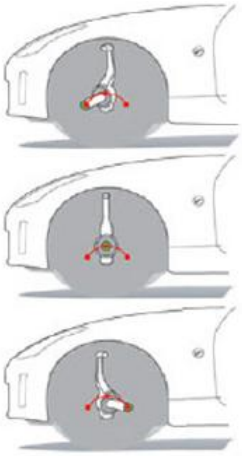


Figure 20: Inverted U-motion due to KPI [16]

For street cars, the kingpin inclination value should be in the range of 7°-15°. BEV has a positive kingpin inclination value of 9.41°, the same as the Honda S2000, which is ideal for a street car. Since kingpin inclination is a non-adjustable parameter, it must be determined during the design phase of the steering knuckle. This value can only be altered by bending the steering knuckle.

I. Scrub Radius

Scrub radius is the distance between the vertical axis and the kingpin axis at the tire contact patch, as viewed from the front (shown in figure 21). When these two axes intersect at the center of the tire on the road surface, the scrub radius is zero. If they intersect below the road surface, the scrub radius is positive. Conversely, if they intersect above the road surface, the scrub radius is negative.

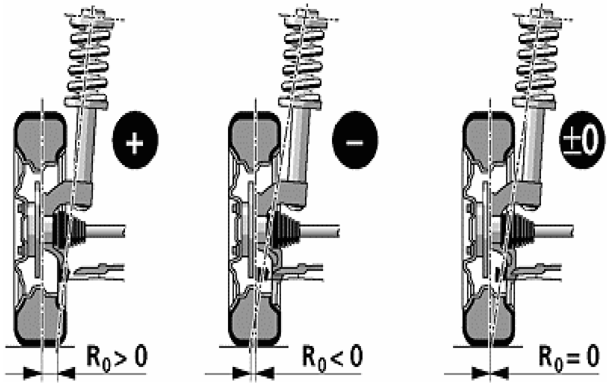


Figure 21: Scrub radius [22]

Scrub radius depends on the kingpin inclination, making it a non-adjustable parameter. A positive scrub radius reduces steering effort at low speeds but provides less self-aligning torque. In contrast, a negative scrub radius requires more effort at lower speeds but ensures better straight-line stability [22][28]. BEV features the same negative scrub radius values of 55 mm for the front and 65 mm for the rear as the Honda S2000. Since scrub radius is non-adjustable, it must be determined during the design phase of the steering knuckle.

J. Sprung and un-sprung mass

Sprung Mass is the total mass of all non-suspension components, such as the chassis, battery, transmission, passengers, and approximately half the mass of suspension components like the shock absorbers, anti-roll bars, and control arms. Un-sprung Mass is the total mass of all suspension components located outside the upper and lower ball joints, plus approximately half the mass of suspension components like the shock absorbers, anti-roll bars, and control arms [22].

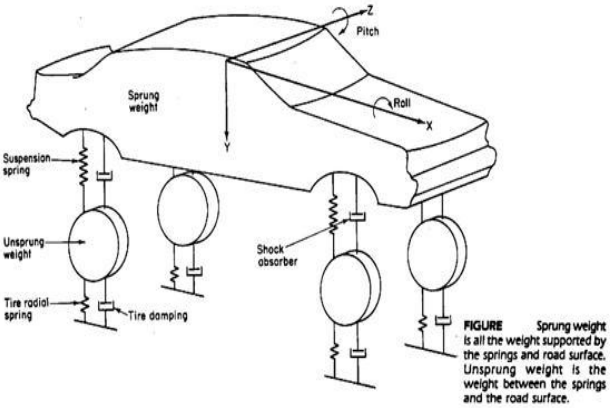


Figure 22: Sprung v/s Un-sprung mass [22]

Sprung mass is isolated from the road via the suspension system, while the un-sprung mass is not supported by the car's suspension, as shown in Figure 22. Sprung mass influences suspension performance and ride comfort. Higher sprung mass results in lower suspension frequency, leading to a bouncy ride and potential motion sickness. Conversely, lower sprung mass results in higher suspension frequency, resulting in a stiff ride. Greater un-sprung mass increases the suspension system's inertia, making it less responsive to changing road surfaces. Conversely, lower un-sprung mass allows the suspension system to respond more readily to uneven surfaces. The sprung mass of BEV, assuming a capacity of four passengers, is approximately 1489.4 kg. The total un-sprung mass of BEV is around 110.6 kg. The total mass of the BEV, with a capacity of four passengers, is about 1600 kg, with a weight distribution of 45%-55%. This mass is slightly higher than the expected mass as a factor of safety in designing the suspension systems and chassis of the BEV.

IV. CONCLUSIONS

Based on the analysis of the suspension parameters for BEV, it is evident that while the actual values closely align with the optimum values, there are slight deviations as shown in table 4 below. The front suspension shows a minor discrepancy in the caster and camber angles, while the toe angle remains optimal. Similarly, the rear suspension displays a slight variance in the camber angle, while the toe angle and kingpin inclination are within the desired range. These minor differences are likely due to the constraints posed by the original design of the suspension components for the Honda S2000. Despite these variances, the suspension system of BEV is well within acceptable parameters, ensuring good handling, stability, and performance. The careful adjustments made during the design phase have contributed to achieving a balance between optimum values and practical implementation.

Table 4: Summary of suspension parameters

Front suspension parameters		
	Optimum value	**Actual value**
Caster angle	6.5°	6.25°
Camber angle	-1°	-0.67°
Toe angle	0°	0°
Rear suspension parameters		
	Optimum value	**Actual value**
Camber angle	-2°	-1.67°
Toe angle	-0.33°	-0.33°
King-pin inclination	7-15°	9.41°

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