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HUMAN-INDUCTIVELY POWERED LIGHTWEIGHT ELECTRIC VEHICLES: SUSTAINABLE TRANSPORTATION FOR THE SMART CITY

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ABSTRACT

An increasing interest in inductive lanes for dynamic wireless power transfer, as a mean of on-the-road charging of electric vehicles, has been observed in recent times. Most of current related research and development efforts have so far been guided by the presumption of a future large-scale adoption of electric vehicle types whose payload and power train characteristics are compatible with the standard internal combustion engine vehicles they are supposed to replace in the coming years. The quest for energy conservation and more sustainable personal transportation, however, opens new possibilities for hybrid human-powered lightweight electric vehicles, such as e-bikes, electric rickshaws and similar lower mass, lower power and lower speed vehicles. These vehicles, when combined with dynamic inductive wireless power transfer lanes are predicted to deliver unprecedented transportation services at low granularity, constituting an alternative to heavier personal cars and even to public transports in some contexts. To allow this modal shift, some urban policies must be implemented, and new architectural guidelines should be adopted to include the inductive electrification of lightweight vehicle lanes. The expected result is a better conservation of energy and the promotion of a safer and healthier lifestyle in the cities of tomorrow.

INTRODUCTION

Until the industrial era, land transportation was entirely restricted to walking, horse riding, horse-powered and other animal-powered vehicles. Ancient cities, even the largest ones, survived, expanded and developed in reasonably sustainable manners for centuries, relying only on these transportation modes for fulfilling their needs for terrestrial displacement of people and goods.

After the introduction of the steam locomotive, in 1804 (Gibbs 2012), and specially, since the middle of the 19th century, railroads started to be increasingly adopted, progressively replacing horse-powered vehicles in long-distance terrestrial transportation tasks (Bogart, Shaw-taylor, and You 2018). However, due to the difficulties and high costs of laying the rail tracks over occupied urban spaces, steam locomotives and railways better served to provide intercity connection or suburban expansion, being somewhat limited to provide intraurban transport. Consequently, the railroads still left plenty of room for the traditional “legged” transport within the cities and their neighborhoods.

The situation changed significantly only when motorized road vehicles (cars), of electric propulsion and thermal engine types, came into scene in the last decade of the 19th century. That happened just a few years after new designs of safety bicycles were introduced – noticeably, the Rover bike, by John K. Starley, in 1885 - that became very popular (Herlihy 2004). The acceptance of both bicycles and motorized vehicles for personal transportation was immediate, because they could replace the horses with advantages, while still using the same roads and streets built for the horse carriages and people.

Along the 20th century, cars became more accessible to the population, establishing a clear dominance over bikes in the cities, as the personal transportation of choice. Bikes and cars, however, continued to coexist in the cities since their introduction. In Figure 1, it is shown that bikes (green bars) still sell more in Europe than cars (yellow bars), with an almost constant yearly demand of 20 million units, over the last 12 years. These numbers were not much affected by economic crisis or other contingences, while cars experienced a decrease in its sales from 2007 to 2013, slowly recovered from 2014 on. So, after about 130 years after its introduction in the market, the interest of the population in bicycles is still pronouncedly high.

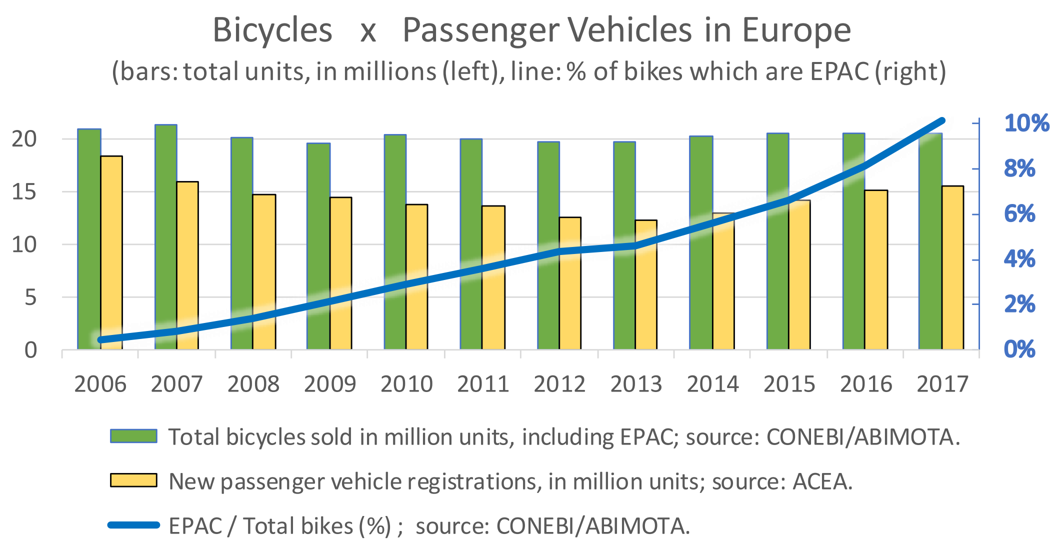

Figure 1: Evolution of Electrically Power Assisted Cycles (EPAC) in the European bicycle market.

Another phenomenon that can also be highlighted is the electrification of bikes. The participation of Electrically Power Assisted Cycles (EPAC) in the market has been increasing year by year (blue line in Figure 1), to a 10.1% of the total bike sales in 2017 (Confederation of the European Bicycle Industry (CONEBI) 2017, 2018). This fact seems to be consistent with an increasing number of people in Europe trying to intensively use bicycles for personal transportation, rather than for recreational activities.

Because electric bikes are inexpensive and much cheaper than heavier electric cars, it can be inferred that their availability will grow until the major part of the bike production will be of EPAC type, and this is likely to happen much earlier than the large-scale adhesion to full size electric vehicles (EV).

While yielding more flexible transportation services and convenience, cars greatly contributed to the degradation of the former and healthier lifestyle in cities, by strongly reducing the habits of walking. So, is it possible to take advantage of the spontaneous bike electrification market, to improve transports and rescue the quality of life in the cities? Can the electrically assisted bike become the mechanical horse of the future, while retaining the health benefits of exercising?

The combination of EPAC, and other lightweight human-powered similar EV, with the ongoing development of the dynamic inductive wireless power transfer (DIWPT) technology is believed to raise the popularity of bikes and other human-powered velomobiles to unprecedent levels, higher than those of horse and horse carriages, back in the 19th century. This sustainable mobility approach, if adopted along with safeguard policies and new urban architecture guidelines, will likely reduce the demand, in urban areas, for heavier, higher power motorized cars, either electric or with fuel-based engines, thus contributing to the humanization and safety of the traffic in the cities.

DYNAMIC INDUCTIVE WIRELESS POWER TRANSFER

Since the first models, electric cars have conquered a great admiration from the public, due to their superlative qualities over their thermal engine counterparts: they are cleaner, more silent and easier to operate and maintain. However, after almost a decade of great expansion of the electrics, their relatively higher cost and lower range, comparatively to thermic engine cars, made their market restricted to specialized niches, until the last decade of the 20th century, when the commercial availability of the new, higher energy density, lithium ion batteries caused a resurgence of electric vehicle designs for general personal transportation.

Apparently, the battery is still a great limiting factor affecting both the initial and the lifecycle costs, as well as the operation range of the EV, in this case due to an energy density more than one order of magnitude lower than Diesel fuel or gasoline. Along its more than a century of existence, electric mobility only consistently prospered in applications where the battery requirements were diminished, such as trains and trams, that harvest energy by galvanic contact from tracks or catenaries that are laid along their paths. But the difficulty in building and expanding complex networks of tracks and catenaries in urban environments has prevented the adoption of this electrification technology for personal electric mobility, leaving it virtually only for mass transportation.

In the 1990's, wireless power transfer, once envisioned by Nikola Tesla, restarted to be experimented and used for industrial applications (Boys and Covic 2015). Soon, this technology started to be investigated to build inductive lanes that could dynamically and wirelessly transfer power to moving vehicles, as a mean of on-the-road battery charging. The most immediate benefit is to increase the EV's autonomy and, at the same time, allow the reduction of the capacity of its battery. This technology, when perfected, is expected to behave functionally similar to the traditional electrification by

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tracks or catenaries, but with many advantages over these "wired" schemes. Its principle of operation is illustrated in Figure 2, extracted from (Cardoso et al. 2017). As an electric vehicle moves forward along its path, its onboard pick-up (secondary) coil will sequentially cross the magnetic field generated by the stationary primary coils placed underneath the vehicle's pathway. An activation schema for the primary coils must be provided to guarantee the energization of only that coils which have an EV in the reach of their near field, ready to harvest from their oscillating magnetic field, commonly in the LF band (30 kHz to 300 kHz).

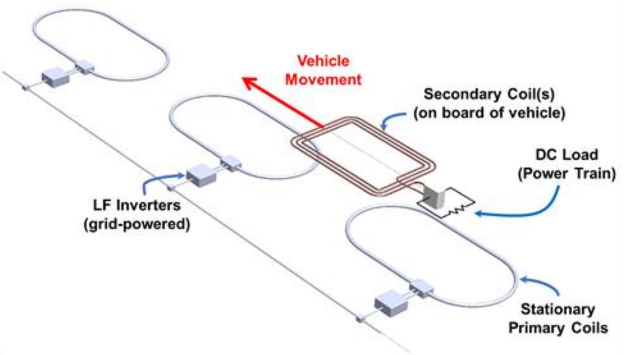


Figure 2: The principle of dynamic inductive wireless power transfer.

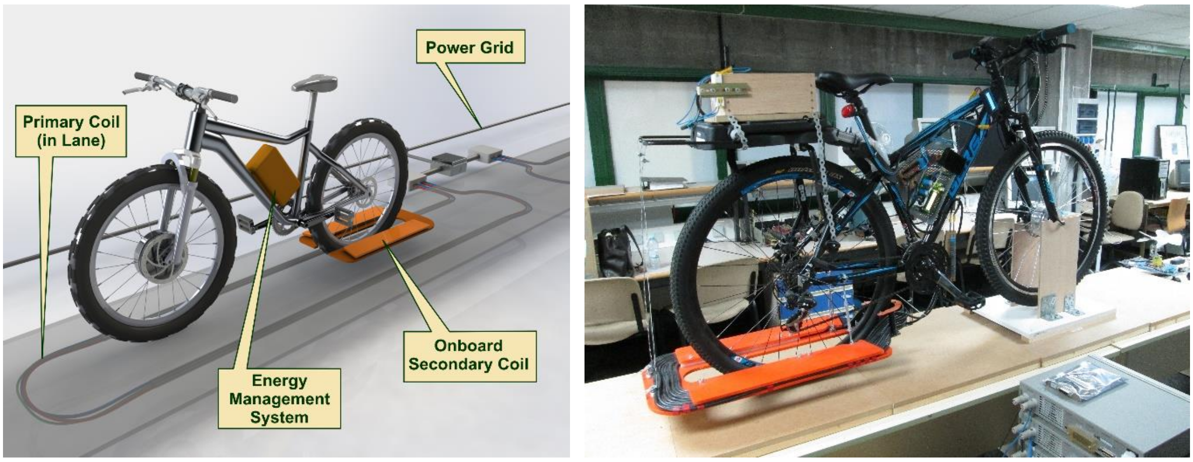
Most of the research and development efforts (Mi et al. 2016) (Song et al. 2016) related to dynamic wireless power transfer, either explicitly or implicitly presume: (i) the future large-scale adoption of EV types whose payload and power train characteristics are compatible with the standard internal combustion engine vehicles they are supposed to replace in the coming years, and (ii) the electrification of existing roads by retrofitting them with such inductive lanes. This would require a tremendous effort in routing the grid and dispatching large amounts of electricity on the roads, as each modern electric passenger car can easily consume 20 kW to 100 kW.

WIRELESS ELECTRIFICATION OF LIGHTWEIGHT ELECTRIC VEHICLES

The current best prototype implementations of DIWPT lanes and vehicle adaptions have demonstrated the capability of handling power levels that are enough to drive some electric versions of standard thermal engine vehicles, up to 20 kW (Laporte et al. 2018). But this is achieved at the expense of a large bill of materials and components per kilometer, what may impair the economic feasibility and even the large-scale sustainability of these designs.

The power demand of a lightweight electric vehicle (LEV) may be 10 to 100 times less than that of standard heavier vehicles, depending on the class of LEV that is being considered. Using DIWPT with lightweight, low power vehicles, will then require much less costly hardware to be deployed on the lane side, making it a more economically feasible implementation. This would also greatly simplify the grid connection of these low power electric lanes, favoring the fast adaptation of existing e-bike lanes and construction of new ones.

As of now, no urban wirelessly electrified lane for LEV is known to have been commercially deployed but the concept has been successfully prototyped for standard two-wheeled EPAC bikes, at continuous nominal electric peak power demand of 400 W (Cardoso et al. 2016). Figure 3 shows the representation of this system (a) and a photo of the implemented prototype (b).



(a) (b)

Figure 3: (a) Concept illustration of DIWPT for EPACs; (b) photo of the implemented prototype.

Adaptation of tricycles and quadricycles to use DIWPT is expectedly easier to accomplish, for the intrinsic stability of these platform and the more available space to accommodate an onboard pickup coil and power circuitry. However careful design and validation is necessary for full compliance to the maximum recommended radiation exposure levels (International Commission on Non-Ionizing Radiation Protection 2010). This maybe more critical in low profile vehicles, such as recumbent bikes and highly aerodynamically efficient quadricycles, due to the potentially greater proximity of the body of the rider to both the onboard secondary coil and the e-lane itself.

Recent design achievements in the LEV segment, such as Sørensen's Podbike (Elpedal AS 2018), Schaeffler's Bio-Hybrid (Schaik 2019), and Organic Transit ELF (Organic Transit 2018) indicate that electric power levels limited to about 750 W (roughly, one horse-power) per passenger can yield enough performance for practical personal urban transportation. So, a future power possible target for wirelessly electrified lanes (e-lanes) should be able to deliver up to 750 W for e-bikes and other mono-seater LEVs and up to 1500 W for two-seater LEVs. These representative human-powered LEVs are illustrated in Figure 4.

Podbike: 500 W / 64 kg (est.)

Bio-Hybrid: 500 W / 100 kg

ELF Solo: 750 W / 81 kg
Tactical ELF: 1250 W / 91 kg

Figure 4: Examples of human-powered electric vehicles of recent design (left to right):Sørensen's Podbike, Schaeffler's Bio-Hybrid and Organic Transit ELF, shown with their assistance power and mass parameters.

The human-powered LEV popularity is just beginning, some of the vehicles being developed are not yet legal to be used in the public streets in some countries, at their native specifications. As more experience is gained with their use, both the vehicles and the legislations are expected to be adjusted. Table 1 presents some currently defined and accepted categories of LEV that could include human-power propulsion, vehicles that are indicated for combined used with dynamic inductive wireless power transfer (European Committee for Standardization 2009), (European Union 2013):

Table 1 Categorization of lightweight electric vehicles, according to EU and USA norms.

Jurisdiction	Norm / Recommendation	Vehicle Categorization	Name	Wheels	Maximum Speed of Electrical Assistance	Maximum Power
European Union	European Committee for Standardization - EN 15194	EPAC	Electrically power assisted cycles (EPAC)	≥ 2	25 km/h	250 W
	EU Regulation No. 168/2013	L1e-A	Powered cycles	2 to 4	25 km/h	1 kW
		L1e-B	Moped	2	45 km/h	4 kW
		L2e	Moped	3	45 km/h	4 kW
		L6e	Light quadricycle	4	45 km/h	4 kW
USA	U.S.Code, Title 15 - Commerce and Trade, Chapter 47, §2085.	Low speed electric bicycle		2 to 3	20 mph* (32 km/h)	750 W

The curb weight (mass) of a typical LEV is usually on the same order of the mass of its payload (passengers). So, if 750 W of power per passenger is adopted in the DIWPT adaption, the power-to-mass ratio of these vehicles will be approximately 750 W / 180 kg ≅ 4.2 W / kg, without pedaling, roughly enough for a vertical climb rate of 0.4 m/s.

SUSTAINABLE TRANSPORTATION FOR THE SMART CITIES: A PROPOSAL

If the rider of a human-powered LEV is a first-class athlete, pedaling can add more than 1 kW of peak power to the power train for about half a minute or more. However, the expected delivered power by an average health man pedaling that can be sustained for a 20-minute interval lays in the conservative 250 W – 300 W range (Wilson 2004). This is good enough only to displace the vehicle in neutral grading lanes, at moderated speeds and to maneuver in parking lots. So, human-powered LEV are usually expected to be on electrical assistance while cruising.

If a LEV operates in DIWPT mode, adapted with a pickup coil and the required power circuitry to harvest energy from the magnetic field generated by the e-lane, it will be possible to completely dismiss the batteries while cruising over these e-lanes. On the other hand, as a human-powered vehicle, the hybrid LEV can also dismiss the battery when away from the e-lanes, by pedaling, if the vehicle is at low speeds. This makes viable the adoption of a new modal variant, the ctively-Powered Lightweight Electric Vehicle (HIPLEV).

A HIPLEV is a highly sustainable transport because:

- It is a human-powered EV, it may be used with no battery. The battery may be optionally added to the vehicle's configuration, to provide more flexibility of employment, but it is not required.

  Some users with low athletic profile or reduced mobility may permanently install a battery in the HIPLEV. This can also be done for special applications or when the HIPLEV is constantly used, or for cargo services. The battery would automatically charge when the HIPLEV is run over some e-lane or a specially installed stationary inductive charger.
- Even the users that don't need a battery in daily basis may eventually rent a battery and provisionally install it in the HIPLEV for special trips or use cases.
- It will use inductively electrified lanes (e-lanes) to move fast with indefinite autonomy, provided the e-lanes get to the intended destination.
- Pedaling hubs can be integrated in the city to connect e-lanes and make it possible for the HIPLEV to relay seamlessly from one e-lane to another, until it comes close enough to its destination. Then, the final segment of the journey is accomplished by pedaling only.
- Similar will happen at departure: If the destination is close enough, the HIPLEV can get there solely by pedaling. If not, the HIPLEV should be able to take the closest e-lane leading to the intended destination.
- Intelligence and smart communication with the e-lane management system should be integrated in the HIPLEV, in order to help the vehicle to calculate the best route to destination and to permit the e-lane system to run more balanced.
- When not running over an e-lane, the HIPLEV can still use standard bike lanes or pathways that can be shared with pedestrians or cars, provided the maximum car speed is regulated on these shared pathways to the same speed limit of the HIPLEV.
- EPAC type bicycles adapted for DIWPT are the entry level of a HIPLEVs. A key point for to assure safety is that common maximum speed is adopted on shared lanes and roads.
- The presence of a magnetic field on e-lanes will facilitate the future implementation of self-driving capacity on a HIPLEV, when it is run over an e-lane.

For safe urban activity of the HIPLEV, a maximum speed limit in the range of 25 km/h (as for L1e-A and EPAC) to 32 km/h (as in the US Low speed e-bike) is recommended. This is less than the speed of the fastest human beings running on short tracks, but well over the average speed a person can sustain in medium distance tracks (Denny 2008).

The HIPLEVs have a reduced footprint in terms of material resources used, they should be much less costly to own, and that will positively impact the economy. This will also promote reduction of pollution, improving urban space organization, human health standards, and being able to fill the gap between the purely human power based soft modes and the convenience of heavier personal transportation. Figure 5 illustrates the use of a HIPLEV for commuting.

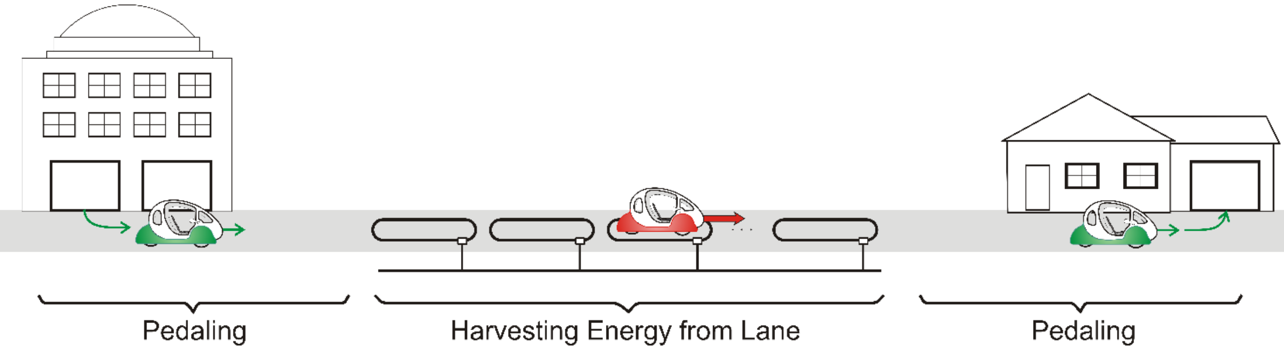


Figure 5: HIPLEV for commuting.

CONCLUSIONS AND FURTHER RESEARCH

Low power lightweight electric vehicles (LEV) may provide a functionally adequate, sustainable and economically favorable substitution for both higher power electrics and thermal engine-based mobility, when used in conjunction with Dynamic Inductive Wireless Power Transfer (DIWPT). This new proposed modal variant, the HIPLEV – Human-Inductively-Powered Lightweight Electric Vehicle may replace a significant part of all short-distance personal transportation modals, if the urban space is adequately redesigned by integrating an infrastructure of smart low power inductively electrified lanes.

Successful adaption of an Electrically Power Assisted Cycle (EPAC bicycle) to use the Dynamic Inductive Wireless Power Transfer (DIWPT) technology has already been reported in 2016, with a prototype being tested at 400 W. Further design effort, however, is still necessary to assure the safety of riders, concerning the compliance with the recommendations of the International Commission on Non-Ionizing Radiation Protection.

Other three and four-wheeled human-powered lightweight EVs, of recent design, can provide full weather protection and more value to the user, and should be considered as the next class of candidate vehicles for DIWPT adaption. The technology for implementing wireless power transfer circuits for the HIPLEV is readily available, at the required power levels of a few kW.

The lightweight electric market is growing, but in order for the users to justify the additional investment in the conversion of e-bikes and other lightweight vehicles to HIPLEVs, smart networks of wirelessly electrified bike lanes have to be implanted and supported by new regulations.

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