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Study of Diamond-Shape Layout Compact Personal Mobility as a New Transportation

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Abstract

Electric vehicle is not merely the change of a power unit from ICE into an electric motor. EV is a new revolution to make the new relationship among human, town and vehicle. This paper describes the new concept of personal mobility that has the smallest space, high driving performance and high level of safety. The vehicle has a unique tire layout that is called diamond-shape. Front and rear tires, and the two side tires make the vehicle stable at low speed, giving high performance at high speed. This vehicle is studied for the urban city use. Now it is at the development stage. This concept is made based on the experiences with several small cars including the first commercialized city car[1] in Japan and a study of personal mobility.

Keywords; BEV, EV, city traffic, mobility, simulation

1 Introduction

Recently the personal mobility is becoming the important topics, and there are several articles and studies about the personal mobility.
The author has been in charge of electric vehicles since 1990, and developed the two small electric vehicles [1)2)] shown in figure 1 and 2.
In this paper, based on the past experience a new advanced personal mobility concept is considered in terms of the relationship between vehicles and society.

Figure 1: Small EV “HYPERMINI” in 2000

2. Definitions of personal mobility

When ICE vehicle was invented and motorization started, most of the vehicles were small. These days the vehicles has become larger and they consume huge energy and need large parking space in a town. In spite of the improvement of fuel efficiency, the total CO_2 emission of the transportation sectors has been increasing year by year.
Currently several efforts are undergoing to change the paradigm of vehicles. One of the ideas is to use Personal Mobility (PM). In spite of several PM efforts, the definition is not still clear. The following criteria will become the key to define the PM.

Figure 2: Ultra Small EV”Micro EV” in 2005

2.1 Usage

Automobiles evolve to be able to be used for multi-purposes. Typical examples are SUVs and Cross-overs. These vehicles are basically designed for the long trip more than 100km. However, most of the trips are very short; especially in the urban area, the trip length is extremely short. Also a large vehicle occupies the precious land just for parking. For example, in the center of Tokyo the parking price is approximately $1,000 per month. One of the solutions is to use vehicles or other transportation separately according to the purposes. For the short-range a small-low-environment impact vehicle will be used and for the long-range high speed, a large and comfortable automobile will be used.

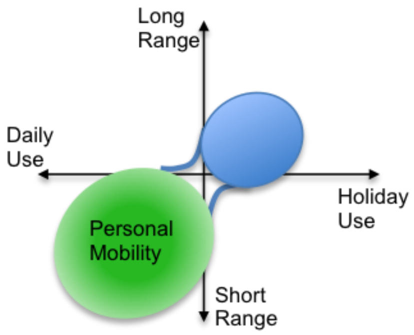


Figure 3. Usage of PM

2.2 Positioning of PM

Vehicles which falls within the intermediate category between the car and motorcycle is not so clear in Japan.
In Japan a daily use covers more than 90% of one's total trips and 70% of the daily travel is less than 10km and 50% of the driving time is less than 10minutes. The main concept of PM is to make a confortable and safe vehicle for this daily travel, and change the type of vehicles based on the purposes.

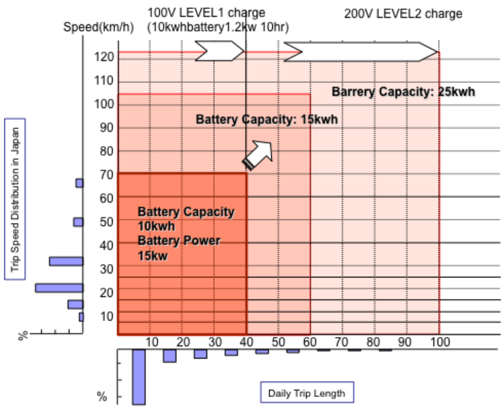


Figure 4. Positioning of PM

PM will be characterized by its minimum size. The space, especially parking space, is one of the major concerns for the daily use. Usually an automobile carries more than 20 times heavier body and holds 10 times larger space than the passenger. If the vehicle size is reduced to the bicycle size, these problems will be solved drastically.
Especially this approach will be helpful for large cities and historical old towns.

In case of the town use, the Personal Mobility's top speed will be desirably around 60km/h.
Regarding the number of passengers, the PM will be one or two.

Each country has a special regulation for PM. In Japan there is a category between automobile and motorcycle. However, this category only implements motorcycle regulations into 3 and 4 wheel vehicle. This regulation limits the number of passengers and the crash safety regulation is not applied. The US has LSV and Europe has Quadricycle Category. These regulations do not restrict the number of passengers, the size limit is larger than Japan and the top speed is limited around 40km/h
I think the current categories are not enough for PM purposes.

Table1: Low Speed regulations

	Category	Max Speed	Passengers	Size
USA	Low Speed Vehicle	40km/h	-	(<2500lb)
EU	Quadricycle (l6e)	45km/h	2	1500X3000
Japan	Mini Car	60km/h	1	1300X2500

3. Merit of PM for environment

Most of PM's energy source is electricity. The biggest drawback of the electric vehicle is heavy and high cost batteries. One of the solutions of this battery problem is to make a small and lightweight vehicle.
For example, the 150kg PM, the battery weight can be reduced into 10kg. Small amount of battery weight is not only good for the vehicle cost but also friendly for the environment.
Figure 5 shows the CO2 emission of PM. The total CO2 emission of one PM is almost the same as that of one human being.

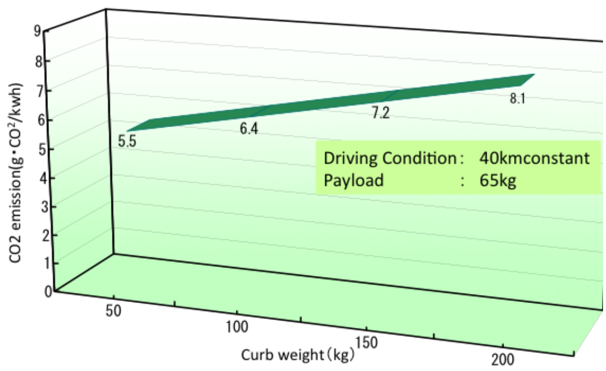


Figure 5. CO2emission of PM

4. Target of the PM for This Study

If we limit the top speed to less than 6km/h, PM can run along the same road with pedestrian without any special concern. Lows speed vehicle which falls in this category is a wheel chairs and a new vehicle such as Segway.
However, this type of a vehicle does not cover the most of daily usage. In this study, we considered PM that covers the usage between bicycle and automobile.

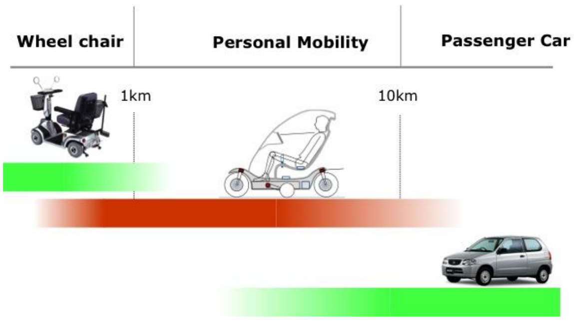


Figure 6. Positioning of PM

4.1 Dimension

To reduce the size is the most essential part of the PM. Two small vehicles that were developed in the past have different characteristics. The size of these vehicles is shown in Table 2. The first small vehicle meets all the safety requirements of passenger cars and started to be sold as the first registered ground-up EV in Japan and the US. The second vehicle was smaller. It was made with very lightweight and met the frontal crashworthiness of passenger cars. The new PM's size is considered based on these past experiences. In this study the width of the car is carefully considered, because it is necessary to reduce the size drastically to utilize the parking space effectively and be closer to human scale. The new concept vehicle's dimensions are as follows.

Table 2. Size of New Concept PM

Vehicle	Length (mm)	Width (mm)	Height (mm)	Curb Weight (kg)
Hypermini	2670	1475	1550	830
Micro EV	2150	1200	1440	140
New Concept	1600	800	1200	120

4.2 Top Speed

When the vehicle is limited in town use, the personal vehicle's top speed will be less than 40km/h. And when we consider the coexistence with the pedestrian, the top speed will be desirably around 6km/h.
However, in this study the top speed is going to be set at higher than 60km/h. Based on the past market experience of previous vehicles, I think the top speed of higher than 60km/h is necessary to run in the current traffic condition.

4.3 Number of Passengers

When we define PM as a private transportation, the number of passengers will be one or two. The average number of passengers of a running car is 1.6. So one or two passenger car will fit for the PM.

Table 3. Performance of New Concept PM

Vehicle	Top speed(km/h)	Passengers
Hypermini	100	2
Micro EV	60	1~2
New Concept	60(100)	1

5. Concept Study of the New PM

5-1.Technical Concepts

New concept PM is aiming at the smallest space, high driving performance and high level of safety. To achieve these goals we consider a vehicle that has a unique tire layout that is called diamond-shape. Front and rear tires, and the two side tires make the vehicle stable at low speed and giving good performance at high speed.
The vehicle layout is shown in figure 7.

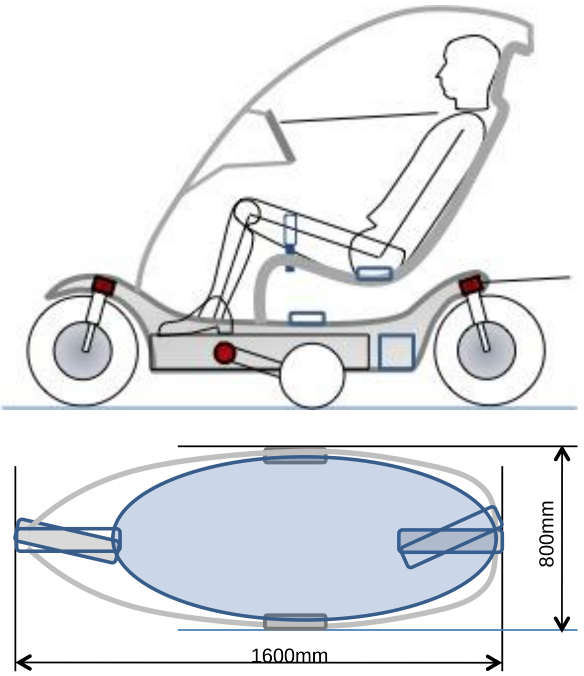


Figure 7. Vehicle Layout

Characteristics of this tire layout are as follows.
The vehicle dynamics is basically the same as motorbike at high speed. This vehicle leans at cornering like a 2-wheeler. By adding 2tires on each side, the stability of the vehicle is increased drastically. Especially at wet conditions, it protects the vehicle from turning over. These tires also contribute to the increase of cornering performance. This tire layout is called diamond-shape. It will make possible narrow width, high-speed cornering and safer vehicle.
The vehicle's steer-angle and lean-angle is controlled by the steer by wire mechanism. The driver can control the vehicle by a joystick. Mainly the front steer controls the lean angle. The rear steer and the front and rear wheel motor also contribute to leaning of the vehicle.

5-2. Unique Sales Point

The unique points of this PM are as follows.

1) Smallest size, especially width, making it possible to park at a motorcycle parking space.
2) Simple and stable lean control by steering and traction torque without any additional lean mechanism.
3) Steer by wire makes it easy to maneuver the vehicle
4) Full cabin protects passengers in case of crash and to make comfortable even in bad weather conditions.
5) Stability under the rainy condition is secured by side wheels that prevent the vehicle from slipping and turning over.
6) The vehicle can turn around the vehicle center by controlling the front and rear wheels' steer angle and torque.

5-2-1. Small Perking Space

This vehicle's width target is only 800mm. It is a little narrower than that of a motorbike. It can park at a motorbike parking lot. It will be very helpful for the center of a city and an old town where the parking space is very limited and precious. By using a motorbike parking lot, it is not necessary to make a special parking structure for this PM. The following picture shows small vehicles parked at motorbike parking lot. This new PM concept will fit for this type of old town. Figure 9 shows the concept of this vehicle's parking.

Figure 8. Parking of Motorbike at old town

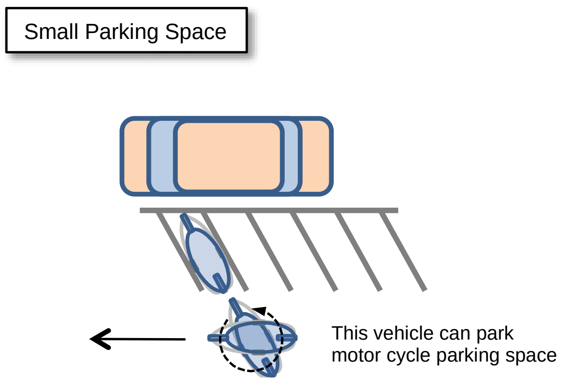
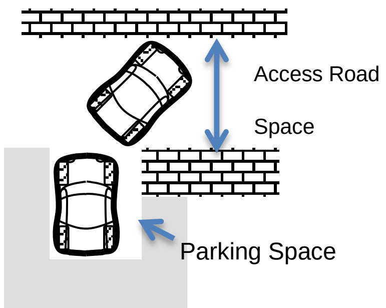


Figure 9. Small Parking Spaces

This vehicle not only saves the parking space, but also the space to access the parking lot. As mentioned later, this vehicle's turning radius is only 0.7m.
This concept can save the parking space drastically compared to other cars. The next table is the comparison between SUV, small EV, Micro EV and the new concept. The new PM requires only 1/7 parking space compared to SUV.

Table 4. Parking Space

Vehicle	Parking Space	Access Road Space
SUV	15.78m2	4.14m
Small EV Hypermini	6.21m2	2.44m
Ultra Small EV Micro EV	4.50m2	2.09m
New PM	2.28m2	1.3m



5-2-2. Stability

To attain high stability with narrow tread this car has a lean mechanism. Usually the 3 wheeler's lean is done mechanically, but the vehicle lean of this PM is controlled in the same way as a motorbike.
Motorbike has a capability to turn at high speed by lean. But the motorbike also has a demerit that is difficult to control for beginner and slips under wet road conditions. This PM controls the lean angle by steer-by-wire. The driver only needs to input the vehicle direction by joystick and the vehicle decides the steer angle and the lean angle based on the calculation.

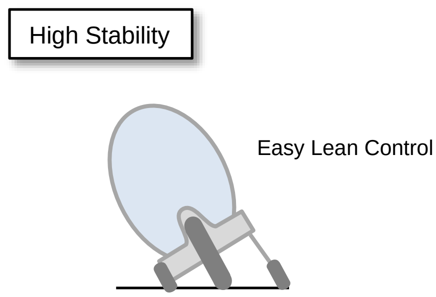


Figure 10. Simple lean control by Steering

The control will be done based on the following parameters shown in figure 11.

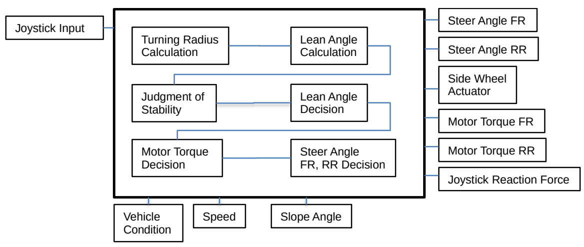


Figure 11. Simple lean control by Steering

5-2-3. Simulation of Vehicle Dynamics

Two models are used to calculate the stability and the lean control of this vehicle. And this PM's steer-by-wire control block diagram is shown in Figure 12. The model is based on SHARP's motorcycle model[3].

The step response of this PM is shown in Figure 12.

$$(M_f + M_r)\ddot{y}_1 + M_f k\ddot{\psi} + (M_f + M_r)\dot{x}_1\dot{\psi} + (M_f j + M_r h)\ddot{\phi} + M_f e\ddot{\delta} - Y_f - Y_r - Y_a = 0$$

$$M_f k\ddot{y}_1 + (M_f k^2 + I_{fx}\sin^2\varepsilon + I_{fz}\cos^2\varepsilon + I_{rz})\ddot{\psi} + M_f k\dot{x}_1\dot{\psi} + \{M_f jk + (I_{fz} - I_{fx})\sin\varepsilon\cos\varepsilon - C_{rxz}\}\ddot{\phi} - \left\{\frac{i_{fy}}{R_f} + \frac{(i_{ry} + i\lambda)}{R_r}\right\}\dot{x}_1\dot{\phi} + (M_f ek + I_{fz}\cos\varepsilon)\ddot{\delta} - \left(\frac{i_{fy}}{R_f}\right)\sin\varepsilon\,\dot{x}_1\dot{\delta} - l_1 Y_f + l_2 Y_r - T_{zf} - T_{zr} - l'Y_a - T_a = 0$$

$$(M_f j + M_r h)\ddot{y}_1 + \{M_f jk + (I_{fz} - I_{fx})\sin\varepsilon\cos\varepsilon - C_{rxz}\}\ddot{\psi} + \left\{M_f j + M_r h + \frac{i_{fy}}{R_f} + \frac{(i_{ry} + i\lambda)}{R_r}\right\}\dot{x}_1\dot{\psi} + (M_f j^2 + M_r h^2 + I_{fx}\cos^2\varepsilon + I_{fz}\sin^2\varepsilon + I_{rx})\ddot{\phi} - (M_f j + M_r h)g\phi + (M_f ej + I_{fz}\sin\varepsilon)\ddot{\delta} + \left(\frac{i_{fy}}{R_f}\right)\cos\varepsilon\,\dot{x}_1\dot{\delta} + (tZ_f - M_f eg)\delta - T_{xf} - T_{xr} - h'Y_a = 0$$

$$M_f e\ddot{y}_1 + (M_f ek + I_{fz}\cos\varepsilon)\ddot{\psi} + \left\{M_f e + \left(\frac{i_{fy}}{R_f}\right)\sin\varepsilon\right\}\dot{x}_1\,\dot{\psi} + (M_f ej + I_{fz}\sin\varepsilon)\ddot{\phi} - \left(\frac{i_{fy}}{R_f}\right)\cos\varepsilon\,\dot{x}_1\dot{\phi} + (tZ_f - M_f eg)\phi + (M_f e^2 + I_{fz})\ddot{\delta} + C_\delta\dot{\delta} + (tZ_f - M_f eg)\sin\varepsilon\,\delta + tY_f - T_{zf}\cos\varepsilon - T_{xf}\sin\varepsilon = \tau$$

$$(M_f j + M_r h)\ddot{y}_1 + \{M_f jk + (I_{fz} - I_{fx})\sin\varepsilon\cos\varepsilon - C_{rxz}\}\ddot{\psi} + \left\{M_f j + M_r h + \frac{i_{fy}}{R_f} + \frac{(i_{ry}+i\lambda)}{R_r}\right\}\dot{x}_1\dot{\psi} + (M_f j^2 + M_r h^2 + I_{fx}\cos^2\varepsilon + I_{fz}\sin^2\varepsilon + I_{rx})\ddot{\phi} - (M_f j + M_r h)g\phi + (M_f ej + I_{fz}\sin\varepsilon)\ddot{\delta} + \left(\frac{i_{fy}}{R_f}\right)\cos\varepsilon\,\dot{x}_1\dot{\delta} + (tZ_f - M_f eg)\delta - T_{xf} - T_{xr} - h'Y_a = 0$$

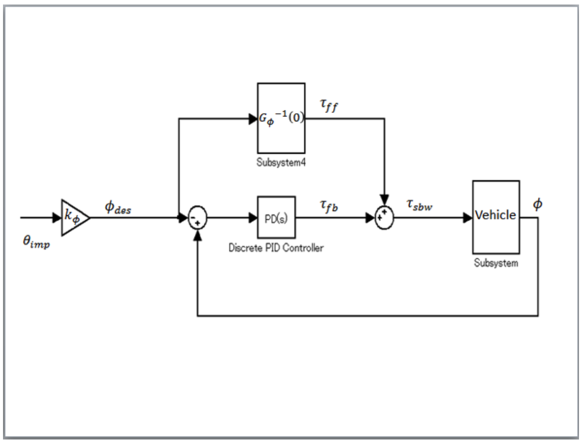


Figure 12. Block Diagram

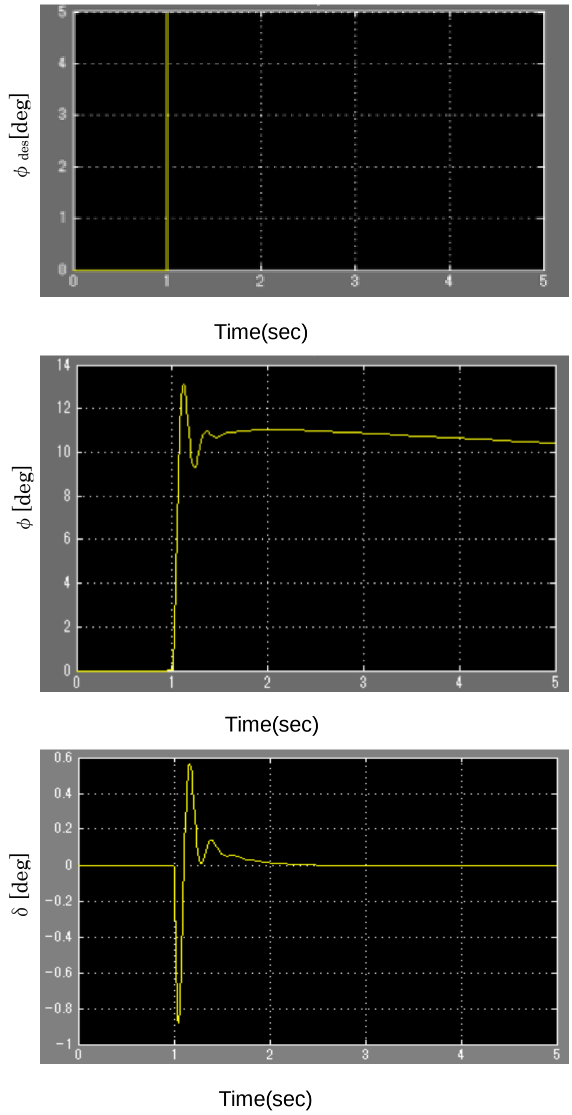


Figure 13. Step Response

In this simulation only a front steering control was considered. However rear steering control and the control of each wheel's torque might be necessary for more precise control in the future.

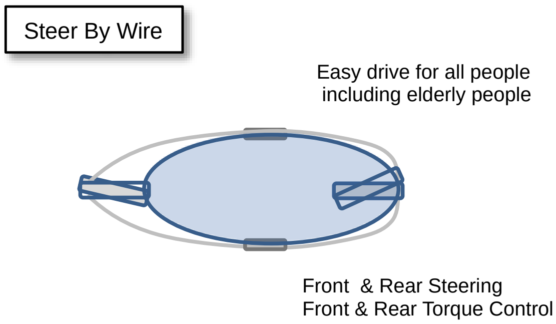


Figure 14. Easy control by steer-by-wire

5-2-4. Full Cabin

This vehicle is be covered with full cabin. Usually it is difficult to cover the whole body of 2 wheel vehicles because of the disturbance, such as lateral wind.

However, we dare to consider the full cabin to improve the crash safety and comfort. The difficulty of the full cabin, such as to gain the stability, can be solved by steer-by-wire and ingress & egress will be improved by the way of the door opening.

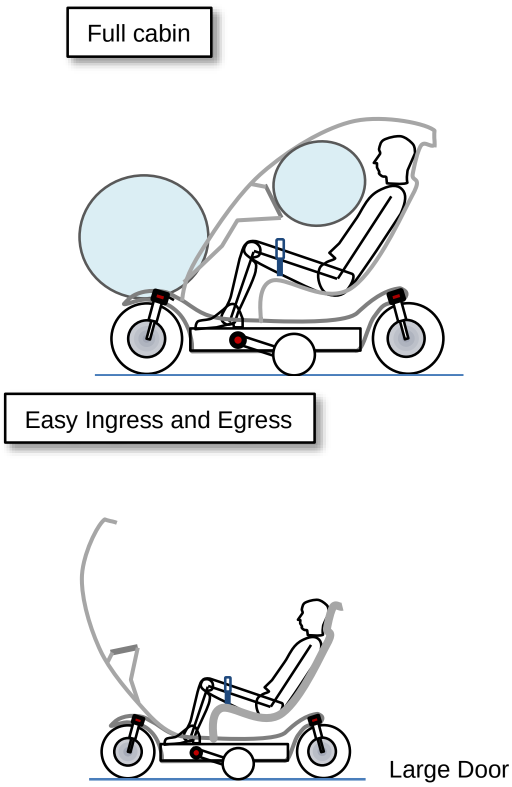


Figure 15. Full cabin

5-2-5. Diamond Shape Tire Layouts

The side wheels of this diamond shape layout make the vehicle stable in unexpected conditions. These wheels slide up and down according to the lean angle. So the weight distribution to these wheels is small, but they always touch the ground.

5-2-6. Small Turning Radius

Front and rear wheel can rotate independently. And each wheel turns 90 degree. Through this mechanism, the vehicle can turn around the vehicle center, and the turning radius is 0.7m. This mechanism can save the space to access parking.

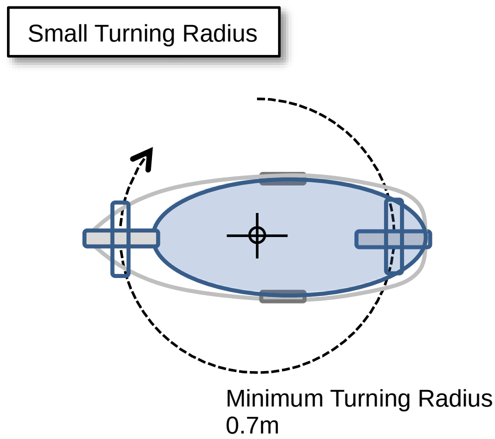


Figure 16. Small Turning Radiuses

5-2-7. Electric Vehicle Performances

The following is the target performance of this vehicle. Top speed is 60km/h and has the performance to reach 100km/h. This speed might be a little faster than other PM concepts. We believe that the capability to run down the highway is important for those who use highways on their daily trips. The Range of a single charge is designed to run 100km on JC08 (Japanese driving cycle) mode.

Table 5. Target Performance

Item	Target Performance
Top Speed (km/h)	60km/h (100km/h)
Acceleration G	0.3G
Max Gradient	20%
Range(JC08 mode)	100km

5-2-8. Design of EV Unit Specification

To decide the driving performance and unit requirement, the following specification is set.

Table 6. Vehicle Specification

Item	Specification
Curb Weight	120kg
Rolling Resistance	0.01
CdA	$0.9m^2$

The performance of a motor and a battery to achieve the target is shown in table7.

Table 7. EV unit specification

Item		Specification
Motor	Rated Power	10kw
	Rated Torque	15Nm
Battery	Capacity	3kwh

6. Conclusion

Electric vehicle is not just a change of the powertrain. It is a new way of transportation.

The symbiosis between automobile and human can be achieved by PM electric vehicles. PM is the solution to conserve the natural resource and improve the quality of life. Also we can change the life style of transportation by using PM. This concept presents the smallest size possible and has high-level active safety, and it is based on author's experiences of small electric vehicle development. Currently people are gradually accepting the small electric vehicles for daily life use.

This kind of PM has a chance to change the paradigm of personal transportation.

The first prototype of the PM is now under development and it is planed to be produced in the next year.

References

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