

The Technology and Economics of In-Wheel Motors

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ABSTRACT

Electric vehicle development is at a crossroads. Consumers want vehicles that offer the same size, performance, range, reliability and cost as their current vehicles. OEMs must make a profit, and the government requires compliance with emissions standards. The result - low volume, compromised vehicles that consumers don't want, with questionable longevity and minimal profitability.

In-wheel motor technology offers a solution to these problems; providing power equivalent to ICE alternatives in a package that does not invade chassis, passenger and cargo space. At the same time in-wheel motors can reduce vehicle part count, complexity and cost, feature integrated power electronics, give complete design freedom and the potential for increased regenerative braking (reducing battery size and cost, or increasing range). Together, these advantages create the tipping point for OEM acceptance of in-wheel-motor technology, offering them an immediate opportunity to build larger electric and hybrid vehicles, including full-size sedans and SUVs -vehicles that consumers want and are profitable to manufacture.

INTRODUCTION

OEMs are currently modifying the architecture and design of their entire range to better respond to customer demand for greener more efficient vehicles and the regulatory actions curbing greenhouse gas emissions. Accordingly, manufacturers are planning to rapidly expand the implementation of advanced vehicle, powertrain and engine technologies. In addition to the implementation of new powertrain technologies, the reduction in mass and size of the vehicle systems, sub-systems and components has also shown very promising opportunities for decreasing total vehicle emissions and running costs. Overriding this, consumers want

vehicles that offer the same size, performance, range, reliability and cost as their current vehicles, but OEMs must make a profit, and the government requires compliance with emissions standards. How can the advanced vehicle technology and diverse and often conflicting requirements come together to create the new fleet of desirable and economically viable vehicles?

This paper will explore in detail the technology of in-wheel motors (IWMs), the challenges of their integration into vehicles and how they can make a real difference to the economic viability of vehicles in a changing consumer and regulatory framework. We aim to show the reader both the opportunities and challenges surrounding IWMs; the benefits around packaging, performance and economics, and how the technical challenges of unsprung mass, brake integration and cost are being addressed in a manner suitable for the eventual adoption by automotive OEM's.

Most vehicles on our roads share a fairly similar basic layout; that of a single engine driving through a gearbox driveshaft, differential, then half shafts to the wheels. Variations of this arrangement have been used for over 100 years with very few changes to the basic layout. In recent years, electric and hybrid vehicle development has gained prominence among major OEMs and specialist companies. The vast majority of these electric/ hybrid vehicles still use variations of this same layout; a large, centrally mounted motor, driving through a gearbox, driveshaft and differential.

An alternative arrangement does exist for these electric/ hybrid vehicles, namely through the use of in-wheel motors; where the electric motors are housed inside the wheels themselves. This allows a far greater level of vehicle design flexibility than is possible with traditional centrally-mounted motors. It also frees more space inside the vehicle's body for batteries and allows each driven wheel to be controlled

entirely independently. This fully independent wheel control allows better traction control, anti-lock braking and antiskid capability than are possible with any other propulsion system. Infinitely variable torque can be applied during both acceleration or braking to each wheel instead of the comparatively crude ‘on or off’ system used by a conventional mechanically-braked ABS system.

Most electric motors of a sufficient power to propel a passenger or commercial vehicle require a large external inverter/ power electronics unit to control the motor. For a vehicle that used in-wheel motors, each motor would require its own inverter, thus taking up space in the vehicle and reducing one of the key benefits of in-wheel motors; the increase in usable volume inside the vehicle body. A solution to this would be for the power electronics to be integrated inside the in-wheel motors. This mounting arrangement would also substantially reduce the length of cable connecting the motors to the inverters, thus reducing the heating ($I^2 \times R$) loss in this cable; considering that an electric vehicle drivetrain would normally use hundreds of Amps to generate the required torque, the losses associated with this could be substantial.

Another significant source of losses in a drivetrain lies in the use of gearing in order to reduce the speed of the propulsion system (either an ICE or electric motor) to a suitable wheel speed. If the in-wheel motor was designed to operate in a direct drive configuration, the need for a gearbox would be eliminated, resulting in a lighter weight, compact and efficient drivetrain. If a direct drive design was not utilized, then each high speed electric in-wheel motor would require its own gearing, potentially resulting in a greater part count with more wearing components in a heavier drivetrain than for a single centrally-mounted electric motor.

When an in-wheel motor is referred to in this document it is assumed to be one having the optimum characteristics of being of a direct drive design with the power electronics mounted inside the motors themselves. An example of this type of motor is the Protean Drive™ from Protean Electric.

This Paper will go on to discuss the following aspects of Electric and Hybrid Vehicles, and In Wheel Motors:

1. The History of In Wheel Motors

2. The Electric and Hybrid Vehicle situation

2.1. The Market and Motivation to produce Electric and Hybrid Vehicles

2.2. The Role of Mass and Footprint in Electric and Hybrid vehicle Development

2.3. The ‘Ideal’ Vehicle Platform for Electric and Hybrid Vehicles

3. Do IWM's provide the ‘tipping point’ for Electric and Hybrid Vehicles?

3.1. Economics

3.2. Vehicle Design and Packaging

3.3. Active Safety and Torque Vectoring

3.4. Regenerative Braking

3.5. Overcoming the Technical Challenges of IWMs

4. Conclusions

1. THE HISTORY OF IN WHEEL MOTORS

The concept of having an individual in-wheel motor driving each wheel of a vehicle is not a new idea. In 1900 at the World's Fair in Paris the ‘System Lohner-Porsche’ was debuted ([reference 1](#)). This vehicle was designed by Ferdinand Porsche; the man who gives his name to the Porsche car company, at his first job in the automotive field working with Jacob Lohner. The ‘System Lohner-Porsche’ was an electric vehicle driven by two in-wheel motors; this vehicle was capable of over 35mph and set several Austrian speed records.

Following the success of this vehicle, Ferdinand Porsche then utilized Daimler's and Panhard's internal combustion engines connected to generators to provide power for the in-wheel motors; thus creating the world's first series hybrid vehicle (SHEV), the “System Mixt”. Porsche's in-wheel motor - driven vehicles in both electric and series hybrid configurations continued to claim more speed records in both two and four wheel drive configurations, eventually resulting in Ferdinand Porsche winning the 1905 Poetting Prize as Austria's outstanding automotive designer.



Figure 1. An early 1900s ‘System Lohner-Porsche’, propelled by in-wheel motors ([reference 2](#))

2. THE ELECTRIC AND HYBRID VEHICLE SITUATION

2.1. THE CURRENT MARKET & MOTIVATION

The US has a unique problem and opportunity when considering the emerging vehicle marketplace and emissions roadmap. As recently reported in the Wall Street Journal, July 2010 (reference 3), the US passenger vehicle market has Light Duty Trucks, SUVs and Crossover vehicles combining to be around 60% of passenger vehicle sales so far in 2010. Cars make up the other 40%, and within that segment, 66% are midsize or larger. In the overall US market, only 13% of vehicles are classed as being in the Small Car Segment and therefore 87% are classed as being 'larger'. Encouragingly, the industry is showing signs of recovery with all segments having sales growth on a year to year basis, the only exception being the Small SUV segment, which has had a 15% reduction.

In order to maximize the available market size and environmental savings in the US, electric vehicles and their technologies need to address the requirements of buyers wanting larger vehicles; there should be no loss of performance, space, comfort, and many would argue most importantly price and running costs.

This paper does not intend to compare overall characteristics of the US, European and Far East Markets; it will concentrate on analyzing popular US vehicles and how they can be best electrified. However, for further motivation it is well worth considering the findings of the International Council on Clean Transportation and their Passenger Vehicle Greenhouse Gas and Fuel Economy Standards report, published 2007 and updated 2010 (reference 4).

“This new study compares passenger vehicle greenhouse gas and fuel economy standards from eight major countries, states and regions. It finds that Japan and Europe are closely tied in the “race to the top” for the world's most efficient new passenger vehicle fleet, while the United States lags behind these two regions by a large margin.

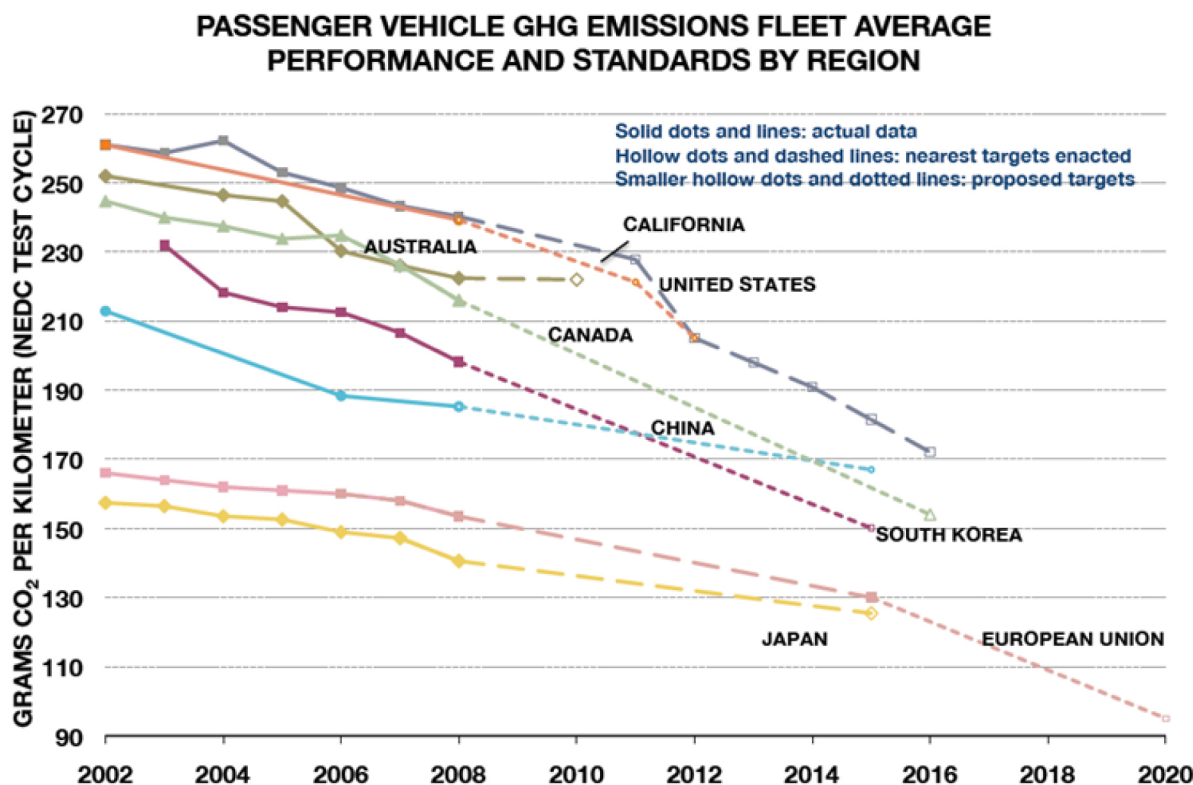
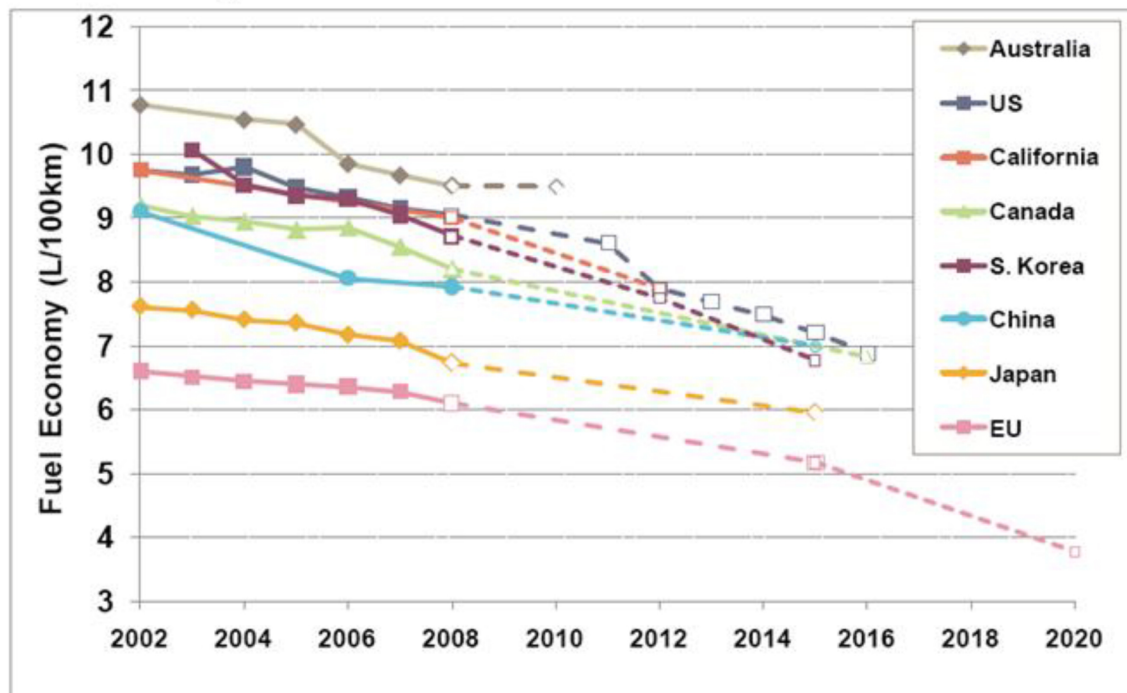


Figure 2. International Council on Clean Transportation and their Passenger Vehicle Greenhouse Gas and Fuel Economy Standards report, published 2007 and updated 2010. (reference 4)

Strong light-duty vehicle fuel economy standards in place in many major economies through 2015



Source: ICCT, 2010; fuel economy figures shown reflect each country's own test procedure; solid lines show history; dashed lines show enacted standards; dotted lines show proposed standards

Figure 3. International Council on Clean Transportation and their Passenger Vehicle Greenhouse Gas and Fuel Economy Standards report, published 2007 and updated 2010. (reference 4)

So why is the US being portrayed as 'lagging' behind in such reports. Again, the ICCT provides some insight into this by looking at the average vehicle mass and engine size for new car sales

Some people may find these figures hard to accept, but, further on in this paper we look at the masses and power for the top 5 selling vehicles in each market, and the figures are remarkably consistent.

Vehicle Efficiency Varies with Mass & Engine Size

New Cars Fleet Average	Japan	EU	US
Weight (kg)	1,280	1,253	1,863
Engine Size (l)	1.5	1.6	3.3
Fuel Consumption (mpg)	41.5	39.8	26.4
CO ₂ emission (g/km)	132	146	208

Representative Cars	Honda Fit, M5, 1.5 Liter	VW Golf, M5, 1.6 Liter	Chrysler 300, L4, 3.5 Liter
Weight (kg)	1,250	1,232	1,818
Engine Size (l)	1.5	1.6	3.5
Fuel Consumption (mpg)	41.2	35.0	25.8
CO ₂ emission (g/km)	133	157	213

Figure 4. International Council on Clean Transportation and their Passenger Vehicle Greenhouse Gas and Fuel Economy Standards report, published 2007 and updated 2010. (reference 4)

Markets are difficult to compare, but the simple figures are that, on average, the US consumer buys cars which are approximately 50% heavier, have 25% more footprint and are >100% more powerful than either the Europeans or Japanese consumers. It is worth noting that the representative EU car above, is a petrol Golf. VW's recently launched award winning Golf Bluemotion 4dr has a 1.6 diesel producing 104 bhp with 99g/km carbon emissions and an official 74.3 mpg combined fuel economy and will seat 4 people in comfort. The representative US vehicle, the Chrysler 300C has a 3.5L V6 with 250bhp and 250 ft lbs torque, returns 25 mpg on the highway and 20 mpg on the combined cycle and will seat 4 people in comfort.

Again, it is not the role of this paper to present an argument to force the US vehicle market into a shape that does not meet its consumers' needs or desires. One must approach the problem from both sides, firstly, government programs and environmental education will lead the market towards more efficient cars, but secondly, technology must supply more efficient and environmentally friendly drivetrains suitable for the larger vehicles that the majority of the US market wants to buy.

The message is thus clear; the US market is and will continue to be, dominated by larger vehicles, with high levels of comfort, space and performance. To be successful in the US, drivetrain technology suppliers must be capable of delivering solutions for vehicles that typically have a GVW of 4800 lbs (small SUV / Crossover) through to Midsize 5750 lbs and onto Large SUVs with a GVW of around 7000 lbs. Looking at typical engine sizes and power gives a similar picture with 2.5L V6's (161 hp) through to 5.3L V8's (320 hp). These vehicles frequently have some off road / towing capability, and can therefore deliver large amounts of torque to the road at low speeds.

2.2. THE ROLE OF MASS & FOOTPRINT

Historically over the last 40 years cars have become heavier and bigger as safety and features have increased. If one looks at the 'compact' car class; the typical mass in 1970 was between 650kg and 800kg, whereas today it's between 1200kg and 1350kg, an increase of around 75%. Considering a specific example, such as a VW Golf, it's interesting to see that a Mk1 Golf GTi 1600 had a curb weight of 966 kgs, a GVW of 1332 kgs, a 0-60 of 9 seconds and achieved 27 mpg.

Today, a Mk 6 Golf 1.4 TSi GT has a curb weight of 1280 kgs, GVW of 1840 kgs, a 0-60 of 8 seconds and achieves 45 mpg on the combined cycle. So despite a large increase in size and weight, engine and drivetrain technology improvements have outpaced the increase in mass.

So, going forward we could conclude that the increases in vehicle mass and size are not a problem from an emissions, or running costs perspective. This would be incorrect. It is roughly estimated that reducing the mass of a ICE vehicle by 70kgs will result in a 1mpg improvement in economy. Likewise, internal work within Protean Electric shows that reducing the mass of a Battery Electric Vehicle (BEV) by 20% will improve the range on an urban cycle by a useful 14%. As fuel prices increase, the consumer is becoming very sensitive to increases in running costs; witness the increase in hybrid vehicle sales the last time fuel hit \$4 per gallon. Compelling as these reasons may be, it is clear that regulations will also play an important role. As the reduction in CO₂ emissions become more important, governments are now using weight and size (footprint) to classify vehicles within a regulatory framework:

Regulatory Best Practice – Vary Standard by Size

Country/ Region	Automobile 2007 sales in million/year (and world share)	Regulated metric	Form of Standard	Program details, reduction in CO ₂ -per-distance emissions
European Union	23 (32%)	GHG emission (CO ₂ e/km)	Weight, continuous	40% reduction, MY 2008-2020 EU NEDC cycle
United States	17 (24%)	Fuel economy (mi/gal) GHG emission (CO ₂ e/mi)	Size-based, continuous	20% reduction, MY 2011-2016 U.S. FTP testing
Japan	6 (8%)	Fuel economy (km/L)	Weight classes	19% reduction, MY 2010-2015 Japan 10-15 cycle
China	5 (7%)	Fuel consump. (L/100km)	Per vehicle, weight class → Average weight class	12% reduction, MY2008-2015 EU NEDC cycle
California	1.8 (3%)	GHG emission (CO ₂ e/mi)	Vehicle class	30% reduction, MY 2009-2016 U.S. FTP testing
Canada	1.6 (2%)	Fuel consump. (gal/mi) GHG emission (CO ₂ e/mi)	Size-based, continuous	Harmonized to U.S. stds U.S. FTP testing
Mexico	1.0 (1%)	TBD	TBD	TBD
Australia	0.9 (1%)	Fuel consump. (L/100km)	Fleet average	10% reduction, MY 2004-2010 EU NEDC
South Korea	0.5 (1%)	Fuel economy (km/L) GHG emission (CO ₂ e/mi)	Weight-based, split by engine size	13% reduction, MY 2012-2015 U.S. FTP testing
Taiwan	0.3 (0.5%)	Fuel economy (km/L)	Engine size based	U.S. FTP testing

Figure 5. International Council on Clean Transportation and their Passenger Vehicle Greenhouse Gas and Fuel Economy Standards report, published 2007 and updated 2010. (reference 4)

2.3. THE IDEAL VEHICLE REQUIREMENTS

In order for in-wheel motors to become a viable option for electric vehicle propulsion, it is necessary to understand the requirements of the vehicle's end users. These requirements (and customer expectations) vary substantially between different markets, thus meaning that the same drivetrain architecture may not necessarily be suitable for every application or every market. A clear illustration of the differing vehicle requirements for different parts of the world can be seen in the three figures below; showing the five highest selling vehicles in Europe, U.S.A and Japan for 2009.

Best Selling Vehicles in 2009 - Europe

Rank	Vehicle	Volume Sold	Average curb weight across model range (kg)	Average power across model range (kW)
1	VW Golf	571,838	1,352	108
2	Ford Fiesta	472,091	1,128	64
3	Peugeot 207	367,160	1,257	67
4	Opel / Vauxhall Corsa	351,807	1,122	68
5	Fiat Punto	323,536	1,112	70
	Average		1,194	75

Figure 6. The most popular vehicles sold in Europe in 2009 (reference 5)

Best Selling Vehicles in 2009 - USA

Rank	Vehicle	Volume Sold	Average curb weight across model range (kg)	Average power across model range (kW)
1	Ford F Series	413,625	2,762	233
2	Toyota Camry	356,824	1,480	152
3	Chevrolet Silverado	316,544	2,173	218
4	Toyota Corolla	296,874	1,270	108
5	Honda Accord	290,056	1,549	137
	Average		1,847	170

Figure 7. The most popular vehicles sold in the U.S.A in 2009 (reference 6)

Best Selling Vehicles in 2009 – Japan

Rank	Vehicle	Volume Sold	Average curb weight across model range (kg)	Average power across model range (kW)
1	Toyota Prius	208,876	1,395	100
2	Honda Fit	157,324	1,136	87
3	Toyota Vitz	117,655	1,038	79
4	Toyota Passo	98,883	940	61
5	Honda Insight	93,283	1,240	65
	Average		1,150	78

Figure 8. The most popular vehicles sold in Japan in 2009 (reference 7)

From the above figures it can clearly be seen that vehicles in the USA tend to be substantially larger and more powerful than those in Europe or Japan. This presents a problem for electric vehicle adoption in the U.S.A as customers seem less willing to dramatically change their expectations of vehicle size and performance. Small compact electric vehicles and city cars would find a far more receptive audience in Japan and Europe than in the U.S.A, as higher population densities, smaller roads and lower typical commuting distances make small electric/ hybrid vehicles less of a departure from what customers are familiar with. For example the least powerful car (in the top five vehicles) sold in the U.S.A is the same power as the most powerful cars (in the top five vehicles) sold in Japan or Europe.

Another point to consider is that in general, Japan appears far more accepting towards new and unfamiliar technology than the U.S.A, illustrated by the fact that the bestselling vehicle in Japan in 2009 was the Toyota Prius hybrid and the 5th bestselling vehicle was the Honda Insight hybrid, whereas in the U.S.A two out of the top five most popular vehicles were full-size pick-up trucks; the Ford F Series and the Chevrolet Silverado.

A traditional centralized electric drivetrain capable of delivering 150 - 200kW (or more) to propel a large sedan or full-size pick-up truck would be of similar size to the ICE and gearbox it replaces, and consist of an electric motor, gearbox and power electronics/ inverter. This powerful drivetrain would take up a substantial amount of space inside the body of a vehicle, making it challenging to package. This vehicle integration/ packaging challenge is compounded by the need to have a correspondingly large battery pack to provide the energy needed for the electric drivetrain. In larger vehicle applications such as this, multiple in-wheel motors could provide the required power/ torque while easing vehicle integration and leaving the entirety of the space inside the vehicle body available for battery packs.