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?

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)]](image-url)
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.

<table>
<thead>
<tr>
<th>New Cars Fleet Average</th>
<th>Japan</th>
<th>EU</th>
<th>US</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weight (kg)</td>
<td>1.280</td>
<td>1.253</td>
<td>1.863</td>
</tr>
<tr>
<td>Engine Size (l)</td>
<td>1.5</td>
<td>1.6</td>
<td>3.3</td>
</tr>
<tr>
<td>Fuel Consumption (mpg)</td>
<td>41.5</td>
<td>39.8</td>
<td>26.4</td>
</tr>
<tr>
<td>CO₂ emission (g/km)</td>
<td>132</td>
<td>146</td>
<td>208</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Representative Cars</th>
<th>Honda Fit, M5, 1.5 Liter</th>
<th>VW Golf, M5, 1.6 Liter</th>
<th>Chrysler 300, L4, 3.5 Liter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weight (kg)</td>
<td>1.250</td>
<td>1.232</td>
<td>1.818</td>
</tr>
<tr>
<td>Engine Size (l)</td>
<td>1.5</td>
<td>1.6</td>
<td>3.5</td>
</tr>
<tr>
<td>Fuel Consumption (mpg)</td>
<td>41.2</td>
<td>35.0</td>
<td>25.8</td>
</tr>
<tr>
<td>CO₂ emission (g/km)</td>
<td>133</td>
<td>157</td>
<td>213</td>
</tr>
</tbody>
</table>
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:

<table>
<thead>
<tr>
<th>Country/Region</th>
<th>Automobile 2007 sales in million/year (and world share)</th>
<th>Regulated metric</th>
<th>Form of Standard</th>
<th>Program details, reduction in CO2-per-distance emissions</th>
</tr>
</thead>
<tbody>
<tr>
<td>European Union</td>
<td>23 (32%)</td>
<td>GHG emission (CO2e/km)</td>
<td>Weight, continuous</td>
<td>40% reduction, MY 2008-2020 EU NEDC cycle</td>
</tr>
<tr>
<td>United States</td>
<td>17 (24%)</td>
<td>Fuel economy (mi/gal)</td>
<td>Size-based, continuous</td>
<td>20% reduction, MY 2011-2016 U.S. FTP testing</td>
</tr>
<tr>
<td>Japan</td>
<td>6 (8%)</td>
<td>GHG emission (CO2e/mi)</td>
<td>Weight classes</td>
<td>19% reduction, MY 2010-2015 Japan 10-15 cycle</td>
</tr>
<tr>
<td>China</td>
<td>5 (7%)</td>
<td>Fuel consump. (L/100km)</td>
<td>Per vehicle, weight class Average weight class</td>
<td>12% reduction, MY2008-2015 EU NEDC cycle</td>
</tr>
<tr>
<td>California</td>
<td>1.8 (3%)</td>
<td>GHG emission (CO2e/mi)</td>
<td>Vehicle class</td>
<td>30% reduction, MY 2009-2016 U.S. FTP testing</td>
</tr>
<tr>
<td>Canada</td>
<td>1.6 (2%)</td>
<td>Fuel consump. (gal/mi)</td>
<td>Size-based, continuous</td>
<td>Harmonized to U.S. stds U.S. FTP testing</td>
</tr>
<tr>
<td>Mexico</td>
<td>1.0 (1%)</td>
<td>GHG emission (CO2e/mi)</td>
<td>TBD</td>
<td>TBD</td>
</tr>
<tr>
<td>Australia</td>
<td>0.9 (1%)</td>
<td>Fuel consump. (L/100km)</td>
<td>Fleet average</td>
<td>10% reduction, MY 2004-2010 EU NEDC</td>
</tr>
<tr>
<td>South Korea</td>
<td>0.5 (1%)</td>
<td>Fuel economy (km/L)</td>
<td>Weight-based, split by engine size</td>
<td>13% reduction, MY 2012-2015 U.S. FTP testing</td>
</tr>
<tr>
<td>Taiwan</td>
<td>0.3 (0.5%)</td>
<td>GHG emission (CO2e/mi)</td>
<td>Engine size based</td>
<td>U.S. FTP testing</td>
</tr>
</tbody>
</table>

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.

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.
An example vehicle

Traditional vehicles' ICE’s are sized around a combination of customer requirements, performance targets, fuel economy, and parts bin choices (e.g. engine and gearbox ranges). Some OEMs will differentiate on performance, others running costs, etc. A key component in all this is the driving experience given by an ICE and gearbox, Manual vs Automatic, 4 speed to 8 speed etc.

A direct drive in-wheel motor drivetrain has different driving characteristics, especially in the way torque is delivered to the wheels. The highest torque is available from standstill, and changes in torque demand are far faster (potentially a couple of msec vs 150msec) than a conventional drivetrain with all the compliance / lag inherent therein. Torque delivery is very smooth, and acceleration is rapid over the vehicle's speed range. Top speed is typically limited by battery SoC / Voltage rather than either torque or power. In order to specify an electric drive we need to establish the torque and power requirements over the whole speed range and ensure these give adequate vehicle performance.

Protean studied the various performance metrics, e.g. 0-60, 50-70, top speed, gradeability, regenerative braking force and concluded that for our direct drive PM motors, the PD18, the limiting cases were peak gradability from standstill and continuous gradeability at around 10mph. Coupling gradeability together with a high efficiency requirement for normal drive cycles, it was found all other metrics ‘took care of themselves’. That is to say, the consequences of the machine design to meet high torque and high efficiency resulted in a motor which also gave very good performance in all other metrics. The detail won't be delved into here, but Protean concluded that requirements for a 30% peak gradient from standstill and 22% continuous gradient at 10mph enabled us to analyze and match the PD18 performance to various vehicles. We also compared the torque and power requirements for the more aggressive / normal driving drive cycles including Hyzem Urban, Road and Motorway, NYCC, US06 and FTP75 City. Together the torque requirements are shown on Figure 9.

![Figure 9. Torque Requirements Vs Market Segments and Drive Cycles.](image-url)
Figure 9 shows that a drivetrain of $4 \times PD18$ motors will provide a good performing drivetrain for vehicles up to approximately 7100 lbs GVW, a figure limited by the PD18's continuous rating which is a thermal limit rather than peak power.

As an illustration let us consider a new model Ford Explorer which has been “converted” analytically to a BEV. The key assumptions and parameters for the stock vehicle and simulation are:

Original vehicle = 4450lbs (2021kgs) curb weight, 60101bs (2730kgs) GVW. The mass of components removed in electric conversion = 480 kg (Based on Protean's F150 project). Aerodynamic Cd.A= 1 m², Coefficient of rolling resistance = 0.011 and Rolling radius 0.381 m, Tires 235/65 R18.

Average ancillary load 2 kW, Install an electric drivetrain powered by $4 \times PD18$ motors each weighing 30Kgs / 68lbs and giving 1000 Nm peak torque (for 20s) and 715 Nm continuous torque, 83 kW peak power at 400 V supply and 1400 rpm maximum speed.

We considered 2 battery cases: Battery (40kWh and 70kWh options). We assumed Lithium Ion chemistry from A123: 97 Wh/kg pack weight, an effective pack resistance 1.5 ohm.kWh (e.g. 0.15 ohm for 10 kWh pack) and SoC 0% to 100% usable.

The stock vehicle has a 4.0L V6 producing 157kW and 344Nm. The vehicle tractive limit with fully loaded rear axles was calculated to be 4250Nm, and the engine/gearbox would give 3950Nm plus whatever the torque converter gives, which is usually somewhat variable between 1 and 2 times.

The PD18 drivetrain will give 4000Nm peak and 2860Nm continuous, with a maximum power of 332kW available, though 216kW continuous.

With the smaller battery, the BEV Explorer will reach 107mph and 0-60 in 5.9sec, and with the larger battery, 109mph and 6.7sec. Both these 0-60 figures beat the stock ICE vehicle's time of 9sec.

In terms of gradeability, both the BEV's would match the stock vehicles peak pullaway gradient of 45 degrees.

So, the above shows that if such a Explorer BEV we're built it would provide the same space and comfort as the stock vehicle, and would exceed the on-road performance in all areas except low speed towing.

3. DO IN WHEEL MOTORS PROVIDE A TIPPING POINT?

The previous section describes a market situation where both the OEMs and consumers are being driven down a path to reduce CO₂ emissions by electrifying the drivetrain. However the current state of play means that consumers cannot buy ‘green’ cars they actually want to drive, and the OEMs cannot truly profit in the electric and hybrid vehicle market.

But can in-wheel motors assist the Industry in providing a tipping point for electric and hybrid vehicles? This section goes on to discuss the issues relating to the application of IWMs to mass market vehicles and whether they can help the industry in providing a tipping point.

3.1. ECONOMICS

In the short term electric vehicles are likely to remain more expensive than the equivalent IC engine vehicles, largely due to a combination of the low volumes in which they will initially be built and the cost of the battery packs. Fundamentally consumers do not want to pay extra for a car with lower specifications than their existing vehicle. In a recent Deloitte survey conducted in the U.S.A respondents were asked “what is the top factor that would prevent you from purchasing an EV?” The answers to this survey are shown below.

![Figure 10. Most common factors preventing purchasing of an EV (reference 10)](image)

The three most common answers were that EVs were too expensive, had a limited range and they didn't want a small car. In contrast to this is another 2009 Deloitte report which stated that the additional features customers would be most willing to pay for would be ones such as “vehicle skid control” (reference 11).
In-wheel motors have the capability to deal with both of these issues, in that they have the capability to propel larger vehicles while leaving space inside the vehicles to allow large enough battery packs to give adequate range. At the same time the inherent ability of in-wheel motors to deliver torque to each driven wheel independently allows features such as traction control, launch control, ABS and torque vectoring to be implemented in an extremely straightforward manner, without adding to the vehicle's construction cost.

This would allow OEMs to recoup some (or potentially all) of the additional battery costs, without alienating customers. In turn end users would get a vehicle with greater capability in the areas they want, without having to compromise on the performance parameters they take for granted. The precedent has already been set for customers paying a premium for more fuel efficient vehicles, as long as they have similar capabilities to their existing vehicles. One example of this can be seen with the Toyota Prius, a vehicle that has an MSRP starting at $22,800 (reference 12) compared to a vehicle of similar size like the Ford Focus, a vehicle that has an MSRP starting at $16,290 (reference 13).

Another aspect to the economic advantages offered by in-wheel motors lies in the parts that can be eliminated from the vehicle during its construction, namely the engine, fuel tank, gearbox driveshaft, differential, and other ancillary components. The result would be a vehicle that is substantially easier to construct, with fewer wearing components in a vehicle that would give designers far greater flexibility with different vehicle layouts. An example of the number of components (along with their weights) that can be removed from a vehicle fitted with in-wheel motors is shown below, this example uses the data from a Ford F150 retrofitted with four in-wheel motors and shown at the 2008 SEMA Show.

The overall increase in drivetrain efficiency resulting from the removal of these components can be shown in figure 12, where the drivetrain losses (expressed in Wh/ mile) for a rear wheel drive electric sports propelled by a conventional high-speed, centrally mounted motor (driving through a gearbox) are compared to the drivetrain losses for the equivalent vehicle fitted with two direct-drive in-wheel motors (original vehicle drivetrain losses can be found in reference 15). It can clearly be seen that the vehicle fitted with the in-wheel motors loses far fewer Wh/ mile through its drivetrain than the centrally mounted motor and that this discrepancy increases as the vehicle speed rises.

### F150 – Removed Components

<table>
<thead>
<tr>
<th>Component</th>
<th>Weight (Kg)</th>
<th>Weight (lbs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Engine and transmission</td>
<td>362</td>
<td>796</td>
</tr>
<tr>
<td>Rear axle</td>
<td>150</td>
<td>331</td>
</tr>
<tr>
<td>Air intake tube</td>
<td>0.9</td>
<td>2</td>
</tr>
<tr>
<td>Fan shroud</td>
<td>2.7</td>
<td>6</td>
</tr>
<tr>
<td>Fan</td>
<td>3.6</td>
<td>8</td>
</tr>
<tr>
<td>Drive shaft</td>
<td>20</td>
<td>43</td>
</tr>
<tr>
<td>Fuel tank assembly</td>
<td>17</td>
<td>38</td>
</tr>
<tr>
<td>Fuel tank straps</td>
<td>1.3</td>
<td>3</td>
</tr>
<tr>
<td>Vapour canister</td>
<td>3.2</td>
<td>7</td>
</tr>
<tr>
<td>Fuel lines</td>
<td>0.9</td>
<td>2</td>
</tr>
<tr>
<td>Engine mount</td>
<td>3.6</td>
<td>8</td>
</tr>
<tr>
<td>Exhaust “y” pipe and catalysts</td>
<td>14.5</td>
<td>32</td>
</tr>
<tr>
<td>Exhaust extension pipe</td>
<td>2.7</td>
<td>6</td>
</tr>
<tr>
<td>Exhaust muffler / tailpipe assembly</td>
<td>17</td>
<td>37</td>
</tr>
<tr>
<td>Exhaust heat shields</td>
<td>1.8</td>
<td>4</td>
</tr>
<tr>
<td>Frame metal brackets</td>
<td>15</td>
<td>33</td>
</tr>
<tr>
<td>Miscellaneous attaching hardware</td>
<td>1.8</td>
<td>4</td>
</tr>
</tbody>
</table>

**Total** 618 Kg 1360 lbs

*Figure 11. Components removed from a Ford F150 retrofitted with four in-wheel motors (Protean Electric data)*
The example above assumes that other losses in the vehicle (such as ones caused by aerodynamic drag and rolling resistance) will remain constant between the two different drivetrain architectures. In this particular example the vehicle fitted with in-wheel motors would be able to have a travel approximately 14% further (when travelling at a constant speed) for a given battery size. This increase in range is due to a combination of the reduced drivetrain mass (resulting in a 3% range improvement) and the increase in drivetrain efficiency (resulting in an 11% range improvement).

If it is assumed that the same Wh/mile losses are present during regenerative braking as the ones shown above for motoring, then the amount of energy returned to the battery during regenerative braking would be greater for the vehicle equipped with in-wheel motors than for the one with an in-board motor. In the vehicle equipped with in-wheel motors, less energy would be wasted in overcoming the drivetrain losses. The increase in range offered by the greater drivetrain efficiency of the in-wheel architecture would be highly dependent on the particular vehicle, battery size and drive cycle, thus it would be extremely difficult to give a ‘rule of thumb’ value for this improvement. Multiple companies round the world are currently investigating the integration of in-wheel motors into vehicles and more precise data will be available once these tests have been completed.

The other economic advantage offered by in-wheel motors is their ability to be easily retrofitted to existing vehicles without an entirely new vehicle being constructed. A good example of this is a through-the-road hybrid (TTRH) retrofit of a light-medium commercial vehicle. In this configuration electric motors are added to the non-powered axle of a two-wheel drive commercial van along with a suitable battery pack. This allows either the vehicle's original drivetrain, or the electric motors, or a combination of both to propel the vehicle. As a TTRH retrofit keeps the original drivetrain intact, there is less available space in the vehicle to package motors and batteries than there would be if the drivetrain was removed, this constraint makes the highly compact design of direct drive in-wheel motors ideal for this application.

Recent studies undertaken in this area by a prestigious aftermarket US vehicle integrator have shown that the high volume cost of converting light commercial vehicles into TTRH vehicles using two direct-drive in-wheel motors would add around $19,000 to the base price of the vehicle (with a 10kWh battery pack). Not only can the TTRH configuration be applied to existing fleet vehicles but it is substantially cheaper than the all-electric version of the same vehicle, which is projected to sell for “between $50,000 and $70,000” (reference 10). The precise reduction in fuel costs facilitated by the TTRH configuration would heavily depend on a wide variety of variables including the mass of the vehicle, the particular drive cycle, the daily driving distance and the exact way the electric motors are utilized (torque assist, low speed driving, etc). What is certain is that the valuable PR benefits of ‘being seen to be green’ could be achieved at a much lower cost than the full electric alternative, while still providing significant fuel savings.

3.2. VEHICLE DESIGN AND PACKAGING

A prominent example of what can be achieved when designers start from scratch with in-wheel motors is the EDAG light car concept (reference 8). As well as using innovative materials and display systems, the vehicle’s drive
concept is based around a pure electric in-wheel drive with a range of 150Km, making it suitable for everyday use. The drivetrain features Protean Electric PD18 motors with integrated control and power electronics. Highly efficient motors and clever battery placement have provided considerable creative scope for designers both internally and externally:

One only needs to study the Lightcar's interior space compared to overall length to see the packaging benefits. The Light Car's 4.0m length is less than a VW Golf 5 door, in fact it's about the same as the VW Polo (3970mm). However it's wheelbase of 2.9m is more than the Mercedes E Class Saloon and about the same as the M-Class (2915mm).

In-wheel motors have played a major part in creating a car with a sub-compact class footprint and mass, but with luxury car class levels of wheelbase and interior passenger space. In the longer term, in-wheel motors will also allow multiple systems such as steering, brakes, drive and suspension to be integrated into a single package to give yet more vehicle packaging advantages.

3.3. VEHICLE PERFORMANCE AND ACTIVE SAFETY

Most people with an interest in vehicle dynamics will be familiar with the often conflicting quest for a balance between ride comfort, response, stability and fuel economy (to name but a few factors). This part of the paper intends to touch on the advantages in-wheel motors provide that reduce the compromise between these often opposed factors.

LONGITUDINAL - Driveline Compliance and Tractive Effort

Longitudinally, the potential for in-wheel motors to improve perceived performance is high. In a typical ICE driveline, the response to a change in throttle demand is slurried first by inlet manifold transit time, then by the need to wind up the engine on its elastic mounts and finally by the need to wind up the driveshafts before the torque is delivered to the wheel. A final, minor source of lag is the delay while the wheel changes speed to deliver a different slip ratio at the contact patch, but this is normally short. Typical road car drivelines can take up to around 300 msec to respond, particularly with automatic gearboxes. In contrast, in-wheel motor response times are typically a few milliseconds to a change in torque demand. It doesn't sound like much, but when driving a motorsport car (with stiffer sideshafs and non-compliant engine mounts), the immediacy of performance feel and the sense of improved response is acute. Similarly with in-wheel motors, any throttle response delays in the system are essentially imperceptible as in-wheel motors are directly coupled to the point at which torque is required, without the need for compliant driveline components or ICE mounts.

In terms of increasing absolute longitudinal performance, in wheel motors offer further advantages. Due to the electromagnetic design opportunities of a radial flux in-wheel electric motor, the tractive effort that can be applied to the road is subtly different to the conventional centralized motor vehicle. In-wheel motors allow a large flat-torque region, which although does not achieve similar magnitude in peak tractive effort when compared to an ICE driven vehicle, extends to much higher speeds (typically 50-70mph). Figure 14 illustrates the advantage. A typical 30-50mph acceleration event is seamless and significantly shorter with in-wheel electric motors, reducing the important “time exposed to danger” during overtaking maneuvers and making joining fast moving traffic easier. Note that although the IWM drivetrain in this example does not reach the first gear effort of the ICE engine, real-world comparisons between the cars would reveal very little difference in low speed acceleration performance. The tractive effort of the ICE car is heavily affected by driver launch (clutch) skill, time taken to change up to 2nd gear and the compliances mentioned above, whereas the IWM tractive effort delivery is effectively instant and seamless.

![Typical tractive effort curves showing the accelerative advantage of an IWM driven car versus a traditional ICE drivetrain car.](image)
Note also that in wheel motors provide a simply implemented four wheel drive system, which increases mobility of all traditionally front or rear-wheel drive vehicles over low-grip surfaces. Also in many cases vehicles fitted with in-wheel motors will offer better mobility than equivalent four wheel drive cars due to the lack of mechanical coupling of the wheels - each tire can use all the grip it has available without effects from the grip of other wheels and without expensive active or locking differentials.

**LATERAL - Active Safety and Torque vectoring**

The addition of separate, highly controllable motors in distributed locations in the vehicle offers a substantial opportunity for improved vehicle dynamics, primarily through the manipulation of longitudinal wheel slip and its consequent impact on lateral force capacity at individual wheels. For agility, fidelity of behavior and high speed yaw damping, such techniques have an excellent potential to strongly manipulate vehicle behavior [Harty, D, “Brand-by-Wire” - A Possibility, Aachener Colloqium 2002, pp. 1009-1024].

Torque vectoring has been used for many years in the form of ESP/ESC etc. by modulating brakes in order to impart yaw moments to a vehicle, however torque vectoring through the application of both drive and brake torque is an emerging technique. This is well suited to electric vehicles with independent wheel torque control, as the cost and control fidelity of active differentials and brakes presents a sizeable problem for widespread implementation with a centralized drivetrain, which is also only able to apply positive torque when the driver is giving an accelerator demand. Torque vectoring has the potential to reduce the conflict between stability and response while enhancing other attributes.

A brief example application of torque vectoring is in active yaw damping. Following a steering input, particularly at high speed, after an initial delay period (100's of msec), vehicle yaw rate can overshoot and oscillate before settling to a steady-state. In extreme examples this can cause a loss of control. Even at lower speeds this can make the car feel unstable and the driver may find they have to make multiple steering adjustments to follow the intended path. This is often addressed through suspension kinematic and static changes which make the car feel more stable, but often at the expense of response “feel”, dulling the car. Figure 15 illustrates how torque vectoring allows the suspension setting to retain better feel and/or fuel efficiency settings, by implementing active yaw damping which addresses the yaw overshoot and oscillation problem with a wholly software based solution:

An alternative approach is to retain a stable/dull base vehicle characteristic and use the yaw authority of the independent IWM to increase yaw response gain during the turn-in transient, illustrated in Figure 16:

The possibilities for modifying vehicle behavior through application of drive and brake torque at each wheel represents a very exciting opportunity for vehicle dynamicists the world over, who up until now have been limited by comparatively slowly responding, low fidelity control of hydraulically actuated brakes, compliant centralized drivetrains and, if they're lucky, complex and expensive active differentials.

### 3.4. REGENERATIVE BRAKING

Regenerative braking in electric vehicles offers the opportunity to extend the range of the vehicle for a given battery capacity or to reduce the battery size (and cost). Typical values are shown in Figure 17 and are derived from simulation of a Ford Explorer BEV at GVW (6000 lbs) powered by four in-wheel electric motors. Losses in the motors and battery are accounted for in these figures.
The ability to recapture the vehicle's kinetic energy using regenerative braking relies on the motors functioning efficiently as generators at torque-speed points typical of braking events in normal driving. Permanent magnet motors suffer losses through ohmic heating of the coils of the electromagnets, hysteresis and eddy currents in the iron, bearing and seal friction and switching in the inverter. Considering the energy equation when the motor is acting as a generator (where mechanical power $\rightarrow$ electrical power + loss) and where mechanical power is provided to the motor from the reducing kinetic energy of the vehicle and the electrical power is provided to the battery, the efficiency of regeneration (determined electrical power/ mechanical power) can even be negative.

This arises when the losses are greater than the mechanical power input and is visible in the efficiency map for regenerative braking for an in-wheel electric motor, shown in Figure 18. In this region the motor is consuming power although it is providing braking torque. In a stationary vehicle on a slope the mechanical power is zero and the electrical power merely services losses in the motors and battery.

The vehicle's range is optimized by

i). Ensuring that the negative efficiency region of the motor is not coincident with torque-speed regions where significant regenerative braking energy is available in normal driving

ii). Using an alternative braking technology where the efficiency of the motor is negative

iii). Using an alternative braking mechanism, a park brake, when the vehicle is stationary.

iv). Points ii and iii should preferably be realized automatically and seamlessly as part of a blended braking strategy, mixing regenerative braking, hydraulic or electro-mechanical braking and a park brake.

Figure 19 shows where, on a torque-speed map, energy is available for regeneration averaged over a number of drive cycles ranging from urban to highway and tame to aggressive. The scale is normalized. This relates to a particular application: a Ford Explorer BEV at GVW powered by four in-wheel motors, and the torque values refer to a single motor. This allows a comparison with Figure 18 which is presented on the same scale. In this case it is clear that the amount of regenerative energy available in the region of negative efficiency is small and that the torque-speed regions where the most energy is available coincide with regions of motor efficiency in excess of about 85%. This means that the motor is well matched to this particular application in terms of gaining as much range advantage through regenerative braking as possible.
motoring. Figure 21 shows where, on a torque-speed map, most mechanical power is produced during an aggregate of a selection of drive cycles. As above, the vehicle is a Ford Explorer BEV at GVW powered by four in-wheel electric motors. As with braking the high efficiency operating region of the motor coincides well with the torque-speed region in which the motors operate most of the time.

**Figure 20. Motoring efficiency (%) for an in-wheel electric motor.**

**Figure 21. Normalized power density per motor as a function of torque and speed in motoring averaged over a selection of drive cycles.**

It can be seen that an in-wheel motor solution using permanent magnet motors is well-placed to maximize the range of the vehicle by recapturing braking energy in the battery. Permanent magnet motors are more efficient than other types of electric motor and the high efficiency operating region of the motor is well matched to the operating points during normal vehicle braking events. Furthermore the in-wheel solution has the advantage over a central electric motor of avoiding drive-line losses.

### 3.5. OVERCOMING THE TECHNICAL CHALLENGES OF IN WHEEL MOTORS

In the short term, as with any leading edge technology there are barriers to market entry and overall acceptance. In terms of vehicle packaging, for in-wheel motors there are two main technical concerns to overcome; the introduction of extra unsprung mass and mechanical brake integration.

**Unsprung Mass**

Reference 9 is a jointly authored paper (Anderson/ Harty) describing the effects of increased unsprung mass. The broad investigations behind this paper involved two completely independent approaches to the perceived problem, which was leveled squarely at in-wheel motor drivetrains and included subjective assessment, objective measurements and predictive analysis.

A common challenge to the packaging advantage of in-wheel motors is the trade off required by moving the drivetrain mass from the sprung to the unsprung mass. This increased unsprung mass is often challenged with weakly supported evidence that there is an unsprung mass/sprung mass ratio “threshold”, which, if you exceed, will result in dangerous, uncomfortable vehicles which will never sell. This part of the paper will summarize the results found during those studies, which show that the perceived problems with unsprung mass are actually blown out of all proportion, and top-of-the-segment performance can be achieved with already defined development techniques.

According to Anderson/Harty, ground vehicle performance can be broadly split into:

**Ride** - The ability of the vehicle to absorb disturbances

**Refinement** - The ability of the vehicle to attenuate noise and vibration

**Active safety** - The ability of the vehicle to stop and steer in emergency situations (in a passive/grip sense, i.e. not implying the presence of “active” safety systems such as ESP)

**Driveability** - The response of the vehicle to the drivers inputs (handwheel, brake and accelerator pedals) in normal situations.

It is with respect to these aspects of vehicle character that the investigations were targeted.

**Subjective Analysis**

The subjective analysis was conducted on a European 2007 MY Ford Focus hatchback, which was fitted with a range of additional hub masses, including a 30kg addition which is
typical of a wheelmotor that fits within an 18" wheel (reference 16). The assessment was carried out by professional vehicle evaluators and was rated on the “Vehicle Evaluation Rating” (VER) scale through a series of well-proven standard tests at a well renowned vehicle development company.

The result of the subjective analysis in the Anderson/ Harty paper (reference 9) was that even with no remedial work, and 30kg of additional unsprung mass, the vehicle was in line with “what might be expected in the middle of a normal development program and gives no particular cause for disquiet.” The largest deficit observed was actually in the weight of the steering feel. The Ford Focus base is noted as a car that occupies the top of the class it resides in, in terms of ride and handling. The addition of 30kg of unsprung mass merely moves this car, subjectively at least, to the middle of the class, and no one factor, or combination of factors, showed any degradation of performance which would not be recoverable back to the standard (unmodified) car through usual development techniques.

Objective Analysis
The objective measurements were also carried out on the same 2007 MY Ford Focus, again with no remedial work, through well proven tests at the same vehicle development establishment.

In line with the subjective tests it was found that “over isolated bumps the modified vehicle gives measurably poorer behavior”, and that “some difference in steering character has been wrought”. However, the overall conclusion from the objective analysis was that “none of the differences are beyond normal deviations from target in a typical vehicle development program”.

Numerical Analysis
The numerical analysis was approached with a ‘simple models, smartly used’ mindset, and was implemented in the MATLAB/ Simulink environment. It involved one or two degree of freedom numerical models based on assumed parameters of the rear axle of a light commercial vehicle. This vehicle was chosen mainly as the variation in payload is large and gives a wide variety of relevant unsprung/sprung mass ratios (the unsprung was varied from 5% to 25% of the sprung mass). The basic parameters and the resulting characteristics from the study are shown in figure 22 and figure 23.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Laden</th>
<th>Unladen</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sprung Mass</td>
<td>1060 kg</td>
<td>310 kg</td>
</tr>
<tr>
<td>Unsprung Mass</td>
<td>50-80 kg</td>
<td>50-80 kg</td>
</tr>
<tr>
<td>Spring Rate</td>
<td>25-75 Nmm⁻¹</td>
<td>25-75 Nmm⁻¹</td>
</tr>
<tr>
<td>Damping Coeff.</td>
<td>0.5-10 Nsm⁻¹</td>
<td>0.5-10 Nsm⁻¹</td>
</tr>
</tbody>
</table>

The study used a variety of “key performance indicators”, which are derived from the results of simulations using simple numerical models such as the vertical “quarter car” model shown in figure 24.

Ride overall: difference in road roughness results in very large differences in scores compared to influence of unsprung mass

Primary ride: no discernible difference on smooth roads, slight degradation in rough road performance
Secondary ride: slight degradation in both rough and smooth road performance may require detail changes to seat or suspension components.

Refinement: some change in suspension component detail may be required to recover small loss in refinement behavior.

Active safety: noticeable but not severe loss in smooth and rough road grip levels; slight increase in damping levels may be required to optimize performance.

Drivability: slight changes to suspension components may be required to restore agility.

A more generalized conclusion from the Anderson/ Harty paper (reference 9) was that:

“While perceptible differences emerge with increased unsprung mass, on the whole they are small and unlikely to be apparent to an average driver. The nature and magnitude of the changes appears to be nothing that cannot be overcome by the application of normal engineering processes within a product development cycle.”

Unsprung Mass Conclusion

The work performed in the making of Anderson/ Harty paper (reference 9) shows that unsprung mass, while it shouldn't not be considered a good thing, is by absolutely no means a ‘show stopper’ for wheelmotor drivetrains. This report also concluded that “the promise of individual wheel motor control shows good potential for substantial improvements in vehicle behavior”. The change in vehicle “performance” (as defined above), while measurable, can be recovered through the use of a normal ‘engineering toolbox’ of development activities which all vehicles must go through at present before being signed off for production. Even retrofitting vehicles without any rectification work does not cause any major cause for concern. Wheelmotor drivetrains do not cross some “threshold” of unsprung mass. Other work, such as that performed by Schalkwyk et al (reference 17) reinforces this conclusion.

Mechanical Brake Integration

When fitting an electric motor ‘in-wheel’ allowance needs to be made for foundation friction brakes to provide the addition retardation force the vehicle requires. To ensure the viability of in-wheel motors (IWM), the foundation braking solution must cohabit the ‘in-wheel’ real estate with the motor, and replicate the performance of the OEM system.

The key engineering challenges centered around packaging, torque transfer and heat. Packaging - simply fitting a foundation brake with an IWM is not a trivial task. Modern automobiles have compact, intricate suspension systems that allow little room for extra components. Torque transfer - In a conventional vehicle tractive effort is applied to the tire via a central shaft and the brake actuates on the interface between wheel rim and bearing. When fitting an IWM and a brake, two significant torque actuating devices now exist in-wheel. Heat - Electric motors are sensitive to heat and their performance is directly related to the temperature of the motors' coils and power electronics. During retardation of the vehicle a friction brake generates significant heat from which the electric motor needs protection.

The preferred solution developed by Protean Electric involved attaching a foundation brake to the IWM rotor via a floating bobbin interface, and using twin, radially opposed, in-side-out calipers to brake the disc (see figure 25). The twin calipers are positioned to avoid suspension components allowing for the packaging of the foundation brake and IWM out board. The brake components are sized to replicate OEM braking performance both in terms of maximum deceleration force available (1G) and adequate thermal mass to carry out repeated Vmax stops. The torque is transferred from the foundation brake disc, through the IWM rotor to the wheel bearing interface as with the torque of the IWM. Twin, radially opposed calipers are used to balance axial forces and guarantee pure torque through the rotor to ensure no closing up the IWM air gap. The floating bobbing disc/rotor interface is used to minimize conductive heat transfer into the IWM. The final cooling loop of the liquid cooled IWM passes next to the brake components to remove heat from the system.

Figure 25. Brake mounting illustrations - CAD render
While the solution highlighted above has not yet been optimized for a volume application, it was designed to demonstrate the possibility of fitting foundation brakes along with IWMs. It is hoped that as IWMs become more prevalent this braking solution too will be advanced and optimized.

**CONCLUSIONS**

It is clear that governments around the world are now convinced of the requirements to reduce CO$_2$ output, and if these targets are to be met, a proportion of those reductions must come from the transport sector. It is therefore clear that in order to meet these targets OEMs must reduce their fleet average CO$_2$ emissions and that will require significant adoption of electric and hybrid vehicles in their ranges. In conjunction with this, consumers want vehicles that offer the same size, performance, range, reliability and cost as their current vehicles and OEMs must make a profit. This paper shows in-wheel motors are now well placed to take advantage of, and indeed catalyze this new and growing electric and hybrid vehicle market.

Existing electric vehicle technology is generally as large and cumbersome as the ICE it replaces, and there is limited scope for the vehicle design changes required to fully exploit the benefits of electric vehicles. 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. Direct-drive in-wheel motors with integrated power electronics are the optimum form of this design as they reduce vehicle part count and complexity while increasing design freedom and increasing the efficiency of the drivetrain through the reduction in drivetrain weight and a reduction in gearbox/differential losses.

There are a number of technical challenges that need to be overcome in order for in-wheel motors to be widely adopted into vehicles, in that the motors have to provide adequate power and torque for the desired vehicle size, while not substantially increasing the unsprung mass. However studies referred to in this report have shown that adding the latest generation of in-wheel motors can be added to vehicles without any significant degradation in the ride or handling performance due to the extra unsprung mass. It has also been shown that the latest in-wheel motor designs can be integrated with a mechanical braking system while still only utilizing the space inside the wheel rim.

The inherent ability to control each wheel independently in a vehicle equipped with in-wheel motors facilitates a far higher level of traction control, anti-skid control and torque vectoring than is possible with any other propulsion system. All these elements are ones that consumers have indicated they are the most willing to pay extra for, thus allowing OEMs to recoup some of the additional costs of the large battery packs required for EVs, at very little additional cost. This principle of permitting consumers to drive vehicles of the same size, but with greater capabilities than their existing ICE vehicles will accelerate the acceptance and adoption of electric/hybrid vehicles in the market.

In addition, the inherently compact nature of direct drive in-wheel motors (with integrated power electronics) makes this technology ideal for retrofitting in applications such as through the road hybrid vehicles. In this case the IC engine and conventional drivetrain can be retained with the added features of pure electric range and/or an electric torque assist without losing load space inside the vehicle. This arrangement allows the customer to enjoy fuel savings, reduced emissions and good green PR value at a substantially lower cost than in if they had to purchase an entirely new vehicle.

In-wheel motors offer OEMs an immediate opportunity to build larger electric and hybrid vehicles, including full-size sedans and SUVs. At the same time allowing these vehicles to have greater capabilities in the areas that customers value and are willing pay for, such as anti-skid control and torque vectoring, while simultaneously easing the market acceptance of electric and hybrid vehicle technology through their application in through the road hybrid vehicles. Together, these factors combine to create the tipping point for OEM acceptance of in-wheel-motor technology.

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**ABBREVIATIONS**

ABS  Anti-Lock Braking System

BEV  Battery Electric Vehicle

EV    Electric Vehicle

GHG  Green House Gasses

OEM  Original Equipment Manufacturer

GVW  Gross Vehicle Weight

ICCT International Council on Clean Transportation

ICE  Internal Combustion Engine

IWM  In Wheel Motor

KPI  Key Performance Indicators

MIRA  Motor Industry Research Association

MSRP Manufacturer's Suggested Retail Price

PM  Permanent Magnet

SHEV  Series Hybrid Electric Vehicle
SUV
Sports Utility Vehicle

TTRH
Through The Road Hybrid

VER
Vehicle Evaluation Rating