***Abstract*—For the metropolitan setting, we propose the introduction of (mostly) one-seater electric vehicles and a sparse road network dedicated to them. These "intelligent commuter vehicles" (ICVs) would be bimodal: human-driven on standard roads, and computer-guided in the network (ICVN), which also charges and powers the vehicles. The commuter would drive to the nearest entry/exit terminal, from where the vehicle would be guided to the terminal closest to the destination, the trip being completed by human driving. The sparsity of the network, combined with the vehicles' narrowness and lightness means that it can be constructed relatively painlessly.

Network-charging both removes the need of a separate urban charging infrastructure and leads to short range-requirement for the vehicles, hence existing, cheap lead-acid batteries can be used; the controlled environment of the network makes the guiding of the vehicles realizable with existing technology. Hence the paradigm does not need any technological breakthroughs; is backward-compatible, since existing roads are still utilized, and a partly-completed network can be used; and forward-compatible, since the vehicles can easily be converted to be fully self-driving, if and when we are technologically and socially ready. We believe that these features make the paradigm the most reasonable solution to the metropolitan gridlock problem.

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ICVS: A Paradigm to Address Urban Traffic Gridlock and Associated Problems

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1. Introduction

Urban gridlock in metropolises is one of the less pleasant facts of modern life. Here, “modern life” should not be read as life in developed countries: The top ten most populous metropolitan areas are Tokyo (Japan), New York (USA), Seoul (South Korea), Mexico City (Mexico), Jakarta (Indonesia), Mumbai (India), Sao Paulo (Brazil), Delhi-New Delhi (India), Osaka-Kobe (Japan) and Shanghai (China) as of 2009, sorted according to population [1].

To address this problem, in this work we propose the introduction of (mostly) one-seater electric vehicles (ICVs) and the construction of a road network (ICVN) dedicated to them. The vehicles would be bimodal, human-driven on standard roads, and computer-guided in the network; and the network would eventually cover the metropolitan area, but be sparse. Most of a commuting trip, except for short sections at the two ends, would take place on the network, which would guide, power and charge the vehicles.

Advantages of the paradigm (ICVS) are (i) increased person-transport capacity due to smaller vehicle footprint per commuter (ii) reduced and displaced pollution due to the smaller mass and electric nature of the vehicles (iii) reduction of accidents/violations (iv) elimination of most of driver fatigue (v) possible automated, high-density parking (vi) elimination of the need for separate charging infrastructure for electric vehicles (EVs), in particular, home-chargers (vii) short range requirement, hence possibility of using smaller or cheaper batteries, including existing standard automotive batteries (viii) backward-compatibility, in the sense that existing roads *and vehicles* do not lose their utility, and (ix) forward-compatibility, in the sense that small electric vehicles are part of the ultimate solution, when they will be fully and reliably automated in the future.

Most of the ideas making up the system proposed here have appeared in the literature, as parts of the Personal Rapid Transit (PRT) and dual-mode systems discussions. Investigations of these fields fluorished in the 1970s due to US government funding for such studies, which however dried up after this decade. The development of the PRT concepts, i.e. the idea of a fleet of automated vehicles moving on a network of dedicated guideways, started in the 1950s with the efforts of Fichter [2]; developed further in the 1970s conferences [3]–[6], where in the last one, the acronym PRT was introduced by Anderson; also see e.g. [7] for a recent review. The dual mode concept, i.e. the idea of PRT-type vehicles also able to operate normally outside the guideways network, was also mainly developed in the 1970s [8]–[11].

However, these discussions have born little fruit in the real world so far. For example, the only long-term operational such system, the Morgantown PRT (see e.g. [7]), is not really “personal”, and this illustrates part of the problem: While PRT addresses some of the drawbacks (switching vehicles, stops for other users) of public transport, the concept cannot compete with the personal and door-to-door nature of the automobile. Another important practical problem is the nonexistence of the guideways network.

This same reason can be postulated to have prevented the Dual Mode paradigm also from being implemented. Our road network has incrementally evolved from the beaten paths of prehistory through the Roman roads to today’s asphalt pavement, yet consists still simply of hardened and smoothed, *passive* surfaces, hence it was easy to invest in it, to the point of constituting a “stable equilibrium” (see [11], Fig. 22), from which an effort is required to escape. Furthermore, the automation technologies in the 20th century probably did not provide enough confidence in the concept.

In the mean time, the automotive industry has progressed, making strides in fuel efficiency and safety technologies (ABS, airbags, EBD, ESP, etc.), and lately exploring automation of various aspects of driving. Cruise-control systems have been used for quite a while, but lately they have become more capable, i.e. *adaptive*; lane-following systems, parking assistants, etc. are becoming the norm. The industry has also been responding to concerns about environmental harm due to use of fossil fuels, developing alternative fuel-cars, in particular EVs and hybrids. These are not simply concept vehicles: most global brands have at least one such model *in production*, even though they are not really mainstream yet, for reasons that are well-known, and discussed briefly in Sect. 2.

Hence, most aspects of the dual-mode *vehicles* are in place in the *real world* now, even though they were developed for regular cars. The computing power at the disposal of the average individual has also increased greatly, and people would therefore be more accepting of at least some degree of automation. Hence it can be argued that the time has come for new incarnations of the Dual Mode concept to be tried. Another reason for this is the explosive increase in car ownership in populous developing nations like China and India [12], making the problem of gridlock more acute, in fact, desperate at some locations; so the public sector might be more willing to support the idea, unlike in the late 1970s US.

We would like to also argue that the ICVS paradigm, with its emphasis on single-person vehicles and on commuting in megacities, is a better way of utilizing EV technology at its present level than trying to replace cars with EVs (which the EV industry seems to be trying to do); and emphasize that the short range requirement for the vehicles and the controlled-environment nature of

FIG 1 The Greater Istanbul Area. O-1, O-2, O-3 and O-4 are 3- or 4-lane limited-access highways. Note the bottleneck nature of the two bridges (for scale: The bridges are both slightly longer than 1 km). Map Data: Google; Imagery: DigitalGlobe, TerraMetrics, Data SIO, NOAA, US Navy, NGA, GEBCO.

the network mean that the system proposed does not require any scientific or technological breakthroughs, e.g. in battery or information technologies; hence, is implementable *now*.

2. The Undesirable Consequences of Urban Gridlock and their Usual Remedies

Urban gridlock has various obvious undesirable consequences: Loss of time[1] in traffic, the associated fatigue, decrease in overall productivity and quality of life [13], accidents under the stressful conditions, hobbling of emergency services in the gridlock, and pollution caused by vehicles. We also would like to point out a usually unappreciated consequence, the "devaluation of law and order": Under gridlock conditions, drivers can be tempted to break traffic laws and regulations, or engage in behavior discourteous to other drivers[2], and law enforcement may be unable to cope due to the sheer number of violations, or reluctant, in order to not to further clog the already slow-moving traffic by pulling motorists over. Rule-abiding motorists even lose extra time because violators later have to cut in. We believe that witnessing day after day the advantage of violating traffic rules versus obeying them, has a negative effect on the value of "law and order" in people's minds; and we also believe that therefore this has a damaging effect on the fabric of the society.

Various remedies come to mind, and are discussed at various levels: One approach would like to strongly discourage personal transport, and see all commuting done by public transport. But public transport lacks the freedom and flexibility that the car promises[3], hence this approach is not realistic in a democratic society. Politicians often think that they can address the problem by building more roads, bridges, tunnels, overpasses, intersections, etc., but construction can never keep up with the growing traffic in a city undergoing unplanned growth.

Since commuter cars usually carry one person, they do not need to be big enough to carry five. A small, one- or

[1]Naturally, the author's experience relates mostly to Istanbul (Turkey), yet should be familiar to residents of other megacities. However, the fact that Istanbul is spread on two continents, separated by the Bosphorus strait, with the two bridges on the Bosphorus forming two traffic bottlenecks, probably exacerbates its traffic problems beyond its rank of 22 [1] among the most populous cities in the world: The author's commute of 10.5 km, a route traversable in 12–15 min on Sunday mornings, takes 60–90 min during rush-hours. Although not the rule, it is not uncommon for motorists to take 30–60 min to cross certain stretches less than a km long. The traffic in the city at times works so close to the limits that the slightest disturbance, e.g. an accident at a critical location, a political rally, a bit of rain or snow, can paralyze a significant portion of the city for hours.

[2]In Istanbul, emergency lane- and queuing violations are rampant, in particular.

[3]but does not always deliver, especially under gridlock conditions!

two-person vehicle—let us call it a 'microcar'—would take up less space on the road than a full-size car, be easier to park, need less parking space and a less powerful engine, cutting down on emissions and pollution, and decreasing the fuel costs. However, this obvious solution has not caught on [14] for lack of "prestige" [15] and collision safety of microcars. But a more massive car is safer only *at the expense of the less massive one* [16], therefore, overall safety cannot be improved by building more and more massive cars. Yet the individual driver seems to need more motivation for using microcars than altruistically contributing to the solution of the problem of gridlock. The small footprint advantage and safety problem are even more valid for two-wheeled vehicles (some of which are driven by two-cycle engines, hence are heavy polluters [17]).

Electric vehicles (EVs) are a possible remedy of the pollution aspect of the problem. Electric motors are more efficient than internal combustion engines [18], EVs use no power when vehicle is at rest (unlike an idling car) and allow reharvesting the vehicle's kinetic energy during braking ("regenerative braking"). They emit no pollutants, so pollution is both *reduced* and *displaced*. Their problem in one word, is the battery. Currently available batteries lag far behind a fossil-fuel tank in terms of both the energy stored per kilogram and "reenergizing time". This means heavy and/or expensive batteries, short range compared to fossil-fuel cars, and having to wait several hours at the end of the range for a "refill". For home-charging, special infrastructure may have to be installed at home, and the power grid must be able to support it; and away-from-home charging can be also socially problematic [19]. One possible solution for the charging problem, quick-swappable batteries[4], did not catch on either. Hybrids, that is, vehicles featuring both electric motors and fossil-fuel engines, the engine also producing electricity, are promising, but they bring extra complication, therefore extra cost and possibly costlier maintenance.

If we had vehicles able to drive themselves reliably, aspects of the problem would be solved or alleviated: There would be no commuter fatigue, no traffic violations, hopefully shorter commutes and fewer accidents. However, while efforts are underway to develop a self-driving ("autonomous") vehicle (e.g. [21]–[23]), it will probably take some time before such vehicles will be accepted by the society: the urban environment is just too unpredictable for people to trust software to drive a vehicle, which after all is a potentially lethal device. Less than perfect reliability, or popular impression thereof will engender worries about responsibility in case of an accident, in particular a fatal one.

[4]This was intended for the Renault Fluence ZE, however the associated company filed for bankruptcy and the car was discontinued [20]. Presumably, one reason was the unwillingness to store the very expensive ($10 000 +) batteries at the swapping stations.

3. ICVS: Synergy of the Remedies

The above discussion of various possible remedies and their shortcomings leads to a synthesis: We need small, electric cars that are as self-driving as reasonably possible today. This last requirement means that the cars should not be doing the self-driving on normal streets, hence we need a network of roads dedicated to them. Obviously, we cannot—and should not—dedicate all roads to them, we want also other vehicles, and of course, there are pedestrians, too. So the network must be sparse. We want the cars to be useful on non-dedicated streets too, especially since the network will be sparse, hence they need to be also human-drivable: A bimodal vehicle. While on the network, the car will be both powered and charged by the network, eliminating the need for any *other* charging infrastructure. Since the car is intended to be used strictly in the city, and never be far from the network, an off-network range of a few grid spacings will be enough. We envision the grid spacing to be a few kilometers, hence the needed range will be 10–15 km. This is about 1/10 of the ranges achievable by current (as of this writing) electric cars with cutting-edge (and expensive) batteries, hence would be possible with cheaper, more mainstream batteries, or smaller ones.

Since we believe that the described system is the only intelligent way to combat traffic gridlock that is also compatible with the general wish for individuality and our level of technology, we call the vehicles *intelligent commuter vehicles* (ICVs)[5] and the dedicated road network the ICV network (ICVN), and the total system ICVS. Below we discuss the system more thoroughly, stating the distinguishing main points.

3.1. The Vehicle: Small, with 200$-Battery

Most people commute alone, so the typical ICV should be a single-seater, built around a standard automotive seat. This will make its width 90–110 cm, about half that of a full-size car. The only commercially available car we know of with this form factor is the Myers NmG, formerly known as the Corbin Sparrow.

A smaller number of two-seaters can also be produced, but because they have to fit the same narrow lanes of the ICVN (see Sect. 3.2.2), they should have same width, i.e. the seats must be in tandem configuration, not side-by-side; e.g. like the Renault Twizy, and unlike the Smart ForTwo. The weight of an ICV would be about half a ton (The NmG masses 610 kg, the Twizy, 450). It can probably be mass-produced at a cost similar to cheapest cars currently on the market, since it does not need a long-range battery: The Twizy has a 7 kWh battery for 100 km quoted range, so a 1 kWh battery should be enough for an ICV. A 1 kWh Li-ion battery, while cheaper, will cost more than 1/7 of a

[5]The phrases "smart urban vehicle" and "smart commuter vehicle" also come to mind, but the acronym SUV is already taken, and the adjective "smart" is overused these days.

FIG 2 A very rough sketch for the ICVN that could be built for Istanbul. The red section is the part we propose to be built first, see Sect. 5. That part, and the blue sections follow existing highways where except for O-1, ample space is available on the two sides; and on O-1, a "ceiling" of the (dedicated) metrobus lanes can be used. Blue rectangles represent the terminals (ICVTs), giving an idea of their spacings. The turquoise sections show the rest of the ICVN. The precise terminal and segment locations would require detailed planning taking local data into account. Map Data and Imagery: Same as Fig.1; Labels Bostancı, Çekmeköy, Kavacık, ITU and BU added by the author.

7 kWh battery; but a single cheap lead-acid automotive battery has about 80 Ah nominal charge capacity, which at 12 V translates into about 1 kWh of energy, and these batteries are widely available and easily replaceable. So, until the cost of (1–2 kWh-capacity) modern batteries comes down to reasonable levels, lead-acid batteries, in their deep-cycle versions[6] could be used.

The ICV will also have a steering wheel that can be recessed into the dashboard when not needed (i.e. when in the ICVN); conductive (possibly retractable) or inductive means of electrical energy reception; an auto-pilot system to be active when in the ICVN, that consists of a lane-following system and an adaptive cruise-control system (both currently existing technologies), at least. The fact that the ICV will spend most of its time on the network, computer-guided and with other ICVs, will allay the safety concerns, mentioned in Sect. 2, that plagued other vehicles with small mass.

[6]The standard automotive (SLI—starting-lighting-ignition) batteries are not designed to be deeply discharged; but deep-cycle versions of same or similar form factor are available for more or less similar prices. One could use SLI batteries together with a deep-discharge warning system, but this would add useless mass.

3.2. The Network (ICVN)

3.2.1. The Network Topology

The simplest choice for the topology of the ICVN seems to be one such that three segments join at every vertex. Then all cells would be hexagons, with extra segments dangling towards terminals serving as exclusive entry and exit points of ICVs into the network. This would simplify the structure of connections at the vertices, and reduce the algorithm for going from one terminal to another to a short list of right turn vs. left turn instructions. However, case-by-case considerations may lead to some higher order vertices or some terminals also being vertices, sometimes of order two (e.g. Fig. 2). A segment may also contain multiple lanes, as parallel lanes can be added as the degree of adoption of the ICVS paradigm, hence the number of ICVs "on the road" increases (see Sect. 5).

3.2.2. Construction Requirements for the ICVN

A lane of the ICVN will be about 20 cm wider than the ICV, with physical barriers on each side included. These barriers serve both as a safety measure in case the lane-following system fails, and as displayers of this safety for reassuring the public; they can even also be guides for the lane-following

It is conceivable, and probably desirable in locations with scarce or expensive available real estate to build the ICVN lane(s) as elevated structures over the regular roads, or their sidewalks[7] or dividers.

system to follow. Multiple lanes serving a segment, if applicable, can be put next to each other, so that parallel-moving ICVs have a spacing of only 10–20 cm, in contrast to lanes on ordinary roads, where allowance has to be made for much larger safety spacing, and also large vehicles that may use the road. For example, the standard lane width on American highways is 3.7 m, whereas the Dodge Ram 3500 DRW, the widest current small vehicle (car/SUV/van/pickup truck) has a width of 2.44 m [24]. Therefore one ordinary lane can be expected to be replaced by three ICVN lanes, if necessary.

Similarly, no allowance needs to be made for the occasional very heavy vehicle, either, since the ICVN will be dedicated to the ICVs. Therefore, the structural requirement for ICVN lanes or segments will be much less severe than ordinary roads. It is conceivable, and probably desirable in locations with scarce or expensive available real estate to build the ICVN lane(s) as elevated structures over the regular roads, or their sidewalks[7] or dividers. At other locations lanes may be built next to the roads, or cross over parks, even cemeteries via bridges supported by unobstructive pylons. When and if the ICVS becomes widespread enough so that traffic of regular cars (see Sect. 5) decreases significantly, one lane of some three-lane streets or urban highways can be replaced by ICVN lanes.

3.3. The Commute

A commuter will start her commute by driving from her starting point to the nearest terminal. There, she will enter a destination terminal into the ICV's computer, which will decide on the route to follow. Since for all but the simplest networks many choices will exist for the route between two terminals, this decision can also take into account the traffic information for various segments of the network, and can be updated during the trip.

During the drive between terminals, the commuter can relax or work. For working or reading or watching TV or playing games, the steering wheel can be taken out of the way by recessing it into the dashboard. After exiting from the destination terminal, which is presumably the one nearest her target, she will complete her commute with a short drive.

[7]In some seasons, such structures may provide protection from the sun or rain for pedestrians!

3.4. The Powering and Charging of the ICV by the Network

When the commuter enters the network through a terminal, electrical contact will be established between the ICV and the network, charging the battery and powering the vehicle. Direct powering of the vehicle by the grid means that the performance of the ICV in the network is not limited by the electrical current capability of the battery, therefore will probably be better than the performance outside. The commuter will exit with more charge in her ICV's battery than when she entered the network, in fact, possibly with a full battery, so will not need to charge the ICV elsewhere. Of course, her bank account or credit card will also be appropriately charged for the trip!

3.5. The Terminals and the ICVN Cell Size

Terminals (ICVTs) should be located at or near major business centers, large institutes of higher education, shopping areas and residential concentrations; the problem of deciding on their location being not much different from the one for subway stations. We estimate that terminals will be typically 2–5 km away from each other, "as the crow flies", the typical cell size will be similar. This means that i.e. for a 25 km commute, one could expect to drive 2–7 km on ordinary roads/streets, depending on one's origin and destination relative to the terminals; and spend the rest on the ICVN, the car driving itself. Or one can use an ICV for running various errands, including shopping, since most such targets will only be a few km away from terminals, given the average terminal spacings. Once the ICVs are adopted by a significant fraction of commuters, the number of regular-size cars will decrease on ordinary roads/streets, making driving there also relatively painless compared to the gridlock situation, both at the beginning/end of a commute, or for the purpose of running errands.

Note that as stated earlier, one should not imagine reconfiguring all streets or roads of a city for ICVs; since the cell size will span many city blocks, the total length of the ICVN will be a few percent of the total street network. Given also the much less stringent space and mechanical demands of the ICVN compared to ordinary roads/streets of similar length, the effort for its construction will be comparable with the continuing construction effort to maintain, upgrade and extend the ordinary street network in a megacity; i.e. we are not talking about an unrealistically expensive undertaking.

3.6. When ICVs are not Appropriate

For multi-person or out-of-town trips, a household might still own a regular-size car (fossil-fueled or hybrid), or rent one when needed, depending on the number of members of the household and the expected frequency of such trips. Since many households currently own more than one car, the widespread adoption of ICVs will both decrease the number of regular-size cars owned, and their number on the city streets, since these cars will spend most of their time either parked, or out-of town.

> The increased capacity follows from the ICVN forming an extra transport channel and the ICVs having a much smaller footprint.

3.7. Some Implementation Details
The main points comprising the paradigm were listed in subsections above, however it was left unspecified how the guiding, charging etc. will work. The main reason is that they are more or less standard engineering procedures once the desiderata are specified. The point of the ICVS paradigm lies not in introducing new technologies, rather, in suggesting how to synergistically combine existing technologies in the way that makes most sense in addressing the problem at hand, and arguing that this *can* be done. For example, it is essential that the ICVs should be guided along a lane in the network, and occasionally merge with those in other lanes (e.g. at vertices); but how these tasks are accomplished is not essential for the paradigm. Still, we make a few comments below.

Lane-following systems have been introduced in cars in recent years; and in the controlled environment of the ICVN, the problem is much simpler, and lanes could even be followed by "low-tech" methods, mechanically following one or both of the barrier-rails on each side of the lane. Cruise control has existed for a long time, and the adaptive variety for the last decade or so, hence speed control and avoiding hitting the vehicle in front is not going to be a problem. There are also standard methods for transferring power to an electric vehicle on the road/track, in widespread use for trains, subways, trams, trolleybuses and even amusement-park bumper cars.

Vertices would be very simple indeed, if they were all of degree three (three segments joining), and if all segments were single-lane and directional. Even though occasional exceptions may be needed, vertices of degree three are realistic, and that is what we will assume. Directional segments would make the commuting trips somewhat longer, and also may necessitate construction of more segments before the network becomes usable (Sect. 5); hence we will assume that all segments have at least one lane each in both directions. Hence vertex design will need careful planning, especially keeping in mind the possibility of more lanes being added in the future.

Encountering a vertex of degree three means a right or left turn. For multilane segments, a certain number of the lanes (depending on demand for either segment) turning right and the others turning left would simplify the vertex, as opposed to every incoming lane of a segment feeding into every outgoing lane of the other segment(s). This will necessitate in-segment lane-changing arrangements at designed locations, which will also help equalize the traffic load between lanes, when necessary. Lane changing and merging are basically the same problem, which can be handled by simple algorithms, as long as nearby ICVs, including those on the merging lane, can be detected and tracked; and even today, some automobiles feature systems that can perform this tracking, ultrasonically or by RF or optical techniques.

4. Advantages of the ICVS
Obviously, any proposal for the solutions of the problem of traffic gridlock and associated pollution should feature increased person-transport capacity and reduced pollution. In the ICVS paradigm, reduced *and* displaced pollution follows from the electric and less-massive nature of the ICVs. The increased capacity follows from the ICVN forming an extra transport channel *and* the ICVs having a much smaller footprint, as elaborated on below. We also list other advantages of the paradigm that make it more desirable, realistic and complete compared to possible remedies that are discussed in section 2, in other words, how the paradigm can solve the other problems detailed in the same section.

4.1. Increased Person-Transport Capacity
The person-carrying capacity of a road is given by

$$C = d\,w\,v \qquad (1)$$

where C is the capacity in persons/unit time, d the person-density (number of people per unit area), w the width of the road, and v the speed of the vehicles. For single-occupancy vehicles, d will be equal to the density of the vehicles, but for multiple-occupancy, it will be multiplied by the number of occupants; hence main advantage of public transport is in the high d.

In cases where a lane of ordinary road is converted to ICVN lanes, an improvement factor of 3–6 could be achieved for that lane just from the increase in d, since three ICVN lanes will fit into an ordinary lane. ICVs on unconverted streets will lead to a density higher by a factor of 2–4. The average speed is less than 30 km/h, sometimes in the single digits, under gridlock conditions; that will certainly increase, bringing another multiplicative factor. So, the capacity of ordinary streets will increase 2–10 times, and the ICVN will bring *extra capacity,* as mentioned above.

The average speed in the network will be a monotonic function of the ratio of the total length of the network lanes to the total number of ICVs:

$$v_{\mathrm{avg}} = f_{\mathrm{mon}}(L_{\mathrm{tot}}/N_{\mathrm{tot}}) \tag{2}$$

The ratio $L_{\mathrm{tot}}/N_{\mathrm{tot}}$ can be kept reasonable, above some critical value: In the build-up phase, both numbers will be growing, and once the network covers all of the metropolitan area with the desired cell size, one will have to add more lanes to existing segments, until the number of ICVs also saturates. This addition can take the form of conversion of one lane of a multilane street into ICVN lanes, if eventually the number of regular cars on the road decreases enough due to adoption of ICVs.

Only if and when it is not possible to increase L_{tot} any more, one should worry about too many ICVs clogging the network, a particular case of the Downs-Thompson paradox [25–27]. Depending on the metropolitan area, it is possible that this situation will never be reached. If it is, the authority/company running the ICVN can keep the ratio $N_{\mathrm{tot}}/L_{\mathrm{tot}}$ under a desired number: The ICVs need to be registered for accounting purposes, so a (running) cap can be put on registrations of ICVs. Note that this is not realistic for ordinary cars, since they can be in principle registered at one location and used at another.

Even if the network is crowded, it should work smoother than ordinary traffic with similar crowding since the motion of the vehicles will be free from human idiosyncrasies.

4.2. Parking Advantages, Automated Parking Possible

Obviously, the small vehicle footprint for the ICVs will enable more efficient use of roadside parking spaces, but the real difference will come from the guided mode of the ICVs: Parking lots can be arranged like miniature ICVNs where one can leave the car at the entrance, the car parks itself guided by the parking-lot computer, and returns to the gate when the owner wants to pick it up. Parking lots can also charge the ICVs. Another feature is that ICV parking—guided or unguided—can be arranged in the basement of many buildings, because of the small size and mass of the vehicles.

4.3. No Need for Separate Charging Infrastructure

Obviously, with ICVs being charged while traveling on the ICVN or parked in lots near/at the workplace, and being used only in the metropolitan area, no charging stations or home-chargers will be needed.

4.4. No Need for Breakthroughs in Battery Technologies

Two run-of-the-mill lead-acid batteries could provide the range an ICV needs (see Sect. 3.1). Also, since the ICVs will be grid-powered on the network, the batteries will be only used for power on a small fraction of the time, increasing battery life.

4.5. No Need to Wait for the ICVN to be Completed Before Using It

Commuting is usually a point-to-point route, repeated every day. Hence even if a small part of the ICVN was initially constructed, for those commuters whose commuting route is included in the network, it would already represent a large utility, hence they would be motivated to buy an ICV without waiting for the network to be completed. This would ease the minds of other potential users, and so on; and a smart ordering of the segments to be built (see Sect. 5) would facilitate adoption.

4.6. Accidents, Fatigue and Emergencies

Reduction of accidents due to the largely eliminated human factor, and significantly decreased commuter fatigue due to shorter commuting time and decreased stress are obvious advantages. Due to smoother traffic flow on the ordinary roads, the response time of emergency services will decrease, reducing fatalities, injuries and property damage in accidents and non-traffic-related emergencies, compared to the gridlock situation.

4.7. Backward and Forward Compatibility

The proposed system is obviously backward-compatible: It does not require that the existing transport infrastructure and hardware be scrapped, and provides for the possibility of a smooth transition (Section 5). The question then is, what future social and/or technological developments would render the paradigm obsolete; relevant since it will not make sense to implement the paradigm if the expected obsolescence time is comparable to the expected transition time. Obviously, the solution of the range and charging-time[8] problems of EVs is irrelevant to problem of traffic gridlock; it would only mean that we would consume less energy and pollute less while we still lose time and get tired/frustrated waiting in traffic.

Even the development of self-driving technology would probably not make the ICVS paradigm obsolete; because with the human factor around, no such technology can be

[8]Note that the charging-time problem is not simply a battery problem: Imagine a 20 kWh battery (that of the Renault Fluence ZE is 22 kWh) can be charged in 3 min, comparable to filling a gas tank. This will mean a power flow of 400 kW, even assuming perfect charging efficiency! This by far exceeds the current power ratings of households, and in real life will have to be even higher, since the process will also have some inefficiency.

100% reliable. Even if the technology were in compulsory use in all vehicles, eliminating human drivers, there would still be unpredictable pedestrians around except on limited-access highways. And even if all these problems were solved, including evolution of pedestrian codes of behavior compatible with self-driving vehicles, development of legal codes for the same and means for their enforcement such as vehicle cameras for determination of fault in case of accidents (let us call this the totally-self-driving, TSD, paradigm), the ICVs could be converted to TSD vehicles, since short of development of teleportation technology, small vehicles would be needed for commuting in megacities even in the TSD paradigm; and the ICVN could still be continued to be used as just another road. Hence the large-scale adoption of the ICVS paradigm would constitute a part of the transition to the TSD paradigm, if and when such is developed. However, this might take a long time, since it may require significant advancement in the fields of artificial intelligence and/or cognitive science, given that TSD vehicles will have to interact with pedestrians.

The private sector will not be motivated to produce the ICVs before significant demand forms for them, which will only happen if a usable fraction of the ICVN is built first, and commuters are convinced of its utility.

5. A Strategy for Transition

Even though we have argued that the construction of an ICVN will be cheaper than roads of the same length, the full network will require a considerable investment. Furthermore, the private sector will not be motivated to produce the ICVs before significant demand forms for them, which will only happen if a usable fraction of the ICVN is built first, and commuters are convinced of its utility. Hence it seems that the public sector will have to kick-start the system.

We envision that the full network, including locations of the terminals, vertices and segments be planned for the whole metropolitan area before beginning any construction. Then some contiguous set of segments should be chosen for having large number of potential users that can be expected to be "early adopters", for example, young professionals and university students/faculty; and construct those sections and terminals. The public authority (municipality, etc.) can have the initial set of a few thousand ICVs be produced on contract, and sell them to these initial users on long leases. Then, others will presumably start demanding ICVs, and the private sector will respond. One could have ICV buyers register their home and work addresses, and use that information to decide which segments and terminals to construct next. The whole network can be expected to be finished in 5–6 years, or at most a decade; some segments getting extra lanes after the first few years.

For example, for İstanbul, the Bostancı-Maslak axis (Figs. 1–2) could be the first part of the network to be constructed. The Maslak business district (to a smaller extent, Kavacık) and the prestigious Istanbul Technical (ITU) and Boğaziçi (BU) universities would be the morning targets, the affluent or upper-middle-class residential neighborhoods of Bostancı, Ataşehir, Çekmeköy and the hinterland of Kavacık evening targets for a significant subset of the young professionals and faculty/staff involved. These people would be expected to have high probability of willingness to serve as "beta testers"; and since BU and ITU are public universities, giving ICVs to their faculty/staff (maybe even students) on long-term easily repayable loans would be socioeconomically and politically acceptable. Also, the whole route follows existing highways (mostly the four-lane O-2), around which ample space is available for the construction of the ICVN lanes.

7. Summary and Conclusions

To address traffic gridlock and associated problems in metropolitan areas, we have proposed the ICVS paradigm, *realizable with present technology and reasonable expense*, but requiring active participation and support by the local governing authorities. The paradigm consists of the introduction of small (standardized width) electric vehicles called ICVs and construction of a sparse road network, the ICVN, dedicated to these vehicles. The vehicles would be bimodal, human-driven on ordinary roads and self-driving in the network, which would constitute a controlled environment, and also charge and power the vehicles. The network would cover the metropolitan area, sparse enough that its construction is not very disturbing and is reasonably affordable, but dense enough that any given point in the area is a few kilometers away from the nearest entry/exit point to the network. Therefore a range of 10–20 km would be enough, so that cheap lead-acid batteries can be used; moreover, a separate charging infrastructure is not needed. The controlled-environment nature of the network would also make the self-driving feature realizable with existing technology.

Advantages of the paradigm are decreases in commuting time, energy use, pollution, commuter fatigue and accident rate; and easier parking. In fact, we suggest that the paradigm is the most reasonable way of utilizing EV technology at its present level, and combines the best of public and personal transport: The paradigm enables people to commute with their personal vehicle, but with the conveniences and without the inconveniences of public transport, that is, without having to drive on one hand, and without having to stand in a public-transport vehicle or waiting for the arrival of one at transfer points, on the other hand.

Unlike most of the dual mode suggestions in the literature, we do not suggest the network should be able to accommodate may kinds and sizes of vehicles. This makes the network easier to build, both space-wise and strength-wise, and also takes into account that an important part of the problem of gridlock is the use of most full-size cars by one person each. In our scheme, such cars, hybrid or otherwise, would only be needed for multi-person or out-of-town trips, therefore would probably be owned at most one per household or rented when needed.

In short, we believe that the ICVS paradigm described in this work is the *only* realistic medium-term solution for the problem of traffic gridlock and associated problems in metropolitan areas; the *only* intelligent way of using EV technology at its current level; and it can be implemented *now*. It *does* require political and fiscal commitment on the part of the public sector, but with the gridlock problem having reached paralyzing proportions in many megacities, the authorities may just be desperate enough to be willing to attempt the jump ([11], Fig. 22) over the potential barrier.

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References

[1] R. L. Forstall, R. P. Greene, and J. B. Pick, "Which are the largest? Why lists of major urban areas vary so greatly," *Tijdschrift voor economische en sociale geografie*, vol. 100, pp. 277–297, 2009.

[2] D. Fichter. (1964). Individualized automatic transit and the city, B. H. Sikes, Chicago, IL. [Online]. Available: http://www.advancedtransit.net/files/IndividualizedAutomatedTransit.pdf

[3] J. E. Anderson et al., eds. *Personal Rapid Transit.* Minneapolis, MN: Institute of Technology, Univ. of Minnesota, 1972. [Selected papers presented at the 1st National Conf. Personal Rapid Transit on Nov. 1–3, 1971, at the Univ. of Minnesota, Minneapolis, MN].

[4] J. E. Anderson and S. H. Romig, eds. *Personal Rapid Transit II.* Minneapolis, MN: Univ. of Minnesota, 1974. [Papers presented at the Int. Conf. Personal Rapid Transit on May 2–4, 1973, at the Univ. of Minnesota, Minneapolis, MN].

[5] Technical Papers. 1975 Int. Conf. Personal Rapid Transit, v. I and II, Univ. of Minnesota, Minneapolis, MN and Univ. of Colorado, Denver, CO [Papers presented at the Int. Conf. Personal Rapid Transit on Sept. 16–19, 1975, at Denver, CO].

[6] (1978). Personal Rapid Transit IV Indianapolis. *Proc. Advances Transit and Urban Revitalization—An Int. Dialogue Conf. "PRT IV."* [Online]. Available: http://www.advancedtransit.net/content/personal-rapid-transit-iv-indianapolis-1978

[7] S. S. McDonald, "Personal rapid transit and its development," in *Transportation Technologies for Sustainability*, M. Ehsani, F.-Y. Wang, and G. L. Brosch, Eds. New York: Springer-Verlag, 2013.

[8] D. Baumann, "Dual mode," in *Proc. Advanced Urban Transportation Systems Conf.*, M. A. Williamson, Ed. Carnegie-Mellon Univ., Pittsburgh, PA, May 25–27, 1970. CMU, Pittsburgh, PA: Transportation Research Institute, 1970.

[9] Transportation Research Board, in *TRB Special Rep. #170—Dual mode transportation: Proc. TRB Conf.*, May 29–31, 1974, Natl. Acad. Sci., Washington, D.C., 1976.

[10] P. Benjamin et al., in *Analysis of Dual Mode Systems in An Urban Area (Four Volumes, Report DOT-TSC-OST-73-16A-1)*, Cambridge, MA: Transportation Systems Center, 1973.

[11] C. Ehlig-Economides and J. Longbottom. (2008). *Dual Mode Vehicle and Infrastructure Alternatives Analysis.* [Online]. Center for Energy, Environment and Transportation Innovation Report, Texas Transportation Institute, TAMU. Available: http://tti.tamu.edu/documents/0-5827-1.pdf

[12] J. Dargay and D. Gately, "Income's effect on car and vehicle ownership, worldwide: 1960-2015," *Transp. Res. Part A*, vol. 33, pp. 101–138, 1999.

[13] M. D. Meyer et al. (1989). A toolbox for alleviating traffic congestion. [Online]. Institute of Transportation Engineers. Available: http://ntl.bts.gov/lib/17000/17800/17841/PB2001104711.pdf

[14] P. Mock, Ed. *European Vehicle Market Statistics Pocketbook 2013.* [Online]. Available: http://www.theicct.org/sites/default/files/publications/EU_vehiclemarket_pocketbook_2013_Web.pdf (Fig. 2.3)

[15] E. Jacobson and J. Kossoff, "Self-percept and consumer attitudes toward small cars," *J. Appl. Psychol.*, vol. 47, pp. 242–245, 1963.

[16] M. J. White, "The 'Arms Race' on American Roads: The effect of sport utility vehicles and pickup trucks on traffic safety," *J. Law Econ.*, vol. 47, pp. 333–355, 2004.

[17] A.-M. Vasic and M. Weilenmann, "Comparison of real-world emissions from two-wheelers and passenger cars," *Env. Sci. Technol.*, vol. 40, pp. 149–154, 2006.

[18] A. Faiz, C. S. Weaver, and M. Walsh, *Air Pollution from Motor Vehicles: Standards and Technologies for Controlling Emissions, Energy Policy*, Appendix 2, World Bank Publications, 1997.

[19] N. Caperello, K. S. Kurani, and J. TyreeHageman, "Do you mind if I plug-in my car? How etiquette shapes PEV drivers' vehicle charging behavior", *Transportation Research Part A: Policy and Practice*, 54, 155-163 (2013).

[20] T B Christensen, P Wells, L Cipcigan, "Can innovative business models overcome resistance to electric vehicles? Better place and battery electric cars in Denmark," *Energy Policy*, vol. 48, pp. 498–505, 2012.

[21] The EN-V concept, GM, The EN-V concept. [Online]. Available: http://www.gm.com/vision/design_technology/emerging_technology.html

[22] DARPA. [Online]. Available: http://archive.darpa.mil/grandchallenge

[23] Wikipedia. Google driverless car. [Online]. Available: http://en.wikipedia.org/wiki/Google_driverless_car

[24] Wikipedia. List of automotive superlatives. [Online]. Available: http://en.wikipedia.org/wiki/Car_superlatives

[25] A Downs, *Stuck in Traffic: Coping with Peak-Hour Traffic Congestion*. Washington, DC: Brookings Institution, 1992.

[26] J. M. Thomson, "Methods of traffic limitation in urban areas," Working Paper 3, Paris, OECD (1972).

[27] Wikipedia. Downs-Thompson paradox. [Online]. Available: http://en.wikipedia.org/wiki/Downs–Thomson_paradox (accessed 31 Mar. 2014)

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