Dossier

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Automatic-Control Challenges in Future Urban Vehicles: A Blend of Chassis, Energy and Networking Management

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Résumé – Les défis de la commande automatique dans les futurs véhicules urbains : un mélange de gestion de châssis, d'énergie et du réseau – Le sujet du présent article est une discussion sur les nouveaux défis auxquels le domaine scientifique de la commande automatique des véhicules va faire face dans les prochaines décennies. L'accent est mis sur les véhicules urbains destinés à une mobilité individuelle, puisque c'est ce type de véhicules qui va faire l'objet des plus grands changements dans les prochaines décennies.

Le présent article s'articule, selon une démarche descendante, en trois sections abordant et discutant brièvement les éléments suivants : les principaux moteurs qui vont imposer un changement en matière de mobilité individuelle ; les principaux types de véhicules qui sont attendus pour répondre au mieux à de tels moteurs et les principaux défis de la commande automatique sur un tel type de véhicules. À dessein, la portée du présent article est non technique. Son but est principalement de discuter les nouveaux défis émergeants, à partir de perspectives des milieux scientifiques et professionnels de la commande automatique. L'objectif du présent article consiste à établir un canevas de discussion sur les problèmes et opportunités qui verront le jour en ce domaine dans un proche avenir.

Abstract – Automatic-Control Challenges in Future Urban Vehicles: A Blend of Chassis, Energy and Networking Management – *The topic of this paper is the discussion of new challenges that the scientific field of automatic-control will face in the next decades, in the area of vehicles control. The focus is on urban vehicles for personal mobility, since this type of vehicles will be subject to the biggest changes in the next decades.*

The paper is articulated in three sections – in a top-down framework – briefly addressing and discussing the following items: the main drivers, which will force a change in urban personal mobility; the main types of vehicles, which are expected to address at best such drivers; the main automatic-control challenges on such type of vehicles.

The scope of this paper is purposely non-technical. Its aim is mainly to discuss the emerging new challenges from the perspective of the automatic-control scientists and practitioners. The goal of the paper is to establish a discussion framework on the problems and opportunities, which will arise in this field, in the near future.

INTRODUCTION AND SCOPE

In the next decades, an unprecedented development of new vehicles, mobility concepts and energy systems is expected. After a century of almost-unchanged paradigms, the traditional model of personal mobility developed by western countries is seriously threatened by oil-shortage and environmental issues.

The topic of this paper is the discussion of new challenges that the scientific field of automatic-control will face in the next decades, in the area of vehicles control. The focus is on urban vehicles for personal mobility, since this type of vehicles will be subject to the biggest changes in the next decades.

The scope of this paper is purposely non-technical, in the classical sense (for a scientific paper) of presenting new technologies, algorithms, etc. Its scope is mainly to discuss the emerging new challenges, from the perspective of the automatic-control scientists and practitioners.

The paper is articulated in three sections, briefly addressing and discussing the following items:

- the main drivers which will force a change in urban personal mobility;
- the main types of vehicles which are expected to address at best such drivers;
- the main automatic-control challenges on such type of vehicles.

This simple structure of the paper follows a top-down approach: to understand the main control challenges, the new classes of vehicles must be defined; on the other hand, to understand which classes of new vehicles will emerge, the main drivers must be understood, from a technological, energetic and environmental point of view.

The paper – needless to say – is the expression of the view-point of the author. This viewpoint, although debatable and somehow naive, might be useful for encouraging discussion on this topic. The automatic-control field can play a major role in the design of new vehicles and new mobility concepts. This – however – can happen only if the control-scientists community will be able to better focus on the most relevant, interesting and challenging research paths.

This paper has been inspired by two seminal works, which can be considered as the main references:

- the presentation of Guzzella ("Towards Sustainable Individual Mobility: The Role of Automatic Control Systems"), within a round-table at the 2008 World IFAC Congress in Seoul, Korea [1];
- the chapter "Automotive Control" edited by Glielmo, within the IEEE CSS paper "The Impact of Control Technology" published in 2011 [2] – see also [3].

1 URBAN MOBILITY REVOLUTION: DRIVERS

The vehicles for personal urban mobility will be developed according to a set of requirements (or "drivers"); these drivers are forced by emerging problems, which require quick and effective solutions.

Urbanization (namely the concentration of the population in a small number of large metropolitan area) seems to be a non-stoppable trend (it is estimated that by 2050, about 80% of world population will be resident in metropolitan areas), which will worsen many problems which are already affecting the personal mobility in a large number of metropolitan areas, both in developed and in developing countries. Among others, the following five issues are likely to be (or to become soon) the most urging and relevant:

- decrease the footprint of the vehicles;
- decrease the vehicle/payload ratio;
- decrease the CO_2 footprint and energy-costs;
- increase the vehicle safety;
- decrease the ownership cost.

1.1 Driver#1: Decrease the Footprint of the Vehicles

Space occupation in the metropolitan-areas (both on the roads and in parking lots) is becoming a major issue *(Fig. 1)* [17]. Traditional "mid-size" cars today have a footprint of about 7-10 m^2; this footprint is extremely large, especially if used (as typically is) by a single passenger. This large footprint is attractive since it allows an all-purpose use of the vehicle; it is affordable and effective in a mobility system where traffic congestion is not an issue but is becoming a non-affordable luxury in over-populated urban areas. The footprint-per-occupant ratio hence must be dramatically decreased (see *Fig. 2* where small-footprint vehicle concepts are depicted).

Figure 1

A classical image of large metropolitan areas: a traffic-jam during rush-hours.

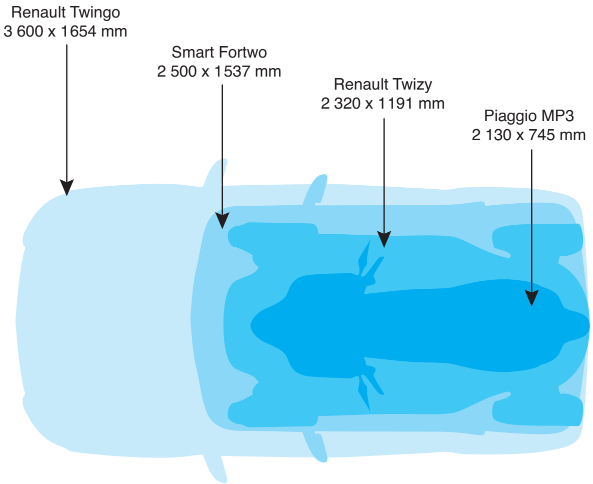

Figure 2

Footprint of four small vehicles (courtesy of the Italian Magazine "DueRuote" – April 2011 issue).

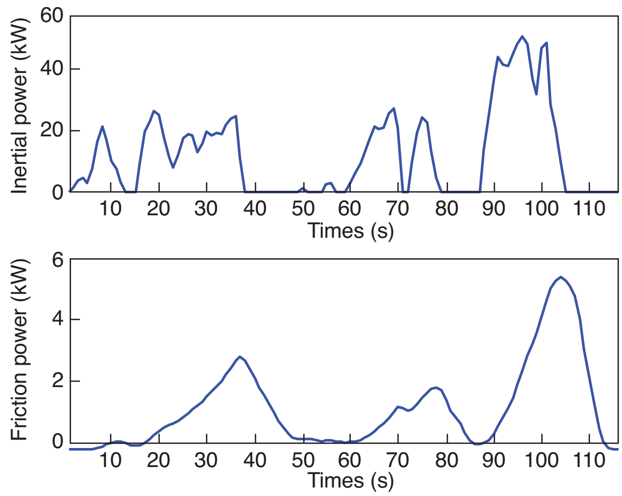

Figure 3

Example of power-requirements for a large urban vehicle; the energy-requirement is split in "inertial-requirement" (power required to accelerate the vehicle) and "friction-power" (power required to keep a constant speed). Notice the large difference between the two scale-ranges.

Figure 4

Examples of personal vehicles with different vehicle/payload ratio (assuming no luggage and single-occupancy): a large SUV (vehicle/payload ratio of about 25:1) and a small scooter (vehicle/payload ratio of about 1:1).

1.2 Driver#2: Decrease the Vehicle/Payload Ratio

In a typical urban-driving mission profile, the energy required to accelerate the vehicle is significantly larger than the energy required to contrast rolling and aerodynamic forces *(Fig. 3)* (see *e.g.* [4] and references therein). On the other hand, the energy required to accelerate the vehicle is directly proportional to the overall mass of the vehicle. This simple technical fact shows how the vehicle/payload ratio is extremely important for energy-saving in urban driving, since the mass-energy sensitivity is about 1:1. As a consequence, for a single-occupancy usage *(Fig. 4)*, it is unreasonable to use 2 tons (or more) vehicles for urban mobility. A growing regulation pressure against high vehicle/payload ratio in metropolitan areas hence is expected in the near future.

1.3 Driver#3: Decrease the CO_2 Footprint and Energy-Costs

Pollutant reduction has been the main focus in the last two decades. In about 20 years, EU moved from a situation where there was no catalytic after treatment of vehicle emissions, to EURO5. With the incoming EURO6 rules, pollutant emissions are expected to become a marginal problem (especially if compared with other non-vehicular sources of air pollutants) for personal urban vehicles.

The new emerging issue is definitely greenhouse effect, where CO_2 plays the central role. A way of dramatically reduce CO_2 emissions (see *Fig. 5*, [5]) is to move from internal-combustion engines to electric vehicles (provided that electric energy is produced with low-CO_2 emissions).

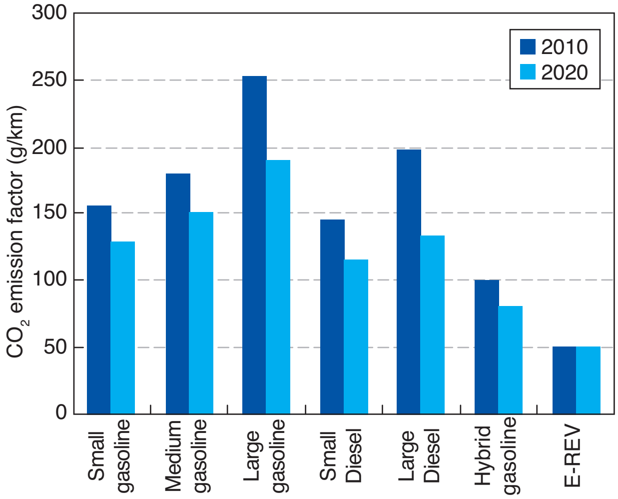

Figure 5

CO_2 estimated emissions of a mid-size car, on a standard EU urban cycle, for different types of engines [5].

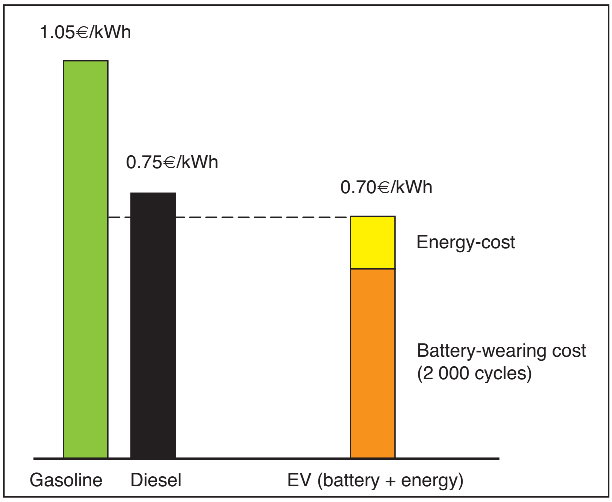

Figure 6

Overall cost of a KWh of energy "at the wheel", for three different engines (estimated – Italy – 2012).

Electric vehicles are quite appealing also for reduction of energy-cost. In Figure 6, it is shown (given current average gasoline and Diesel cost is Italy and electric energy cost for the user) how an electric vehicle can be already cost-effective. Notice that the battery-consumption is the dominant cost in an electric vehicle, since it is much larger than the electric-energy cost. Nonetheless, also the cumulated cost of battery-wearing and electric energy is smaller than the equivalent energy cost (at the wheel) for gasoline/Diesel vehicles. Hence, electric vehicles are expected to grow enormously in the next decade, in the segment of small urban vehicles.

Figure 7

An image of an urban accident.

1.4 Driver#4: Increase the Vehicle Safety

Safety is constantly a main driver in vehicle-developments; this objective been strongly emphasized in developed countries in the last decades *(Fig. 7)*. This trend is expected to continue, according to the "zero-accident-vision" claimed by western countries. However, it is worth pointing out that safety has a significant cost in the design, manufacturing and maintenance of a vehicle; a "near-zero-accident" objective is becoming critical in developed countries, where purchasing-power is declining.

1.5 Driver#5: Decrease the Ownership Cost

Western (developed) countries are – on average – suffering a general decline of the purchasing power. 2008 and 2011 financial crisis have been showing that in the next decade a quick re-balancing of purchasing power is expected worldwide, between developed and developing countries (where the leading role of developing countries is played by the BRIC – Brazil, Russia, India, China)

On the other hand, developing countries are increasing their purchasing power but – in absolute – it is still much smaller than that of western countries.

The issue of reducing ownership cost of vehicles hence is becoming a major issue. Notice that this driver is in contrast with the requirement of safer and cleaner vehicles, which are expected to demand for more sophisticated (hence more expensive) vehicles. It is interesting to observe that a large part of private vehicles have a small annual mileage (less than 10 000 km/year – see also *Fig. 8*). The combination of these compelling drivers suggest a radical shift in the classical

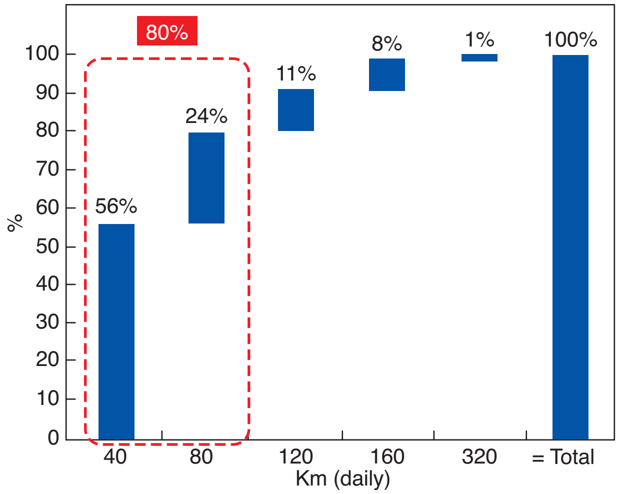

Figure 8

Daily usage of cars in Europe (source: Deloitte survey, 2010).

private-ownership paradigms, in favor of vehicle sharing forms of ownerships. This seems to be the only viable solution to reduce ownership costs, while maintaining high-tech, safe and clean vehicles on our roads.

2 URBAN MOBILITY REVOLUTION: VEHICLES

Given the drivers outlined in the previous section, the portfolio of personal urban vehicles which are expected to grow in the next decades can be quite easily defined, as a mere consequence of such drivers. Such classes of personal urban vehicles are now briefly classified and outlined.

2.1 Classical (Small) Electric Cars

After decades of failed attempts to put on the market successful electric cars, it seems that the second decade of the new millennium will be remembered as the electric-vehicles (re)birth decade. The focus on electric vehicles will be on small (no more than 2.5-3 m long) and light (no more than 400-500 kg) vehicles. The restriction to this size of cars will be mainly driven by a very difficult trade-off among:

- energy-consumption;
- expected travelling range;
- size/cost of the battery-pack.

Using the latest Lithium technology, it is not technically difficult to build effective "full-size" electric cars with 2-300 km of range and satisfactory performances. However, the cost of the battery-pack would have a devastating effect on the car economics, leading to niche-vehicles only (a successful example in this class of niche vehicles is given by Tesla). The best compromise seems to be given by small electric vehicles with a comparatively short (60-100 km max) range, possibly equipped with optional Range Extenders (RE) (see *Fig. 9*).

2.2 Narrow-Track "Tandem" Two-Seaters

Assuming that the appeal of two-seaters vehicles is going to grow for urban mobility (where single or double occupancy of the vehicle is – by far – the most typical occupancy), the debate shifts on the relative positions of the two seats; while side-seats is the most classical configuration, tandem-seats are attractive since the track of the vehicle can be significantly narrowed, with a significant advantage of agility in urban traffic. Many OEMs and designers have been developing this unusual but appealing concept (see *Fig. 10*).

2.3 Tilting 3-4 Wheelers

The main limit of narrow-track vehicles is that – at high speed – they are dangerously prone to rollover, due to their high ratio between center-of-gravity-height and track-width. Non-tilting narrow-track vehicles hence must have a limited (and low) speed and are mainly suitable for urban-only roads, with 45-50 km/h limitation. For higher speeds, tilting is mandatory. Tilting narrow-track vehicles can be open "scooter-like" vehicles (see *Fig. 11*) or all-weather ceilinged vehicles with rigid roof (see *Fig. 12*).

2.4 Electric Scooters

Electric scooter are – by far – the most used private vehicles propelled with electric motors. They are extremely popular in eastern developing countries like China and India. They range from large extra-urban scooters, to ultra-light (almost-bicycle-like) foldable vehicles (see *Fig. 13*). Thanks to their low vehicle/payload ratio, they provide the best compromise between performance, range and vehicle cost (including battery-pack).

2.5 Electric Pedal Assisted Cycles (EPACs)

EPACs are as popular as electric scooters in eastern developing countries and their popularity is rapidly growing also in western countries *(Fig. 14)*. The classical EPAC design ("boxy" and heavy) is being developed into more sophisticated, slim and stylish design, with a growing interest also towards all-weather ceilinged solutions (typically 3-wheelers, to improve the vehicle stability).

It is also very interesting the trend (see *Fig. 15*) towards self-sustaining-charge EPACs (like the Copenhagen wheel) and towards even more sophisticated concepts like the self-sustaining charge with optimized bio-efficiency (like the recently presented Bike+). The current regulation in EU restricts the performances of EPACs to 25 km/h and 250 Watt; however, it is expected a quick evolution of EPACs regulations, with the creation of a new class of vehicles, positioned

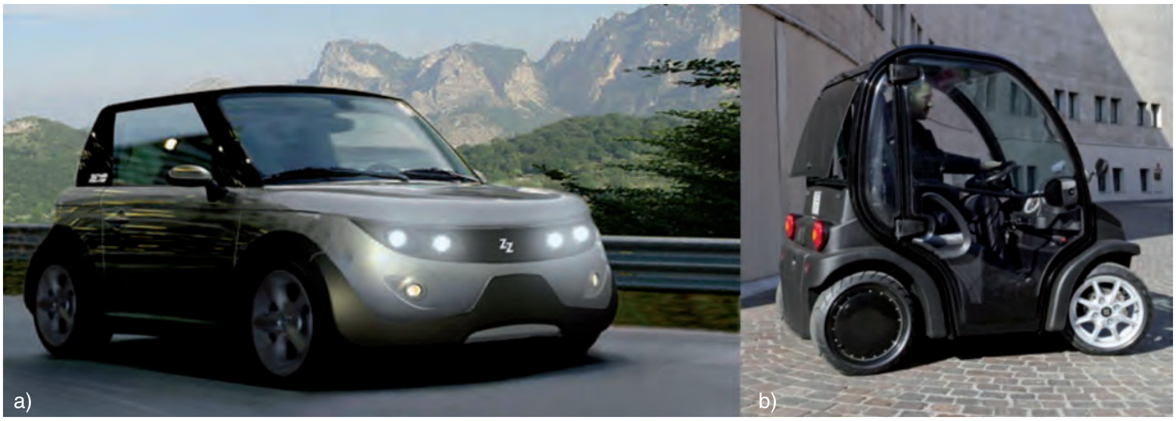

Figure 9

An example of full-electric small city-vehicles. a) Tazzari “Zero”; b) Estrima “Birò”.

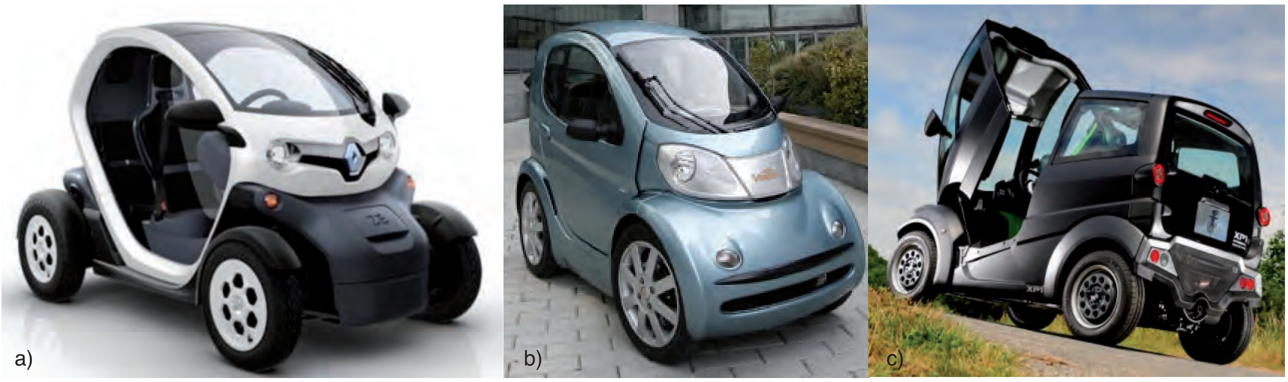

Figure 10

Examples of narrow-track vehicles. a) Renault Twizy; b) VOLPE; c) Gordon Murray-design T25.

Figure 11

Examples of “Power-Two-Wheelers” (PTW) with one or two added wheels. a) Piaggio MP3; b) Quadro 4D.

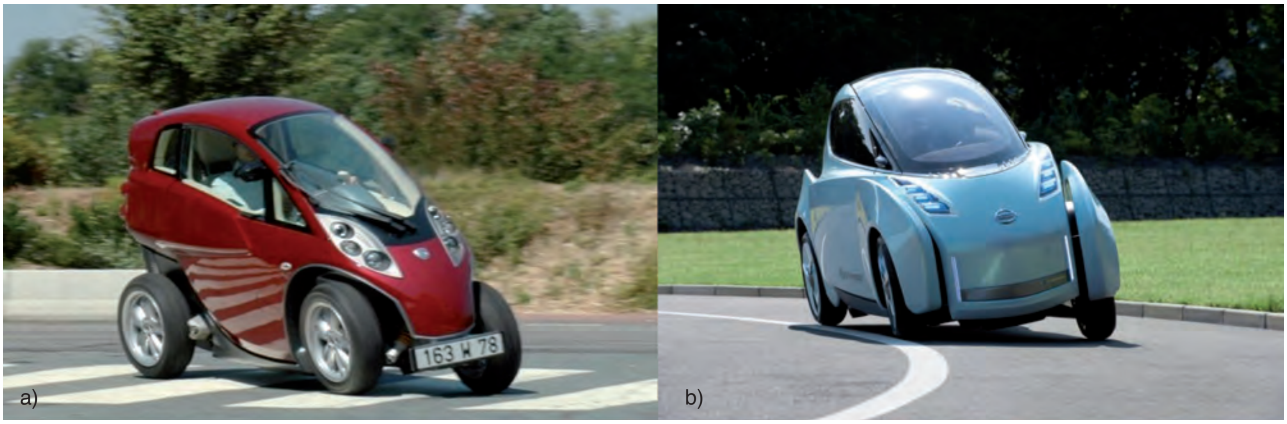

Figure 12

Examples of narrow-track ceilinged tilting vehicles. a) Lumeneo “Smera”; b) Nissan “Land Glider”.

Figure 13

Examples of electric scooters, in decreasing order of size. a) Vectrix; b) Smart; c) VW.

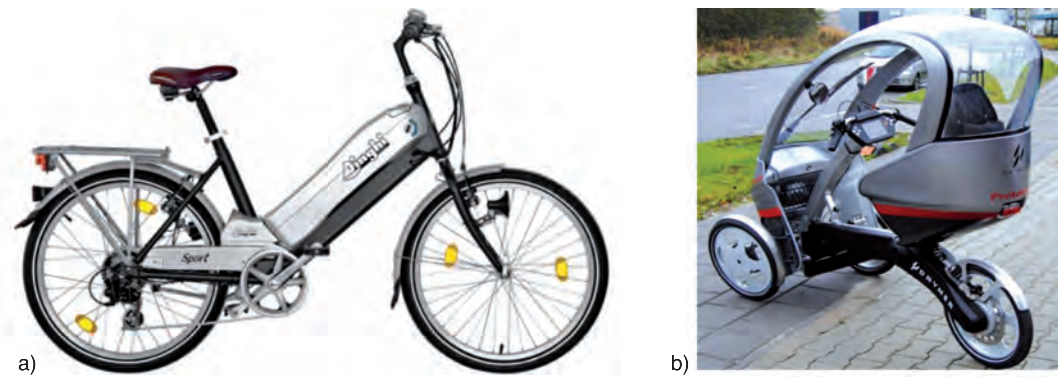

Figure 14

Examples of EPACs. a) Classical shape; by Fresbee; b) ceilinged 3-wheeler by Drymer.

Figure 15

Examples of advanced concepts of EPACs. a) MIT Copenhagen Wheel; b) Politecnico di Milano Bike+.

Figure 16

Examples of "actively-stabilized" personal vehicles. a) Segway Puma; b) Honda U3-X; c) Toyota Winglet.

Figure 17

Example of ultra-light electric vehicle for short-range indoor mobility: Hambry "the flyboard" (2011 – by Politecnico di Milano).

in-between scooters and 250 Watt classical EPACs. Overall, Hybrid Human Power Vehicles (HHPV), thanks to their low cost, low environmental impact and their high versatility, are expected to grow significantly in the next decade [6].

2.6 Innovative Small-Vehicle Architectures

At the end of any "clustering exercise", a class of "others" cannot be missed.

In the last few years, an enormous amount of prototypes of small personal electric vehicles have been developed and proposed. None of them have still reached the stage of mass production (probably with the debatable exception of the "Segway") but they have been playing an important seminal role. Most of these innovative vehicles are "actively-stabilized" vehicles: they are somehow a vehicular transposition of the "inverted pendulum" concept, a classical benchmark and toy example in the control community (see *Fig. 16*). Their ability of staying stable is – of course – quite surprising for non-experts in control theory. This appealing feature is – however – also their main drawback: their intrinsic instability must be continuously governed by feedback control systems, with a significant waste of energy also when the vehicle stays still.

Among these innovative vehicles, it worth mentioning a recently presented [7] vehicle (see *Fig. 17*): it is ultra-light (less than 5 kg) conceived for indoor mobility and its most innovative feature is the extreme mechanical simplicity and its completely de-materialized HMI (the vehicle can be driven with the shift of foot pressure or using a smartphone like a 3D joystick).

3 URBAN MOBILITY REVOLUTION: AUTOMATIC-CONTROL CHALLENGES

Given the drivers, which will push urban mobility towards new directions and the classes of vehicles which will address the new trends and needs, for automatic-control scientists and engineers new areas of control problems will open.

The traditional clustering of vehicles-control areas is represented by the following three classes of problems:

- chassis control;
- engine-control;
- transmission-control.

For decades, these areas have been developed (with some obvious overlaps) almost independently. This classification is rapidly getting obsolete (see *e.g.* [8]) and a new set of control problems will arise: they mix vehicle-dynamics, energy-management, human-machine-interaction and networking problems [9].

From the control-engineering perspective of the author of this paper, the control problems listed in the rest of this section will play a fundamental role in vehicles-control of the next decade. Such control areas represent problems which are challenging, relevant and tailored to the new type of vehicles (or to the new vehicles architectures) which will develop in the future. These control-problem areas are now stated and briefly discussed.

3.1 Stability Control for Tilting Vehicles

In the area of chassis dynamics, a large number of challenging problems have been addressed and solved in the last two decades. Traditionally, the main classical control-problems in chassis control are (see *e.g.* [10, 11]):

- suspension control (adaptive, semi-active, active);
- braking and traction control (longitudinal dynamics control);
- stability control (yaw-and-lateral dynamics control).

These problems have been largely studied for passenger cars. Even if there is still room for improvement, it is safe to say that most of the control problems have been already satisfactorily solved. The only almost-unexplored issue is stability control for two-wheels (or for narrow-track tilting) vehicles. This control problem is extremely interesting – from the control scientist point of view – for two reasons: it is extremely challenging (two-wheel-vehicle dynamics are substantially different and more complex than car-dynamics) and it addresses a fundamental safety problem in two-wheel vehicles, which – among other issues – limits the acceptance and diffusion of two-wheel vehicles *(Fig. 18)*. The expected growth of small narrow-track tilting vehicles (two, three or four-wheelers) will boots dramatically the interest for advanced stability control systems for this type of vehicles [12, 13].

3.2 The X-by-Wire Issue: System Centralized Redundancy

Although drive-by wire has become a standard approach to torque-request by the driver to the engine, brake-by-wire and steer-by-wire are still mostly confined to fancy R&D prototypes. Safety is – obviously enough – the main obstacle towards mass production of such systems. The safety problem can be obviously and satisfactorily solved using system-duplication or, in general, system redundancy. This approach is largely used in aerospace systems where "fly-by-wire" today is widely used. However, this approach can hardly transferred into mass-production vehicles. The obstacles are non-technical but merely economical: advantages and benefits coming from X-by-wire systems are still outbalanced by significant additional costs of system redundancy. As a consequence, at present, no full-by wire vehicle is available on the market.

The real challenge for control engineer will be the achievement of the requested/adequate level of safety, without

Figure 18

A spectacular loss of stability of a motorcycle: the "high-side" phenomenon (Casey Stoner – Phillip Island, 2007).

Figure 19

The full-by-wire prototype, Nissan PIVO (first introduced at the 2005 Tokyo Motor Show).

sub-system duplication. The most promising research direction is to use "peer-subsystems" as back-up systems to manage possible sub-system failures. As a matter of fact, traditionally, an X-by-wire system is designed to be intrinsically safe and "self-consistent". A different approach is to shift the safety issue at the vehicle or "system" level: in a vehicle equipped with 4 independent brake-by-wire subsystems, 2 or 4 independent electric motors (which can deliver also large positive/ negative torques for a short amount of time) and a steer-by-wire system (which, in the most complete configuration, is constituted by 4 independently steering wheels – see *e.g.* the Nissan Pivo in *Fig. 19*), a failure of one of these sub-components (*e.g.* the failure or even the locking of a brake on a corner) can be managed by counter-acting with all the others "peer" yaw-rate actuators. This approach is already know and studied (labeled as "Global Chassis Control" – GCO) for the management of multiple subsystems or control actuators, in non-failure conditions. The big challenge is to use the same approach to overcome the safety concerns which seems to be dooming X-by-wire systems.

3.3 Energy and Battery-Life Feedback- Management in Electric Vehicles

Electric vehicles – especially small vehicles for urban mobility – are unrivaled from many different viewpoints: they are quiet, clean, fun-to-drive and require less maintenance due to their intrinsic simplicity. Their Achilles' heel is – needless to say – batteries. Lead batteries (but also the more advanced Ni-mh batteries) have a too low energy density (from 20-30 Wh/kg up to 80-100 Wh/kg) to make an electric vehicle really appealing. Low-density batteries have confined electric vehicles to a very small niche of special applications vehicles or vehicles for enthusiast of electric-mobility, willing to pay extra money for small-range and heavy vehicles.

The advent of Lithium batteries (with energy density currently beyond 200 Wh/kg and an estimated short-term realistic target up to 300 Wh/kg) have dramatically changed the attitude towards electric vehicles. As Lithium batteries have revolutionized personal mobile devices (laptops, mobile phones, cameras, etc.), they represents a quantum-leap also for electric mobility.

However, despite the dramatic increase of energy-density of batteries, electric vehicles still suffer (and this limit is not expected to be overcome in the next decade) of three main limits:

– *cost of the battery pack*. The cost-per-KWh today can be estimated around 400-600 € for the OEM, which easily becomes 1 000+ € for the final customer/user. This means that the battery-cost is a dominant cost for an electric vehicle and may require different selling-models (like a long-term rental of the battery-pack). Apart from the cost issue, there are no significant limitations for delivering a vehicle with 300-400 km of range. Interestingly enough, with 2 000+ available cycles of recharging, the life of a last-generation Lithium battery is too long for the average life-time of a vehicle. 2 000 recharging cycles correspond to a lifetime of about 200 000 km, for a battery-pack delivering 100 km of travelling range (for short-range mobility, a vehicle is unlikely to have a travelling lifetime of 200 000 km);

- *empty-battery fear*. Given the severe limitations of the size of a battery-pack (a large battery pack is too expensive and have a too-long life), urban electric vehicles are expected to be designed for a 50-70 km range, which satisfies most of the needs of a urban-traveler. Assuming that a widespread network of fast-recharging stations is not going to be available in the near future, the accurate management of the available travelling range is of paramount importance for the best usage of the (small) battery-pack;
- *battery ageing*. Small battery-packs also means reduced traveling-life of the battery pack. Moreover, the 2 000+ nominal recharging cycles can be strongly reduced if the battery is subject to temperature, currents and extreme SoC over-excitations. Since the wearing-cost of the battery-pack is more than the cost of the electric energy spilled by the grid, it is clear that the accurate management of the state-of-wearing (also called State-of-Health – SoH) of the battery pack has a strong influence on the economics of the vehicle over its lifetime.

Given the above three main limits in electric vehicles, the most relevant and challenging open issue for control-system designer are going to be:

- closed-loop management of state-of-discharge of the battery-pack. In other words, the classical paradigm of "range-prediction" (which is obviously dependent on many exogenous drivers like temperature, traffic conditions, drive-style, etc.) must be inverted in the paradigm of the "guaranteed range", where the range is an input for the driver and the electronic control systems takes care of guaranteeing that range, by modulating the drive-style in closed-loop [14];
- closed-loop management of the battery-wearing. Similarly to the concept of "guaranteed discharge rate", since battery-wearing is a significant cost for the vehicle owner, closed-loop control of the wearing-rate is going to be the next major control challenge in the near future, for electric vehicles [9].

3.4 Human-Engine/Electric-Engine Interaction

It has been largely proven that a light pedal vehicle is the vehicle that guarantees the minimum amount of energy-per-km, to transport a person *(Fig. 20)*. In the last part of the last century, in western countries, bicycles have been relegated mostly to leisure vehicles. The shortage of fossil fuel and – in general – the pressure towards energy-saving, is fueling the re-discover of pedal-vehicles as the backbone of short-range urban mobility. Thanks to the advances in the electric-motor technology, battery-technology and microcontroller-based-electronic control systems, a new generation of Electric-Pedal-Assisted-Cycles (EPACs) is emerging.

EPACs have been – so far, very simple vehicles: the electric-motor assistance is regulated with basic strategies, bounded by law-prescribed limitations (*e.g.* 25 km/h and 250 Watt in most of EU countries).

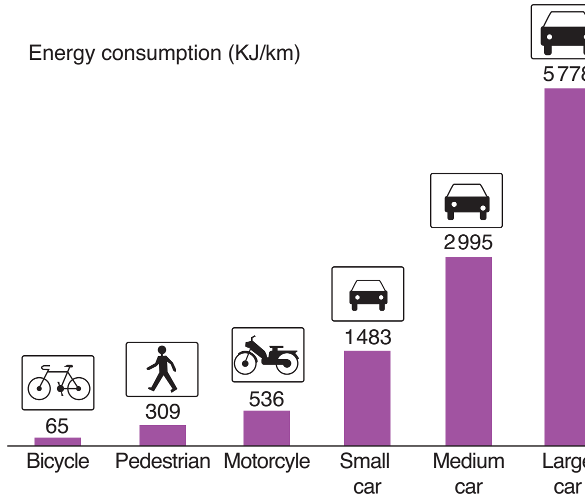

Figure 20

Normalized energy-requirements for different types of vehicles, suitable for personal urban mobility.

EPAC, however, are – highly-complex "hybrid" vehicles, where the electric energy is mixed with metabolic energy delivered by the cyclist. The availability of modern control and ICT technologies is opening the way to a new generation of EPACs, where the assistance strategy is designed to optimize specific goals like metabolic-efficiency, fatigue perception, heart-beat oscillations and peaks, etc. Interestingly, this research stream in interleaved with biometric measurements and know-how, which will become more and more important in the future developments of pedal-assisted vehicles. From this point of view, modern technology is helping, with the development of light and not-invasive equipment (smartphones, biometric sensors, etc.), which can be easily wireless-connected with the vehicle ECU.

3.5 The System-Level: Supervisory Control of Fleets (Reservation; Take/Leave; Tracking; State-of-Charge Planning; etc.)

Traditionally, vehicle electronics have been mainly focused on the "local" control of vehicle subsystems and vehicle dynamics (*e.g.* engine control, stability control, etc.) or on human-machine-interface (also called "vehicle-to-driver" interaction). All in all, the vehicle and the driver have been considered as autonomous entities, independent from the other vehicles.

The last decade has experienced an exponential growth of wireless digital communication. A complete range of wireless communications technologies and protocols have been developed: large-range networks (like GSM, UMTS, etc.) short range per-to-peer or multi point communication (like BlueTooth or WiFi networks), up to ultra-near low-bandwidth wireless transmission based on RFID or NFC technology [15].

Thanks to this enormous growth of digital wireless communication, an always-on ubiquitous communication between vehicles and infrastructure is today feasible and economically affordable. This has opened the way to an enormous portfolio of applications and services, boosted by the cheap and easy availability of global positioning *via* GPS transponders.

This shift from the "vehicle" to the "system" has generated an enormous amount of new "control-problems", such as:

– control of interaction of vehicles to prevent accidents [16]; prediction of traffic conditions;
– optimization and control of optimal routing of a vehicle;
– global energy-optimization of a journey;
– global optimization of grid-to-vehicle and vehicle-to-grid energy flows [4].

This new area of application has been recently labeled as "Intelligent Transport Systems" (ITS) and requires the interaction of traditional scientific disciplines like automatic control, computer sciences, telecommunication and networking, optimization, etc. The ultimate challenge for automatic-control scientists hence will be the application of the traditional control-systems know-how to new problems which still needs a formal definitions and requires a tight interaction with other scientific areas.

CONCLUSIONS

In this paper, a discussion of new challenges that the scientific field of automatic-control will face in the next decades, in the area of vehicles control, has been presented. The focus is on urban vehicles for personal mobility.

In a top-down framework, the discussion has been focused on: the main drivers which will force a change in urban personal mobility; the main types of vehicles which are expected to address at best such drivers; the main automatic-control challenges on such type of vehicles.

The picture outlined in the paper is a potential big opportunity for automatic-control scientist to play a fundamental role in this field, in the next decades. The key success factor seems to be the ability to interleave system & control know-how with tools and techniques taken from other scientific disciplines.

Finally, it is interesting to recall the list of "selected recommendations for research in automotive control", presented at the end of the 2011 seminal paper [8] by Glielmo *et al.*:

– powertrain architectures with multiple power sources are becoming increasingly popular; these will require sophisticated coordinated control approaches to manage the heterogeneous power sources;
– correct estimation of the state of charge of a battery is one of the most difficult and important research needs in battery management systems for electric and hybrid-electric vehicles;
– motorbikes and tilting vehicles represent an emerging and exciting opportunity for control technology, especially for active yaw-roll control.

In this paper, these challenges are confirmed and extended in wider set of directions.

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REFERENCES

1 Guzzella L. (2008) Towards Sustainable Individual Mobility: The Role of Automatic Control Systems. Within Round-table Presentations by IFAC Coordinating Committee on Transportation and Vehicle Systems (panelists: Jae Kyun Chang, Gerdes C., Guzzella L., Ohata A.), *17th IFAC World Congress*, Seoul, 6-11 July.

2 Glielmo L., Butts K., Canudas-de-Wit C., Kolmanovsky I., Lohmann B., Stewart G. (2011) Automotive control, in *The Impact of Control Technology*, Samad T., Annaswamy A.M. (eds), IEEE Control Systems Society.

3 Glielmo L. (Ed.) (2011) *A Perspective View on the Future of Control in Transportation Systems*, Report from the International Workshop on the Future of Control in Transportation Systems, Benevento, Italy.

4 Manzoni M., Corti A., Savaresi S.M., De Nigris M., Gianinoni I.M. (2011) A Preliminary Analysis of Grid Impact of Electric Vehicles *via* Inertial Measurements, *18th IFAC World Congress*, Milano, Italy, 28 Aug.- 2 Sept., pp. 9709-9714.

5 Mellios G., Samaras C., Ntziachristos L. (2011) *Projection of CO_2 emissions from road transport*, Report No. 10.RE.0034.V4, Thessaloniki University, http://www.emisia.com/docs/ETC CO2 projections_final.pdf.

6 Alli G., Formentin S., Savaresi S.M. (2010) On the suitability of EPACs in urban use, *5th IFAC Symposium on Mechatronic Systems*, Cambridge, MA, 13-15 Sept., pp. 277-284.

7 Spelta C., Boniolo I., Savaresi S.M., Alli G., Vanzulli M. (2011) A Planar Electric Vehicle with Differential Steering and Plantar Command, *IEEE Multi-conference on Systems and Control (MSC)*, Denver, CO, 28-30 Sept., (to appear).

8 Savaresi S.M. (2006) The role of real-time communication for distributed or centralized architectures in vehicle dynamics control systems, *6th IEEE International Workshop on Factory Communication Systems (WFCS 2006)*, Torino, Italy, 28-30 June, (plenary presentation), pp. 1-6.

9 Charette R.N. (2009) This Car Runs on Code, *IEEE Spectrum*, February.

10 Savaresi S.M., Poussot-Vassal C., Spelta C., Sename O., Dugard L. (2010) *Semi-Active Suspension Control for Vehicules*, Elsevier (Butterworth-Heinemann), UK, ISBN: 978-0-08-096678-6.

11 Savaresi S.M., Tanelli M. (2010) *Active Braking Control System Design for Vehicules*, 1st ed., Springer-Verlag, ISBN: 978-1-84996-349-7.

12 Boniolo I., Savaresi S.M. (2010) *Estimate of the lean angle of motorcycles*, VDM Verlag, Germany, ISBN 978-3-639-26328-2.

13 De Filippi P., Tanelli M., Corno M., Savaresi S.M. (2011) Enhancing active safety of two-wheeled vehicles *via* electronic stability control, *18th IFAC World Congress*, Milano, Italy, 28 Aug.- 2 Sept., pp. 638-643.

14 Dardanelli A., Tanelli M., Picasso B., Savaresi S.M., di Tanna O., Santucci M. (2012) A smartphone-in-the-loop active state-of-charge manager for electric vehicles, *IEEE/ASME Trans. Mechatronics* (to appear).

15 Spelta C., Manzoni V., Corti A., Savaresi S.M. (2010) A Driver-to-Infrastructure Interaction System for Motorcycles based on Smartphone, *13th International IEEE Conference on Intelligent Transportation Systems (ITSC 2010)*, Madeira Island, Portugal, 19-22 Sept., pp. 1442-1447.

16 Corti A., Manzoni V., Savaresi S.M., Santucci M., Di Tanna O. (2011) A Centralized Real-time Advanced Driver Assistance System Based on Smartphones. First Workshop on Pervasive Urban Applications (PURBA), *9th International Conference on Pervasive Computing*, San Francisco, CA, USA, 12-15 June, pp. 69-76.

17 White J.B. (2006) One billion cars, *The Wall Street Journal* [Online], 17 April.

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