An Alternative Battery Locating Approaches for Weight Distributions of Electric Vehicles

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Abstract. Nowadays, electric vehicles (EVs) are becoming increasingly important. Most prevailing EV models feature similar structures, allocating batteries and motors, bringing similar weight distributions. This leads to similar dynamics among EVs compared to those between internal combustion engine cars. However, unique weight distribution and driving dynamics are the major features of special automobile models, and many of those models have not been electrified. This research aims to discuss the possibility of achieving unique weight distribution with EVs. The following approach is taken by this paper: the weight of body materials and batteries are collected, and various criteria are evaluated upon different designs regarding body design and battery allocation. The research finds out that when car models are electrified, solutions do exist for maintaining their characteristic weight distributions, with the center of gravity closer to the rear axle for middle engine rear wheel drive cars. Keeping the characteristic weight distributions can keep the unique driving dynamics, which have been selling points of sports cars, of the models when they are electrified, despite inevitable expenses from multiple aspects. The solution could be accomplished more easily in the future if breakthroughs take place in battery developments and the cost of lightweight materials is cut down. The research innovatively prioritizes keeping the characteristic driving dynamics of sports cars when the models are being electrified and provides a comprehensive understanding of the possibilities and tradeoffs of the approach for manufacturers that are experiencing electrification.

Keywords: Driving dynamics, Weight distribution, Sports car, Electric vehicle.

1. Introduction

Battery electric vehicles are driven by electric motors, powered by batteries, and have controllers [1]. This type of vehicle has been gaining momentum in recent years. Sales numbers are improving and the percentage of electric vehicles in new cars is increasing [2]. Traditional automotive manufacturers are investing efforts in electric vehicles. A few emerging brands joined the competition as well. Earlier mass-production electric vehicles were electrified in a way that was modified from their internal combustion engine counterparts [1]. Using the same body, the internal combustion engine was replaced by an electric motor and battery package [1]. A higher and stiffer suspension was installed to increase ground clearance as the package is installed under the floor and encounters the extra weight of a battery. This method leads to disadvantages in aesthetic, riding experience, and safety aspects. Higher suspension sets the wheel farther apart from the wheel arch, and the added battery is hard to integrate with the original exterior design. Stiffer suspension, along with increased tire pressure, negatively impacts the comfortability and driving stability of the vehicle. Battery protection was not considered in the original body design, leading to battery safety concerns in crashes.

The current mainstream is to develop platforms exclusively for electric vehicles. The electrical systems are further integrated into the car body. The battery package is placed in the floor layer and is surrounded by side beams. The batteries are bound by the most rigid parts of the body of a vehicle, and the package also serves as a part that further improves the rigidity of the car. As regular household vehicles, commuting functionality is set to be the primary goal. It is vital to design EVs in a way that can equip batteries with the highest capacity possible. The general approach is to utilize all the space below the cabin floor. The battery is located flat below the floor in the middle of the car, and electric motors are located at the front and/or rear axle. This approach contributes to uniform weight distribution. The weight distributed to the front axle is the same as the weight on the rear axle.

Nevertheless, some internal combustion engine (ICE) vehicle models feature unique driving dynamics brought by different weight distributions. Apart from providing characteristic driving dynamics for the vehicle product, weight distribution acts as an important factor in a car's cornering performance [3]. When those models are electrified, the feature is unlikely to be restored with the currently prevailing approach for structural design and placement of electrical systems.

This paper aims to explore alternative possibilities of positioning batteries and body design for various types of cars, providing the desired distribution of weight and looking into the tradeoffs of such designs. Weight distributions of typical ICE vehicle models are considered, and how electric vehicles can achieve similar weight distribution is discussed including the trade-offs. Depending on the specific case, battery allocations are decided. Corresponding body structures are envisioned, and different materials are selected for different parts of the body. Mathematical calculations are applied to calculate the approximate center of mass representing weight distributions in consideration of battery weight, battery placements, body design, and material properties. To determine the shortcomings, those designs are put into hypothetical consumer scenarios and compared with conventional EVs. This research demonstrates the possibility of maintaining the featured weight distribution of sports car models with unconventional battery allocations when the models are electrified and lead to a comprehensive understanding of potential drawbacks.

2. Method

The weights of vehicles are broken down into several parts: Powertrain, M_P, body, M_{body}, and others, M_O. The vehicle weight, M_{Total}, and weight distributions, D_F for percent weight distributed to the front axle, D_R for percent weight distributed to the rear axle, of the corresponding vehicle models are collected. Table 1 provides a reference for the weight occupation of components of different categories in a car.

Table 1. Percentage Weight of Different Categories of Components in an Automobile.

Category	Percentage	Components
Body	23-28% [4]	Structural panel and frame beams
Powertrain	24-28% [4]	Engine, transmission, fuel tank, exhaust
Suspension	22-27% [4]	Shock absorber, spring, brake, tires, steering
Interior	10-15% [4]	Seats, dashboard, panels, insulations, airbags
Closures	8% [4]	Door panels, hood, trunk,
Miscellaneous	7-8% [4]	Electrical, window, air conditioning, lighting

The frontal and rear weight, M_F and M_R can be calculated with the following formula:

$$M_F = M_{Total} \times D_F \tag{1}$$

$$M_R = M_{Total} \times D_R \tag{2}$$

where M_{Total} refers to the total weight of the vehicle, D_F refers to percent weight distributed to the front axle, D_R refers to percent weight distributed to the rear axle.

With weight data on frame, engine and drivetrain, the weight of other parts M_O could be determined by subtracting:

$$M_O = M_{Total} - M_P - M_{body} \tag{3}$$

where M_{Total} refers to the total weight of the vehicle, M_P refers to the weight of the powertrain and M_{body} refers the body-in-white weight

Assuming even weight distribution of other parts, the remaining weight on the front axle, M_{F1}, and the remaining weight on the rear axle, M_{R1}, can be calculated with the following formula:

$$M_{F1} = M_F - 0.5M_O \tag{4}$$

$$M_{R1} = M_R - 0.5M_O \tag{5}$$

where M_F and M_R refer to the frontal and rear weight, respectively and M_O refers to the weight of others.

The weight of the powertrain is subtracted in the next step. Parameter k_p is introduced for different powertrain placements. k_p is dependent on powertrain location, which is the ratio of the distance between the engine center of mass and rear axle to the wheelbase of the vehicle. Forms like front engine front wheel drive, front engine rear-wheel drive, mid-engine rear-wheel drive ,and rear engine rear wheel drive will get different k.

$$M_{F2} = M_{F1} - k_p M_P \tag{6}$$

where M_P refers to powertrain weight, M_{F1} refers to the front axle weight after miscellaneous parts are removed,M_{F2} refers to the weight on front axle after the internal combustion engine is further removed.

Similarly:

$$M_{R2} = M_{R1} - \left(1 - k_p\right) M_P \tag{7}$$

where M_P refers to powertrain weight, M_{R1} refers to the rear axle weight after miscellaneous parts are removed,M_{R2} refers to the weight on rear axle after the internal combustion engine is further removed.

Then, the battery pack is allocated to the body. The battery weight, M_B with additional structures is determined, and the position of the center of gravity of the battery pack is calculated. Battery data reference is shown in Table 2.

Table 2. Reference Battery Properties

Cell Chemistry	Cell cathode	NCA
	Cell anode	Si-C
Cells	Producer	Panasonic
	Type	Cylindrical
	Capacity (Ah)	4.75 [5]
	Voltage (V)	3.6 [5]
Battery Packs	Energy Density (Wh/kg)	260 [5]
	Energy Density (Wh/L)	683 [5]
	Energy (kWh)	75-100 [5]
	Range (km)	350-500 [5]

The approximate density of battery package is calculated by dividing volume energy density with mass energy density:

$$\rho_{battery} = \frac{683\frac{Wh}{L}}{260\frac{Wh}{kg}} = 2.63\ kg \cdot L^{-1} = 2.63 \times 10^3\ kg \cdot m^{-3} \tag{8}$$

The battery weight is calculated.

$$M_B = \rho_{battery} \cdot v \tag{9}$$

where battery density is represented by $\rho_{battery}$, and battery volume is represented by v.

Parameter k_b is introduced, and this parameter is the ratio of the distance between the battery center of mass and rear axle to the wheelbase of the vehicle. After the battery installation, the new vehicle's total weight, $M_{Total}{}'$, the new weight on the front axis, M_{F3}, and the new weight on rear axis, M_{R3}, are calculated:

$$M_{F3} = M_{F2} + k_b M_B + 0.5M_O \tag{10}$$

$$M_{R3} = M_{R2} + (1 - k_b)M_B + 0.5M_O \tag{11}$$

$$M'_{Total} = M_{F3} + M_{R3} \tag{12}$$

where M_{F2} and M_{R2} represents the front load and rear load with the internal combustion engine and miscellaneous removed, M_O represents the weight of miscellaneous parts. M_B refers to the weight of the battery package.

The front and rear weight distribution, $D_F{}'$ and $D_R{}'$, after electrifying, could be calculated:

$$D'_F = \frac{M_{F3}}{M'_{Total}} \tag{13}$$

$$D'_R = \frac{M_{R3}}{M'_{Total}} \tag{14}$$

where M_{F3} and M_{R3} represent the new front and rear axle weight with battery pack, and M'_{Total} represents the new total weight of the vehicle.

Introducing weight distribution ratio D:

$$D = \frac{D_F}{D_R} \tag{15}$$

where D_F is the percentage of total weight on the front axle, while D_R is the percentage of total weight on the rear axle.

The weight distribution factors with internal combustion engine powertrain and with electric powertrain are compared so that the battery is located to provide similar weight distribution factors before and after electrification. Then, the final total weight, M'_{Total}, is compared with the initial vehicle weight, M_{Total}.

When the data of a car can be collected comprehensively, the following formula is provided for calculating the weight distribution more efficiently [6]:

$$X = \frac{\sum(m \cdot x)}{M_{Total}} \tag{16}$$

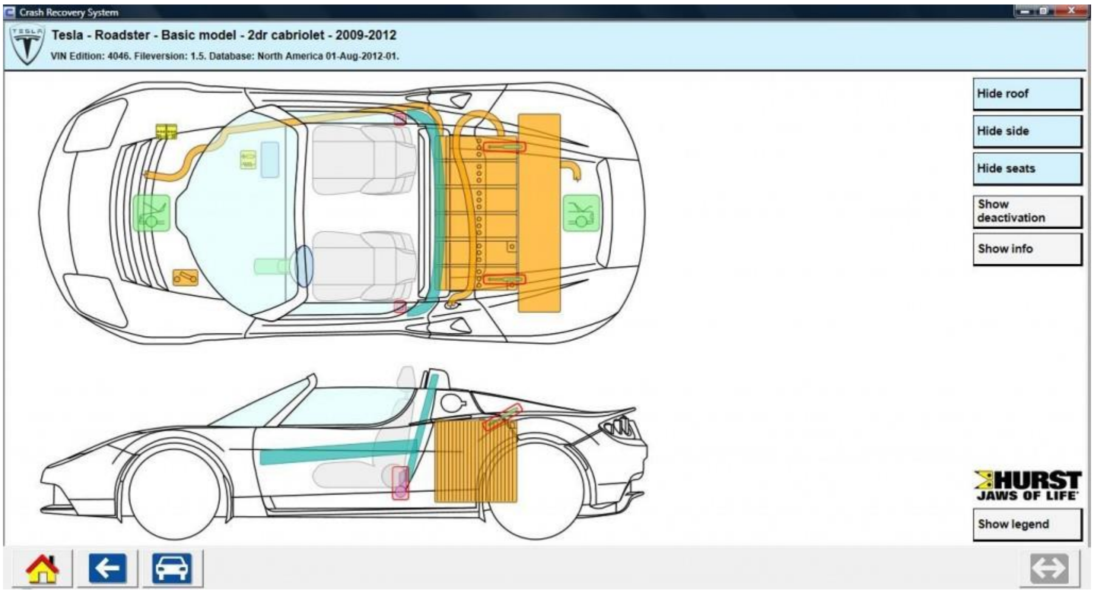
where x represents the position of the center of mass from the front axle of different components, $mand$ represents the mass of different components, X represents the center of mass position of the entire vehicle [6].

Verifying the method with real-life examples:

Tesla Roadster is a battery-powered sports car that is based on Lotus Elise series 2, which is powered by internal combustion engines. Table 3 shows the published engineering data of both models that will be used in the calculations. Fig. 1 demonstrates the allocation of the electrical powertrain of the Tesla Roadster, while Fig. 2 shows the allocation of the internal combustion powertrain of the Lotus Elise.

Table 3. Published Data of Lotus Elise and Tesla Roadster

Category	Lotus Elise 2008	Tesla Roadster 2.0
Total Weight	901kg [7]	1235kg [8]
Weight distributions	Front: 38% [9] Rear: 62% [9]	Front 519kg [8] Rear 974kg [8] (max load) Calculated weight distribution F/R: 34:66
Center of Gravity Position (Distance from front axle) (Calculated from weight distributions)	1426mm	1552mm
Engine weight	115kg [10]	N/A
Engine Center of Gravity Position from front axle (Calculated)	2140	N/A
Power Battery weight	N/A	408kg [8]
Battery Center of Gravity Position from front axle (Calculated)	N/A	1998
Wheelbase	2300mm [9]	2351mm [8]


Crash Recovery System

Tesla - Roadster - Basic model - 2dr cabriolet - 2009-2012

VIN Edition: 4046. Fileversion: 1.5. Database: North America 01-Aug-2012-01.

Fig. 1 Demonstration of Tesla Roadster Battery Package Location [11]

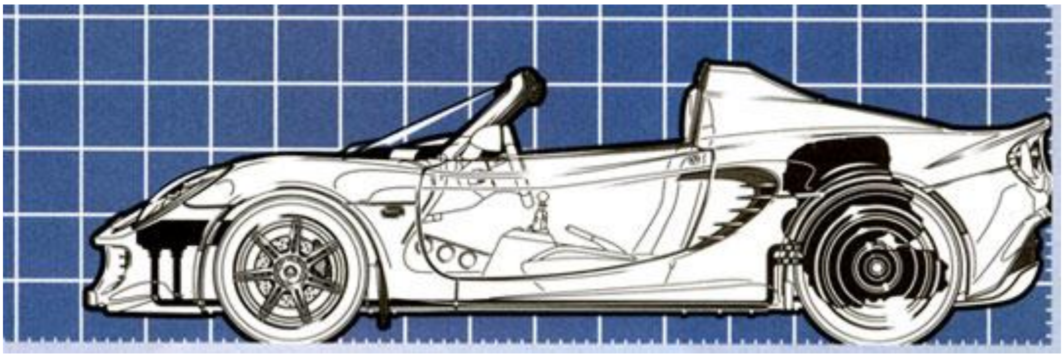


Fig. 2 Demonstration of Lotus Elise Internal Combustion Engine Location [12]

With the published data above, the method is tested by calculating the theoretical weight distribution of Tesla Roadster and comparing it with published data. The calculated results are shown in Table 4.

Table 4. Calculation with Proposed Method

Category	Calculation Data for Tesla Roadster
Weight with engine removed:	786kg
Center of Gravity Position (distance from the front axle) with engine removed:	1321mm
Center of Gravity Position (distance from the front axle) with battery added:	1552mm
Weight Distribution	33:67
Total Weight	1194

The calculated total weight and center of gravity data with the proposed method for the Tesla Roadster is compared to the published data. The difference is within 5% and is considered satisfactory. Thus, the method is verified to be reliable.

3. Results

The following result is based on Honda NSX 1990. With the method above, the ICE sports car is electrified hypothetically. The battery package is demonstrated in Fig. 3

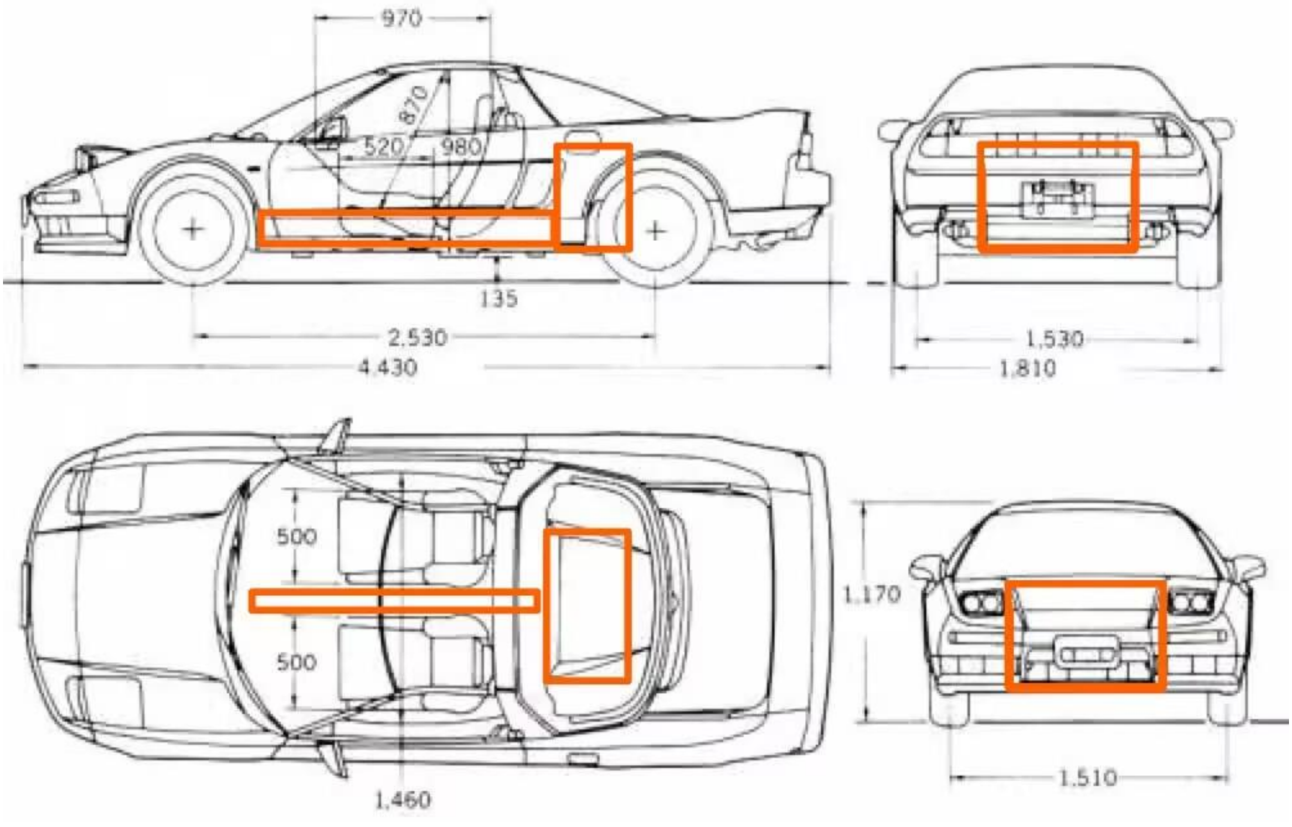


Fig. 3 Demonstration of Battery Location [13]

The following engineering data of the internal combustion engine model shown in Table 5 are used in the calculations. The battery data shown in Table 6 are used in the calculations for electrifying the model.

Table 5. Engineering Facts of the Car

Model	1990 Honda NSX
Overall Vehicle Weight (kg)	1365 [4]
Body-in-white Weight (kg)	210 [4]
Engine Weight (kg)	195 [14]
Weight Distribution (F/R)	42:58 [4]

Table 6. Data of Battery Placement

Battery Package 1 Dimension (length/width/height) (mm)	1600/150/130
Battery Package 1 Center of Mass (COM) Position (Distance from front axle) (mm)	1200
Battery Package 2 Dimension (length/width/height) (mm)	300/700/500
Battery Package 2 COM Position (Distance from the front axle) (mm)	2150
Battery COM Position (Distance from the front axle) (mm)	1932
Battery Weight (kg)	358
Battery Capacity (kWh)	93

The calculated result of electrifying the car is demonstrated in Table 7.

Table 7. Calculated Data of Vehicle Weight Distribution After Battery Placement

Engine COM (Distance from the front axle) (mm)	2150
Vehicle COM under ICE Specification (Distance from the front axle) (mm)	1467
Vehicle Weight with engine removed (kg)	1170
Vehicle COM with engine removed (Distance from front axle) (mm)	1353
Vehicle Weight with Battery Added (kg) Percent Increase of Total Weight (%)	1528 11.9
Vehicle COM with battery added (Distance from the front axle) (mm)	1488
Weight Distribution After Electrified (F/R)	41:59

The electrification designs succeeded in allocating electronical components so that a weight distribution resembling the original internal combustion version of the car was achieved. Rather than a 50/50 weight distribution of common electric vehicles, a 41/59 weight distribution is achieved by alternative methods of locating batteries. This weight distribution resembles the internal combustion engine counterpart and is expected to contribute to vehicle dynamic in a middle-engine sports car style. Thus, hypothetical electrified models of cars are proved to be able to resemble their internal combustion engine counterparts in weight distribution while an elevated total mass is observed, along with other non-obvious setbacks in theoretical assets.

4. Discussion

Despite the advancements the research reveals, the increased vehicle weight, the room the batteries are taking, and the positions of the batteries relating to safety issues are worth noting.

With other factors remaining the same, the vehicle weight is increased when a battery package of appropriate capacity is applied to the body. In real life conditions, the weight will be increased to a higher extent, as the body shall be reinforced to carry the additional weight brought by the battery. Thus, more additional weight would be brought. Increased weight will have negative impacts on cornering speed, stability, and radius [15]. The performance, or track lap times, will be impacted. More power is required to counter the impacts of increased weight as well.

To maintain the driving range, while the battery is unable to utilize the full area under the floor for weight distribution purposes, the battery must be stacked in a vertical direction. This challenges the available space for passengers. When a vertical stack of batteries happens in front of the driver’s seat, the room for leg and foot for passengers will be reduced. When a vertical stack of battery happens in the middle column of a car, the sense of space in the cabin is reduced and the passengers have less flexibility to move their legs as horizontal space is reduced. When the vertical stack of battery happens under seat zones, the sitting position is elevated, leading to a worsening riding experience for passengers and a reduced space for the head.

The compromised allocation of battery for weight distribution is more likely to place the battery at less safe locations with the body. The routine approach is that the package is placed within the safety zone [16]. Nevertheless, the compromised placements are likely to allocate batteries nearer or within the part of the body that absorbs the energy in crashes [16]. In situations that the batteries are stacked on locations in front of/near the front axle, or placed back of /near the rear axle, the body deformation caused by crashes can cause the battery package to deform, leading to a spill of chemicals, fire risks, and potential electric shock to passengers [16].

To address safety issues, two possibilities are raised by the author. The first method is to build the body exclusively for battery allocation or develop the car around the primary goal of replicating the weight distribution. The battery placing area near or in impact absorbing part of the body should be included in the high-strength cabin, so that the possibility of battery deformation could be reduced [17]. Another possibility to address the safety concerns when a battery is placed outside the primary safe zone is to utilize battery packages that are more tolerant to crashes [18].

As for weight reduction, and serving for weight distribution purposes, various materials could be implemented. The conventional approach is to apply lightweight and strong materials [19]. Dismantling different properties when designing a body represents another possibility. The body could be separated into modules that each module could utilize materials of varying characteristics. For instance, suspension mountings and battery package mounting areas could be integrated into the cabin module, where all the components are required to stay in rigid parts of the car body. Take an EV design with its cabin composed of composite materials, and its ribs carbon-fiber reinforced polymer as an example [19]. Instead of designing alloy suspension mounts placed in front of the cabin, it is possible to design suspension mounting points directly on the carbon fiber body. In this way, the material selection of the frontal structure can be less focused on strength and shift the focus more onto weight and cost.

To reduce space occupation while, the energy density of battery, electricity per unit of volume could be improved in the future. In the short term, the focus should be put on optimizing the currently mature form of battery, improving the electrolyte and anode materials [5].

5. Conclusion

Based on mathematical analysis, this research studies the impact of the alternative way of placing batteries on sports cars on the weight distribution. Non-uniform weight distributions serving driving dynamics and performance purposes can be realized when the analyzed models of ICE vehicles are electrified. The weight distribution of the specific model has been kept the same after electrification. Trade-offs in terms of the driving range are expected as the practical battery capacity is expected to be smaller than the theoretical value in the calculations. The vehicle weight has increased by more than 10% compared to the original ICE model, and safety risks in crashes due to battery packs are noticed. The cost is increased to address those issues. Currently, setting weight distribution as a design goal is expected to be practical for high-end sports cars. From a futuristic perspective, the tradeoff of addressing weight distribution in EV design could be reduced with the development of advanced materials, design logic, and battery technology. Consequently, the weight increment due to electrification could be reduced. The battery can be placed more securely to improve safety and improve the acceleration and driving range of sports EVs.

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