# Sustainable Urban Mobility through Light Electric Vehicles

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A typical American automobile weighs twenty times as much as its driver. Although a comfortable chair occupies only about 10 square feet, a parked car generally uses up 200 square feet of valuable urban real estate. Furthermore it is parked about 80 percent of the time – not only taking up space that could be put to better use, but also costing money, consuming materials, and embodying energy. Although urban speed limits are usually set at 25 to 35 miles per hour, it is engineered for a top speed of over a hundred miles per hour. Although urban trips are measured in miles or tens of miles, it has a 300-mile range. And, of course, it is powered by gasoline – a rapidly diminishing, non-renewable resource that arrives through increasingly problematic supply chains and emits greenhouse gases from the tailpipe.

It is not my purpose here to demonize automobile designers or car companies for foisting this massive over-engineering upon us. We have arrived at this point through a century-long evolutionary process involving diverse protagonists, and it has complex social, political, and economic roots. But I do want to argue that it is time for a radical change. We should take this moment of economic crisis – one that is particularly strongly felt in Detroit – as an opportunity to reinvent urban personal mobility from the ground up. We can and should create systems that provide very high levels of mobility service while minimizing energy consumption and supporting a large-scale shift to clean, renewable, more local energy sources.

Lightweight, smart battery-electric vehicles are one obvious and essential part of such systems. Recharging infrastructure is a second part. The integration of electric vehicles and their recharging infrastructure with smart electric grids – to enhance the efficiency of grids and to make them friendlier to clean, renewable, but intermittent energy sources – constitutes a third part. The organization of electric vehicles into highly efficient mobility-on-demand systems is a fourth part. Finally, a powerful computational back-end – one that senses and meters the current state of the system, processes large amounts of information in real time, computes optimum responses to evolving demands and conditions, and controls overall system operation – is necessary for effective operation of these systems.

Integrating (1) smart battery-electric vehicles, (2) recharging infrastructure, (3) smart electric grids, and (4) mobility-on-demand through (5) urban-scale electronic "nervous systems" provides the foundation for creating smart sustainable cities. These cities achieve high levels of operational efficiency – and, in particular, energy efficiency and carbon minimization – through optimized realtime response to the dynamically varying demands created by the daily activities of their citizens and by variation in the climate and other exogenous factors.

**The GreenWheel electric bicycle**

The most obvious starting point for creation of such systems is the bicycle. This is an extraordinarily elegant and efficient vehicle type with a tiny footprint. (Compare a bicycle lane to a car lane, and a bicycle rack to a carpark.) However, it suffers from some obvious limitations. It is unattractive in bad weather. In many urban contexts the streets and roads don't accommodate it gracefully and safely. It works beautifully for the fittest among us, but not so well – particularly where it is hilly or hot – for those with physical limitations.

But all of these limitations can be overcome. First, it is a very inexpensive vehicle type, so it does not have to be used in all weathers. Where it is not expected to be the exclusive means of personal mobility, and forms part of an ecosystem of energy-efficient vehicles, it can be used only when and where it makes sense.

The problem with bicycles on urban streets and roads exists because these thoroughfares are predominantly occupied by much larger, heavier, faster vehicles. But this isn't a given. Under the strategy that I shall develop here, vehicles generally become smaller and lighter, making most streets and roads much friendlier to both pedestrians and bicycles. This will not happen instantly, but eventually we will reach a tipping point.

Finally, it is now possible to equip bicycles with sophisticated electric assist, thus making them useful and attractive to many more people. Electric-assist bicycles are not a new idea, and in fact, tens of millions of them are sold every year in China. But the development and convergence of several new technologies has recently opened up some powerful new design approaches.

The GreenWheel, developed by the MIT Media Laboratory's Smart Cities group, demonstrates this (figure 1). The GreenWheel is a compact, modular hub unit that provides electric assist and regenerative braking, and also contains lithium-ion batteries. Its gearing is arranged to minimize spinning mass, so that it does not affect the ride dynamics.

GreenWheels are mechanically and electrically self-contained, and can be fitted to any standard bicycle. They do not require bicycle redesign, the purchase and installation of complex kits, or purchase of entire new bicycles. You just remove the back wheel of your bike and replace it with a GreenWheel. Thus GreenWheels provide a quick, easy, inexpensive way of upgrading the world's vast existing bicycle fleet, and an opportunity to enhance the functionality of existing bicycle models.

The electric motor of a GreenWheel is digitally controlled, which enables precise management of torque. This is usually provided from a wireless controller on the handlebars (much like a motorcycle throttle), which allows the rider to control the motor with one hand, and eliminates the need for a wire running to the hub. Where local regulations require it, a wire can of course be added. It is also possible to provide control from the pedals.

*Figure 1: The GreenWheel modular electric bicycle wheel.*

In combination with GPS and sensors, GreenWheel digital controllers can also manage entire trips. They can, for example, be programmed to require a constant level of physical exertion throughout the trip – whether going uphill, downhill, or on the flat. The level of effort may be set to zero (full electric assist, no pedaling), to some intermediate level that is comfortable for the particular rider, or to serious exercise level (the motor functions as a generator, providing resistance like an exercise machine and charging the batteries).

GreenWheels do not consume much electricity, and can easily be recharged overnight, from a standard 110-volt outlet, for the following day's riding. They can also be charged inductively from specially designed bike racks. When these racks are widely deployed, GreenWheel bicycles become like electric toothbrushes in their holders: whenever they are not in use they are replenishing their charge.

Introducing GreenWheels is an easy first step towards creating electric vehicle fleets for urban personal mobility. The technology is simple, and the costs and risks are low.

Individuals can purchase GreenWheels for their own use, and employers, merchants, and government agencies can encourage consumer acceptance by deploying recharging racks at convenient locations.

**The RoboScooter folding electric scooter**

In many cities throughout the world, motor scooters provide the least expensive form of powered personal mobility. They are inexpensive to acquire and operate, and they provide higher speeds and greater carrying capacity than bicycles. Their road and parking space demands are minimal since they have footprints not much larger than bicycles: they are not constrained to wide lanes like automobiles: and they can park (often illegally) in very small spaces that could not accommodate automobiles.

One downside of scooters is that, unlike enclosed powered vehicles, they do not provide weather protection – making them most suitable for use in temperate climates. They provide a little more crash protection than bicycles, but not nearly as much as automobiles. And gasoline-powered motor scooters are a major source of urban noise, local air pollution, and carbon emissions.

The tradeoff points that scooters represent make them particularly popular in the developing world. They are also popular in European cities, where narrow streets and crowded conditions are inhospitable to automobiles. In the United States they have a limited use as primary personal transportation, they have recreational uses, and in cities with severe winters their use is mostly seasonal.

The RoboScooter folding electric scooter, developed by the Smart Cities group, maximizes the advantages of the scooter while minimizing some of its disadvantages (figure 2). It features in-wheel electric motors, lithium-ion batteries, and a cast aluminum frame. To minimize parking footprint – which is a key consideration in many contexts where scooters are popular – it folds up into a very compact configuration. For contexts where this is not necessary, the RoboScooter can also be produced in non-folding models.

RoboScooters are designed to serve as approximate functional equivalents of 50cc gasoline-powered scooters. They are, however, clean, silent, and occupy less parking space. They are also much simpler – consisting of about 150 parts, compared to the 1,000 to 1,500 of an equivalent gasoline-powered scooter – which simplifies supply chains and assembly processes, reduces vehicle costs, and simplifies maintenance.

Like GreenWheels, RoboScooters can be recharged in their racks. Their battery packs are also small enough to be conveniently removable, which opens up the possibilities of charging spare batteries at home, and of battery vending machines that accept discharged batteries and provide fully charged ones.

*Figure 2: The RoboScooter folding electric motor scooter.*

**The CityCar electric automobile**

The CityCar electric automobile, developed and prototyped by Smart Cities, is designed to meet the demand for enclosed personal mobility – with weather protection, climate control and comfort, secure storage, and crash protection – in the cleanest and most economical way possible (figure 3). It weighs less than a thousand pounds, parks in much less space than a Smart Car, and is expected to get the equivalent of 150 to 200 miles per gallon of gasoline. Since it is battery-electric, it produces no tailpipe emissions.

The architecture of the CityCar is radical (figure 4). It does not have a central engine and traditional power train, but is powered by four in-wheel electric motors. Each wheel unit contains drive motor (which also enables regenerative braking), steering, and suspension, and is independently digitally controlled. This enables maneuvers like spinning on its own axis (an O-turn instead of a U-turn), moving sideways into parallel parking spaces, and lane changes while facing straight ahead.

Shifting drive to the corners in this way enables the CityCar to fold to minimize parking footprint, and to provide front ingress and egress (since there is no engine in the way). This dramatically changes its relationship to streets and cities. It can park nose-in to the curb in far less than the width of a traditional parking bay, and it can park at very high densities. It is possible to park three or four CityCars in the length of a traditional parking bay.

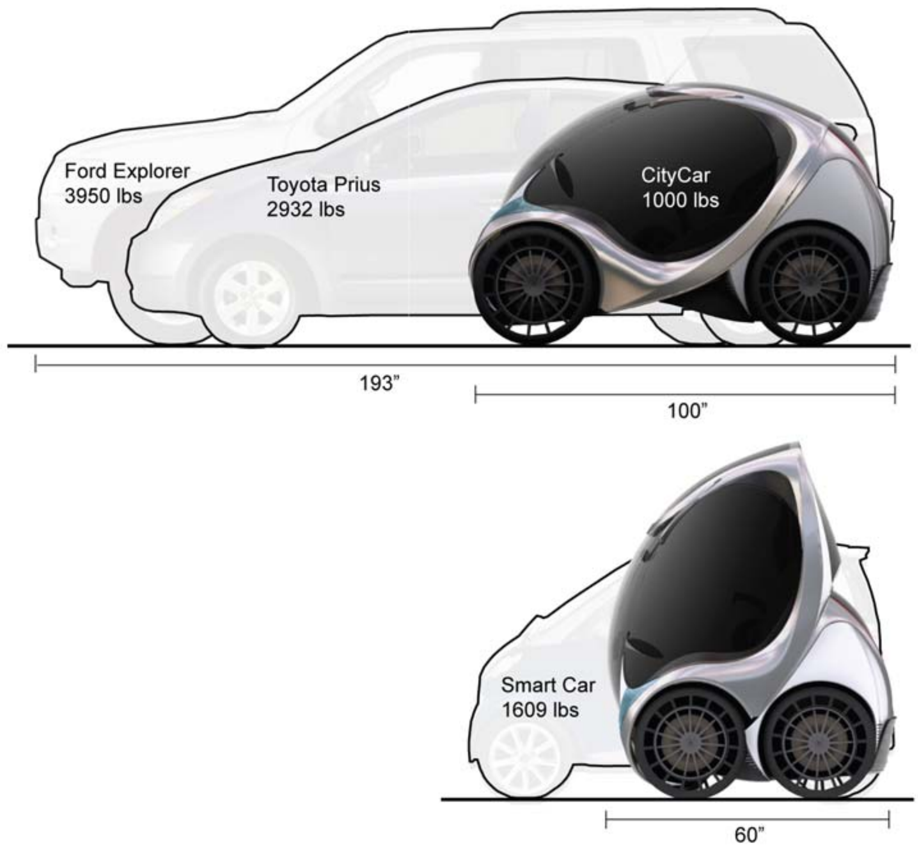


*Figure 3: The CityCar compared to traditional automobiles.*

The front compartment of a CityCar accommodates passengers and the rear compartment provides generous storage for baggage, groceries, and so on. When a CityCar folds, the baggage compartment remains level and low for easy access.

CityCars accommodate two passengers, which suits them to meeting the requirements of the vast majority of urban trips without excess capacity. They are designed for intra-urban trips, which are fairly short between recharge opportunities. This fits them gracefully to the capabilities of battery technologies that are presently available or likely to be available in the near future. They are not designed for inter-city travel, for which different technologies are more appropriate.

Overall, CityCars are smaller and simpler than traditional automobiles, and in principal much more economical to manufacture. Most of the mechanical complexity is encapsulated in the wheel units. These can be designed to have a standard interface to the chassis, and their cost can be driven down through competition and innovation – much as with disk drives for personal computers.

*Figure 4: The features of the CityCar.*

Lithium-ion batteries are housed in the floor of the CityCar, which provides a large amount of space, keeps the center of mass low, and facilitates cooling. Recharging can be accomplished with inexpensive home charging units, and with units installed at workplace parking structures. More interestingly, it seems feasible to provide automatic recharging in parking spaces, much like the recharging of electric toothbrushes in their holders. This extends the principle of rack recharging as employed with the GreenWheel and the RoboScooter.

Two-seat CityCars do not, of course, meet the requirements of urban trips. But we assume that a diverse, carefully balanced urban vehicle fleet will also contain a component of four-seaters and larger vehicles. By providing two-seat CityCars, particularly in mobility-on-demand systems, we can take care of a large proportion of the demand with great efficiency.

**Recharging infrastructure**

Obviously battery-electric vehicles have finite ranges, and due to the relatively low energy density of batteries, these ranges tend to be significantly less than those of gasoline-powered vehicles. Furthermore, it generally takes longer to recharge batteries than to fill tanks with gasoline. An associated problem is that of “range anxiety” – the worry of drivers that they will run out of charge and be stranded by the side of the road. Recharging infrastructure must be designed to deal with these issues. Strategies will vary with vehicle type.

The difficulties are minimal with GreenWheels and other electric-assist bicycles. Electricity consumption is not high, and bicycle trips are usually quite short, so it is not necessary to carry large quantities of batteries that take a long time to charge. Range anxiety is not a big problem, since you can always pedal if you run out of charge. Overnight recharging at home from safe, inexpensive 110-volt chargers, combined with recharging in bike racks, should suffice to meet the needs of GreenWheel riders. GreenWheels thus provide an inexpensive, low-risk way for cities and electric utilities to begin experimenting with the deployment and management of electric vehicle recharging infrastructure.

Since RoboScooters are heavier, and are used for longer trips, they make more demands on recharging infrastructure. However, the combination of home and workplace charging units, combined with recharging racks, still seems workable. You cannot pedal a scooter if you run out of charge, and you cannot push it very far, but removable battery packs provide emergency backup and alleviate range anxiety.

Battery-electric automobiles, such as the CityCar, provide the greatest recharging infrastructure challenge since they are larger, heavier, require better acceleration and higher speeds, and travel longer distances. And traditional approaches to sizing batteries and providing recharging infrastructure have some severe disadvantages.

One traditional approach, as exemplified by the Tesla electric sports car, is to design electric automobiles for something like the 300-mile range of gasoline-powered automobiles. This results in battery-heavy, extremely expensive automobiles that cannot effectively meet the requirements of inexpensive, daily personal mobility on a large scale. It puts large numbers of batteries, which eventually have to be recycled, into circulation. And it means either that recharging times are long or extremely expensive high-speed chargers must be used.

Another approach is battery swapping – a very old idea that has recently been revived. A major problem with swapping large, heavy batteries into and out of automobiles is that it requires complex, potentially unreliable, mechanical equipment to accomplish the task. (It is not like swapping a small battery pack in and out of a RoboScooter by hand.) It does little to minimize the number of batteries in circulation. And it relies – probably unrealistically – upon most drivers following good battery management practices, so that poorly managed, bad batteries do not get swapped into the vehicles of unsuspecting motorists.

A third approach is to employ plug-in hybrids, extended range electric vehicles like GM's Volt, and other vehicle types that reduce the need for recharging infrastructure by augmenting vehicle batteries with gasoline engines. But these vehicles are heavy and expensive by comparison with CityCars. Furthermore, to the extent that they still rely upon combustion of gasoline, they continue to be dependent upon petroleum and they continue to emit greenhouse gases.

A more attractive approach, I believe, is to provide ubiquitous, automatic recharging in parking spaces. Assuming that urban trips are relatively short, and that vehicles are typically parked long enough between trips to transfer sufficient energy, this provides effectively infinite range within urban areas. It means that drivers never have to worry about filling up, plugging in, or running out of energy. And it shifts as much hardware as possible out of the moving vehicle and into the fixed infrastructure, where it does not have to be carried around. Recharging infrastructure can be deployed incrementally, beginning with locations where demand is highest and proceeding over time to locations where demand is lower.

This raises the total cost of recharging infrastructure, since it requires more recharging stations, and perhaps expensive high-speed stations. And unlike home recharging at night, it shifts responsibility for investing in recharging infrastructure to the public sector, to employers and merchants, and to private parking facility operators. Or, under appropriate business models, the responsibility could be shouldered by electric utilities.

This shift does not seem unreasonable. Public investment in recharging infrastructure is analogous to the massive investments in roads, bridges, interstate highways, and so on that was an essential enabler of the large-scale uptake of gasoline-powered automobiles in the early decades of the twentieth century. It provides an avenue for public-sector investment to encourage a shift to a clean, green economy. At the municipal level, investment in recharging infrastructure can provide a town or city with a competitive advantage. From the perspective of merchants it is a way to attract customers. And for parking facility operators it enables a valuable additional service.

From the perspective of electric utilities, ubiquitous automatic recharging enables the integration of a large amount of battery storage capacity with the grid. This provides many advantages, as will be discussed in the next section.

## Integrating electric vehicles and smart electric grids

Because demand for electricity fluctuates, because electricity supply must always meet demand, and because grids generally do not have storage capacity that could be used to buffer shortfalls in supply, balancing loads in electric grids presents a well-known, fundamental difficulty. Generally there is a component of base load, which generators running continuously can efficiently meet, but above that there is fluctuating load that can only be met through the expensive expedient of maintaining reserve capacity and bringing it online and offline as required.

Clean, renewable, but intermittent energy sources such as solar cells and wind turbines exacerbate this problem by introducing uncontrolled fluctuations on the supply side as well. The sun does not necessarily shine when there is demand for electricity, nor does the wind blow.

However, large-scale use of battery-electric vehicles (particularly automobiles), combined with ubiquitous automatic recharging, introduces a large amount of battery storage capacity into the grid. In principle, this can be used to keep supply and demand in balance. When load on the grid is low and vehicles require recharging, they can transfer electricity from the grid to recharge. Conversely, when load on the grid is high and vehicles have excess stored energy, they can transfer electricity back to the grid.

This is not the only advantage to the grid. This battery capacity can also be utilized to provide voltage and frequency regulation – thus enhancing the quality of the electrical supply.

This sort of system can be managed optimally through dynamic pricing. When overall electricity demand is high, electricity prices rise and price signals motivate vehicles to sell. Conversely, when overall demand is low, prices drop and price signals motivate vehicles to buy. Intelligent vehicles can be programmed with optimal electricity trading strategies that take account of their use patterns and attempt to minimize overall energy costs over some time horizon.

This is not possible with old-fashioned electric grids, of the kind that still operate in most parts of the world, but it becomes feasible with emerging smart grids. In smart grids there is an overlay of information networking on the electric supply network. This enables much more sophisticated metering at buildings and vehicle-charging stations, two-way flow of electricity (since buildings and vehicles now may not only be electricity consumption points, but also production and storage points), and the dynamic pricing that is necessary for effective management.

This also enables a grid that relies less upon large, centralized generation plants and makes more use of decentralized sources. Buildings can begin to effectively integrate solar panels, wind turbines, micro-CHP (combined heat and power) systems, and so on. Potentially large efficiencies can be achieved through the clever combination of smart grids, decentralized sustainable sources, and the battery capacity of electric vehicles.

It is sometimes objected that lightweight, efficient electric vehicles consume so little electricity, and therefore have such low operating costs, that price signals might provide insufficient motivation to sell electricity back to the utility. Why not simply hoard it in order to provide maximum available range at any moment? With ubiquitous automatic recharging, however, there will be little motivation to hoard. Furthermore, small price differences multiplied over large numbers of electric vehicles *do* add up to significant amounts of money. This means that fleet operators, such as those operating the mobility-on-demand systems discussed in the next section, will be motivated to develop optimal recharging strategies that respond to price signals, for their vehicles.

**Mobility-on-demand systems**

Smart electric vehicles – GreenWheels, RoboScooters, or CityCars – can simply be marketed as appealing consumer products. But they can also be employed to launch new kinds of mobility services – mobility-on-demand systems that enable convenient point-to-point travel within urban areas, enable very high vehicle utilization rates, and extend availability to those who cannot or don't want to own their own vehicles. This category of users includes visitors to a city who generally don't bring their own vehicles with them, occasional riders and drivers who cannot justify the cost of ownership, those who don't have anywhere to store a vehicle, and those who don't want the responsibility and bother of ownership and maintenance.

Large-scale systems employing traditional, non-electric bicycles – for example Vélib in Paris, Vélov in Lyon, Bicing in Barcelona, and Bixi in Montreal – have already demonstrated the feasibility of mobility-on-demand. In these systems, racks of bicycles are spaced around the city such that potential users are rarely more than a short walk away from a rack. In order to make a trip, a user walks to a nearby rack, swipes a card to provide identification and unlock a bicycle, rides to a rack near the trip destination, drops off the bicycle, and walks the rest of the way.

Substitution of lightweight electric vehicles bicycles increases the range and utility of these systems, and makes them useable by more people. Where this begins with GreenWheel bicycles it requires little additional infrastructure, since racks for traditional mobility-on-demand bicycle fleets require power supply and data connection in any case. It is straightforward to upgrade them to provide battery charging as well.

Since acquiring real estate for vehicle pickup and dropoff points, and providing power supply at these points, are key issues in the implementation of mobility-on-demand systems, starting with a relatively simple, low-investment, GreenWheel-based system makes sense. This establishes the foundation for later expanding the system to scooters or automobiles.

Retail location theory suggests that, where pickup and dropoff points are of equal capacity, they should serve equal population catchments. This means that they will be closely spaced in areas of high population density and more sparsely spaced in areas of low population density. Alternatively, pickup and dropoff points might be evenly spaced, at intervals determined by comfortable walking distance, and varied in size according to surrounding population density.

Once pickup and dropoff points have been deployed and stocked, the fundamental management challenge with mobility-on-demand systems is to keep the system balanced. Across the system's service area, demand for vehicles – as expressed by customers showing up and wanting to pick up vehicles – varies dynamically from location to location and over time. Similarly, the supply of vehicles and parking spaces – as expressed by stocks available at access locations – varies dynamically. The task is to keep supply and demand in balance, such that customers never have to wait for unacceptable lengths of time for vehicles or parking spaces, and the numbers of vehicles and parking spaces required to achieve this balance are minimized. (This task is closely analogous to the task, discussed earlier, of load balancing in electric grids.)

The difficulty of the balancing task depends upon the skewness of the distribution of demand in space and time. Where desired trip origins and destinations are randomly distributed, the system can be expected to self-organize – keeping vehicles distributed fairly evenly throughout the service area. But where demand is highly skewed – for example, when it is dominated by morning and evening commutes – keeping the system balanced requires effort and costs money.

One way to balance the system is to move riderless vehicles to where they are needed, for example by loading bikes on trucks. This can be done by setting up the system in the small hours of the morning, letting it become gradually less balanced during the day, and then resetting it the following evening. Alternatively, vehicles can be moved continually – in effect, resetting it less sweepingly but at shorter time intervals. In either case, balancing is easier when there are buffers of excess vehicles and parking spaces in the system to absorb minor imbalances.

A more elegant approach is to exploit elasticities in times and locations of trips, and to manage demand through dynamic pricing. Under this strategy, it becomes more expensive for customers to pick up vehicles from locations where demand for them is currently high, and less expensive to pick them up from locations where demand is low. Similarly, it becomes more expensive to drop off vehicles at locations where parking spaces are currently heavily in demand, and less expensive to drop them off at locations where spaces are less in demand. Price signals thus motivate customer behavior patterns that keep supply and demand in equilibrium. Here the cost of system balancing is not that of moving riderless vehicles, but of providing the necessary price incentives.

All of these strategies require the support of a sophisticated, networked information technology. Both for billing of customers and for monitoring the distribution of vehicles and parking spaces in the system, it is necessary to track vehicle pickups and dropoffs in real time. The system must also compute optimum balancing strategies, and either make price adjustments or send instructions to redistribution truck operators.

Mobility-on-demand systems can and should coexist with privately owned vehicles. Through appropriate standards, and use of appropriate information technology, they can share parking spaces and recharging infrastructure. Such a joint system is likely to be more effective in meeting all aspects of demand, and it facilitates economies of scale in both vehicle supply and infrastructure development.

*Figure 5: Mobility-on-Demand Network consisting of CityCars.*

**The computational back end – a realtime urban nervous system**

A fundamental task of the computational back end behind electric vehicle mobility-on-demand systems integrated with smart grids is to track the use of resources – that is, electricity, vehicles, and parking spaces – in real time. Smart meters can monitor electricity consumption by buildings and vehicle recharging stations, and electricity supply back to the grid from these locations. Loads on the mobility system can be monitored by electronically tracking vehicle pickups and dropoffs, and the fluctuating stocks of vehicles and parking spaces at mobility-on-demand stations.

The high-level management task is one of organizing electricity, vehicle, and parking space supply so that supplies meet demands that are unevenly distributed in space and fluctuate over time. It is a large-scale, complex stock-and-flow management problem. At any moment there are stocks of electricity stored in vehicle batteries, of available vehicles at pickup points, and of available parking spaces at dropoff points. There are transfers of electricity into and out of batteries, and of vehicles among access points. The directions, magnitudes and rates of these transfers are controlled by price signals that establish realtime feedback loops. The idea is to regulate the system optimally by means of these feedback loops.

From the perspective of a mobility system user, the system should make an adequately charged vehicle available at a pickup station truly “on demand” – wherever and whenever the user needs it. From the perspective of the electric utility, the system should accomplish this in the most cost-effective way possible, and with minimum carbon emissions. And from the perspective of the mobility-on-demand system operator, the system should accomplish this with the minimum number of vehicles and parking spaces.

The first computational challenge in this is one of data processing scale. The system must harvest data on a very large scale, organize it into databases, and query those database to extract useful management information – all under very tight time constraints. The second challenge is one of optimization. Based upon these inputs from the field, the system must compute optimal pricing strategies for electricity and vehicle trips over some time horizon. And the third challenge is one of achieving dispersed control. The system must send price signals to tens of thousands (at least) of buildings and vehicles dispersed across the system’s service area.

These challenges are not insurmountable, but they are formidable. And there is, as yet, very little practical experience of building and operating large-scale systems of this type.

**Conclusion: smart sustainable cities for the twenty-first century**

The strategies that I have described achieve efficiently integrated operation of major urban mobility and energy systems through use of lightweight energy-efficient hardware, ubiquitous intelligence, digital networking, and realtime control. They are technologically feasible, and the provide major sustainability benefits. They initiate the process of transforming cities into systems that are closely analogous to modern aircraft and spacecraft, racecars, and chemical process plants – that is, responsive, high-performance systems that rely upon their advanced realtime control capabilities.