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 resurge 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

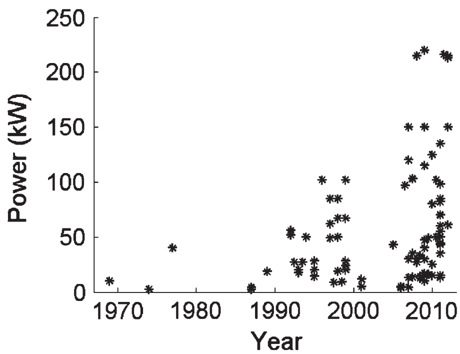

Fig. 1. Power rating of EVs released on the market.

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.

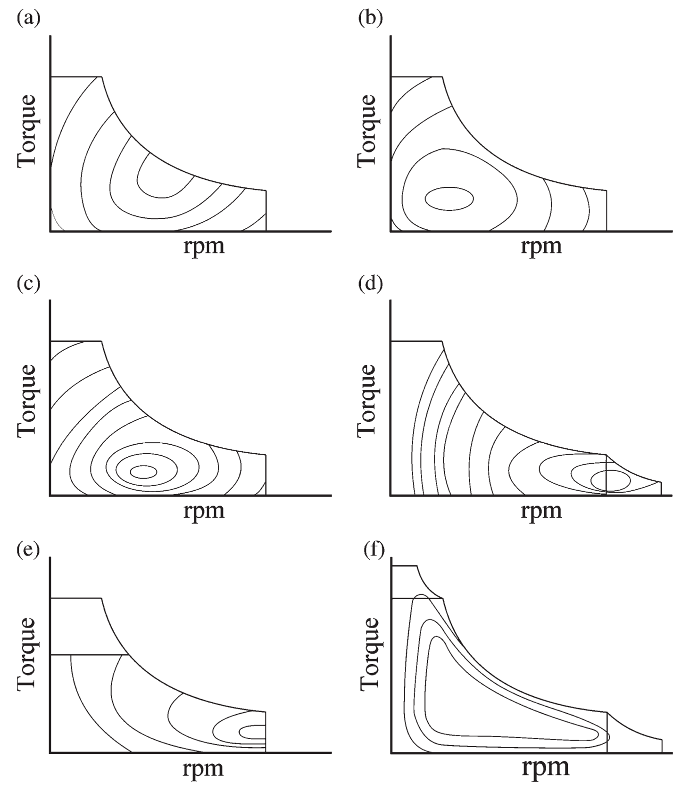

Fig. 2. Efficiency map for (a) surface-mounted PM, (b) internal-mounted PM, (c), IM, (d) RM, (e) DC, and (f) SM motors.

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

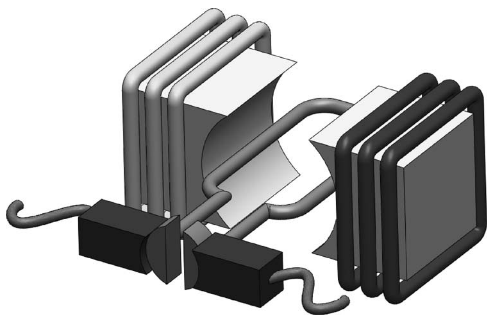

Fig. 3. Schematic representation of a dc motor.

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

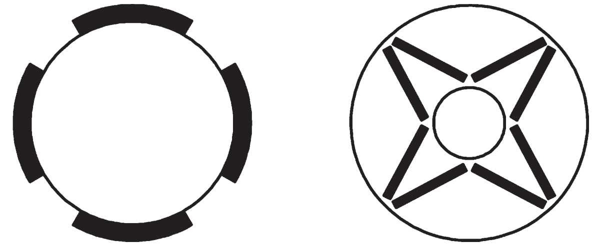

Fig. 4. Radial-flux rotors with surface- and internal-mounted magnets.

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].

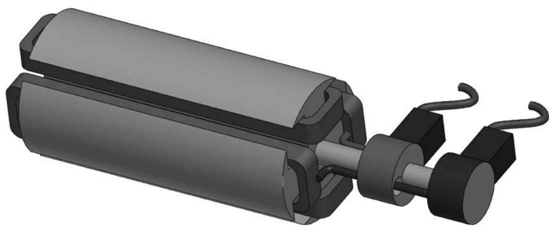

Fig. 5. Schematic representation of an SBM.

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

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

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

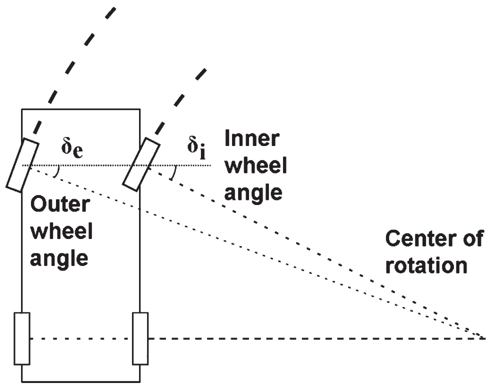

Fig. 6. Different trajectories of the inner and outer wheels under the turning regime.

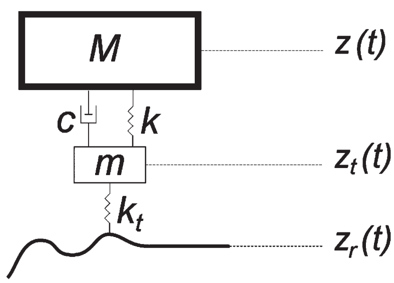

Fig. 7. Simplified vertical quarter-car dynamic model.

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:

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

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

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 clamed 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

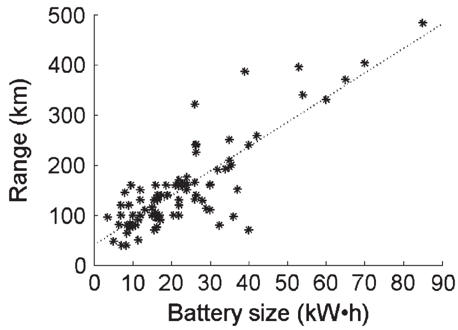

Fig. 8. Battery energy capacity versus range for commercial EVs.

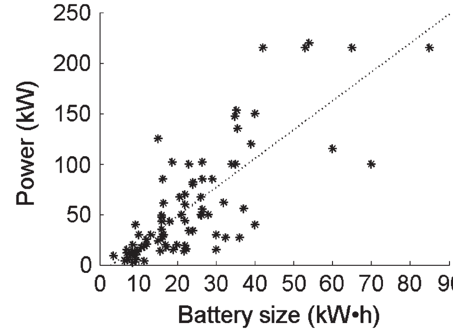

Fig. 9. Battery capacity and motor power for EVs in the market.

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.

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

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: Inductioni 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.

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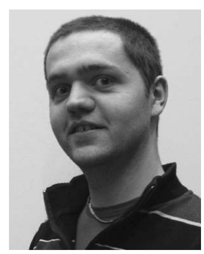

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