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[Technical Article]

Development of Two-seat Electric Vehicles with In-Wheel Motors

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Compact electric vehicles are thought to be suitable as small models due to the advantages of quietness, low-heat generation and no exhaust gas. In particular, in-wheel motors realize smaller space requirements for power trains and drive trains. Moreover, in-wheel motors can achieve high-performance drive through independent steering mechanisms for all wheels. An **NTN** development team of young engineers has designed a two-seat electric vehicle that provides "pivot turning" and "lateral movement" capabilities with in-wheel motors. This paper introduces the features and structure of this electric vehicle.

1. Introduction

With automobile manufacturers having started mass-producing passenger car-type electric vehicles (EVs) recently, EVs are seeing rapid popularization. On the other hand, some automobile manufacturers have proposed small EVs with one or two seats and electric two-wheel vehicles that are intended for short-distance travel, [1)-4)] and some have already been brought to market.

Electrification is suitable for small vehicles as electric power is quiet, generates little heat, and has no exhaust gasses when compared to similar vehicles with internal combustion engines. Such compact vehicles are expected to be used as means of transportation not only on public roads but also in indoor spaces, such as hospitals and factories. In particular, the application of in-wheel motors as power sources offers the possibility of two great advantages. One of the advantages is freedom from the necessity of installing differentials and constant velocity joints (CVJ) for the drive wheels, so space is easily made between the drive wheels. The other is the wide steering angle range, which is not limited by CVJ operating angles.

Several EVs that are equipped with in-wheel motors and said to be capable of four-wheel independent wide-angle steering have been proposed thus far. For example, the development of a city-commuter-type vehicle on which both the track width and the wheel base are variable as a result of adopting a four-wheel-driven, two-tier, four-wheel independent steering mechanism has been reported. [5)]

Having been engaged in the development of systems for EV use such as in-wheel motor drive systems [6)] and steer-by-wire systems, [7)] **NTN** has realized vehicles equipped with its EV-specific systems to demonstrate the features and advantages of such newly-developed systems.

Given these conditions, **NTN** has organized a development team consisting of young engineers to investigate, the uses for small EVs equipped with in-wheel-motor-driven systems. As a result, they have invented the "Electric Mobility," a small two-seat vehicle that makes the most of the features of in-wheel motors, is capable of four-wheel independent wide-angle steering, and is compact and excellent in small-radius turn performance.

This paper presents the concept of **NTN**'s newly-developed two-seat Electric Mobility and the features of its mechanisms.

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2. Vehicle Concept

The considerations of the development team have led to the conclusion that for the popularization of EVs it is important that **NTN** study the commercial usefulness of small vehicles. These vehicles excel in handling in an urban environment due to their compact bodies and feature sets that contain certain levels of road running performance and load-bearing capacity.

The two-seat Electric Mobility vehicle presented in this paper has a compact body that excels in the capability of turning in a small radius in a limited space. Furthermore, an advantage of in-wheel-motor-equipped vehicles is that the four-wheel independent wide-angle steering feature makes it possible to pivot-turn and to move laterally. Such compact electric vehicles will work not only as means of everyday transportation, they also have the potential to be used in other practical applications, such as medical services and tourism.

Fig. 1 shows the orientations of different wheels during pivot turns and lateral movements. A pivot turn is a rotational movement of a vehicle with the vehicle center as the center of rotation. The “vehicle center” here refers to the point of intersection of the bisector between the front and rear wheel axes and of the center line between the right and left wheels. When a vehicle pivot-turns, the number of drive wheels does not affect whether or not it is possible. In other words, if the rotation axes of all wheels are directed toward the turning center of the vehicle, a pivot-turn is possible regardless of whether the vehicle is in two-wheel-drive, four-wheel-drive or even one-wheel-drive mode. The steering angle required to achieve a pivot-turn is determined by the wheelbase and the track width. For example, when the wheelbase equals the track width, the steering angle required is 45 degrees. When the wheelbase is longer than the track width as in common passenger automobiles, a steering angle of between 45 degrees and 90 degrees is required. For lateral movement, the four wheels are all turned to 90-degree angles.

Table 1 shows the rotation directions of individual wheels in different running modes.

The rotation directions of individual wheels during pivot-turning and lateral movement differ from those during normal running.

These movements cannot be achieved in ordinary four-wheeled vehicles equipped with differentials. They are achieved only by the combination of the in-wheel-motor drive system, which is characterized by independent drive for the right and left wheels, and a mechanism that steers the four wheels in wide angles independently.

Table 1 Rotational direction of wheels

Running mode	Front left wheel	Front right wheel	Rear left wheel	Rear right wheel
Normal running (forward)	CCW	CW	CCW	CW
Pivot-turning (right)	CCW	CCW	CCW	CCW
Lateral movement (rightward)	CCW	CCW	CW	CW

CW: Clockwise as seen from the outside of the vehicle
CCW: Counterclockwise as seen from the outside of the vehicle
Note: Rotation is reversed for backing up, left pivot turns and left lateral movements

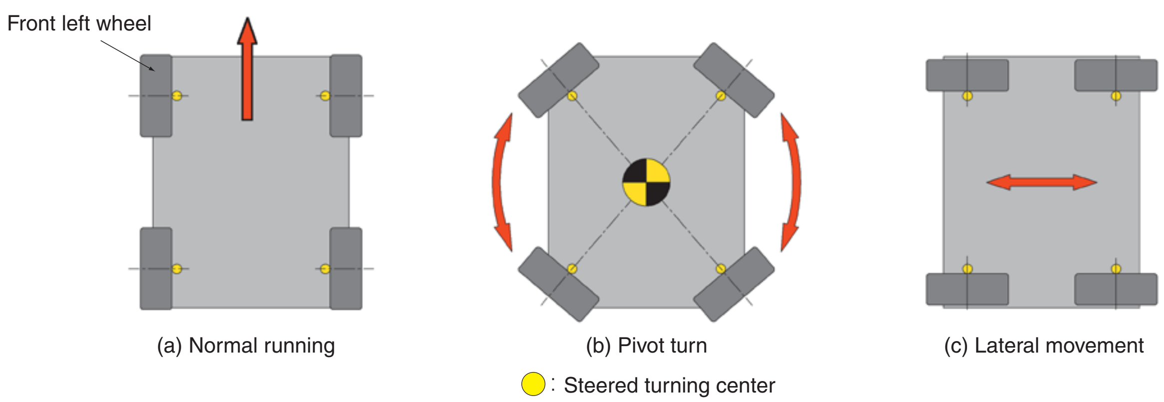

Fig. 1 Pivot turn and lateral movement

3. Test Vehicle

3.1 Vehicle layout

Fig. 2 shows the test vehicle. The vehicle is equipped with two rear wheels that have in-wheel motors. To enable four-wheel independent steering, all four wheels are equipped with steering actuators. Furthermore, in order to reduce space, the steering actuators are located near the wheels.

The major dimensions of the body are about 1700 mm in total length, about 1200 mm in total width and about 1900 mm in total height. Including space sufficient for two passenger seats, an inverter, a battery and other components, the vehicle was designed for maximum compactness. Since the battery is the heaviest component, it was installed in the lowest part at the center of the body, with the space above the battery serving as the passenger leg space.

Furthermore, by providing the seating space above the rear wheels and installing the inverter above the front wheels, the space needed for this vehicle is as small as the area occupied by two ordinary mopeds.

3.2 Suspension

The steering mechanism for conventional vehicles is a tie rod system in which the thrust from the steering gearbox is transmitted via a tie rod to the hub carrier to produce steering torque around the kingpin shaft. In this test vehicle, however, the steering range is wide, and moreover, it is necessary for the right and left wheels to be steered independently of each other. For this reason, a steering system with a tie rod scheme results in a very long operating stroke in the steering gearbox, requiring a large area. In this test vehicle, therefore, the four wheels are each equipped with a steering actuator with the aim of minimizing the area occupied by the steering system and thereby making full use of the space around each wheel.

Fig. 3 shows the layout of an in-wheel motor and steering actuator. The suspension is structured on the basis of a four-wheel double wishbone system.

The in-wheel motors and the steering actuators are built into an integral structure, and the rotation around the kingpin shafts of the output members of the steering actuators connected to the upper arm joints is regulated. Thereby, this structural arrangement allows the upper arms to support the steering reaction force. This arrangement allows the steering actuator bodies to rotate around the kingpin shafts, allowing the in-wheel motors connected to the steering actuators and the wheels connected to the in-wheel motors to be steered.

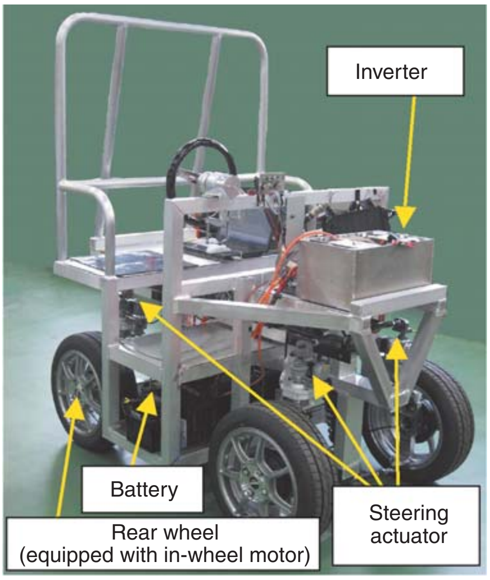

Fig. 2 Test vehicle

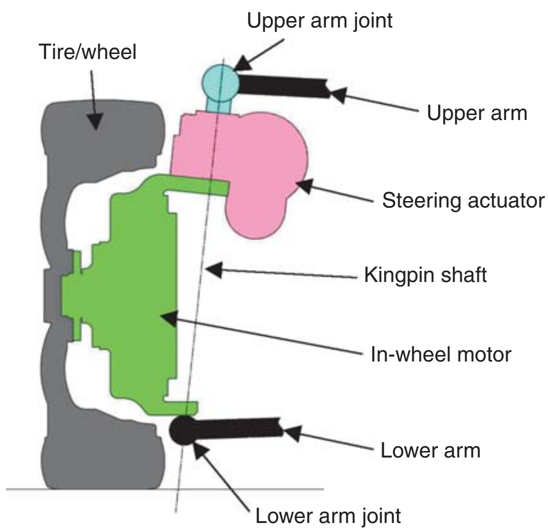

Fig. 3 Suspension layout

3.3 Kingpin offset

Fig. 4 schematically illustrates the kingpin offset. The kingpin offset refers to the distance between the intersection of the kingpin axis with the ground and the center of the tire tread. It is general practice to minimize the kingpin offset with the steering wheel. The offset is determined through comprehensive considerations around possibly conflicting factors such as straight running stability and minimum necessary steering wheel operation effort. To reduce the kingpin offset, the joint of the lower arm must be placed inside the wheel.

However, because the range of the steering angle on this vehicle exceeds 120 degrees, the location of the lower arm joint is greatly limited. For example, when the clearance between the outer circumference of the motor and the wheel bore surface is small and the lower arm joint is located in the bottom of the wheel in order to minimize the kingpin offset, if the steering handle is turned greatly, then the lower arm can interfere with the inside surface of the wheel.

In this test vehicle, the lower arm joint is situated outside the wheel (inside the vehicle) so that the lower arm does not interfere with the wheel when the steering wheel is turned at a large angle. The resulting greater kingpin offset can be one factor that contributes to an increase in steering torque. This effect is particularly apparent when the steering wheel is turned sharply while the vehicle is stationary and the brake is applied. For this reason, the tires on this vehicle are set free with the brakes not applied when steering in a wide angle to avoid an increase in the steering torque.

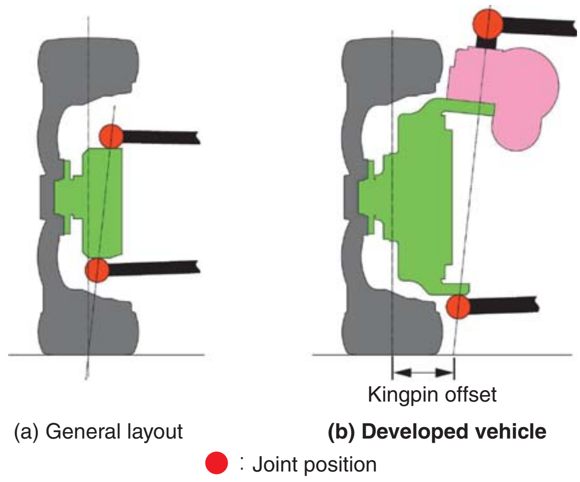

Fig. 4 Kingpin offset and joint position

3.4 In-wheel motor unit

An in-wheel motor composed of a motor, a reducer and a hub is used for the drive wheels. With the condition that it is used with a wheel of 14-inch diameter or greater, this in-wheel motor was designed with emphasis placed on a greater reduction of the dimension in the axial direction than in the motor outside diameter.

3.5 Steering actuator

Fig. 5 shows the structure of the steering actuator. In the steering actuator, the motor output speed is reduced by a worm gear to produce steering torque. With the shaft of the worm wheel forming part of the kingpin shaft, the worm wheel is fastened to the upper arm so that only the upper arm joint is free to pivot. This configuration restrains the rotation of the worm wheel. For this reason, as the motor built into the steering actuator rotates, the housing covering the part from the worm gear to the motor and the coupled in-wheel motor rotate around the kingpin shaft.

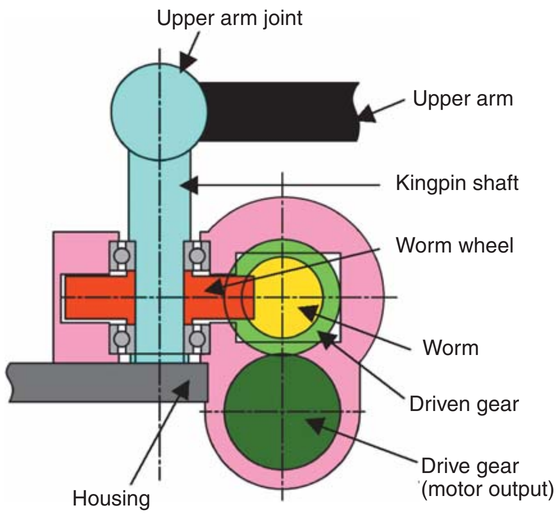

Fig. 5 Structure of the steering actuator

4. Mode Operation Control

This test vehicle is equipped with steering mechanisms that are mechanically independent on the four wheels, and the four wheels are steered by electric signals transmitted through the steer-by-wire control system.

Fig. 6 shows the basic control configuration in which the in-wheel motor is installed in all four wheels. The vehicle is integrally controlled by the vehicle control unit (VCU), which provides overall control of the in-wheel motors and the steering actuators according to the three running modes—normal running mode, pivot-turning mode, and lateral movement mode.

According to the running mode selected by the operator and the running commands, including the accelerator stroke, the VCU gives commands for the drive power and the rotational direction needed for individual in-wheel motors to the inverter. Based on these commands, the inverter generates the necessary AC outputs. At the same time, in response to the steering commands from the VCU, the steering drivers in turn control the steering actuators so that the target steering angle is achieved.

4.1 Control of drive wheels

When the vehicle advances (or backs up) in normal running mode, the drive wheels on both sides drive the vehicle forward (or backward) in a manner identical to that of the drive wheels of conventional vehicles. On the other hand, in pivot-turning mode and lateral movement mode, the drive wheels move in the directions necessary for these modes as shown in Table 1.

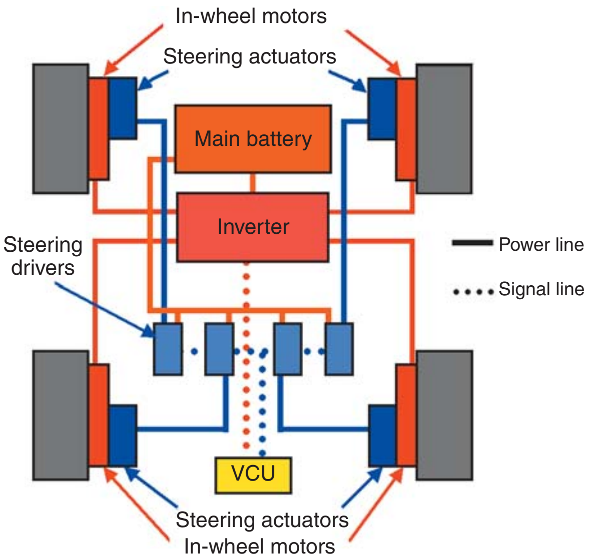

Fig. 6 Control system configuration diagram

4.2 Steering control

The steering system of this vehicle is provided by a steer-by-wire scheme, with the individual wheels being capable of independent steering. In the normal running mode, however, only the front wheels are steered, as with conventional vehicles, according to the steering input. However, it is possible to reduce the turning radius by steering the front and the rear wheels in mutually opposite phases. In addition, in a situation such as a lane change, it is possible to reduce the yaw of the vehicle and improve road holding by steering the front and the rear wheels in the direction of the same phase.

In contrast, the pivot-turning mode enables all four wheels to be steered so that their axes are oriented toward the turning center of the vehicle. In lateral movement mode, the steering angle is increased beyond that used in pivot-turning mode, with all four wheels turned a full 90 degrees from normal mode.

Figs. 7 and 8 show how the rear wheels of the test vehicle are steered in pivot-turning mode and lateral movement mode, respectively. The front wheels can be steered in the same way, and it is even possible for all four wheels to be turned by over 90 degrees within a limited vehicle space.

Fig. 7 Steering in pivot-turning mode

Fig. 8 Steering in lateral movement mode

5. Two-seat Electric Mobility

Fig. 9 shows an example of a vehicle design embodying the vehicle concept described in this paper, and **Table 2** lists the major specifications for this design. This vehicle is equipped with in-wheel motors installed in all four wheels, is four-wheel-driven, and is steered using the four-wheel independent wide-angle steering principle. With a layout following that of the test vehicle, this vehicle was designed so as to locate the battery and the inverter below the floor to lower the center of gravity of the vehicle with the aim of improving the load-capacity and securing space for two seats.

Fig. 9 Two-seat Electric Mobility

Table 2 Main specifications of the vehicle

Battery	DC 96 V (Serving both the in-wheel motors and the steering actuator)	
In-wheel motors	Maximum output/shaft	2 kW
	Drive wheel	Four-wheel drive
Steering system	Four-wheel independent wide-angle steering mechanism	
Cooling system	In-wheel motor	Air-cooled
	Inverter	Water-cooled
Seating capacity	Two people	

6. Conclusion

A two-seat electric vehicle with a compact body was fabricated that uses a four-wheel, wide-angle steering mechanism and in-wheel motors, making it capable of both pivot-turning and lateral movement.

Equipping each wheel with a small-footprint steering actuator makes it possible to turn all four wheels over 90 degrees in a limited vehicle space.

In the future, this test vehicle will be used to confirm the function of EV systems.

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