

# Electrical Motor Drivelines in Commercial All-Electric Vehicles: A Review

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**Abstract**—This paper presents a critical review of the drivelines in all-electric vehicles (EVs). The motor topologies that are the best candidates to be used in EVs are presented. The advantages and disadvantages of each electric motor type are discussed from a system perspective. A survey of the electric motors used in commercial EVs is presented. The survey shows that car manufacturers are very conservative when it comes to introducing new technologies. Most of the EVs on the market mount a single induction or permanent-magnet (PM) motor with a traditional mechanic driveline with a differential. This paper illustrates that comparisons between the different motors are difficult by the large number of parameters and the lack of a recommended test scheme. The authors propose that a standardized drive cycle be used to test and compare motors.

**Index Terms**—Motor drives, road vehicle electric propulsion, road vehicle power systems, traction motors.

## I. INTRODUCTION

THERE is an increasing interest in electric vehicles (EV). Hybrid EV (HEV) driveline topologies have been widely studied as the topology comparison found in [1]. General motor drive studies for EVs and HEVs have been presented in [2]–[4]. This paper presents an up-to-date review of EV drivelines based on a survey of commercial EVs. This paper reviews the history of the EV with emphasis on future electric motors. This paper describes the mechanical parts of the driveline in EVs and discusses the advantages and disadvantages of technology trends.

Since the mass production of Ford T, the automobile industry has been a major driving force in research. EVs, now seen as the future of the automobile, are rapidly gaining industrial momentum.

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There are three main stages in the EV's history. In the early days of mechanic traction, until the beginning of 1900s, steam, internal combustion (IC), and electric motors had equivalent market penetration. The IC motor has been recently developed. Steam automobiles were dangerous, dirty, and expensive to maintain. EVs had many technical advantages. The short range of EVs was less of a limitation as only big cities were properly paved, i.e., long journeys were infrequent. However, the expansion of modern road systems with a dense network of petrol stations, the development of the IC (specially with the automatic starter), and the drop in prices due to mass production propelled the IC cars as the preferred and only technology for years [5], [6].

The first HEV was developed as early as 1899. Engineers at Porsche had, at this early stage, realized that higher efficiency values could be achieved if IC motors operated in combination with electric traction motors.

The second resurgence of EVs was triggered by the development of power electronics. The automotive industry pioneered the research of motor control for EVs in the 1960s [7]. The oil crisis in the 1970s maintained the interest and founding in the research of EVs. Prototypes developed in this period set the basis of modern EVs. However, the low energy density and high prices of batteries prevented EVs from being competitive with IC vehicles [8].

Currently, HEVs and EVs are making a comeback in mainstream transportation. The high population density of modern cities makes the use of IC engine a health problem. In many western countries, smoking is prohibited indoors. Likewise, the use of IC engines could be outlawed in future cities: the European Commission intends to eliminate conventionally fueled cars in cities by 2050 [9]. The social concern over IC engine pollution in city centers has been met by the promotion of bicycles. There is also a political will for environmentally friendly transportation with subsidies and tax reductions for HEVs and EVs [10]–[12].

Social and economic factors are also making EVs attractive. Currently, all major manufacturers have an EV in their portfolio. Toyota Prius has been the first economic success of an HEV. This milestone has demonstrated a renewed interest in efficient electric drives.

The stator of electric motors has not changed much since Jonas Wenström invented the slotted armature in 1880 [13]. Vehicle propulsion has specific requirements that distinguish stationary and onboard motors. Every kilogram onboard represents an increase in structural loads and a loss in the system because of friction. High efficiency is equivalent to a reduction in

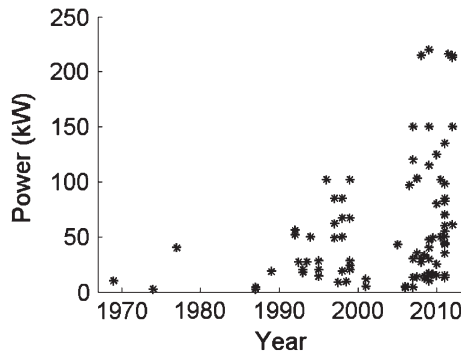


Fig. 1. Power rating of EVs released on the market.

energy demands and, thus, battery weight. Permanent-magnet (PM) motors, which have the highest efficiency, thus appear to be the best option. However, the market is dominated by asynchronous machines. The explanation for this paradox could be expressed in terms of the low utilization factor of the motor in vehicles and the prize of materials. A vehicle fleet of 4.5 million cars gives a picture of the low utilization factor of the traction motor in vehicles. This is the vehicle fleet of Sweden, which is a country with a rather small population [14]. Considering an average power of 70 kW, the vehicle fleet's installed power is in the same order of magnitude as all the world's nuclear power plants (315–370 GW) [15]. It is speculated that a shift in technology to EVs and HEVs for all the industrialized countries could lead to an increase in prices and shortage of raw materials for PM motors if these are based on rare-earth materials [16].

## II. MOTOR TOPOLOGIES

More than 100 different electric motors can be found in modern vehicles [17]. Thus, the topic is quite broad, although only traction motors are discussed here. The great variety of motor topologies and the different specifications of EVs result in a segmented market with the dc motor, induction motor (IM), synchronous PM (SPM), and synchronous brushed motor (SBM) already commercially available [18]. A fifth topology, i.e., the reluctance motor (RM), has been proposed due to favorable characteristics but has yet to be commercially released in EVs.

Variable-speed motors have intrinsically neither nominal speed nor nominal power. The catalog power corresponds to the maximum power that the drive system provides, i.e., the limit that the control system allows in a tradeoff between performance and lifetime of the battery. The motor is designed by balancing efficiency and lightweight. The motor peak power capability is always higher than the system rating.

The power rating of EVs varies from a few kilowatts for small quadricycles to over 200 kW in high-performance cars. The EV market is growing in number of potential niches, far from converging to standardization. The power in early prototypes was determined by technical requirements, whereas now, it responds to market demands. The evolution of the power installed in the traction motors with time is shown in Fig. 1. The power rating has not increased but, rather, is spread with different applications.

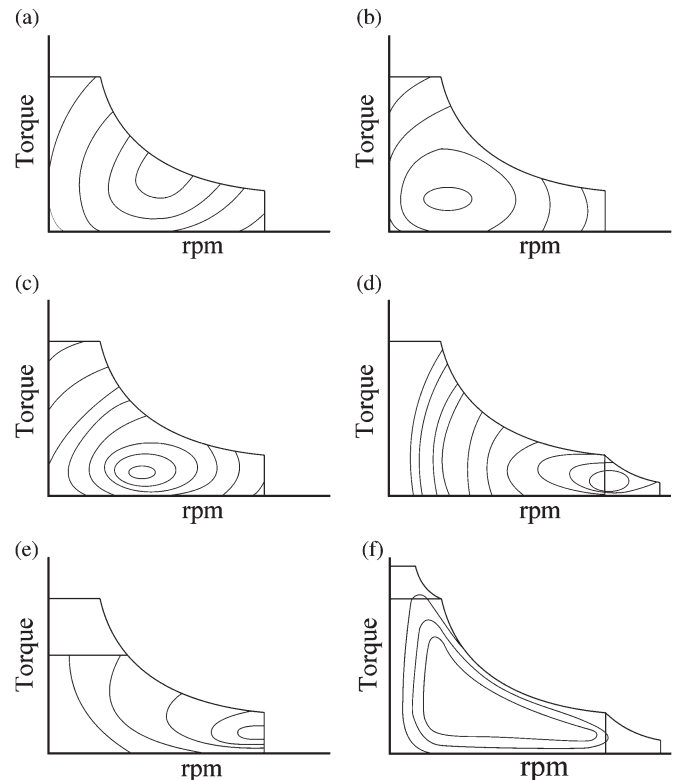


Fig. 2. Efficiency map for (a) surface-mounted PM, (b) internal-mounted PM, (c) IM, (d) RM, (e) DC, and (f) SM motors.

The efficiency of electric motors depends on the working points that each driving cycle applies to the motor, as in IC motors. There is no standard stand-alone figure of the efficiency rating for variable-speed motors. They are characterized with power–speed or torque–speed efficiency maps. Electric motors have an optimum working condition. The efficiency decays at working points out of the optimal region, depending on the type of motor. The performance of the motor for a wide range of speeds and powers is defined by the design, although each type of motor has a characteristic torque–speed relation. Fig. 2 shows the characteristic footprint of several machines [19]–[22]. If motors with the same peak efficiency are compared, PM motors are more efficient in overload transients at constant speed, whereas RMs have better performances at high-speed overloads. RMs' control allows high-speed operation, but the efficiency rapidly decays at low speed. SBMs have lower peak efficiency than PM motors, but the efficiency remains high in a wide operational range, and their control allows high-speed operation.

The efficiency is also dependent on the voltage level. High-voltage rated drivelines are intrinsically more efficient. On the other hand, the efficiency drops when the driveline is operated below the rated voltage. This happens at a low state of charge (SoC) [23], [24].

In the following, the major motor topologies are discussed in terms of rotor and stator topology.

### A. Rotor

1) *DC Motors*: DC motors consist of a stator with a stationary field and a wound rotor with a brush commutation

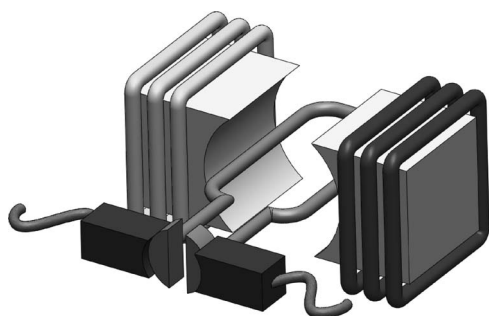


Fig. 3. Schematic representation of a dc motor.

system, as shown in Fig. 3. The field in the stator is generally induced by coils, although small machines may have a PM excitation. The field winding may be series or shunt connected with the rotor coils depending on the required characteristics. The commutator is made up of a set of copper segments, inducing more friction than slip rings and consequently producing dust.

The main advantages of this type of motors are given as follows: 1) well-established technology; 2) reliability; 3) inexpensiveness; and 4) simple and robust control. DC motors were the preferred option in variable-speed operation applications before the development of advanced power electronics. The main disadvantages are low power density compared with alternative technologies, costly maintenance of the coal brushes (about every 3000 h), and low efficiency, although efficiency values over 85% are feasible [22]. The low utilization factor of private vehicles makes the coal brushes essentially maintenance free. DC motors still have a wide market of lower and middle power range commutation vehicles.

2) *Induction*: The main advantage of IMs, which are also known as asynchronous or squirrel-cage motors, is construction simplicity. The rotor consists of a stack of laminated steel with short-circuited aluminum bars in the shape of a squirrel cage. The magnetic field of the stator rotates at a slightly higher speed than the rotor. The slip between rotor and stator frequencies induces rotor currents that produce the motor torque [25].

IM technology is mature and standardized; the National Electrical Manufacturers Association in the U.S. and the European Committee of Manufacturers of Electrical Machines and Power Electronic (CEMEP) in the European Union have a general efficiency classification system. IMs are inexpensive, very robust, require little maintenance, and are reliable. The International Electrotechnical Commission standard IE3 sets the efficiency at over 95% for static applications. In EVs, the peak efficiency is sacrificed to obtain a better performance curve over a wider speed range. Seventy-five percent efficiency is considered a good figure-of-merit for a small variable-speed motor [26].

3) *SPM*: PM motors are characterized by their constant rotor magnetization. PMs in the rotor induce high magnetic fields in the air gap, without excitation currents, leading to high power density. Excitation currents represent about half of the losses in the form of Joule losses for non-self-excited synchronous motors. Thus, PM motors are intrinsically very

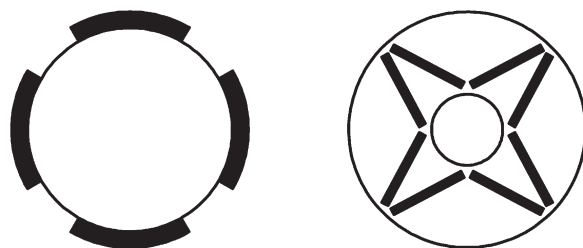


Fig. 4. Radial-flux rotors with surface- and internal-mounted magnets.

efficient and require less cooling due to the lack of exciting currents. This comes at the cost of more complex control as the excitation field may not be regulated [27].

In the early stages of power control, PM motors were fed from an electronically commutated dc source. The winding currents were sequentially commutated, resulting in a rectangular armature MMF. For historical reasons, the term brushless permanent magnet (BPM) is still in use and refers to a machine with a rectangular back electromotive force, whereas SPM motors refer to machines fed with a sinusoidal MMF. Other than this, there is no difference between BPM and SPM motors [28]–[30].

The development of high-coercivity neodymium–iron–boron magnets in the early 1980s opened up new possibilities for PM motors, and they are now being increasingly used in automotive applications. The new PMs are brittle and temperature sensitive. Deficient cooling may lead to reduction in performance and permanent demagnetization [21].

There is a great variety of PM arrangements and possible geometries. With regard to the flux path, most common types of machines are radial or axial flux. Other topologies such as transversal and spherical flux paths have been described, but their use is limited. There are many different strategies of mounting magnets on the rotor. Axial-flux machines usually have magnets mounted on the surface of the rotor, whereas radial-flux machines may have the magnets either surface mounted or internal mounted, as shown in Fig. 4 [27], [31].

SPMs allow great flexibility in design. SPM motors are adequate to fit in limited spaces, such as “electric rear wheel drive” and “in-wheel motors” (IWMs), where no other alternative is possible [32].

4) *Reluctance*: RMs have gained attention due to the concern of price increase or shortage of magnetic material when the EVs enter mass production [16]. RMs’ main characteristic is the use of rotor salient poles. The torque is solely produced by the difference between the direct axis and quadrature axis synchronous reactance as the rotor lacks excitation. The very robust rotor is cheap to produce and not temperature sensitive [33], [34]. The peak efficiency is equivalent to the IM, whereas the efficiency remains high over a wide speed range. Efficiency values over 95% have been reported [35]. The high rotor inductance ratio makes sensorless control easier to implement [35], [36]. The high ripple torque resulting in higher noise and vibrations is the main drawback.

The RM has not been used in EVs, despite high interest for the good performance reported in the literature and successfully demonstrated prototypes [37]–[39].

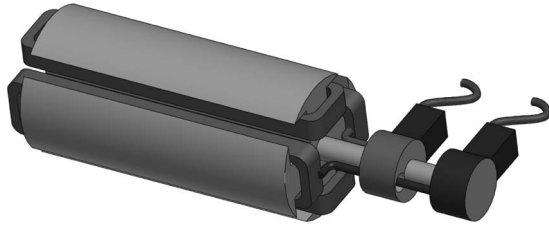


Fig. 5. Schematic representation of an SBM.

5) *Synchronous Brushed*: The SBM is chosen by Renault for their next middle-sized models [40]. This type of motor has a coil in the rotor connected to a stationary voltage source through a slip ring. The electric current flows from a stationary coal brush through a rotating slip ring in steel. The magnetic field in the rotor is induced by the field current through the rotor coil. The rotor is robust, and the temperature is only limited by the conductor insulation [24], [41]. A schematic representation of an SBM is shown in Fig. 5.

The possibility to regulate the magnetic flux linkage is the main advantage of this technology. The reduction of the flux linkage allows high-speed operation at constant power without field-weakening operation as in PM machines. At partial load operation, the iron and excitation losses can be reduced, extending the high-efficiency operational range. The technology also offers a high starting torque. The control is simpler and more robust than that for the SPM.

The magnetizing current is subjected to Joule losses. Thus, full-load operation efficiency is lower than for comparable machines without currents in the stator, i.e., RMs and SPMs. The coal brushes in the slip rings wear less than those in dc commutators and are virtually maintenance free.

### B. Stator

1) *Coreless*: In coreless machines (CMs), the windings are placed in a nonmagnetic material stator [42], [43]. There are no iron losses in this topology. The lack of iron in the stator teeth increases the reluctance of the magnetic circuit. CMs will, for a given power rating, require more active material as the larger air gap has to be compensated. The absence of iron weight and iron losses in the stator compensates for the increased use of expensive active material. Coreless motors are present in high-performance applications, where weight and efficiency prevail over economic considerations [44], [45].

2) *Multiple Phases*: The standard three-phase power systems have many advantages: three is the minimum number of phases that deliver constant power over each cycle. An increase in the number of phases increases the complexity of the system. It is only recommended when special performance is required. Intrinsic advantages of three phases are a reduction in the harmonic content, low acoustic noise, and an increase in efficiency and torque density. However, the fault tolerance and lower power rating per phase have been identified as the main factors of the market niche [46], [47]. Fault tolerance plays a key role in fulfilling the safety requirements for airplanes. Lower power ratings per phase allow the use of robust and less-expensive power electronic devices. Sometimes, multiple-

TABLE I  
REFERENCE EFFICIENCY FIGURES OF ELECTRIC  
MOTORS AND DRIVES RATED FROM 1 TO 5

	Motor	Electronics	System
SPM	5	4	4
SBM	4	4	4
RM	4	3.5	3
IM	3.5	4	3
DC	2	5	2

phase systems consist of duplicate three-phase systems with an angle shift. In principle, any number of phases above four is possible.

Systems with more than three phases are uncommon in road vehicles but are used in propulsion motors for ships and planes. The high torque capability makes them a suitable candidate for IWMs [48], [49].

3) *In-Wheel*: In IWMs, the outer diameter is limited to the space available inside the wheel. IWMs may be directly driven, although some designs include a planetary gear and a brake disk [50].

In principle, all topologies are suitable, but PM motors with outer rotors or axial-flux configurations have a better power density and volume utilization. Additionally, there are in-wheel induction and RM configurations [51]–[53].

### C. Efficiency

The efficiency of electric motors is highly dependent on the size and the working point, as shown in Fig. 2. It is not possible to describe the performance of a motor with a single figure. Nevertheless, to have a quantitative approximation of the different technologies, Table I rates the efficiency of different motor types from 1 to 5. Electric motors are about three times more efficient than IC engines. As a reference, dc drives reach up to 78% in the range of 40–50 kW, and this is the simplest and least efficient technology [19], [24], [40], [43], [54].

## III. DRIVELINE CONFIGURATION

Electric motors allow more flexible configurations than IC engines. Configurations with one electric motor dedicated to each wheel offer a simpler, lighter, and more efficient transmission without a differential. Electric motors may be manufactured in a wide range of geometries allowing new car body styles. However, most of the cars in the market follow traditional car configurations, despite design possibilities. Commonly, propulsion is provided by a single traction motor coupled with a single-speed gear reduction and a differential. An alternative configuration is a motor in each wheel. The concept of IWM has been introduced to reduce space, weight, and friction losses in the transmission gears.

While turning, the speed of the internal wheel is lower than that of the external wheel. The different trajectories of the inner and outer wheels under the turning regime are shown in Fig. 6. Drivelines with two motors require independent control and an electric differential to avoid slip and ensure stability [55]. Although obvious for synchronous motors, it also applies to IMs [53], [56]. The torque/slip characteristic of IMs indicates



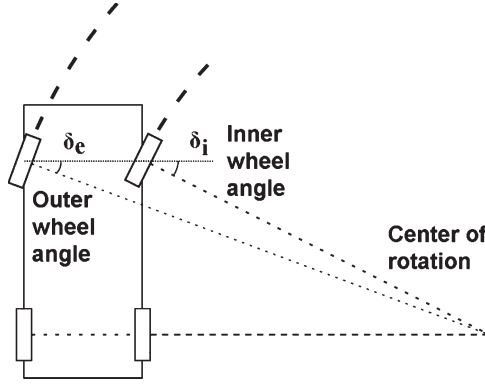


Fig. 6. Different trajectories of the inner and outer wheels under the turning regime.

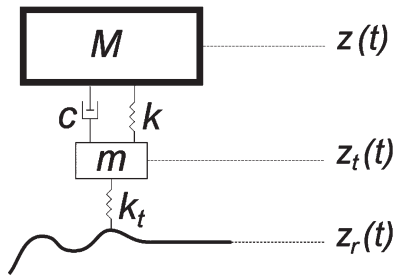


Fig. 7. Simplified vertical quarter-car dynamic model.

an instability behavior in the turning regime. The faster wheel would have less slip and, therefore, less torque, and the slower wheel would have a higher torque with the risk of losing its grip.

IWMs have been proposed in concept cars and test vehicles such as the GM's Hy-wire platform [57], Mitsubishi's IWM EV [50], and the Massachusetts Institute of Technology's concept car [58]. The IWM presents worse dynamic performance than traditional power trains, particularly at high speeds. The IWM considerably increases the vehicle's unsprung mass. The following equations govern the dynamics of the simplified vertical quarter-car model shown in Fig. 7:

$$M \cdot \ddot{z}(t) = F_k(t) + F_c(t) - M \cdot g \quad (1)$$

$$m \cdot \ddot{z}_t(t) = -F_k(t) - F_c(t) + F_{kt}(t) - m \cdot g \quad (2)$$

where  $F_k(t)$  and  $F_c(t)$  are functions describing the suspension spring and damper vertical forces, respectively. In a linear model,  $F_k(t) = -k \cdot z(t)$  and  $F_c(t) = -c \cdot \dot{z}(t)$ .  $F_{kt}(t)$  is the function describing the tire stiffness.  $M$  is one fourth of the chassis mass, and  $m$  is the wheel mass, which is also referred to as the unsprung mass. The solutions of (1) and (2) show the importance of  $m$  in the dynamic of the system [59].

One strategy to mitigate the problems associated with high unsprung mass is the use of active suspension systems. In active suspension systems,  $F_k(t)$  and  $F_c(t)$  are controllable functions rather than constants. The system dynamics may be electronically controlled. There are wheel motor prototypes, with Michelin Active Wheel System, Siemens VDO eCorner, and Hi-Pa Drive as commercial names [60], [61].

TABLE II  
CHARACTERISTICS OF VARIOUS TYPES OF BATTERIES

Battery	Application	Wh/kg	W/kg	\$/kWh
Lead acid				150
Panasonic	HEV	26,3	389	
Panasonic	EV	34,2	250	
Nickel Metal				1500
Panasonic	HEV	46	1093	
Panasonic	EV	68	240	
Ovonic	HEV	45	1000	
Ovonic	EV	68	200	
Lithium ion				2000
Saft	HEV	77	1550	
Saft	EV	140	476	
Shin-Kobe	HEV	56	3920	
Shin-Kobe	EV	105	1344	

IWMs have higher efficiency and lower mass than mechanic drive trains. IWMs have found use in applications where performance is prioritized over comfort, such as sport cars, and are the unbeatable topology in solar car competitions [44].

#### IV. BATTERY SELECTION

Battery selection has been thoroughly studied for HEVs and plug-in HEVs (PHEVs) to find the proper balance between the electric drive and the IC motor range extender. The size of the battery compromises the mechanical design and the cost of the entire vehicle. Economic studies suggest that the optimum battery size corresponds to a short electric battery range [62], [63].

There are several battery technologies available for EVs [64], [65]. In 1997, Honda claimed to be the first major automaker introducing nickel metal hydride batteries instead of lead acid. This was the preferred option for high-performance vehicles until the development of lithium-ion technology. The market overview in the Appendix shows the present market to be almost polarized into lead-acid batteries and lithium batteries. Lead-acid batteries are safer and less expensive but have lower energy density. They are losing popularity, and current applications are restricted to small vehicles. Lithium-ion batteries require careful charging cycles and are potentially explosive, but the higher energy density makes them the preferred option for most of general and high-performance car manufacturers. Table II shows the energy and power density obtained for different technologies [66], [67].

The chemistry of the battery gives a nonlinear equivalent circuit behavior. Power transients dramatically reduce lifetime. Batteries designed to withstand power transients have lower energy density. Batteries in EVs have more severe working cycles than equivalent HEVs. Table II shows the compromise between energy density and power density in different applications to obtain a reasonable battery lifetime. Supercapacitors [68]–[70] and flywheels [71]–[75] are proposed to be used as a power buffers, whereas batteries may be designed for high energy and low power density.

The range of EVs is completely determined by the capacity of the battery. Therefore, battery selection must take into account the application of the vehicle plus a safety margin. The driver's fear to empty the battery before reaching the destination

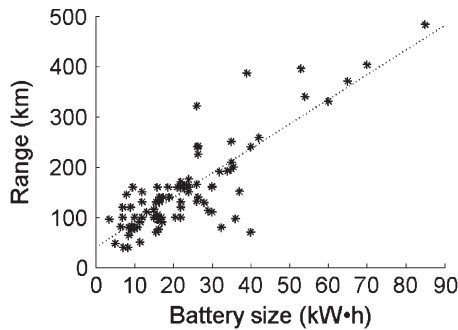


Fig. 8. Battery energy capacity versus range for commercial EVs.

is a determinant factor in the customer's attitude toward EVs. The vehicle range is thus a commercial rather than technical decision. The battery capacity versus range of commercial EVs is plotted in Fig. 8. There is a wide variety of values, from small quadricycles to high-performance sport cars. The range is overdimensioned with respect to the standard commuting distances for 95% of the journeys, both in Europe and in the U.S. [76]–[78].

## V. MARKET OVERVIEW

Research is focused on low-emission and fuel-efficient cars in response to environmental concerns and strict emission legislation levels. In this context, the hybrid configurations have reemerged. It achieved the first commercial success with the Toyota Prius in 1997. The tendency in the first decade of the 2000s was the introduction of hydrogen fuel and the start of pilot programs by main manufacturers [79], [80]. The development of the battery technology, which was led by the electronic industry, has renewed the interest of full EVs. The market has become more mature with a niche market for zero-emission cars [12].

The limited range and the pronounced recharge time are the main technical disadvantages of electric cars compared with ICs. Manufacturers try to make EVs commercially attractive by combining the electric traction with an IC engine. The PHEVs allows a short range of electric drives with a high-efficiency hybrid drive. The extended range EV (EREV) has a full electric driveline with a small auxiliary IC engine that is only operated when the battery is empty. The IC engine in the EREV has a positive psychological effect as drivers fear the electric range [81].

The pure EV has two market tendencies. On the one hand, models designed for commuting purposes with low battery weight and short range. These are lightweight city vehicles with a limited speed for city traffic. On the other hand, there are long-range electric cars with high-capacity batteries. The weight and price of the batteries orient this product to the high-performance market. Fig. 9 shows the correlation between battery capacity and motor power for EVs on the market.

## VI. FUTURE TRENDS IN ELECTRIC VEHICLE POLICIES

Vehicle restrictions due to congestion, air pollution, or both have been implemented for many years. These policies are

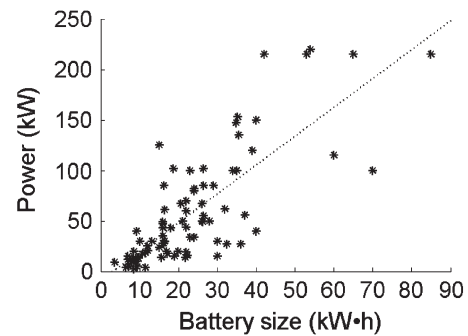


Fig. 9. Battery capacity and motor power for EVs in the market.



Fig. 10. Traffic sign prohibiting studded winter tires for environmental concerns in the city center of some cities in Sweden. Pollution charge program “Ecopass” in Milan, Italy. Pioneer congestion charge sign in central London.

becoming more widespread for highly populated cities with incentives toward zero-emission vehicles [82]. The restriction to polluting IC vehicles creates an interesting monopoly market for EVs. Fig. 10 shows some examples of current traffic restrictions in cities. This tendency is growing [9]. However, the EVs have inherent disadvantages of initial cost, time to refill, and limited range. There are different proposals on how to solve these conflicts of performance.

1) *Cohabitation of Different Energy Sources*: Commuting represents only one third of the driven miles for private drivers [83]. State-of-the-art EVs are not an option for freight and long-distance journeys. Hydrogen as an energy vector eliminates regional emission and has some of the advantages of petrol, such as high energy density [84], [85]. Electricity and hydrogen fuel stations may coexist.

2) *Active Roads*: Roads with power supply, either with a pantograph or with inductive coupling, as trolleybuses, are proposed [86]–[88]. Contactless electric transmission has an expected efficiency value above 90% [89], [90], which is higher than batteries. Highways equipped with power transfer systems would allow EVs with lower battery ratings designed for short commuting distance to have an infinite range at a relatively low cost. Traditional vehicles and EVs equipped with inductive power transfer systems could share the roads. The system has been tested with positive results [90], [91]. The high initial investment requirements have been concluded to be the main drawback.

3) *Battery Handling*: The battery is one of the most expensive components of EVs. Leasing programs have been proposed and tested for vehicle fleets. Leasing gives a number of advantages.

1) The perception of the EV price is reduced.

TABLE III  
DATA OF THE MOST REPRESENTATIVE EV MODELS ON THE MARKET

Model	Battery type	Energy storage (kWh)	Nominal range (km)	Market release	Power (kW)	Motor type							
							AC Propulsion eBox	Li	35	250	2007	150	IM
							ZAP! OBVIO! 828E	Li	39	386	2007	120	IM
							Phoenix sut	Li	35	209	2007	100	
							Phoenix sut	Li	70	403	2007	100	
Tesla Model S	Li	42	258	2012	215	IM	Smart ED	Na	13,2	110	2007	30	PM
Tesla Model S	Li	65	370	2012	215	IM	Kewet Buddy	Pb	8,4	40	2007	13	DC
Tesla Model S	Li	85	483	2012	215	IM	The Kurrent	Pb		60	2007	4,1	
Lightning GT	Li	40	240	2012	150	PM	CityCar	Li	7	120	2007		
Hyundai BlueOn	Li	16,4	140	2012	61	PM	ZAP Xebra	Pb	7,2	40	2006	5	DC
Honda Fit EV			113	2012		IM	NICE Mega City	Pb	6,5	81	2006	4	DC
Toyota RAV4 EV	Li	30	160	2012		IM	Commuter	Pb	16	100	2005	43	DC
Saab 9-3 ePower	Li	35,5	200	2011	135		Cars Tango						
CODA Sedan	Li	34	193	2011	100		Cree SAM	Li	7	100	2001	11,6	PM
Ford Focus Electric	Li	23	160	2011	100	IM	G-Wiz	Pb	9,3	77	2001	4,8	DC
Skoda Octavia Green E Line							Dynasty IT	Pb	5	48	2001		
Volvo C30	Li	24	150	2011	82		General Motors EV1	NiMH	26,4	225	1999	102	IM
DRIVE Electric							Ford Ranger EV	NiMH	26	132	1999	67	IM
Renault Fluence Z.E.	Li	22	161	2011	70	SB	Peugeot Partner	NiCd	16,2	96	1999	28	DC
Renault ZOE	Li	22	160	2011	60	SB	Hypermini	Li	15	115	1999	24	PM
Tata Indica Vista EV	Li	26,5	241	2011	55	PM	Myers Motors NmG	Pb	8,6	64	1999	20	DC
Ford Tournéo Connect EV	Li	21	160	2011	50	IM	Peugeot 106	NiCd	12	150	1999	20	DC
Kangoo Express Z.E	Li	22	170	2011	44	SB	GM S-10	NiMH	29	113	1998	85	IM
Fiat Doblò	Li	18	140	2011	43	IM	Ford Ranger EV	Pb	20,6	100	1998	67	IM
Peugeot iOn	Li	16	130	2011	35	PM	Toyota RAV4 EV	NiMH	26	165	1998	50	PM
Renault Twizy	Li	7	100	2011	15		Renault Express Electr	Pb	22	100	1998	19	
REVA NXR	Pb	9,6	160	2011	13	IM	GEM Car	Pb		48	1998	9	DC
BYD F3M	Li	15	100	2010	125	PM	CityCom Mini-EI	Pb	3,6	96	1998	9	PM
Nissan Leaf	Li	24	175	2010	80	PM	GM S-10	Pb	16,2	76	1997	85	IM
Ford Transit Connect EV	Li	28	129	2010	50	IM	Nissan Altra	Li	32	190	1997	62	PM
Citroen C zero	Li	16	130	2010	49	PM	Honda EV Plus	NiMH	26,2	240	1997	49	DC
Gordon Murray T-27	Li	12	130	2010	25		General Motors EV1	Pb	18,7	160	1996	102	IM
Wheego Whip LiFe	Li	30	161	2010	15	IM	Citroen Berlingo	NiCd	16	100	1995	28	DC
Venturi Fétish	Li	54	340	2009	220		Citroen Saxo	NiMH	17	100	1995	20	DC
Mini E	Li	35	195	2009	150	IM	Subaru minivan 200	Pb	15,6	70	1995	14	DC
BYD e6	Li	60	330	2009	115	PM	Solectria Sunrise	NiMH	26	321	1994	50	IM
Mitsubishi i MIEV	Li	16	160	2009	47	PM	Chrysler TEVan	NiMH	32,4	80	1993	27	DC
Subaru Stella EV	Li	9,2	80	2009	40		Chrysler TEVan	NiMH	36	97	1993	27	DC
Smart ED	Li	16,5	135	2009	30	PM	Citroen AX	NiCd	12	100	1993	20	DC
Citroën C1 ev'ie	Li	30	110	2009	30	IM	VW Golf CityStromer	Pb	17,2	90	1993	17,5	PM
Zytel Gorila Electric	Pb	10,8	80	2009	17		Ford Ecostar	Na	37	151	1992	56	IM
Micro-Vett Fiat Panda	Li	22	120	2009	15	IM	Bertone Blitz	Pb		130	1992	52	DC
Micro-Vett Fiat 500	Li	22	130	2009	15	IM	VW Golf CityStromer	Pb	11,5	50	1989	18,5	PM
Tazzari Zero	Li	19	140	2009	15	IM	CityEI	Pb	11,5	90	1987	4	DC
Chana Benni	Pb	9	120	2009	10		CityEI	Pb	8,6	80	1987	2,5	DC
Tesla Roadster	Li	53	395	2008	215	IM	Oka NEV ZEV				1987		
Th!nk City	Na	24	160	2008	34	IM	Lucas Chloride	Pb	40	70	1977	40	DC
Th!nk City	Li	23	160	2008	34	IM	Citicar	Pb			1974	2,5	DC
Lumeneo SMERA	Li	10	100	2008	30	PM	Enfield 8000	Pb	8	145	1969	10	DC
Stevens Zecar	Pb		80	2008	27	IM	Legend: <b>Battery type:</b> Li: based on lithium, Pb: lead-acid, Na: sodium-nickel chloride Zebra batteries and sodium-sulphur in the Ford Ecostar;						
REVAi	Pb	9,3	80	2008	13	IM	<b>Motor type:</b> IM: Inductioni motor, PM: Permanent Magnet motor, SB: Synchronous Brushed motor.						
REVAi	Li	9,3	80	2008	13	IM							
ZENN	Pb		64	2008		IM							

Legend: **Battery type:** Li: based on lithium, Pb: lead-acid, Na: sodium-nickel chloride Zebra batteries and sodium-sulphur in the Ford Ecostar; **Motor type:** IM: Induction motor, PM: Permanent Magnet motor, SB: Synchronous Brushed motor.

- 2) It allows replacing the empty battery pack for charged ones instead of recharging. This way, the charge time would be equivalent to filling up the tank in a petrol car.
- 3) Electric utilities may use the storage capacity of batteries to regulate peak power. In the smart electric grid concept, the car user may sell electricity at high prices and buy at low night prices [92], [93].

The use of the energy storage capacity of EVs' battery may be used to regulate the electricity demand and help in the penetration of intermittent renewable-energy generators [94]. Users may be reluctant to risk their own battery life. However, leasing may be an attractive alternative for both users and utilities.

## VII. CONCLUSION

There is a political and market demand toward EVs. However, a technical review of EVs on the market shows that technology standards are not yet set. Motor candidates for all EVs are presented, as well as alternative topologies. The car survey shows that manufacturers are conservative in the technology employed in commercial EVs. IMs are still the predominant technology even with less than 75% of efficiency [26]. DC motors are still in use in some small vehicles.

The state-of-the-art PM motors, RMs, and SBMs present better performance than IMs. The price of raw materials for PMs will determine if PM motors will become the standard technology [16] or if there will be a market breakthrough of RMs and SBMs.

Electric motors allow flexibility in the design. IWMs reduce weight and clear space in the car, making new car body styles possible.

There is no equivalent miles per gallon or liters per kilometer to measure the performance of EVs. The first gallon of gas in the tank has the same properties as the last one, but the "quality" of electric kilowatts depends on the SoC. Efficiency decreases with the SoC, and the lifetime of the battery depends on the power strategy. Regenerative braking increases efficiency but reduces the battery life. This efficiency measurement is even more critical in HEVs where two power sources are combined. To make the comparison between EVs possible, the authors propose the adaption of a standardized drive cycle or other standardized methods of efficiency measurement.

Recent battery development has the most credit for EV success. Energy density and price will be most crucial in the future vehicle trends. Future trends seem to be RMs, active roads, or small EVs for city traffic.

## APPENDIX

Table III shows a survey on EVs on the market. Data have been obtained from manufacturers' datasheets, motor magazines, and direct surveys. The list of vehicles includes several models from the same manufacturer under different commercial names. The list is not complete as several new and notable models are missing. Data may be inaccurate and missing as manufacturers are reluctant to give technical data. For these reasons, the survey has only a qualitative value.

## REFERENCES

- [1] C. C. Chan, A. Bouscayrol, and K. Chen, "Electric, hybrid, and fuel-cell vehicles: Architectures and modeling," *IEEE Trans. Veh. Technol.*, vol. 59, no. 2, pp. 589–598, Feb. 2010.
- [2] M. Zeraouia, M. E. H. Benbouzid, and D. Diallo, "Electric motor drive selection issues for HEV propulsion systems: A comparative study," *IEEE Trans. Veh. Technol.*, vol. 55, no. 6, pp. 1756–1764, Nov. 2006.
- [3] C. C. Chan and Y. S. Wong, "The state of the art of electric vehicles technology," in *Proc. 4th IPEMC*, 2004, vol. 1, pp. 46–57.
- [4] C. C. Chan, "The state of the art of electric and hybrid vehicles," *Proc. IEEE*, vol. 90, no. 2, pp. 247–275, Feb. 2002.
- [5] C. Sulzberger, "An early road warrior: Electric vehicles in the early years of the automobile," *IEEE Power Energy Mag.*, vol. 2, no. 3, pp. 66–71, May/Jun. 2004.
- [6] L. Situ, "Electric vehicle development: The past, present and future," in *Proc. 3rd Int. Conf. PESA*, 2009, pp. 1–3.
- [7] E. Hesla, "Electric propulsion [history]," *IEEE Ind. Appl. Mag.*, vol. 15, no. 4, pp. 10–13, Jul./Aug. 2009.
- [8] K. Rajashekara, "History of electric vehicles in General Motors," in *Conf. Rec. IEEE IAS Annu. Meeting*, 1993, vol. 1, pp. 447–454.
- [9] Eur. Commission, *White Paper: Roadmap to a Single European Transport Area—Towards a Competitive and Resource Efficient Transport System*, Brussels, Belgium, Mar. 28, 2011.
- [10] M. Åhman, "Government policy and the development of electric vehicles in Japan," *Energy Policy*, vol. 34, no. 4, pp. 433–443, Mar. 2006.
- [11] Accenture, *Changing the Game Plug-in Electric Vehicle Pilots*, 2011.
- [12] U.S. Dept. Energy, *One Million Electric Vehicles By 2015, Feb. 2011 Status Report*, Washington, DC, 2011.
- [13] R. Curley, *The Britannica Guide to Inventions That Changed the Modern World*. New York: Britannica, 2010, p. 162.
- [14] Vägverket, Presentation of the Swedish National Road Administration (SNRA). [Online]. Available: <http://www.piacr.org/library/aipcr/1/A1AB718mKU58ou7P8aIHIN0I.pdf>
- [15] Int. Atomic Energy Agency (IAEA), Reference Data Series No. 2, *Nuclear Power Reactors in the World*, Vienna, Austria, Apr. 2006.
- [16] Y. Takano, M. Takeno, N. Hoshi, A. Chiba, M. Takemoto, S. Ogasawara, and M. A. Rahman, "Design and analysis of a switched reluctance motor for next generation hybrid vehicle without PM materials," in *Proc. IPEC*, 2010, pp. 1801–1806.
- [17] H. Thieme, "Influence of automotive 42 V powernet on small PM DC motors," in *Proc. IEEE IEMDC*, 2001, pp. 591–593.
- [18] K. T. Chau, C. C. Chan, and C. Liu, "Overview of permanent-magnet brushless drives for electric and hybrid electric vehicles," *IEEE Trans. Ind. Electron.*, vol. 55, no. 6, pp. 2246–2257, Jun. 2008.
- [19] J. G. W. West, "DC, induction, reluctance and PM motors for electric vehicles," *Power Eng. J.*, vol. 8, no. 2, pp. 77–88, Apr. 1994.
- [20] S. M. Lukic and A. Emado, "Modeling of electric machines for automotive applications using efficiency maps," in *Proc. Elect. Insul. Conf. Elect. Manuf. Coil Winding Technol. Conf.*, 2003, pp. 543–550.
- [21] M. A. Rahman and M. A. Masrur, "Advances on IPM technology for hybrid electric vehicles," in *Proc. IEEE VPPC*, 2009, pp. 92–97.
- [22] J. Fenton and R. Hodgkinson, "Current EV design approaches," in *Light-weight Electric/Hybrid Vehicle Design: Automotive Engineering Series*. Oxford, U.K.: Elsevier, 2000, ch. 1.
- [23] S. S. Williamson, A. Emadi, and K. Rajashekara, "Comprehensive efficiency modeling of electric traction motor drives for hybrid electric vehicle propulsion applications," *IEEE Trans. Veh. Technol.*, vol. 56, no. 4, pp. 1561–1572, Jul. 2007.
- [24] G. Friedrich, "Comparative study of three control strategies for the synchronous salient poles and wound rotor machine in automotive applications with on board energy," in *Proc. 5th Int. Conf. Power Electron. Variable-Speed Drives*, 1994, pp. 706–709.
- [25] R. Curiac and H. Li, "Specific design considerations for AC induction motors connected to adjustable frequency drives," in *Conf. Rec. Annu. PPIC*, 2010, pp. 1–6.
- [26] S. Pathak and R. Prakash, "Development of high performance AC drive train," in *Proc. IEEE ICEHV*, 2006, pp. 1–3.
- [27] C. C. Chan and K. T. Chau, "An overview of power electronics in electric vehicles," *IEEE Trans. Ind. Electron.*, vol. 44, no. 1, pp. 3–13, Feb. 1997.
- [28] J. F. Gieras and M. Wing, *Permanent Magnet Motor Technology Revised*, 2nd ed. Boca Raton, FL: CRC, Jan. 15, 2002, ch. 1.
- [29] N. A. Demerdash and T. W. Nehl, "Dynamic modeling of brushless DC motors for aerospace actuation," *IEEE Trans. Aerosp. Electron. Syst.*, vol. AES-16, no. 6, pp. 811–821, Nov. 1980.



- [30] F. Deng, "Commutation-caused eddy-current losses in permanent-magnet brushless DC motors," *IEEE Trans. Magn.*, vol. 33, no. 5, pp. 4310–4318, Sep. 1997.
- [31] International application number: PCT/SE2011/050658. Swedish Patent Office, "A rotary electric machine, a rotor for a such, and a Vehicle/craft with such a machine."
- [32] F. Márquez-Fernández, A. Reinap, and M. Alaküla, "Design, optimization and construction of an electric motor for an electric rear wheel drive unit application for a hybrid passenger car," in *Proc. XIX ICEM*, 2010, pp. 1–6.
- [33] J. J. Gu and H. Chen, "Implementation of the three-phase switched reluctance machine system for motors and generators," *IEEE/ASME Trans. Mechatronics*, vol. 15, no. 3, pp. 421–432, Jun. 2010.
- [34] H. H. Moghbelli and M. H. Rashid, "Performance review of the switched reluctance motor drives," in *Proc. 34th Midwest Symp. Circuits Syst.*, 1991, vol. 1, pp. 162–165.
- [35] Z. Qianfan, C. Shumei, and T. Xinjia, "Hybrid switched reluctance motor applied in electric vehicles," in *Proc. IEEE VPPC*, 2007, pp. 359–363.
- [36] J. Haataja, "A comparative performance study of four-pole induction motors and synchronous reluctance motors in variable speed drives," Ph.D. dissertation, Lappeenranta Univ. Technol., Acta Universitatis Lappeenrantaensis 153, Lappeenranta, Finland, 2003.
- [37] J. Malan and M. J. Kamper, "Performance of a hybrid electric vehicle using reluctance synchronous machine technology," *IEEE Trans. Ind. Appl.*, vol. 37, no. 5, pp. 1319–1324, Sep./Oct. 2001.
- [38] H. Hannoun, H. Hilairret, and C. Marchand, "Experimental validation of a switched reluctance machine operating in continuous conduction mode," *IEEE Trans. Veh. Technol.*, vol. 60, no. 4, pp. 1453–1460, May 2011.
- [39] C. Pollock, H. Pollock, R. Barron, J. R. Coles, D. Moule, A. Court, and R. Sutton, "Flux-switching motors for automotive applications," *IEEE Trans. Ind. Appl.*, vol. 42, no. 5, pp. 1177–1184, Sep./Oct. 2006.
- [40] Rault, The 2010 Paris Motor Show, Press Release, Sep. 30, 2010.
- [41] C. Rossi, D. Casadei, A. Pilati, and M. Marano, "Wound rotor salient pole synchronous machine drive for electric traction," in *Conf. Rec. 41st IEEE IAS Annu. Meeting*, 2006, pp. 1235–1241.
- [42] W. Xiaoyuan, C. Jing, and G. Yu, "The analysis and simulation of the armature magnetic field in coreless permanent magnet synchronous motor," in *Proc. ICEMS*, 2009, pp. 1–4.
- [43] J. Santiago and H. Bernhoff, "Comparison between axial and radial flux PM coreless machines for flywheel energy storage," *J. Elect. Syst.*, vol. 6, no. 2, pp. 1–13, Dec. 2010.
- [44] H. Lovatt, V. Ramsden, and B. Mecrow, "Design of an in-wheel motor for a solar-powered electric vehicle," in *Proc. 8th Int. Conf. Elect. Mach. Drives (Conf. Publ. No. 444)*, 1997, pp. 234–238.
- [45] C. S. Cambrier, "Brushless motors and controllers designed for GM Sunrayce," *IEEE Aerosp. Electron. Syst. Mag.*, vol. 5, no. 8, pp. 13–15, Aug. 1990.
- [46] O. Lopez, J. Alvarez, J. Doval-Gandoy, and F. Freijedo, "Multilevel multiphase space vector PWM algorithm with switching state redundancy," *IEEE Trans. Ind. Electron.*, vol. 56, no. 3, pp. 792–804, Mar. 2009.
- [47] E. Levi, "Multiphase electric machines for variable-speed applications," *IEEE Trans. Ind. Electron.*, vol. 55, no. 5, pp. 1893–1909, May 2008.
- [48] M. Simoes and P. Vieira, "A high-torque low-speed multiphase brushless machine—A perspective application for electric vehicles," *IEEE Trans. Ind. Electron.*, vol. 49, no. 5, pp. 1154–1164, Oct. 2002.
- [49] E. Levi, R. Bojoi, F. Profumo, H. Toliyat, and S. Williamson, "Multiphase induction motor drives—A technology status review," *IET Elect. Power Appl.*, vol. 1, no. 4, pp. 489–516, Jul. 2007.
- [50] Y. K. Kim, J. W. Lee, Y. K. Lee, Y. Y. Choe, and H. S. Mok, "Drive system of 25 kW in wheel type IPMSM for electric vehicle," in *Proc. ICEMS*, 2010, pp. 904–907.
- [51] L. Chang, "Comparison of AC drives for electric vehicles—A report on experts' opinion survey," *IEEE Aerosp. Electron. Syst. Mag.*, vol. 9, no. 8, pp. 7–11, Aug. 1994.
- [52] [Online]. Available: <http://www.evans-electric.com.au/>
- [53] K. Cakir and A. Sabanovic, "In-wheel motor design for electric vehicles," in *Proc. 9th IEEE Int. Workshop Adv. Motion Control*, 2006, pp. 613–618.
- [54] X. D. Xue, J. K. Lin, Z. Zhang, T. W. Ng, K. F. Luk, K. Cheng, and N. C. Cheung, "Study of motoring operation of in-wheel switched reluctance motor drives for electric vehicles," in *Proc. 3rd Int. Conf. PESA*, 2009, pp. 1–6.
- [55] P. He, Y. Hori, M. Kamachi, K. Walters, and H. Yoshida, "Future motion control to be realized by in-wheel motored electric vehicle," in *Proc. 31st IEEE IECON*, 2005, p. 6.
- [56] B. Tabbache, A. Kheloui, and M. Benbouzid, "An adaptive electric differential for electric vehicles motion stabilization," *IEEE Trans. Veh. Technol.*, vol. 60, no. 1, pp. 104–110, Jan. 2011.
- [57] B. Sørensen, "Systems," in *Hydrogen and Fuel Cells: Emerging Technologies and Applications*. New York: Academic, 2005, ch. 4.
- [58] P. A. Schmitt and W. J. Mitchell, "Autonomous modular vehicle wheel assembly," U.S. Patent Application 20100116572, May 13, 2010.
- [59] S. M. Savaresi, C. Poussot-Vassal, C. Spelta, O. Sename, and L. Dugard, *Semi-Active Suspension Control Design for Vehicles*. Oxford, U.K.: Butterworth-Heinemann, 2010.
- [60] Michelin Active Wheel, Press Kit, 2008, Paris Motor Show, Paris, France, Oct. 2008.
- [61] D. Harris, REV SAE Front Drive, Final Year Project Thesis, School of Mechanical Engineering, Univ. Western Australia, May 31, 2010.
- [62] S. J. Moura, D. S. Callaway, H. K. Fathy, and J. L. Stein, "Tradeoffs between battery energy capacity and stochastic optimal power management in plug-in hybrid electric vehicles," *J. Power Sources*, vol. 195, no. 9, pp. 2979–2988, May 2010.
- [63] C. N. Shiao, C. Samaras, R. Haufler, and J. J. Michalek, "Impact of battery weight and charging patterns on the economic and environmental benefits of plug-in hybrid vehicles," *Energy Policy*, vol. 37, no. 7, pp. 2653–2663, Jul. 2009.
- [64] J. Fenton and R. Hodkinson, *Lightweight Electric/Hybrid Vehicle Design*. Oxford, U.K.: Elsevier, 2000.
- [65] S. Amjad, S. Neelakrishnan, and R. Rudramoorthy, "Review of design considerations and technological challenges for successful development and deployment of plug-in hybrid electric vehicles," *Renew. Sustainable Energy Rev.*, vol. 14, no. 3, pp. 1104–1110, Apr. 2010.
- [66] A. F. Burke, "Batteries and ultracapacitors for electric, hybrid, and fuel cell vehicles," *Proc. IEEE*, vol. 95, no. 4, pp. 806–820, Apr. 2007.
- [67] J. Dixon, "Energy storage for electric vehicles," in *Proc. IEEE ICIT*, 2010, pp. 20–26.
- [68] C. M. Krishna, "Managing battery and supercapacitor resources for real-time sporadic workloads," *IEEE Embedded Syst. Lett.*, vol. 3, no. 1, pp. 32–36, Mar. 2011.
- [69] M. B. Camara, H. Gualous, F. Gustin, A. Berthon, and B. Dakyo, "DC/DC converter design for supercapacitor and battery power management in hybrid vehicle applications—Polynomial control strategy," *IEEE Trans. Ind. Electron.*, vol. 57, no. 2, pp. 587–597, Feb. 2010.
- [70] L. Wang, E. G. Collins, and H. Li, "Optimal design and real time control for energy management in electric vehicles," *IEEE Trans. Veh. Technol.*, vol. 60, no. 4, pp. 1419–1429, May 2011.
- [71] P. H. Mellor, N. Schofield, and D. Howe, "Flywheel and supercapacitor peak power buffer technologies," in *Proc. IEE Semin. Elect., Hybrid Fuel Cell Vehicles (Ref. No. 2000/050)*, 2000, pp. 8/1–8/5.
- [72] J. Van Mierlo, P. Van den Bossche, and G. Maggetto, "Models of energy sources for EV and HEV: Fuel cells, batteries, ultracapacitors, flywheels and engine-generators," *J. Power Sources*, vol. 128, no. 1, pp. 76–89, Mar. 2004.
- [73] B. Szabados and U. Schaible, "Peak power bi-directional transfer from high speed flywheel to electrical regulated bus voltage system: A practical proposal for vehicular technology," *IEEE Trans. Energy Convers.*, vol. 13, no. 1, pp. 34–41, Mar. 1998.
- [74] J. G. Oliveira, J. Abrahamsson, and H. Bernhoff, "Battery discharging power control in a double-wound flywheel system applied to electric vehicles," *J. Emerging Elect. Power Syst.*, vol. 12, no. 1, pp. 1–15, 2011.
- [75] J. Abrahamsson, J. de Santiago, J. G. Oliveira, J. Lundin, and H. Bernhoff, "Prototype of electric driveline with magnetically levitated double wound motor," in *Proc. XIX ICEM*, 2010, pp. 1–5.
- [76] W. A. V. Clark, Y. Huang, S. Withers, Y. H. William, S. W. William, and A. V. Clark, "Does commuting distance matter?: Commuting tolerance and residential change," *Regional Sci. Urban Econ.*, vol. 33, no. 2, pp. 199–221, Mar. 2003.
- [77] V. Helminen and M. Ristimäki, "Relationships between commuting distance, frequency and telework in Finland," *J. Transp. Geography*, vol. 15, no. 5, pp. 331–342, Sep. 2007.
- [78] B. W. Hamilton, "Wasteful commuting again," *J. Political Econ.*, vol. 97, no. 6, pp. 1497–1504, Dec. 1989.
- [79] T. S. Perry, "General Motors on the HY-wire," *IEEE Spectr.*, vol. 41, no. 1, pp. 64–65, Jan. 2004.
- [80] S. Bakker, "The car industry and the blow-out of the hydrogen hype," *Energy Policy*, vol. 38, no. 11, pp. 6540–6544, Nov. 2010.
- [81] P. Fairley, "Good to the last volt," *IEEE Spectr.*, vol. 47, no. 4, p. 16, Apr. 2010.
- [82] A. Mahendra, "Vehicle restrictions in four Latin American cities: Is congestion pricing possible?" *Transp. Rev.: Transnational Transdisciplinary J.*, vol. 28, no. 1, pp. 105–133, 2008.

- [83] A. Brooker, M. Thornton, and J. Rugh, "Technology improvement pathways to cost-effective vehicle electrification," in *Proc. SAE World Congr. Exhib.*, Detroit, MI, Apr. 13–15, 2010.
- [84] T. J. Wallington, M. Grahn, J. E. Anderson, S. A. Mueller, M. I. Willander, and K. Lindgren, "Low-CO<sub>2</sub> electricity and hydrogen: A help or hindrance for electric and hydrogen vehicles?" *Environ. Sci. Technol.*, vol. 44, no. 7, pp. 2702–2708, Apr. 2010.
- [85] D. U. Eberle and D. R. von Helmolt, "Sustainable transportation based on electric vehicle concepts: A brief overview," *Energy Environ. Sci.*, vol. 3, no. 6, pp. 689–699, 2010.
- [86] G. A. Covic, J. T. Boys, M. L. G. Kissin, and H. G. Lu, "A three-phase inductive power transfer system for roadway-powered vehicles," *IEEE Trans. Ind. Electron.*, vol. 54, no. 6, pp. 3370–3378, Dec. 2007.
- [87] O. H. Stielau, G. A. Covic, and C.-S. Wang, "Design considerations for a contactless electric vehicle battery charger," *IEEE Trans. Ind. Electron.*, vol. 52, no. 5, pp. 1308–1314, Oct. 2005.
- [88] G. Elliott, S. Raabe, G. A. Covic, and J. T. Boys, "Multiphase pickups for large lateral tolerance contactless power-transfer systems," *IEEE Trans. Ind. Electron.*, vol. 57, no. 5, pp. 1590–1598, May 2010.
- [89] H. Ayano, K. Yamamoto, N. Hino, and I. Yamato, "Highly efficient contactless electrical energy transmission system," in *Proc. 28th IEEE IECON*, 2002, vol. 2, pp. 1364–1369.
- [90] J. G. Bolger, L. S. Ng, D. B. Turner, and R. I. Wallace, "Testing a prototype inductive power coupling for an electric highway system," in *Proc. 29th IEEE Veh. Technol. Conf.*, 1979, vol. 29, pp. 48–56.
- [91] F. Sato, J. Murakami, T. Suzuki, H. Matsuki, S. Kikuchi, K. Harakawa, H. Osada, and K. Seki, "Contactless energy transmission to mobile loads by CLPS-test driving of an EV with starter batteries," *IEEE Trans. Magn.*, vol. 33, no. 5, pp. 4203–4205, Sep. 1997.
- [92] B. K. Sovacool and R. F. Hirsh, "Beyond batteries: An examination of the benefits and barriers to plug-in hybrid electric vehicles (PHEVs) and a vehicle-to-grid (V2G) transition," *Energy Policy*, vol. 37, no. 3, pp. 1095–1103, Mar. 2009.
- [93] S. Brown, D. Pyke, and P. Steenhof, "Electric vehicles: The role and importance of standards in an emerging market," *Energy Policy*, vol. 38, no. 7, pp. 3797–3806, Jul. 2010.
- [94] C. K. Ekman, "On the synergy between large electric vehicle fleet and high wind penetration—An analysis of the Danish case," *Renew. Energy*, vol. 36, no. 2, pp. 546–553, Feb. 2011.



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