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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 in the market mount a single induction or permanent magnet motor with a traditional mechanic driveline with a differential. This study 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 is 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 Electric Vehicle (HEV) driveline topologies have been widely studied as the topology comparison found in [1]. General motor drive studies for EV and HEV have been presented in [2] - [4]. This paper presents an up to date review of EV drivelines based on a survey of commercial EVs. The paper reviews the history of the EV with emphasis on future electric motors. The paper describes the mechanical parts of the driveline in EVs and discusses the advantages and disadvantages of technology trends.

Since the mass production of the Ford T, the automobile industry has been a major driving force in research. Electric vehicles (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 1900's, steam, Internal Combustion (IC) and electric motors had equivalent market penetration. The IC motor had recently been developed. Steam automobiles were dangerous, dirty and expensive to maintain. Electric vehicles had many technical advantages. The short range of EV 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 Hybrid Electric Vehicle (HEV) was developed as early as 1899. Engineers at Porsche had, at this early stage, realized that higher efficiencies 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 60's [7]. The oil crisis in the 70's maintained the interest and founding in the research of EVs. Prototypes developed in this period set the basis of modern electric vehicles. 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-fuelled cars in cities by 2050 [9]. The social concern over IC engines 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 the EVs attractive. Currently all major manufacturers have an EV in their portfolio. Toyota Prius has been the first economic success of a 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 have specific requirements which

distinguish stationary and on board 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 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, 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 worlds nuclear power plants (315 to 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 DC, Induction (IM), synchronous Permanent Magnet (PM) and Synchronous Brushed (SBM) motors already commercially available [18]. A fifth topology, the Reluctance motor (RM), has been proposed due to favorable characteristics but has not yet been released commercially 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 trade-of between performance and life time of the battery. The motor is designed balancing efficiency and light weight. The motor peak power capability is always higher than the system rating.

The power rating of EVs varies from a few kW 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, while 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 spread with different applications.

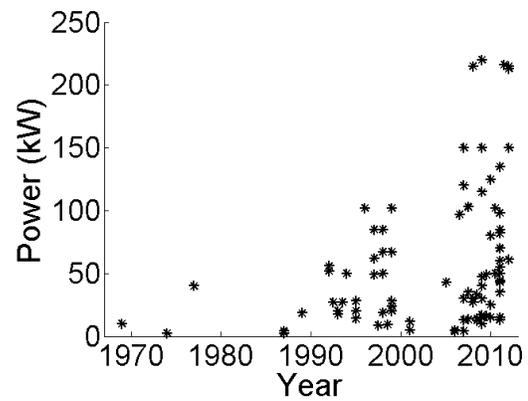


Fig. 1. Power rating of EVs released on the market.

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 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, while RM motors have better performances at high speed overloads. RMs' control allows high speed operation but the efficiency decays rapidly at low speed. SB motors 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 dependant 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 rated voltage. This happens at low State of Charge [23], [24].

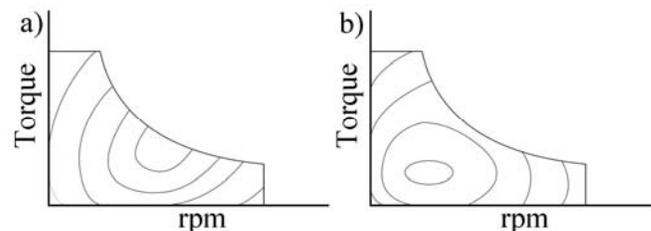


Fig. 2. Efficiency map for (a) surface mounted PM, (b) internal mounted PM, (c), IM, (d) RM, (e) DC, and (f) SM motors.

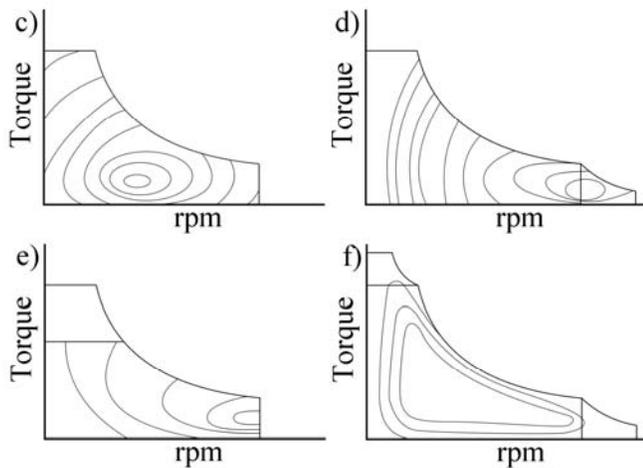


Fig. 2 (Cont.). Efficiency map for (a) surface mounted PM, (b) internal mounted PM, (c), IM, (d) RM, (e) DC, and (f) SM motors.

Below, the major motor topologies are discussed in terms of rotor and stator topology:

Rotor

A. DC motors

DC motors consist of a stator with a stationary field and a wound rotor with a brush commutation system as presented in Fig. 3. The field in the stator is generally induced by coils although small machines may have a permanent magnet 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: the technology is well established, reliability, inexpensive and have a 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 3,000 hours) and low efficiency, although efficiencies 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.

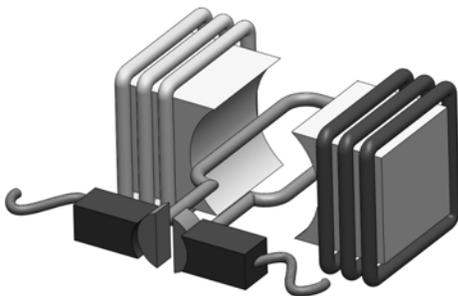


Fig. 3. Schematic representation of a DC motor.

B. Induction

Induction motors (IM), also known as asynchronous motors or squirrel cage motors, main advantage 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 frequency induces rotor currents which produce the motor torque [25].

Induction motors technology is mature and standardized; NEMA in the US and CEMEP in the European Union have a general efficiency classification system. Induction motors are inexpensive, very robust, require little maintenance and are reliable. The International Electrotechnical Commission (IEC) 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. 75% efficiency is considered a good figure of merit for a small variable speed motor [26].

C. Synchronous Permanent Magnet

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

In 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 EMF while Synchronous PM (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 1980's opened up new possibilities for PM motors and they are now being increasingly used in automotive applications. The new PM's 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. Regarding 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, while radial-flux machines may have the magnets either surface mounted or internal mounted as presented in Fig. 4 [27], [31].

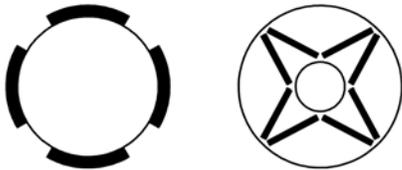


Fig. 4. Radial flux rotors with surface mounted and internal mounted magnets.

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

D. Reluctance

Reluctance Motors (RM) have gained attention due to the concern of price increase or shortage of magnetic material when the electric vehicles enter mass production [16]. RMs main characteristic is the use of rotor salient poles. The torque is produced solely 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 IM while the efficiency remains high over a wide speed range. Efficiencies 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 reluctance motor has not been used in electric vehicles, despite high interest for the good performance reported in literature and successfully demonstrated prototypes [37] - [39].

E. Synchronous brushed

The Synchronous Brushed Motor (SBM) is chosen by Renault for their next middle size 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 a SBM is presented 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 permanent magnet 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 for 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 in DC commutators and are virtually maintenance free.

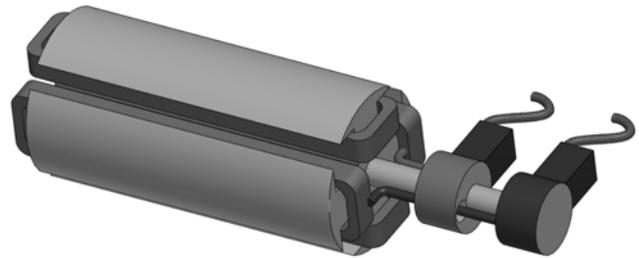


Fig. 5. Schematic representation of a synchronous brushed motor.

Stator

A. Coreless

In coreless machines (CM), the windings are placed in a non-magnetic 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].

B. 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, increase of 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]. The 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.

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 in-wheel motors [48], [49].

C. In wheel

In in-wheel motors (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 reluctance motor configurations [51] - [53].

Efficiency

The efficiency of electric motors is highly dependent on the size and on the working point as shown in Fig. 2. It is not possible to describe the performance of a motor with a single figure. Nevertheless, in order 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 3 times more efficient than IC engines. As a reference, DC drives reaches up to 78% in the range of 40 to 50 kW, and this is the simplest and least efficient technology [19], [24], [40], [43] and [54].

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

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 to a single speed gear reduction and a differential. An alternative configuration is a motor in each wheel. The concept of in-wheel motor has been introduced in order 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 wheel under turning regime are presented 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 induction motors [53], [56]. The torque/slip characteristic of induction motors indicates an instability behavior in the turning regime. The faster wheel would have less slip and therefore less torque and the slower wheel would have higher torque with the risk of loosing its grip.

In-wheel motors have been proposed in concept cars and test vehicles such as the GM's hy-wire platform [57], Mitsubishi's In-wheel motor EV (MIEV) [50] and MIT's concept car [58]. The in-wheel motor presents worse dynamic performance than traditional power trains, especially at high speeds. The in-wheel motor considerably increases the vehicle's unsprung mass. Equations (1) and (2) govern the dynamics of the simplified vertical quarter-car model presented in Fig. 7.

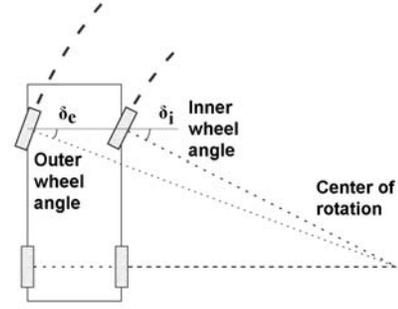


Fig. 6. The different trajectories of the inner and outer wheel under turning regime.

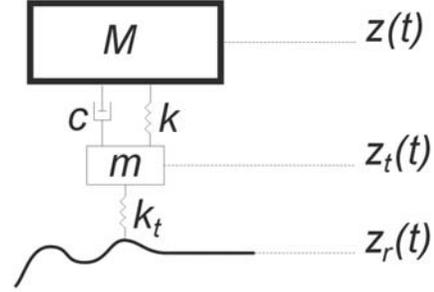


Fig. 7. Simplified vertical quarter-car dynamic model.

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

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

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, also referred as unsprung mass. The solution of equations (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].

In-wheel motors have higher efficiency and lower mass than mechanic drive trains. In-wheel motors have found use in applications where performance is prioritized over comfort such as sport cars and are the unbeatable topology in solar car competitions [62].

IV. BATTERY SELECTION

The battery selection has been studied thoroughly for HEVs and Plug-in Hybrid Electric Vehicles (PHEVs) to find the proper balance between electric drive and IC motor range extender. The size of the battery compromises the mechanical design as well as the cost of the entire vehicle. Economic studies suggest that the optimum battery size corresponds to a

short electric battery range [63], [64].

There are several battery technologies available for EVs [65], [66]. In 1997 Honda claimed to be the first major automaker introducing nickel metal hydride (NMH) 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 [67], [68]:

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	

The chemistry of the battery gives a non linear equivalent circuit behavior. Power transients dramatically reduce life time. 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 life time. Supercapacitors [69] - [71] and Flywheels [72] - [76] are proposed to be used as a power buffers while 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, the 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 is a determinant factor in the customer attitude towards 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 over-dimensioned with respect to the standard commuting distances for 95% of the journeys, both in Europe and in USA [77] - [79].

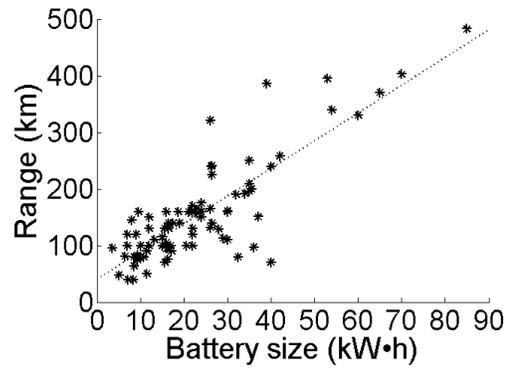


Fig. 8. Battery energy capacity versus range for commercial EVs.

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 2000's was the introduction of hydrogen fuel and the start of pilot programs by main manufacturers [80], [81]. The development of the battery technology, led by the electronic industry, has renewed the interest of full electric vehicles. The market has become more mature with a niche market for zero emission cars [12].

Limited range and the pronounced recharge time are the main technical disadvantages of electric cars compare to 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 drive with a high efficiency hybrid drive. The Extended Range Electric Vehicle (EREV) has full electric drive line with a small auxiliary IC engine which 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 [82].

The pure EV has two market tendencies. On one hand models designed for commuting purposes with low battery weight and short range. These are light weight city vehicles with 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.

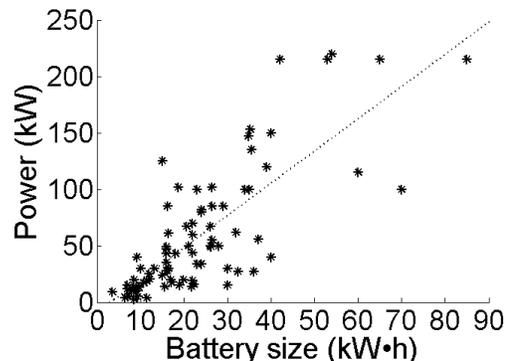


Fig. 9. Battery capacity and motor power for EV in the market.

VI. FUTURE TRENDS IN EV 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 towards zero emission vehicles [83]. 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:

A. Cohabitation of different energy sources

Commuting represents only one third of the driven miles for private drivers [84]. 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 [85], [86]. Electricity and hydrogen fuel stations may coexist.

B. Active roads

Roads with power supply, either with a pantograph or with inductive coupling, as trolleybuses, are proposed [87] - [89]. Contactless electric transmission has an expected efficiency above 90% [90], [91], 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 [91], [92]. The high initial investment requirements have been concluded to be the main drawback.

C. 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 such as:

- The perception of the EV price is reduced.
- It allows replacing the empty battery pack for charged ones instead of recharging. In this way the charge time would be equivalent to filling up the tank in a petrol car.
- 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 [93], [94].

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 [95]. Users may be reluctant to risk their own battery life. However, leasing may be an attractive alternative for both user and utilities.



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.

VII. CONCLUSION

There is a political and market demand towards Electric Vehicles (EV). However, a technical review of EVs in the market shows that technology standards are not set yet. 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. Induction motors 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 IM. The price of raw materials for PM will determine if PM motors will become the standard technology [16] or there will be a market breakthrough of RM and SBM.

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

There is no equivalent Miles per Gallon (MPG) or liters per kilometer (l/kg) 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 kW depends on the State of Charge (SoC). Efficiency decreases with the SoC and the life time 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. In order to make the comparison between EVs possible, the authors propose the adoption of a standardized drive cycle or other standardized methods of efficiency measurement.

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

APPENDIX

Table III shows a survey on EVs on the market. The data has 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.

TABLE III. DATA OF THE MOST REPRESENTATIVE EVs MODELS IN THE MARKET.

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

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generators.

Prof. Leijon received the Chalmers award *John Ericsson Medal* in 1984, the *Porjus International Hydro Power Prize* in 1998, the *Royal University of Technology Grand Prize* in 1998, the *Finnish Academy of Science Walter Alstrom Prize* in 1999, and the 2000 *Chalmers Gustav Dahlen Medal*. He has also received the *Grand Energy Prize* in Sweden and the *Polhem Prize* and the *Thureus Prize*. He is a Member of the *Institution of Electrical Engineers (IEE)*, *World Energy Council (WEC)*, the *International Council on Large Electric Systems—Cigre*, and the *Swedish Royal Academy of Engineering Science*.