4-wheel Independent In-wheel-motor Drive and Independent Steering Electric Vehicle Safety Analysis Method Based on Mass Re-distribution Experiment

Design for Electric Vehicles with Advances in Drives and Steering Mechanism

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Abstract - **This paper presents a safety analysis method based on mass re-distribution experiment of the novel 4-Wheel Independent in-wheel-motor Drive and Independent Steering Electrical Vehicle (4WIDIS EV), which has four independent wheel units with the central engine, gearbox and steering mechanism all removed, as each independent unit has an in-wheel motor with its own steering control system. A central control unit is used to coordinate the 4 wheels and translate the driver's input to the wheels so that there is no mechanical link between these wheel units. In such a design, as compare to traditional vehicle, the mass distribution could be more flexible. Based on this flexibility and extra space, the method is proposed to experiment the distribution of mass by re-arranging the battery pack(s) in the vehicle to improve the safety**

Keywords - Electric Vehicles; In-wheel-motor; Independent Drive; Independent Steering; Safety Analysis Method; Mass Re-distribution

I. INTRODUCTION

In most traditional vehicle applications, a central internal-combustion engine is mechanically coupled to the wheels by a gearbox and a mechanical differential, and these components have to be located at the fixed position in the vehicle to establish the mechanical link in between, to optimise the simplicity of the structure and power transmission efficiency. Instead of adopting the internal-combustion engine, the 4-Wheel Independent in-wheel-motor Drive and Independent Steering Electrical Vehicle (4WIDIS EV) has many advantages, including no mechanical linkages, all wheel independent steering, independent and precise torque control of each wheel. Furthermore, advanced control functions like Antilock Braking System (ABS), Anti Slip Regulation (ASR), Electronic Stability Program (ESP), and, most importantly, 4-wheel independent steering are feasible. As a result of the engineering design, a cooperative model is required between the steering motors and the in-wheel propulsion motors to reduce the power demands in an in-situ steering operation [1], e.g. a parallel parking and a differential control is carried out by means of regenerative braking [2]. However, an independent suspension is needed to reduce the uneven tire wear caused by unbalanced suspension [3]. As the mechanical links is no more required with the replacement of signal and power cabling, such a novel EV has a capability to have a better arrangement flexibility for most of component in the EV. Due to the revolutionary significant mechanical structure difference to the traditional vehicle, the 4WIDIS EV needs a safety analysis method based on the mass re-distribution to improve the Centre of Gravity (CG) position, by make use of the flexibility of re-arranging the component configuration in the vehicle, to improve the overall safety.

The traditional car, e.g. a wagon, has a relationship between the height of the centre of gravity of the loaded wagon and the vertical dynamic load coefficient [4]. The large mass vehicle, e.g. a bus, dynamics was analysed and the dynamic model was established according to basic dynamic characteristics of a bus [5]. For a special case of an unmanned ground vehicle, research presented a theoretical analysis and experimental results of executing extreme dynamic maneuvers by altering its internal mass and inertial properties during locomotion [6]. It was determined that having the CG as low and close to the centre of the vehicle as possible resulted in optimal safety and controllability.

This paper presents a safety analysis method based on mass re-distribution experiment of the novel 4WIDIS EV, which has four independent wheel units with in-wheel hub motor, four independent steering systems, power battery pack, a driver and a passenger seat. As the CG position is a result of the configuration of these components or loads, a safety analysis method is proposed, to ensure that CG is as low and close to centre of vehicle as possible. Beside that, a case study of experiments and analysis were established to confirm the proposed method, based on the engineering prototype 4WIDIS EV as shown in Figure 1.

Figure 1 – The engineering prototype of 4WIDIS EV

II. THE BASIC STRUNCTURE OF THE 4WIDIS EV

A. The independent wheel units

The 4WIDIS EV has four independent power-on-wheel units. Each independent unit has an in-wheel motor with its own steering control system. As shown in Figure 2, the wheel unit consists of an in-wheel motor with brake, a steering motor with a gearbox and a suspension system.

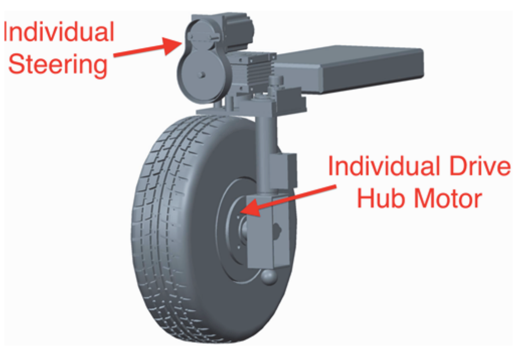

Figure 2 - A power-on-wheel unit

B. The car body design

The car body has been designed to be the housing of four independent power-on-wheel drive independent steering wheel units as shown in Figure 3. Such an EV has four independent power-on-wheel units. Each independent unit can be positioned where a traditional car has its wheels. Since a central electronic control unit with driver's interface is used to coordinate the four wheels and translate the driver's input to the wheels, no mechanical link is required between these wheel units and the driver's interface. To design the vehicle, once the space for the power-on-wheel units is defined, additional space is needed in the vehicle to house the battery pack(s), central control unit with driver's interface, and electronic control units (ECU) for each wheel.

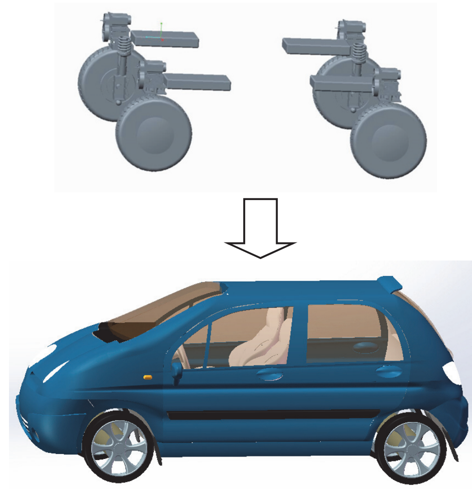

Figure 2 – Four wheel units in a 4WIDIS EV

III. METHODOLOGY

A. The CG of 4WIDIS EV

This 4WIDIS EV carries four hub motors instead of the traditional central engine, central gearbox and power transmission system. Thus, the mass of the traditional engine and transmission system at the front of the vehicle will be distributed to the four in-wheel hub motors. Beside that, this 4WIDIS EV has four separate steering systems at each of the four wheels respectively. Similarly, the weight of central steering system at the front of the traditional vehicle is also distributed to the four wheels for this configuration. Therefore, the mass traditionally on the front of the vehicle is redistributed to the four wheels, which is more or less fixed at the four wheels.

In 4WIDIS EV, the fuel tank on the traditional vehicle is replaced with a single motor power battery pack, which can be located at anywhere in the vehicle, as there is reasonably enough spaces in the engine compartment as discribed above, and below the trunk boot where the fuel tank of raditional automobiles is located. Or, the single battery pack can be separated into four packs to replace the single fuel tank in the traditional vehicle, to associate with each of its wheel for powering up these units individually.

Hence, the positioning of the power battery pack(s) could influence the CG of the EV, and contribute to the optimisation of the CG position for the best design of safety.

B. Experiment Design

The prototype of the 4WIDIS EV had been previously described and is used here as the platform to conduct the experiments to confirm the method.

For the convenience of the CG analysis, a three-axis coordinate system of the EV is defined as shown in Figure 4. The origin positioned at the centre of the contact surface between the right front wheel and the ground.

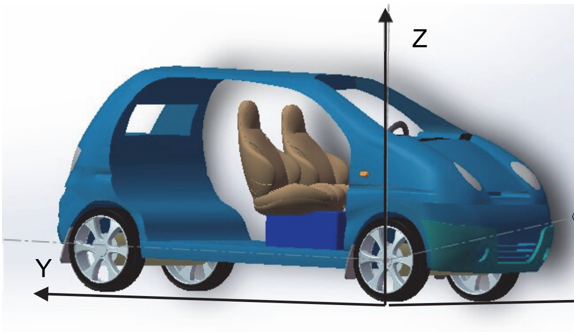

Figure 3 – Defined 3-axis coordinate system of EV

Secondly, the gravity force at the four individual wheels is measured with the vehicle in different configurations and orientations as shown in Figure 5.

Figure 4 – Gravity force measurement at the individual wheel

With this data, the CG of the EV can be located in the 3D coordinate system, with the methodology of moment force balance. The proposed steps are as follows:

Step One – Finding the Y-axis element of CG:

The EV can be simplified into a two-dimensional problem to determine the location of the CG along the Y-axis. As shown in Figure 6, by measuring and summing the weighing scale reaction forces, the load for the two front wheels can be calculated independent of the two back wheels. The location of Y_{CG} can be found by balancing the moment force reactions created by these two sums of forces. The equations are shown in (1).

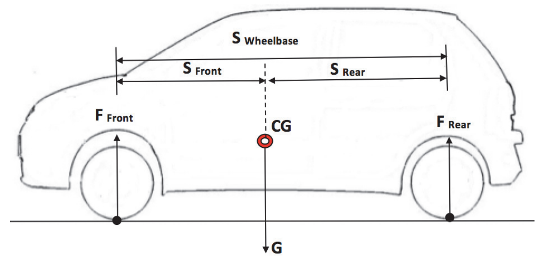

Figure 5 – Force measurement and moment arms associated to Y_{CG}

$$\begin{cases} F_{Front} \times S_{Front} = F_{Rear} \times S_{Rear} \\ S_{Front} + S_{Rear} = S_{Wheelbase} \\ Y_{CG} = S_{Front} \end{cases} \quad (1)$$

Step Two – Finding the X-axis element of CG:

The EV can be simplified into a two-dimensional problem, to find out the X-axis element of the CG point. As shown in Figure 7, by measuring and summing the weighing scale reaction forces, the load for the two left wheels can be calculated independent of the two right wheels. The location of X_{CG} can be found by balancing the moment force reactions created by these two sums of forces. The equations are as following (2).

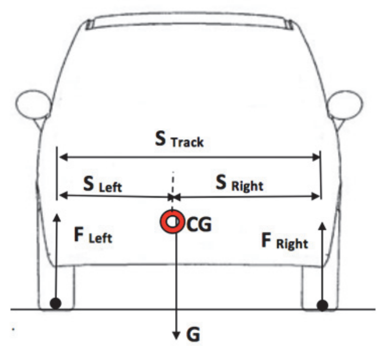

Figure 6 – Force measurement and moment arms associated to X_{CG} (view from rear of vehicle)

$$\begin{cases} F_{Left} \times S_{Left} = F_{Right} \times S_{Right} \\ S_{Left} + S_{Right} = S_{Track} \\ X_{CG} = S_{Right} \end{cases} \quad (2)$$

Step Three – Finding the Z-axis element of CG:

Finding the height of CG Z_{CG} can be simplified into a two-dimensional model positioned in the Y- and Z-axis. By fixing the front wheels and elevating the rear wheels to make the EV tilt forward at an angle, the CG point of the EV will move forward and upward. As shown in Figure 8 and 9, by measuring and summing weighing scale reaction forces, the load for the two rear wheels in the lifted position can be calculated for comparison against the same load when the vehicle was in the horizontal position. The location of Z_{CG} can be found by balancing the moment force reactions created by these two sums of forces.

The equations are as following (3) and (4).

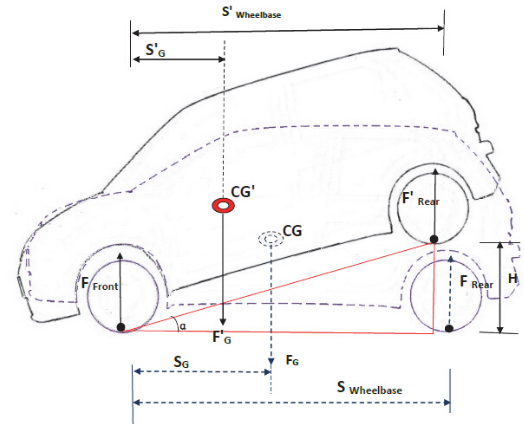

Figure 7 – Force measurement and moment arms associated to Z_{CG}

$$\begin{cases} F_{Rear} \times S_{Wheelbase} = F_G \times S_G \\ F'_{Rear} \times S'_{Wheelbase} = F'_G \times S'_G \\ \frac{H}{S_{Wheelbase}} = \mathrm{Sin}\,\alpha \\ \frac{S'_{Wheelbase}}{S_{Wheelbase}} = \mathrm{Cos}\,\alpha \\ F_G = F'_G \\ S_G = Y_{CG} \end{cases} \quad (3)$$

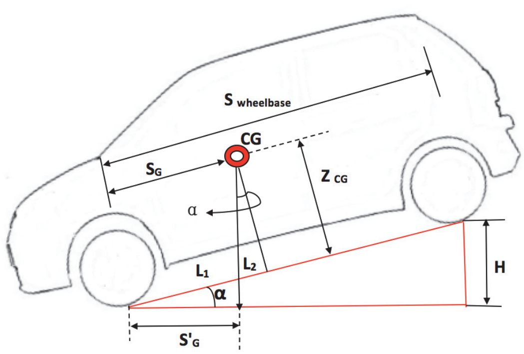

Figure 8 – Geometry link between S'_G and Z_{CG}

$$\begin{cases} \frac{S'_G}{L_1} = \mathrm{Cos}\,\alpha \\ L_2 = S_G - L_1 \\ \frac{L_2}{Z_{CG}} = \mathrm{Tan}\,\alpha \end{cases} \quad (4)$$

After the completion of above three steps, the CG position (X_{CG}, Y_{CG}, Z_{CG}) can be identified in a three-dimensional coordinate axis as shown in Figure 10.

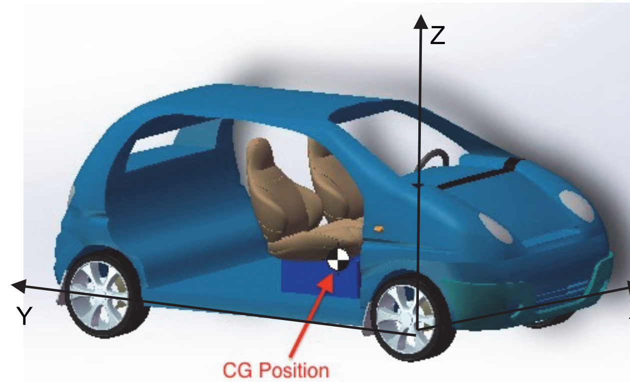

Figure 9 – CG position in the 3-axis coordinate system

IV. EXPERIMENT

A. The implementation of experiment

In the current established prototype, the motor power battery pack has been installed under the front-right passenger seat. Firstly, based on the above-proposed methodology, the first experiment was performed to find out the CG position in three-dimensional coordinate with parameters as listed below.

- Weight of Chassis: 902kgf
- Weight of Battery Pack at Front Right: 70kgf
- Weight of Driver at Front Left: 65kgf
- Weight of Passenger at Front Right: 60kgf
- EV Track Distance: 1530mm
- EV Wheelbase Distance: 2730mm
- EV Rear Wheels lifted Height in Step 3: 240mm

The data in different steps of the first experiment are listed in Table 1 and the calculated CG position is presented as shown in Figure 11.

Table 1 - Measurement and Calculated CG Position for Experiment 1

Step	Gravity Force Measurement (kgf)				Dis-tance (mm)	Moment Forces (N)		Calculated Result (mm)
1	Front Left	Front Right	Rear Left	Rear Right	-	F_{Front}	F_{Rear}	Y_{CG}
	240	282	246	295		5121	5307	1389.3
2	Front Left	Front Right	Rear Left	Rear Right	-	F_{Left}	F_{Right}	X_{CG}
	240	282	246	295		4768	5660	699.6
3	Rear Left (Horizontal)	Rear Right (Horizontal)	Rear Left (Tilt Angle)	Rear Right (Tilt Angle)	H	F_{Rear}	F'_{Rear}	Z_{CG}
	246	295	233	283	240	5307	5062	727.3

Table 2 - Measurement and Calculated CG Position for Experiment 2

Step	Gravitiy Force Measurement (kgf)				Dis-tance (mm)	Moment Forces (N)		Calculated Result (mm)
1	Front Left	Front Right	Rear Left	Rear Right	-	F_{Front}	F_{Rear}	Y_{CG}
	269	270	290	284		5287	5631	1408.0
2	Front Left	Front Right	Rear Left	Rear Right	-	F_{Left}	F_{Right}	X_{CG}
	269	270	290	284		5484	5435	768.4
3	Rear Left (Horizontal)	Rear Right (Horizontal)	Rear Left (Tilt Angle)	Rear Right (Tilt Angle)	H	F_{Rear}	F'_{Rear}	Z_{CG}
	290	284	271	277	240	5631	5376	723.0

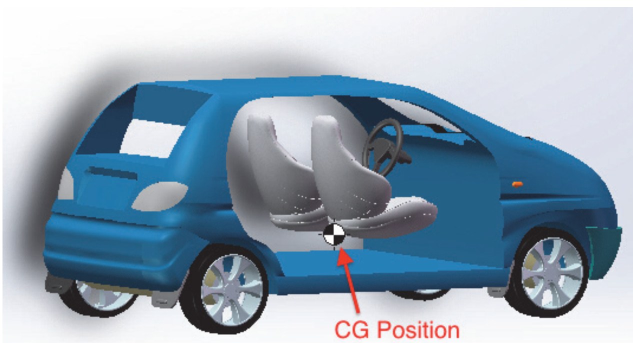

Figure 11 – CG position illustration of experiment 1

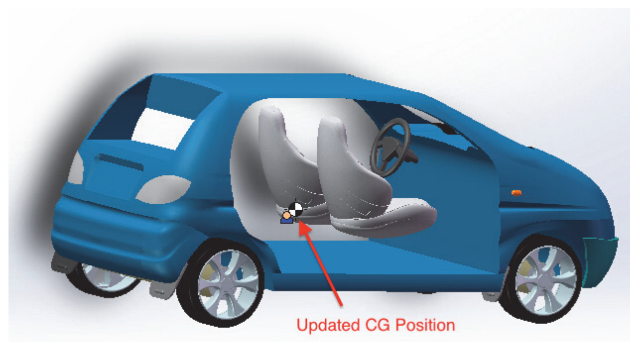

Figure 12 – CG position illustration of experiment 2

The installation position of the motor power battery pack is under the front right passenger seat currently. Another experiment is designed to move the motor power battery pack to the rear centret. The experimental parameters are listed as follows:

- Weight of Chassis: 902kgf
- Weight of Battery Pack at Rear Centre: 65kgf
- Weight of Driver at Front Left: 60kgf
- Weight of Passenger at Front Right: 70kgf
- EV Track Distance: 1530mm
- EV Wheelbase Distance: 2730mm
- EV Rear Wheels lifted Height in Step 3: 240mm

The same experiment procedures with modified EV mass distribution configuration were repeated. Another group of data was obtained. The data from the experiment 2 are listed in Table 2 and the calculated CG position is presented as shown in Figure 12.

B. *Result of experiment*

Normally, the ideal CG position of vehicle is located at the centre to balance the load across the four wheels, and with the height as lower as possible to reduce the risk when turning. Especially, the balance on X-axis is required. According to the existing EV track distance of 1530mm and wheelbase distance of 2730mm, the ideal coordinate of CG on X- and Y-axis is (765mm, 1365mm), with minimised value at Z-axis.

In the first experiment with the original configuration, due to the placement of battery pack under the front right passenger seat, the CG is located at (699.6mm, 1389.3mm) on X- and Y-axis with height of 727.3mm on Z-axis. This CG position is deflected to right by 65.4mm and to back by 24.3mm reference to the ideal CG position, with the height of 727.3mm above ground. The CG height and deflection to back is quite reasonable, and will not cause potential problem. But the deflection to right of the CG is not very much satisfied, as a good balance in X-axis is required for the vehicle stabilisation.

In the next experiment with the re-configuration of mass distribution by changing the battery position, the CG is re-located at (768.4mm, 1408.0mm) on X- and Y-axis with height of 723.0mm on Z-axis. This CG position is very close to the centre with difference of only 3.4mm on X-axis, which shows better mass distribution with improved safety.

C. Future possible safety improvement based on the proposed method

Due to the space constrain in the current established 4WIDIS EV prototype, the current single power battery pack is not able to be separated into four, and locate them in the engine compartment and trunk boot, as these spaces are filled up with ECUs for each wheel units in the current prototype. But it is possible to redesign and reduce the size of the ECUs of wheel units, which are not be able to shift to anywhere else in the vehicle, to have some extra spaces in the engine compartment and trunk boot. And replace the current central power battery pack with the four individual power battery packs for each wheel units, which can be located as low and close to the wheel units as possible in above mentioned space, to even out the distribution of battery mass. And ultimately to improve the CG position further for safety, stability and controllability.

V. CONCLUSION AND FURTHER WORKS

This paper presents a safety analysis method based on mass re-distribution experiment of the novel 4-Wheel Independent in-wheel-motor Drive and Independent Steering Electrical Vehicle (4WIDIS EV), which suggests that the goal to improve the safety by moving the Centre of Gravity (CG) as low and close to the centre of the EV as possible can be achieved by experimentations of battery configuration to distribute the mass of battery at the different location in the 4WIDIS EV.

However, as a replacement of the physical experiment, it is recommended to design a software in the future to model and simulate such battery configuration and mass distribution virtually in the computer for this method adoptaion, to improve the efficiency from the physical experimentation, and ultimately improving the effectiveness of position of the physical 4WIDIS EV CG for better safety, stability and controllability.

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