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# Development and Performance of an Electric Trike with In-Wheel Motors

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**Abstract**

A three wheel vehicle, namely a trike has a feature which is small turning radius. Recently quantity of delivery good is sharply increased because of spread of sales by using internet. Delivery company conveys goods to many houses which are located along not only wide road but also narrow road. The trike is convenient for narrow road delivery because of its small turning radius and preventing traffic jam, especially in the clouded town and city. Recently reduction of noxious exhaust gas emission, energy consumption and noise from automobile is big social problem. Therefore, in this research a electric trike for delivery use is carried out to develop. Inside of rear wheels of the developed vehicle has motors driven by lithium-ion battery. Turning radius of the vehicle is quite small and low energy cost and noise.

*Keywords: car, DC motor, electric drive, vehicle performance*

## 1 Introduction

Recently due to spread of IT technology, such as Internet and mobile telephones number of delivery handling to home and office extremely increases[1].

A vehicle for delivery handling is required to have high energy efficiency and low noise and pollution. Therefore, in our laboratory, research and development of a electric trike, herein called "electrike" is carried out and evaluation of its performance is done. This electrike has in-wheel motors and having both superior sharp turn performance and low environmental pollution including global warming.

This project was started at 2006 as three years one that is cooperated between university and Japan View-Tech Co. Ltd.. Target of it is achievement of basic model vehicle that will be able to be sell in the market. First vehicle in 2006 is very simple one constructed using original handmade parts and others taken from used small cars that use electric motor and internal combustion engine. By this car the performance of turning, height of gravity center and other requirement for electric tricycle development are examined. In 2007 the research and development was performed based on the first vehicle and second electric tricycle vehicle that has equivalent running performance to the target one sold on the market was manufactured. The first and second vehicles are shown in Figure 1 and Figure 2, respectively. In 2008 improved vehicle was designed and manufactured.

Figure 1 First vehicle produced in 2006

Figure 2 Second vehicle produced in 2006

# 2 Development of third vehicle

## 2.1 Concept of vehicle

User of electric tricycle is assumes to be home delivery services including mail delivery service. The vehicle has to run not only wide but also many narrow roads in the town and city. Therefore the vehicle should be compact and can make sharp turn. The vehicle has low noise and no pollutant emission because that runs in including quiet residential area. Furthermore energy consumption should be required to be low. The electric tricycle satisfies those requirements.

## 2.2 Design of vehicle

### 2.2.1 Design specification

A design essential specifications demanded at the time of research and development of the third electric tricycle is shown as the below.

Maximum speed: 60 km/h
Running distance: 45 km
Minimum radius of turn: 2,000mm
Maximum payload: 1470 N
The vehicle design that is fitted car standard and safety regulation[2].

### 2.2.2 Layout of vehicle

In consideration of a vehicle concept and the car standard of the low displacement car, the vehicle layout was examined with 3D - CAD.
Measures of an anti-steering wheel shimmy, a low gravity center and light weighting of the vehicle have first priority based on a vehicle layout of the second electric tricycle are examined.
Measure on battery, vehicle rider and placement of the load that give big effect on the position of vehicle gravity center is also examined.
Because it is difficult to grasp by only 3D - CAD about the vehicle rider placement such as drivability, and the front and back visibility, a woodenness mock-up is produced and they were examined. Examination about the load-carrying platform which gave a effect on car standard was done.
Furthermore, the design considered the change of the car gravity center at the time of no load and the maximum load was performed.
A vehicle layout based on the above-mentioned result is shown in Figure 3.

Figure 3 Layout of ET-2008 model

### 2.2.3 Frame

For the frame of the vehicle, truss structure was adopted.
Reduction of the frame weight was planned to use FEM structure analysis attached to the 3D - CAD.
Ladder frame structure was adopted from the viewpoint of productivity and ease of the strength security.
For the frame material a square shape steel tube was selected considering weldability, productivity and ease of acquisition.
An example of the frame analyzed by FEM is shown in Figure 4.

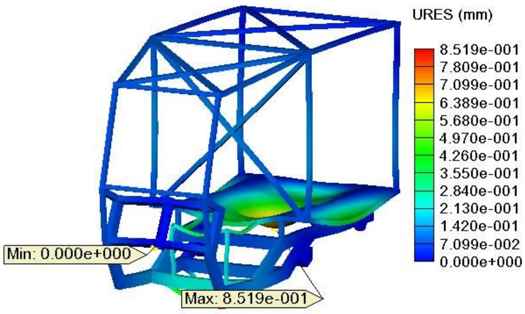


Figure 4 Structural analysis of frame

### 2.2.4 Brake

The vehicle brake system which divided a braking force was designed so that a front wheel locked it earlier from considering vehicle weight, environment of the vehicle use and safety.

Ideal and real braking force distributions at case no load and load for the third vehicle (hereafter called the vehicle) were calculated and then size of master cylinder, calliper and brake disc rotor was decided. The brakes of the three wheels become to lock at the same when deceleration is 0.9G at time of the maximum load. The brake force distribution diagram and specifications of each brake part are shown in Figure 5 and Table 1, respectively.

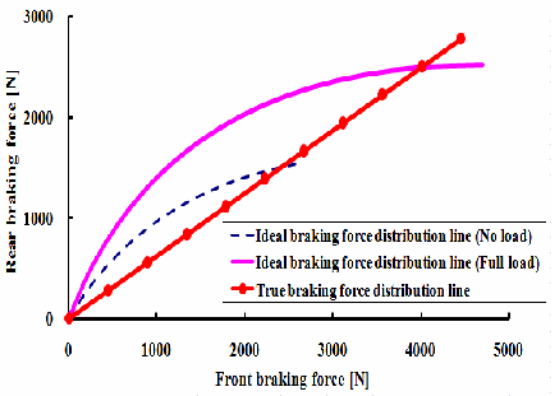


Figure 5 Brake force distribution

Table 1 Specifications of brake

| | |
|---|---|
| Master cylinder diameter | 12.7 mm |
| Front cylinder diameter | 24.5 mm |
| Rear cylinder diameter | 16.9 mm |
| Front disk rotor effective aperture | 110 mm |
| Rear disk rotor effective aperture | 90 mm |

### 2.2.5 Front suspension

For a front suspension to put on the vehicle, the front fork of the 250cc BIC motor scooter manufactured by YAMAHA Motors was used like the second one.

However, unreasonable falling down is assumed to occurred when perfectly same front fork is installed to the second vehicle. Therefore tuning to nominate oil pressure and the air pressure of the front fork for was performed and anti-power of it was improved.

This tuning was performed so that anti-power at the front desk becomes about 1,400 N when the deceleration is 0.9G. Front fork stroke versus the load before and after the tuning is shown in Table 2. Quantity of stroke can be decreased more by inserting a collar in the cylinder of the front fork, and taking a pre-road.

Table 2 Stroke of front fork versus load

| | Before | After |
|---|---|---|
| Normal load (1000 N) | 90 mm | 80 mm |
| Full brake load (1400 N) | Hit bottom | 90 mm |

### 2.2.6 Rear suspension

Because change of the spring load is big, a leaf spring is used for spring of the rear. The suspension laid it out by the rigid acceleration type that is easy to be equipped with a leaf spring.

Divided beam is installed to be equipped with an in-wheel motor. In addition, because the upper mount of the damper was made to rod-end, installation of it to the frame becomes simple, and a few amount of vehicle height adjustment is possible. Installation of rear suspension and the in-wheel motor are shown in Figure 6 and Figure 7, respectively.

Figure 6 Rear suspension layout

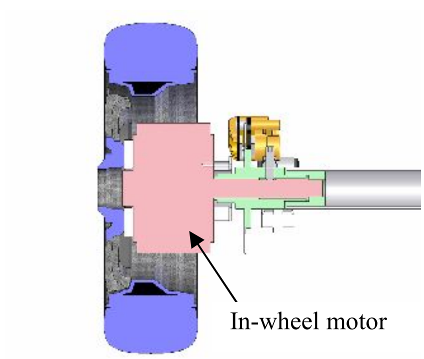


Figure 7 In-wheel motor layout

## 2.3 Electric devices

### 2.3.1 In-wheel motor

The output which could comply with a flow of the traffic in a general public road was calculated after considering the vehicle weight and driving resistance[3] .

A DC brushless DD in-wheel motor (the rating output: 5.0kW, max power: 10.0kW) was selected with an exclusive motor driver from a DC brushless outer rotor motors that are superior in protection against dust and waterproofing.

The appearance of the in-wheel motor is shown in Figure 8 and the output inspection content of the in-wheel motor is described below.

The output which was necessary for an in wheel motor used for the vehicle was calculated by next equation.

$$P = (\mu mg\cos\theta + C_D A\frac{\rho v^2}{2} + m\alpha + mg\sin\theta)\times v \quad (1)$$

Where, μ: rolling friction coefficient, m: vehicle mass, g: acceleration of gravity, θ: climbing incline, ρ: air density, A: front projection area of vehicle, $C_D$: air drag coefficient, v: vehicle speed, α: acceleration.

After considering the vehicle design conditions and main use environment, the maximum speed and climbing incline are 60km/h and 10% (nearly 5.7 degrees), respectively. In addition, each coefficient and quantity is assumed as follows.

$\mu$=0.015, m=505kg (maximum load), g=9.8 $m/s^2$, $\theta$=5.7 degrees, $\rho$=1.25kg/$m^3$, A=2$m^2$, $C_D$ =0.3, v=16.7 m/s, $\alpha$=0.238 $m/s^2$

The maximum necessary power ($P_{max}$) is calculated to be about 14.0kW.

Because the power of motor adopted here is 10.0kW, maximum power of motors installed in back two wheels is 20 KW. Therefore, the third vehicle can has enough power for running at the maximum speed ($v_{max}$) 60km/h.

Figure 8 Photo of in-wheel motor

### 2.3.2 Main battery

The electric capacity that is necessary for a run was calculated based on the run mode which assumed the use in the city area. The lithium ion battery that the voltage of full charge becomes 4.25V after having considered order electric power to the motor driver is adopted and 15 units of it were installed.

In addition, by adopting of the lithium ion battery, battery management system (BMS) is installed for control each battery voltage, current and temperature. The appearance of the lithium ion battery is shown in Figure 9 and content of electric power capacity inspection of the lithium ion battery is described below.

The aim of the driving distance is set with 45km in design condition. The electricity energy that is necessary for a run was calculated from the next equation based on ten-mode method which is the city area run model of 10 & 15 modes of running pattern.

$$L = (\mu mg + C_D A\frac{\rho v^2}{2} + ma)v \cdot t \quad (2)$$

Where, t denotes time and other quantities were described above.

The electricity energy (L) that the vehicle is necessary for 50km to run is 4,014 Wh as an aim from equation 2. The choice of the lithium ion battery was able to be narrowed down by the specifications of the motor driver to use to some extent. The voltage of power supply of the motor driver adopted here is appointed with more than 43V. The lithium ion battery of 4.25V that mentioned above is connected to series 15 and the voltage is 63.75 V when they are fully charged. It is enough voltage for the motor driver.

It is found that necessary battery capacity should be about 63 Ah to run distance of 50 km as a distance of aim when necessary electricity energy (L) 4,014 Wh calculated from equation 2 is divided by this voltage. Because electric capacity of the lithium ion battery adopted here is 60 Ah, the vehicle can drive about 45km.

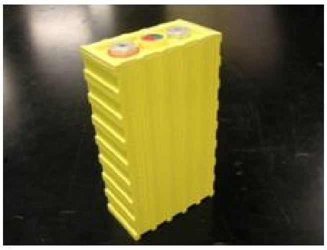

Figure 9 Photo of Li-ion battery

### 2.3.3 Supplemental electric devices

Headlamp, winkers, tail lamp unit, light for illuminating number plate, clearance lamps, back-up lamp, wiper and horn were equipped as accessories of the electric devices which are necessary for the run of the car determined by the car safety regulation [2]. In addition, the display unit which is suitable to confirm the normal working of various electric devices is equipped according the same regulation.
Power of main battery of the vehicle is not enough to supply the power for above electric devices. Therefore a condenser is charged transforming by a converter and its power is supplied to the electric devices. However, the voltage of the condenser suddenly falls when headlamp and others which necessary big power is used.
Because electricity may not be supplied in other electric devices under the influence, the life of the driver is jeopardized depending on a case.
Therefore it is necessary to use supplemental battery together from view point of safety in order to prevent such a situation. In addition, possibility to affect a running distance was occurred because consumption of electricity for electric devices than that first estimated.
Lead battery for cars is equipped for accessory of electric devices keeping running distance and considering improvement of safety. Main specifications of the supplemental battery for accessory of electric device are shown in Table 3.

Table 3 Specifications of supplemental battery

| | |
|---|---|
| Model | 95D31L |
| Voltage | 12.0 V |
| Rate capacity for five hours | 64.0 Ah |
| Usual charging current | 8.0 A |
| Mass of battery | 186.2 N |

## 2.4 Electric circuit for power system

Two in-wheel motors and the motor drivers are controlled in right and left wheel independently.
The slide type resistance was used for power adjustment to the in-wheel motors.
The mechanism which give same electric current to the right and left in-wheel motor by squeezing the throttle equipped to the bar steering handle is adopted. In addition, a non-fuse breaker (NFB) is installed between the wiring that connects main battery to a motor screwdriver
By installing NFB effect of over electric current on the in-wheel motor and others can be prevented and also a situation jeopardizing the life of the drivers such as electric shocks with it is protected. Electric circuit of driving power is shown in Figure 10.

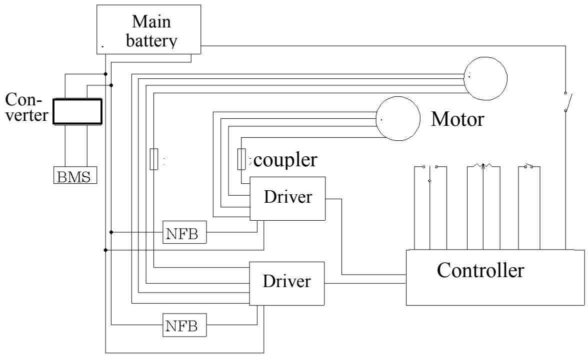


Figure 10 Electric circuit of power system

## 2.5 Manufacture of vehicle

The vehicle of manufactured based on the above-mentioned design and its main specifications are shown in Figure 11 and Table 4.

Figure 11 photo of completed electric trike

Table 4 Specifications of third electric vehicle

| | |
|---|---|
| Overall length | 2680 mm |
| Overall width | 1320 mm |
| Overall height | 1820 mm |
| Wheelbase | 1650 mm |
| Tread | 1160 mm |
| Wheel | 13×4.5J |
| Max. motor output | 10.0×2 kW |
| Battery | Li-ion4.25 V-60 Ah×15 |
| Max. speed | 60 km/h |
| Cruising distance | 45 km |
| Weight | 4194 N |
| Loading capacity | 1470 N |

# 3 Running test

Run tests of straight, turning, slalom, climbing incline and braking were performed. However, time for preparing periodical evaluation method and the measurement of the vehicle performance was not enough. Therefore the vehicle evaluation was performed from feeling at the time of the operation of the driver and movie with video camera.

The state of straight and slalom run test is shown in Figure 12 and Figure 13, respectively. The vehicle can run at 60 km/h which was measured from video movie.

Turning performance is described below as an example of the performance evaluation.

Figure 12 Straight road test

Figure 13 Pylon slalom test

## 3.1 Turning performance

Turning performance of the third vehicle was evaluated to examine validity and problems of independently controlling the right and left in-wheel motors.

### 3.1.1 Evaluation method

According evaluation content, drive method was changed like 1) pushed by hand, 2) rotating two in-wheel motors at same phase, 3) rotating only one in-wheel motor which is put outside and 4) rotating two in-wheel motors reversely. And the rudder angle of the steering wheel is brought close in various drive methods to the limit, and the vehicle is made 180 degrees turn slowly.

Turning performance in various evaluation mentioned in the above was compared and evaluated. The grasp of the trace which each wheel draws at the turning is important on evaluation of turning performance.

Powder of chalk was put to the tire surface. Several times traces drawn on the road surface were measured and minimum turning radius of the vehicle is decided by calculating the mean of those measured ones.

### 3.1.2 Result of evaluation

The result that four methods of turning radius of each ring in various evaluation measured in a foregoing paragraph are shown in Table 5 to Table 8, and Figure 14 shows Trace of turn gathered up the tire trace from above tables.

Table 5 Radius of turn (Human pushing)

| | Radius of turn |
|---|---|
| Front wheel | 1700 mm |
| Rear outside wheel | 830 mm |
| Rear inside wheel | 367 mm |

Table 6 Radius of turn (Both wheels)

| | Radius of turn |
|---|---|
| Front wheel | 1770 mm |
| Rear outside wheel | 928 mm |
| Rear inside wheel | 287 mm |

Table 7 Radius of turn (One wheel)

| | Radius of turn |
|---|---|
| Front wheel | 1710 mm |
| Rear outside wheel | 835 mm |
| Rear inside wheel | 367 mm |

Table 8 Radius of turn (Reverse turn of each wheel)

| | Radius of turn |
|---|---|
| Front wheel | 1720 mm |
| Rear outside wheel | 813 mm |
| Rear inside wheel | 374 mm |

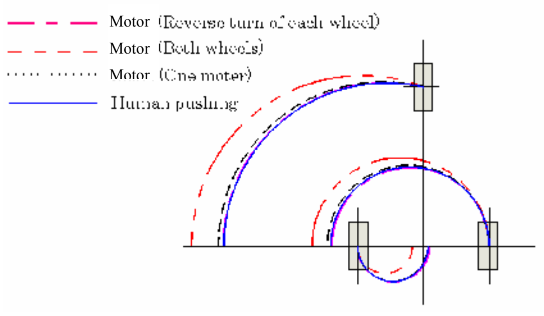

Figure 14 Trace for each turn

It is found that the turning center is existed in the inside of the vehicle from this turning performance evaluation.
In cases of driving by human hand, controlling the outer wheel motor and controlling the two wheel motors with reverse rotation phase tire trace is approximately similar.
For a phenomenon mentioned above, the inner wheel which should move forward in case of rotation of both wheels with same phase has a rotation with reverse phase toward the outer wheel. Also the behaviour of the reverse phase turn is shown with an inner and outer wheel in case of hand pushing and the outer wheel motor driving.
It is thought that this phenomenon is caused because the turning center of the vehicle exists in the inside of the vehicle. In addition, it is seen that a pushing under-steering is appeared.
It is found from above results that when a steering angle is added to a steerage wheel to the limit angle, excessive load does not suffer from the motor and can improve turning performance by taking the method to let the reverse phase turn for the right and left motor with suitable torque and stopping the power to the motor trough independent control of both motors.

### 3.2 Future subject to make the vehicle for market

Many sensors like speed, acceleration, and strain gauge should be equipped to the vehicle. Then dynamic characteristics and strength of frame and others will be examined. This information will be useful for making better vehicle for market.

## 4 Conclusions

From mentioned above main results are summarised as follows.

(1) The three vehicles were made and could store much information for electric tricycle.
(2) The third vehicle developed in 2008 can satisfy the target specifications.
(3) From various run tests the developed vehicle has superior turning performance. Especially super pivot turn was realized by controlling both in-wheel motors independently.
(4) The vehicle will be able to use not only for delivery but also conveying the good in building of airport, hospital, a factory, etc. because of small turning radius and low noise.

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