Inductive Automatic Charging: The Way to Safe, Efficient and User-Friendly Electric Vehicle Infrastructure

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Abstract

The EVIAC ("Electric Vehicle Inductive Automatic Charging") research project, supported by the European Union, has been aimed to fix the optimising friendliness of inductive charging systems with automatic connection (i.e. without driver intervention apart from parking the vehicle).
The comparative assessment of several distinct technological solutions for automatic inductive charging has allowed to realise an application-oriented approach of these issues.
The paper presents the various aspects of these systems, highlighting issues such as energy consumption, operational characteristics and electromagnetical compatibility. A particular interest will be devoted to the trade-off between a number of aspects and design goals (energy efficiency, user friendliness, …) which will lead to the optimisation of design in function of the application needs.
The paper also focuses the different aspects related with standardisation and regulation of this type of technology.
EVIAC made clear that inductive charging technology has got the potential to be developed into a product which is both safe, technically reliable and economically feasible. It allows the presentation of a global overview of current European research into inductive charging technology and its potential to open up the market for electric vehicles to a number of application domains where the current manual connection systems are presenting too much constraints.

Keywords: inductive charger, infrastructure, battery charge,EU

1 Introduction

Most present day charging infrastructure for electric vehicles use conductive connection of the vehicle which implies the need for driver intervention and the use of a galvanic connection with cord or cable and plug.
Three main directions have been investigated:

- normal charging from the AC grid
- fast charging from the AC grid
- fast charging with an external charger.

These three methods are certainly adequate for the needs of the privately owned vehicle which can thus be charged on the street and at home with the same onboard charger.
For systems like automatic-rent-a-car systems, where the charging process must be totally transparent to the user for reasons of safety and user-friendliness, however, these conductive systems show some drawbacks.
In these, and other similar cases, it is necessary to develop means of charging that need no driver intervention, and are working on inductive transfer mode of energy i.e. without galvanic connection.
Electric and hybrid electric taxis or buses can equally benefit from such systems as the vehicles can be automatically charged during the waiting periods.
The systems developed may also be a precursor for urban charging systems of all types of vehicles, including the private car, freight transport vehicles and buses.
Hybrid vehicles, in so far they need to recharge separately their batteries, are also potential users of automatic charging units.

Finally, in the industrial and goods distribution worlds electric forklifts using automatic chargers could recharge their batteries on a safer way.
The objective of the EVIAC research programme is to develop the technology necessary for totally automatic inductive charging systems or stations and the associated controls required to optimise the energy usage.

2 Inductive charging systems on the market

Inductive charging systems rely on inductive power transfer through more or less loosely coupled inductors. The present market of inductive charging system shows two approaches which have led to industrial developments. None of these two however fully meets the specifications of the fully automatic charging system.

- ♦ Systems using mains frequency (50 Hz)
  50 Hz inductive chargers are available for industrial vehicle applications.
  These devices have several interesting operational aspects (energy efficiency up to 90 %, high tolerances on alignment) but are characterised by a large size and weight (about 25 kg per inductor for a 3 kW unit) which compromises their installation on lighter road vehicles.
- ♦ Systems using high frequencies are offered on the market in Japan and in the USA for power ranges up to 120 kW.
  These offer exceptional power transfer capability in a small and light unit, but a plug in operation is still needed which cannot be easily automated and a connection cable is still existing.

3 Classification of the Inductive Couplers

The inductive couplers considered can be characterized in different ways in the family of inductive couplers.
The operating frequency and the coupling mechanism are the most important basic factors that will affect the overall system design and performances.

Based on the frequency, three subfamilies can be defined:

- **Low frequency** 50/60 Hz, which are the typical mains frequencies.
- **Medium Frequency** 400 Hz, which is the classical aircraft electric power frequency.
- **High Frequency** >20 kHz, which can be supplied by switched-mode inverters.

Based on the mechanical way of coupling the ground inductor and the vehicle inductor, the inductive couplers can be classified into three types:

- **Insertion type**: The ground inductor is hand inserted into a port which houses the vehicle inductor; this is mainly developed in USA and Japan.
- **Proximity type**: The ground inductor and the vehicle inductors are coupled by properly positioning the vehicle, without the help of hands nor the help of servo actuators.
- **Chained-Ring type:** The ground inductor and the vehicle inductor are linked to each other, after positioning properly the vehicle, with the help of an actuator.

4 Acceptability of equipment from the city's point of view

In order to define the needs and constraints of the city fleet users, and to fix the optimising friendliness of usage and energy management of the considered transport systems using electric vehicles, the opinion of

CITELEC member cities has been evaluated through a questionnaire (47 % of them have given a response). This questionnaire deals with the following types of charging equipment:

- conventional conductive
- inductive charging using a high-frequency inductive connector and cable
- special charging posts (n° 1 on fig. 1.)
- fixed devices, flush with road surface (n°2 on fig. 1.)
- fixed devices, not flush with road surface (n°3 on fig. 1.)
- devices on road surface which include moving parts (n°4 on fig. 1.)
- special kerb designs (n°5 on fig. 1 .)

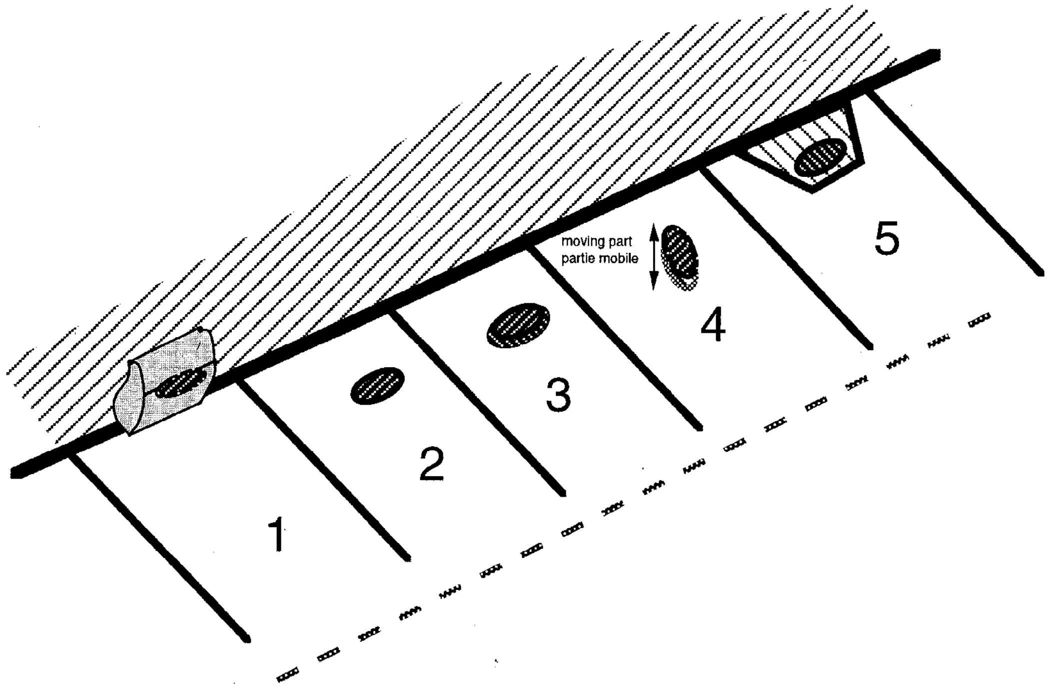


Figure 1 : Inductive charging configurations
Ground side

The acceptability of equipments depends on whether the parking places for electric vehicles are located off the public highway or on the public thoroughfare.
Charging infrastructure is more tolerable off-highway than on the street. Cable-bearing devices as well as systems with moving or protruding parts are less desirable than the other three types of charging equipment.
There is a strong desirability of charging devices that **cause the smallest interference with existing road infrastructure.** That is the reason why the fixed devices, flush with the road surface is the most appreciated, followed by the special kerb designs and the special charging posts. Systems that involve the use of cables are much less appreciated.

5 Technical options adopted

Several types of inductive couplers are considered, according to specific requirements of the application.

5.1 Charger with passive mechanical alignment

The problem of inductive recharging is how to set up a situation in which the inductive transmitter and receiver are facing one another. When parking takes place without mechanical guidance, the positioning of the vehicle is uncertain. There is no guarantee that the receiver and the transmitter are opposite one another. The mechanical system will therefore need to compensate for the uncertain positioning, by offering a degree of latitude in final adjustment.
The automated induction recharging system developed by Electricité de France's Research Department has been designed for incorporation into a Renault Clio electric vehicle.
Figure 2 shows some Renault Clio belonging to the fleet demonstrated at St-Quentin-en-Yvelines.

Figure 2 : Ground side mobile component and guidance block

The work with Renault covered the incorporation of the charging system into the Clio, in all its mechanical and electrical aspects.
Two alternative solutions belonging to the proximity type were possible for the prototype mechanism :

- either fixed component on ground, and mobile component on underside of car,
- or mobile component on ground, and fixed component on underside of car.

The second solution was agreed for the implementation as realised in St-Quentin-en-Yvelines.

The alignment mechanism comprises:

- ground mobile component integrated into the guidance block,
- underbody fixed component (guidance plate, guidance skid and inductive receiver).

This mechanism ensures the precise alignment of the inductive transmitter to the receiver fixed on to the vehicle underbody.

The vehicle is a RENAULT passenger vehicle, the electric Clio,. fitted with a 114 V battery, and an on-board charger, which under normal circumstances is connected to the 230 V alternating current network for recharging purposes. This equipment uses the battery load curve to manage the whole charging procedure.
The Clio's on-board charger was not modified for this application. It can therefore operate either on the 230V single phase network, or as an output from the inductive coupler. When the charger operates with

the voltage from the inductive coupler, the rectifier at the input stage of the charger is shunted. The inductive coupler has therefore been designed to give an output voltage equivalent to the rectified 230V. Figure 3 presents the overall architecture of vehicle battery recharging, when operating on the output from the inductive coupler.

The on-board computer manages remote recharging for a vehicle fleet.

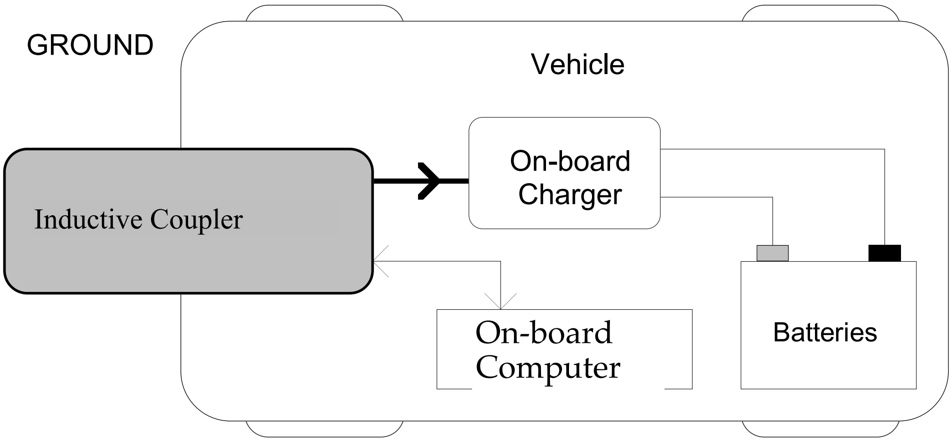


Figure 3 : Functional interface of recharging equipment with vehicle

5.2 Asymmetrical charger

The main reason for considering this structure is to get simultaneously good coupling quality and a structure allowing easily automatic positioning. The structure is shown in figure 4. It belongs to the chained-ring type family.

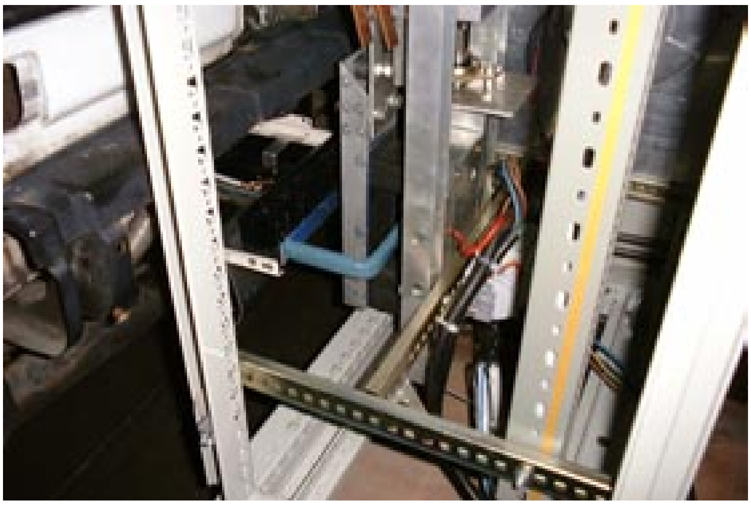


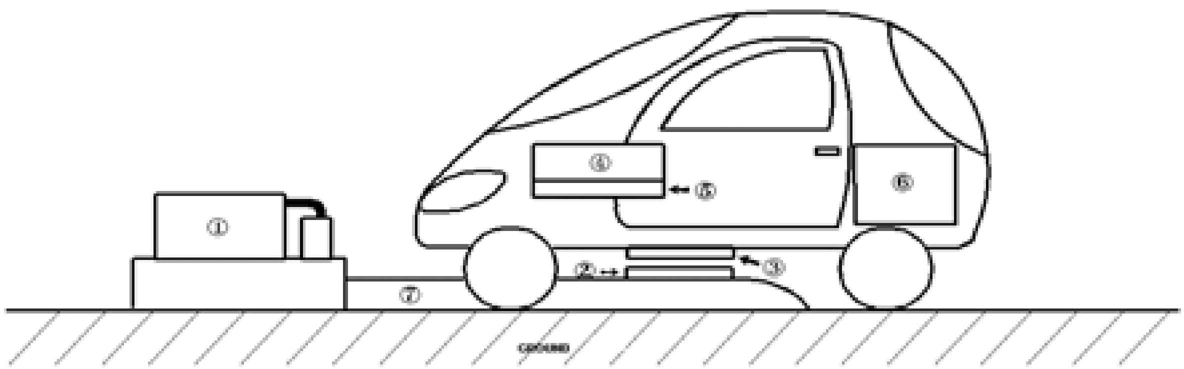
Figure 4 : Ground casing (underpart)
Moving core in “closed” position

The core is composed of two parts, a fixed part and a movable part. The movement can be a rotation or a translation. The last one has been chosen. The primary winding is closely wound on the fixed part of the core. The secondary winding forms a movable ring (the copper ring). The ring can be mounted on the vehicle integrated in the bumper or protected by the bumper. When the copper ring is chained to the core, the two parts of the core form a ring too (iron ring). When the copper ring is moved away the iron ring is open and its moving part is in the position ready to be chained again.

5.3 Asymmetrical large air-gap charger

The third system developed is an experimental high frequency high tolerance asymmetrical system belonging to the proximity type family.

This system uses a coil that can be imbedded in the roadway. It is therefore totally non obtrusive. The reception coils are larger than the transmission coils and accept very large parking errors without resorting to mechanical alignment, from there results the so-called asymmetrical characteristic. This system is particularly well adapted to roadside parallel parking.



① Outboard charger: primary system ② Primary coil: inductor ③ Secondary coil
④ & ⑤ Onboard charger: secondary system ⑥ Battery ⑦ Wheels guide sidewalk

Figure 5 : Large air-gap charger

Figure 5 shows the distribution of the different components taking part in the charging function. Figure 6 shows a TULIP prototype car parked at its charging station.

Figure 6 : External outlook

The communication between the primary system and the secondary system is realised by a transistor in the onboard charger which short-circuited the resonant circuit, so the power transmission. The primary system detected this power's variation and switches his current's orders.
The efficiency of this system is constant when the air gap varies from 30 to 60 mm.
We have proven in this European project that the asymmetrical large air gap inductive charging system used in the TULIP program is reliable and efficient.

5.4 Alternative Medium-Frequency coupling system

The fourth system developed is an intermediate-frequency (400 Hz) system.
This system retains some interesting features of the mains-frequency systems while considerably reducing weight and size. It can be integrated with 400 Hz generating equipment which is an industry standard.

The inductive coupler is based on a conical shape to allow for the docking accuracy along the vertical and horizontal axes as shown in figure 7.

The coupler is excited by a load resonant converter operating in the frequency range of 400 to 600 Hz. The conical shape also offers the possibilities of minimising the magnetising current through the choice the cone angle.

Control loop

For the control loop a communication system s necessary between the car, i.e. the battery, and the ground structure, i.e. the primary coil and the associated resonant converter performing the power conversion from the AC mains; this structure is similar for all types of inductive charger.
This can be realised by an IR or RF communication link.

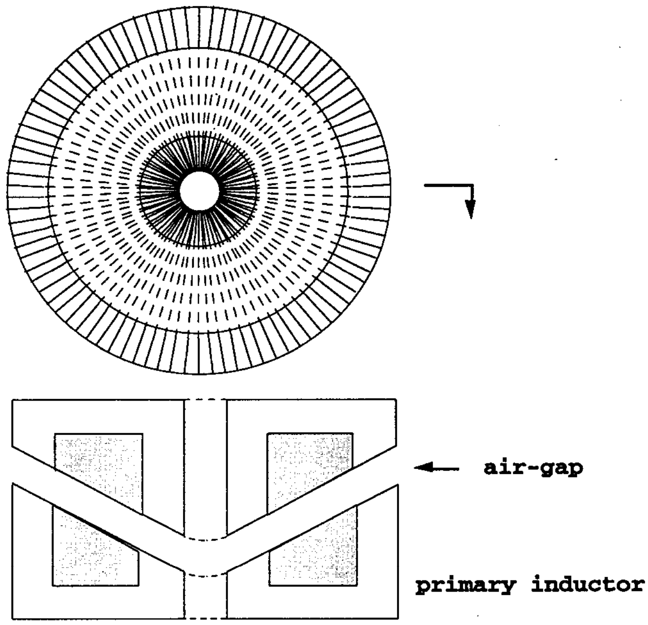


Figure 7 : Structure of the 400 Hz pot-core coupler

Figure 9 shows the principle structure of the control loop.

- A board computer can control the charging procedure of the battery.In this case the secondary voltage and current are measured and sent to the base station by RS232 and handled on an adhoc way.
- In an other structure, a voltage and current measuring PCB with microcontoller and RF link is foreseen in order to allow testing the charger system as a stand alone system.

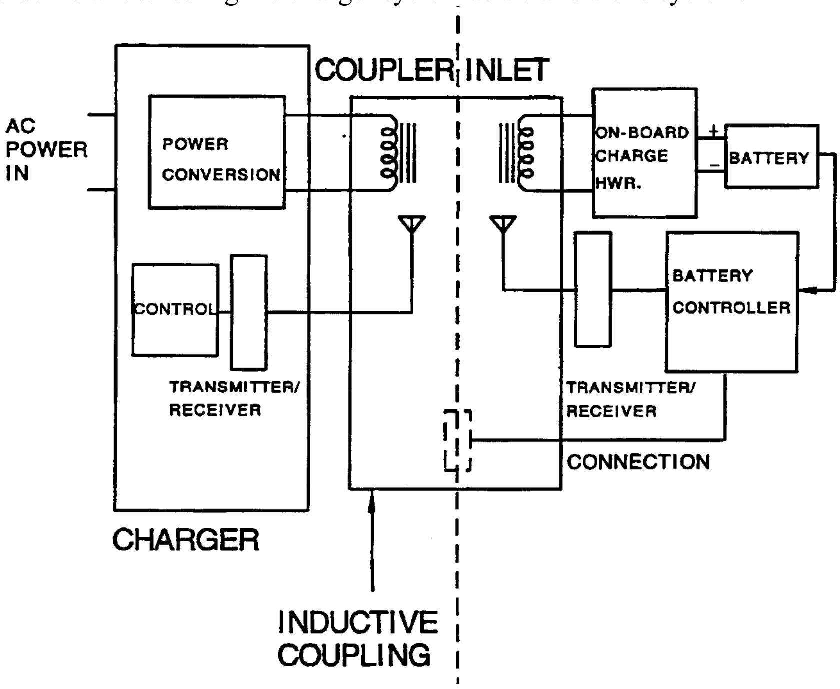


Figure 9 : General aspect of inductive charging system

6 Comparison between the different types

6.1 Positioning and alignment requirements.

Compared to the other types of couplers, the insertion type needs a strict alignment of the inductors onboard the vehicle. It lends itself difficulty to an automatic positioning by an auxiliary device and needs to be inserted manually. Because the ground inductor is connected to the ground station with a flexible cable and hand-inserted into the vehicle inductor, there is no special requirement for the vehicle positioning.

The disc-shaped proximity type coupler tolerates some millimetres misalignment between the inductors. However, because the alignment of the coupler is done by drive-on, the requirement for the vehicle positioning is strict. The vehicle must be guided and blocked by auxiliary devices.

The chained-ring type coupler tolerates much more misalignment between the inductors. More important, there can be a flexible compromise between the coupling parameters and the margin of misalignment. The vehicle positioning margin can be designed to fit the statistical vehicle positioning behaviour (refer to [3] for detail). To avoid failure and damaging hit, simple measure should be taken to help the vehicle positioning. The coupling of the inductors is no more accomplished by a single drive-on movement like what happens with the proximity type. It is a two-stage movement: first the vehicle is positioned and then the vehicle inductor is chained to the iron-ring by a rotating actuator.

The positioning and alignment characteristics of different types of coupler are summarised in table-I.

Table-I : Summary of the positioning requirements

type	vehicle positioning	inductor alignment
insertion	tolerant	strict, manually,
proximity	strict, auxiliary help,	medium tolerant hand free
chained-ring	medium tolerant auxiliary help	tolerant, actuator hand free

6.2 Performances

High frequency inductive couplers are working in conjunction with electronic power converters. The performances of the whole system should be evaluated at the end-to-end scale. But some of the system performances are inherently determined (or limited) by the inductive couplers.
The system power efficiency is influenced by each stage of the system. The inductive coupler, besides its own losses causes some losses elsewhere in the system. The magnetising current, for instance, contributes for a part of the reactive power in the resonant loop which causes power losses (refer to [8] for detail).
The insertion type coupler produces the lowest losses within itself because of the compact structure and shows the lowest magnetising power because of the highest coupling coefficient.
The disc -shaped proximity type coupler produces higher copper losses because of the spreading of its windings and needs higher magnetising power because of its lower coupling coefficient.
The chained-ring type coupler produces higher losses in the secondary winding and the core because of the length of respectively copper or magnetic loops but needs medium magnetising power because of its coupling characteristics.
The power transfer capacity is inherently limited by the inductive coupler. But there is no clear cut relation between the parameters and the peak power that the coupler can transfer. The system design is a compromise within the design space determined by the components, and operational parameters and

constrained by various specifications. Generally speaking, when the coupling quality is becoming worse, the design space is shrinking. The decreased peak power capacity is one of the results of the compromise within the shrunken design space.
The power capacity of the three types, resulting from the possible values of their parameters, can be relatively classified as high 100 Kw), medium to high and low (5 Kw) for the insertion, chained-ring and proximity types respectively. The disc-shaped proximity type differs from the other types by the dependence of the coupling quality on the volt per turn (V/T) value. For example, a single turn secondary winding is possible for the insertion and chained-ring types, but not for the proximity type.
Efficiency is rather high as can be stated by the 94% measured for chained-ring type.
Thermal constraints can play a key role which limits the power capacity of the inductive couplers. The insertion type, because of the most compact structure, has the worst natural cooling condition. The chained-ring type, on the contrary, has the best natural cooling condition because of its loosely structure.
Regarding the EMC, the situation is just opposite to the thermal condition. The structure of the insertion type is compact and magnetically closed, thus the EMC is the easiest to be controlled. The structure of the chained-ring type is loosely and magnetically exposed, thus the EMC requires more attention to be controlled.
The performances of different types of coupler are listed in table-II for a quick comparison.

Table-II : Summary of the performances of the inductive couplers

type	**power rate**	**power efficiency**	**thermal condition**	**EMC**
insertion	high	high	bad	good
proximity	low	medium	medium	medium
chained-ring	medium to high	medium to high	good	bad to medium

7 Overview of industrial applications for the EVIAC systems

7.1 Automatic rent-a-car systems

Automatic rent-a-car systems feature frequent usage of electric vehicles by a large number of users, with the application of opportunity charging. Each vehicle may know a large number of rides, with charging connection in between, during one day. This requires the system to present following features:

- Total transparency to the user: maximum user friendliness, minimal actions to be performed by the driver.
- Full safety, taking into account that the average user is a non-specialist person.

The automatic inductive charging systems are perfectly suited for this field of application; one of the systems developed in the framework of EVIAC has in fact been successfully deployed in an experimental rent-a-car fleet in St-Quentin-en-Yvelines, France. On an European scale, the potential for such vehicles in major cities will be between 2000 and 20000 per city.

7.2 Taxi fleets

The viability of the use of battery-electric vehicles for taxi services can equally benefit from automatic inductive systems as the vehicles can be automatically charged during the waiting periods at taxi ranks. The possibility to perform opportunity charging is in fact essential for a taxi service, where the available range is to be optimally exploited.

7.3 Distribution fleets

The battery-electric vehicle is very well suited for deployment on mail or goods distribution routes in urban areas. European demonstration programmes like EVD-Post or ELCIDIS have successfully illustrated this fact. However, the practical tests have shown that transparency and user-friendliness of charging procedures are significant for project success; the introduction of the EVIAC systems will offer interesting opportunities.

7.4 Individual vehicles

Public charging stations fitted with automatic inductive systems can also be made accessible to private electric vehicle users. This opportunity will be largely dependent on the integration of the inductive inlet into the vehicle and the possibility of inductive connectors (i.e. the fixed primary part of the inductive coupler) to accommodate several types of vehicle.

7.5 Hybrid vehicles

The hybrid vehicle makes use of different energy sources and one could state that it thus has less need, if at all, to access charging stations. It has to be said however that the supply of electric energy to the vehicle will in most cases present a lower impact on the environment and on primary energy usage, and also a lower energy cost than the supply of fuel to the vehicle. The ability of hybrid vehicles to access the automatic inductive charging stations to charge their batteries thus offers interesting opportunities. The great market potential of the hybrid vehicle (which can in fact displace all conventional vehicles) significantly enhances the use potential of the EVIAC technologies.

7.6 Industrial vehicles

The largest number of battery-electric vehicles in the world are found in industrial environments: forklift trucks, personnel carriers, utility trucks, AGV (automatic guided vehicles), etc… The heavy industrial use of these vehicles often dictates the use of opportunity charging. The deployment of automatic inductive systems will greatly increase safety and efficiency in these applications. This is particularly the case for AGVs, which can charge autonomously without the need for operator intervention to plug in the cable. The market for industrial electric vehicles is very extensive. European market leaders in the field, such as Jungheinrich or Linde, deliver over 200.000 electric motors destined to the electric vehicle market.
A particularly interesting niche application for inductive systems are industrial electric vehicles operating in hazardous or environmentally demanding conditions (sea-side applications, airports, flammable or explosive environments).

7.7 Marine applications

Electric propulsion for marine applications is gaining popularity all over Europe, as there is now a growing demand for clean and energy-efficient solution for marine propulsion systems, considering that the concern for the preservation of sensitive marine environments, both freshwater and saltwater, is becoming significant. Electric vessels can make major contributions towards achieving key EU objectives aimed at energy savings, a reduction of CO_2 emissions and other pollutants, the diversification of energy supply, and an overall sustainable development. The marine propulsion is an effective niche market where the electric propulsion systems offer efficient, reliable and cost-effective solutions.
Inductive charging systems are particularly interesting for such applications, where their excellent safety properties will be highlighted through the elimination of cable-shore connections for charging. One example of inductively charged vessel has been commissionned in La Rochelle, France.

8 Conclusions

Introducing a user-friendly charging system for EV/HEV reduces the resistance of the citizen to accept it and helps introcuding in the city ZEV systems able to reduce the number of vehicles in the city and to improve the mobility.
Inductive charging system can become a key element of charging infrastructure in the cities.
Automatic-Rent-a-Car systems are an intermediate step between classic public transportation system and private cars. It is an extension of public transport that splits the latter into possibilities for local trips not coverable by public means.
It should be financed in the same way public transportation systems are financed.
With respect to costs: the maintenance costs are very similar to the costs of classic electric material; the energy costs are related to the benefit (more or less 50%) connected with the introduction of EV's.
For all other applications - buses, taxis, fleets – the infrastructure is very similar to parking meters infrastructure i.e. with similar investments and maintenance costs.
The environmental advantages of inductive charging systems are strongly related with the advantages of introducing electric and hybrid transport systems in cities.
They do not introduce particular urban problems considering the easy integration they allow.
The choice of the exact inductive technology to be selected will be mostly dependent on the particular requirements of each system application.

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