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Estimating the technology frontier for personal electric vehicles

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Abstract

The *personal electric vehicle* (PEV) emerged as a new category of transportation device in the late 1990s. PEVs transport a single passenger over trip distances of 1–10 km and employ electricity as the motive energy source. The category is principally comprised of electric-powered scooters and cycles. Personal electric vehicles offer several potential benefits to consumers and to society including lower transportation costs, reduced trip times, and lower environmental impact. The PEV therefore offers many intriguing possibilities for extending the human range of mobility from about 1 km (via walking) to 10 km or more. However, the full potential of the category has not been realized, to a large extent because the vehicles are not yet light enough, do not go far enough, and cost too much. The main question addressed by this article is what are the technological limits on personal electric vehicle design? And more specifically, How light can PEVs be? How far can they go? How little can they cost? What are the trade-offs across these dimensions of performance at the efficient frontier? The methodological approach of the paper is to combine a technology assessment of the major subsystems of a PEV with a technical model of vehicle performance in order to estimate the cost and mass of a vehicle for a given set of functional requirements.
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Keywords: Personal electric vehicles; Electric vehicles; Personal transportation; Technical model; Cost model; Electric scooter; Electric bicycle

1. Introduction

The *personal electric vehicle* (PEV) emerged as a new category of transportation device in the late 1990s. PEVs transport a single passenger over trip distances of 1–10 km and employ electricity as the motive energy source. The PEV is typically open to the weather and operates at less-than-highway speeds on local roadways and pathways. The category is principally comprised of electric-powered scooters and cycles. Large existing companies such as Yamaha have entered the category as well as start-ups such as Segway.

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Personal electric vehicles offer several potential benefits to consumers and to society:

- *Lower total operating costs than automobiles.* Most PEVs can be purchased for less than US$2000 and do not require large expenditures for licensing, insurance, parking or maintenance.
- *Use as auxiliary transportation with public transportation.* As distance from the center of an urban area increases, access to public transportation by walking becomes more difficult. Yet most people in suburban areas live within 5 km of public transportation routes. Through the use of PEVs, these people can access public transportation easily and efficiently without the expense of an automobile.
- *Use as auxiliary transportation with an automobile.* Driving in congested urban areas can be slow and costly. Parking in the financial district of San Francisco, for example, can cost US$40–50 per day. However, at distances of less than 5 km from the centers of many cities, parking is much less expensive (e.g., US$5) and driving much more convenient. PEVs can be used in combination with automobiles by parking in satellite areas and traveling the last few kilometers by PEV.
- *Lower door-to-door trip times for short distances and/or in dense urban environments.* For those who live and work in dense urban environments, trips of 3–5 km present challenges. They are slightly too long to travel by walking, yet the time and cost associated with driving are relatively high. For example, walking to a parking garage, extracting a car, driving, parking at a destination, and walking from the parking location to the destination can take 30 min for a 5 km trip. The same trip by PEV can take as little as 12 min, assuming the PEV can be parked near the door or taken indoors.
- *Reduction of automobile use in congested urban environments.* Use of automobiles can impose substantial societal costs associated with air pollution, noise, consumption of non-renewable resources, congestion, parking, and traffic accidents. These costs are especially high in dense urban environments, rising to as much as US$1 per km (Ozbay et al., 2001). PEVs offer the prospect of delivering transportation services more efficiently in these environments, for at least some trips.
- *Quiet and clean transportation.* To a certain extent the above benefits have been available for decades to users of human-powered and internal-combustion-powered scooters and cycles. However PEVs offer the additional benefits of operating in near silence and without noxious fumes, high-temperature exhaust components, or dripping fluids.
- *Mobility for those with limited ability to walk.* Many people, especially those aged 65 and older, have diminished ability to walk long distances, yet are not so disabled that they require the use of a power wheelchair. PEVs offer the prospect of extended mobility for these people.

The PEV therefore offers many intriguing possibilities for extending the human range of mobility from about 1 km (via walking) to 10 km or more. However, although some of the commercially available PEVs have achieved modest levels of adoption, the full potential of the category has not been realized, to a large extent because the vehicles are not yet light enough, do not go far enough, and cost too much.

The main question addressed by this article is what are the technological limits on personal electric vehicle design? And more specifically, How light can PEVs be? How far can they go? How little can they cost? What are the trade-offs across these dimensions of performance at the efficient frontier?

1.1. Approach

The methodological approach of the paper is to combine a technology assessment of the major subsystems of a PEV with a technical model of vehicle performance in order to estimate the cost and mass of a vehicle for a given set of functional requirements. Because the space of possible sets of functional requirements is essentially infinite, I consider three discrete market segments as points of comparison. These segments do exist in the current market yet they are different enough that they reflect a reasonable range of possible future vehicles. The three segments are: (1) stand-on scooters, (2) sit-on cycles, and (3) mobility scooters. The distinguishing characteristics of these segments are shown in Table 1. Fig. 1 shows an example of two commercial products from each segment.

The remainder of the paper is organized as follows. In Section 2, I develop the technical model of vehicle performance. In Section 3, I outline the basic technology choices in PEV design and their implications for performance. Section 4 contains the results of the analysis. Section 5 is a discussion of implications.

Table 1
Assumed properties for three vehicle segments

		Stand-on scooter	Sit-on cycles	Mobility scooters
Top speed	km/h	30	42	8
Cruising range	km	20	40	8
Cruising speed	km/h	25	35	6
Minimum wheel diameter	mm	200	250	180
Maximum hill angle	percent	10	10	10
Riding position		Standing straight ahead	Seated, feet in front of body or straddling vehicle	Seated, as in a chair
Terrain		Urban pavement	Urban pavement	Indoors, Shopping Malls, Sidewalks
Existing products (these products may or may not exhibit the typical performance shown in the table)		Xootr eX3 Badsey Hot Scoot Currie Flyer Segway	Voloci eGo II Yamaha Passol	Easy Travel (Tzora) Scootie (Shoprider)

Fig. 1. Examples of commercial products from each segment. (Photos courtesy of Xootr LLC.)

2. Physics of personal transportation

The power required at the wheels of a vehicle can be modeled as the sum of the power required to overcome rolling resistance, the power to overcome air drag, the power associated with climbing or descending a slope, and the power associated with accelerating or decelerating the vehicle.

$$P = P_{\text{rolling}} + P_{\text{air-drag}} + P_{\text{slope}} + P_{\text{acceleration}} \tag{1}$$

Rolling resistance can be approximated by

$$P_{\text{rolling}} \approx MgC_{\text{r}}v \tag{2}$$

where M is the total vehicle and rider mass, g is the gravitational constant, v is the velocity of the vehicle and C_{r} is the coefficient of rolling resistance (Whitt and Wilson, 1982).

Air drag can be approximated by

$$P_{\text{air-drag}} \approx \frac{1}{2}\rho C_{\text{d}}Av^3 \tag{3}$$

where ρ is the density of air, C_{d} is the non-dimensional coefficient of drag, and A is the frontal area of the vehicle and rider. Often $C_{\text{d}}A$ is treated as a single term—the *effective frontal area*.

The power associated with going up or down a slope is simply the rate of change of potential energy, given by $sMgv$, where s is the slope expressed as the change in vertical distance per unit of horizontal distance. The power associated with acceleration is simply the rate of change of kinetic energy.

The overall power equation can therefore be approximated by

$$P \approx MgC_{\text{r}}v + \frac{1}{2}\rho C_{\text{d}}Av^3 + sMgv + Mv\frac{\text{d}v}{\text{d}t} \tag{4}$$

Another useful quantity is the energy required per unit distance (i.e., J/m), which can be obtained by dividing the power at the wheels by the vehicle velocity (i.e., P/v) (see Fig. 2).

On flat surfaces at constant velocity, rolling resistance and air drag are the two principal components of power. At low speeds, rolling resistance dominates the power requirement and at high speeds air drag dominates. For the speed range of interest for most personal transportation devices (5–50 km/h), both components are significant. Kreuzotter (2003) provides a web-based calculator for estimating power requirements for human-powered vehicles, however the analysis is essentially identical for PEVs (see Table 2).

The power and energy required at the wheels are determined by the basic physics of moving a wheeled vehicle over the road surface and through the air. These physics hold for human-powered vehicles, automobiles, motorcycles, scooters, or any other type of wheeled vehicle. Note that for personal electric vehicles, the energy that must be stored in the vehicle is greater than that required at the road surface, with the difference accounted for by losses in the control electronics, motor, and mechanical transmission. Given typical efficiencies, this power train transmits only about 65 percent of the energy stored to the road, and so an energy

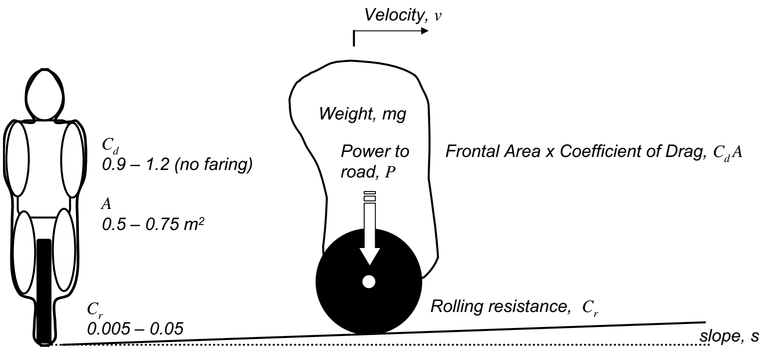

Fig. 2. Schematic representation of physics of personal transportation.

Table 2
Nominal power and energy requirements for three vehicle segments

		Stand-on scooter	Sit-on scooter	Mobility scooter
Cruising speed	km/h	25	35	6
Typical coefficient of rolling resistance	N/N	0.03	0.015	0.04
Typical effective frontal area (C_dA)	m^2	0.68	0.63	0.80
Typical vehicle mass	kg	20	50	40
$P_{rolling}$	W	218	179	77
$P_{air\text{-}drag}$	W	138	354	2
Total power at wheels (at cruise on level ground)	W	357	533	79
Energy/distance (at wheels)	J/m	51	55	47

Actual power and energy depend on specific technology choices.

requirement of 50 J/m at the road surface would result in a requirement of 77 J/m of energy actually stored on board.

3. Technology choices

The typical architecture of a personal electric vehicle is shown in Fig. 3. The vehicle is comprised of the basic functions of energy storage, drive system, and chassis. An ancillary function is charging, which may be accomplished by an on-board or off-board device, which for battery-powered vehicles is typically connected to a standard electrical outlet when charging the vehicle batteries. The drive system is comprised in turn of one or more motors coupled through a mechanical transmission to the wheels. In all cases, the power from the energy storage device is modulated through some kind of controller, implemented as an electronic device. The vehicle chassis can be thought of as consisting of the rider interface (e.g., seat, controls), wheels, braking system, and the structure that supports and locates all of the other elements of the vehicle. In this section, we consider the critical technology choices that explain most of the variation in performance of personal electric vehicles.

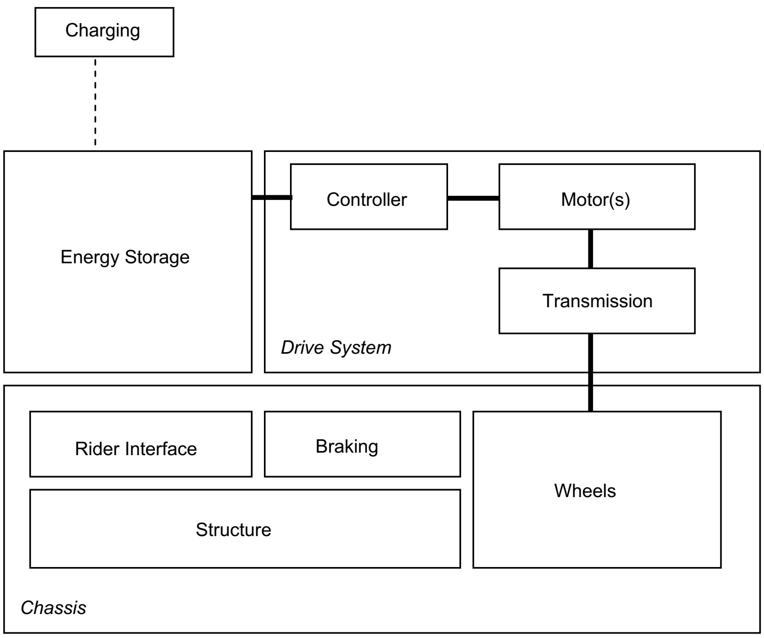

Fig. 3. System architecture for personal electric vehicles.

To a large extent, the functional requirements of the vehicle dictate its mass and cost. For example, faster vehicles clearly require more energy storage than slower vehicles, all else equal.

However, technology choices are also critical determinants of cost and mass. There are four categories of critical technology choices, which together strongly influence the cost and mass of a personal electric vehicle, given its functional requirements. The causal structure relating requirements and technology choices to vehicle mass is shown in Fig. 4. The functional requirements of terrain, maximum speed, rider position, range, and maximum hill climbing in turn dictate basic parameters of the vehicle system. When combined with the technology choices for (1) wheels, (2) batteries, (3) drive system, and (4) structure, these requirements strongly constrain the mass and cost of the vehicle. I discuss each of these four technology choices in turn.

3.1. Wheel technology

The characteristics of the wheels essentially dictate the coefficient of rolling resistance of the vehicle. Rolling resistance arises from hysteresis at the wheel–road interface. Deformation of the wheel and/or road as the wheel rolls results in energy losses. These losses are roughly inversely proportional to wheel diameter for given wheel and road materials, so larger wheels are always better, all else equal. For a given wheel diameter and road material, losses vary with wheel (or tire) composition. For small-diameter wheels (i.e., less than 250 mm), solid urethane tires cast onto a plastic or metal wheel are highly efficient. For larger wheels, pneumatic tires provide low rolling resistance and the capacity to absorb shock and vibration.

The designer must balance the desirable size and weight associated with small-diameter wheels with the low rolling resistance of large wheels. In the interest of developing a set of discrete choices, consider these wheel alternatives, with approximate costs:

1. Very small (e.g., 200 mm) soft-urethane "wheel chair" wheels ($C_r = 0.04$, Cost US$8.00/wheel)
2. Small-diameter (e.g., 250 mm) pneumatic-tired wheels at 3 bar pressure ($C_r = 0.03$, Cost US$5.00/wheel)

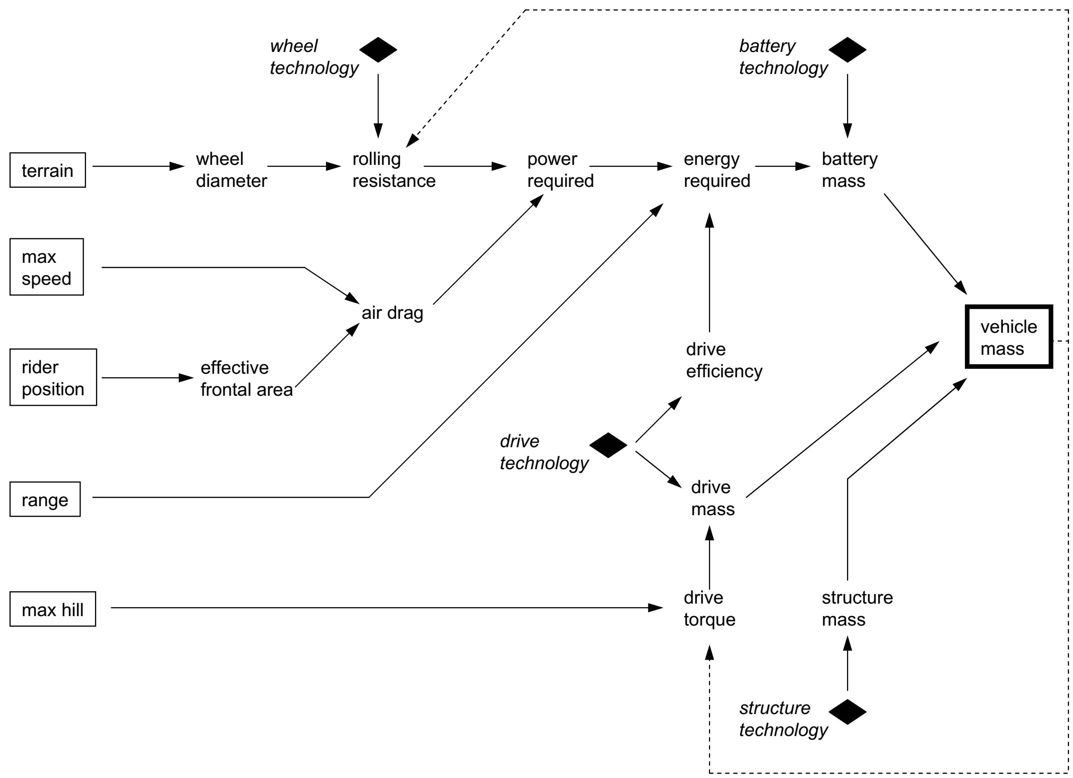

Fig. 4. Causal model of vehicle mass. Both performance requirements and technology choices drive vehicle mass.

3. Small-diameter (e.g., 250 mm) solid urethane-tired wheels ($C_r = 0.015$, Cost US$10.00/wheel)
4. Medium-diameter (e.g., 400 mm) pneumatic-tired wheels at 5 bar pressure ($C_r = 0.015$, Cost US$10.00/wheel)
5. Large-diameter (e.g., 550 mm) pneumatic-tired wheels at 5 bar pressure ($C_r = 0.010$, Cost US$18.00/wheel)

Data on a wide variety of bicycle tires at different inflation pressures are given by Lafford (2000). Whitt and Wilson (1982) provide additional data for other wheel sizes and materials.

3.2. Energy storage technology

Three categories of energy storage technologies have been used in commercial electric vehicles: batteries, combustion-powered generators (as in hybrid vehicles), and fuel cells. Generator-powered hybrids and fuel cells are not commercially viable for personal electric vehicles at this time. (I discuss the reasons for this and the long-term prospects for these technologies in Section 5.) Therefore, batteries of various types are the principal means of energy storage available to the personal electric vehicle designer.

The standard battery for traction applications is a sealed-lead-acid (SLA) battery. These batteries have been refined over several decades and are widely used in forklifts, golf carts, and other small electric vehicles. SLA batteries are inexpensive and reliable. A further benefit is that they can be charged with a simple charge algorithm (application of constant voltage). Their major disadvantage is that they are heavy.

Nickel metal-hydride (NiMH) batteries are lighter than SLA batteries, but cost more. (Comparative performance specifications for batteries are shown in Table 3.) They also require a more complex charging process and more sophisticated state-of-charge monitoring, which results in more costly electronics for supporting the batteries. Nevertheless, NiMH batteries are now the standard for most cordless power tools and many portable computers. NiMH batteries are relatively mature, with improvements of at best 5–10 percent likely in the future (Vyas et al., 1997, 2000).

Lithium-ion (LiIon) batteries are currently the lightest high-power batteries available commercially and are used widely in portable computers and other mobile electronic devices. They are used in a few personal electric vehicles (e.g., Yamaha Passol). LiIon batteries are substantially more expensive than NiMH batteries and require yet more complex electronics for charging and state-of-charge monitoring. LiIon cells are likely to improve another 10–20 percent in energy density and power density (Vyas et al., 1997, 2000).

In addition to SLA, NiMH, and LiIon, Nickel Zinc batteries are used in a few vehicles. They are essentially similar in power and energy density to NiMH batteries, and are currently available from only one manufacturer (Evercell). Sodium sulfer batteries have been proposed for use in electric vehicles, but they operate at very high temperatures and I do not believe they are practical for small, open vehicles.

A second-order performance characteristic of batteries is their *cycle life*—the number of charge–discharge cycles that the battery can endure before the energy density is substantially degraded. (The usual cut-off for defining cycle life is 80 percent of the original energy capacity.) Although cycle life is critically important to the economics of high-mileage vehicles like automobiles (Cuenca et al., 1999), it has proven to be of secondary importance in personal electric vehicles. I believe that this is because consumers seem to discount substantially, at the time of purchase, costs that they may experience at some point in the relatively distant future.

Table 3
Properties of three battery technologies for personal transportation applications

		Sealed lead acid	Nickel metal hydride	Lithium ion
Energy density @ 1C discharge rate	kJ/kg	87	207	448
Power density (continuous)	W/kg	200	200	500
Cost per unit mass	US$/kg	2.50	30.00	90.00
Cost per unit energy	US$/MJ	29	145	201
Number of charge–discharge cycles possible (until only 80 percent of original capacity is available)	Cycles	150–200	200–400	500+
Maturity of technology	Years use in transportation applications	≈80	5	2

However, in the long run, I expect that consumers may adopt a more sophisticated perception of the lifecycle costs of battery ownership.

Another key performance dimension in many battery-powered applications is power density—how much power can be drawn from a battery cell. Some batteries with low energy density (e.g., SLA batteries) have relatively high-power density, allowing a great deal of current to flow without damaging the cells. In most PEV design, power density is of secondary importance. This is because to achieve sufficient range, most vehicles will need to operate for an hour or more, which is often a long enough period that the discharge rate of the batteries is well within their design range.

3.3. Drive technology

The central technology choice for the drive system is between a *brushed* DC motor and a *brushless* DC motor. (For larger vehicles such as electric automobiles, AC synchronous motors are also used.) The difference between these technologies lies in the way the motor is commutated. Commutation is the switching of electric power to the appropriate coil in the motor winding at the appropriate angle of revolution of the motor rotor. Commutation is done electronically for brushless motors by sensing the rotor position and electronically switching power to the appropriate motor winding. With a brushed motor, the commutation is done through a sliding "brush" (usually actually a block of carbon) contacting one of a set of discrete contact points on the motor rotor.

For brushless motors, the windings (i.e., the coils of copper wire) are most commonly in the stator and permanent magnets are in the rotor. This arrangement provides better cooling, and therefore higher power levels for a given mass of copper and steel, than does an arrangement in which the motor windings are on the rotor and the magnets on the stator.

Motor torque is proportional to motor current. For brushed motors, high levels of current result in substantial inefficiencies due to resistive losses in the brushes. For this reason and because of cooling limitations, brushed motors are most efficient when run at relatively high speeds (5000–20,000 rpm) and low torques (and therefore low currents). In contrast, brushless motors can operate efficiently at high torques (and therefore high currents) and speeds as low as 1000 rpm. This difference in minimum efficient speed leads to a substantial difference in transmission requirements. Given the speed of the vehicle and the wheel diameter, drive wheels on personal electric vehicles operate at speeds of roughly 500 rpm. Given their inherent ability to operate efficiently at lower speeds, brushless motors can often be configured with a single-stage transmission such as a single pair of spur gears, pulleys, or sprockets, whereas brushed motors are typically best matched to a two or three-stage gear drive with sufficient gear reduction to match the motor speed to the speed of the drive wheel(s).

There are two disadvantages to brushless motors. First, because commutation is performed electronically, the motor controller for a brushless motor requires some computation and more complex switching of the motor current than the controller for a brushed motor. This electronic complexity adds to the cost of the controller. Second, brushless motors for traction applications have not been made in as large quantities as brushed motors. As a result, although actually slightly more complex mechanically, standard brushed motors can be less expensive, especially in smaller quantities, than brushless motors. Table 4 presents a comparison of the two technologies. Fuchs and Blatter (1998) provide a technical discussion of highly efficient electric drives.

3.4. Structure technology

Like most structures, frames for electric vehicles can be designed using a variety of alternative materials and geometries. Most vehicles use some kind of metal frame fabricated from tubing. A few vehicles have used integral cast structures (e.g., Xootr eX3).

Structure technologies for personal electric vehicles closely mirror those for bicycles and motorcycles. For a tubular metal frame, the most basic technology choice is between steel and aluminum tubing. Steel frames are inexpensive but heavy. Aluminum frames are lighter but more expensive.

Further mass reduction is possible through the use of titanium, carbon-fiber composites, and complex tubing geometries. This mass reduction comes at a substantially higher cost than what is possible in moving from

Table 4
Comparison of brushed and brushless drive technologies

	Brushed drive	Brushless drive
Typical motor configuration	Copper windings on rotor Permanent magnets on stator Carbon "brushes" connect power to windings	Permanent magnets on rotor Copper windings on stator Power is switched to appropriate winding electronically
Thermal management	Principally convective heat transfer, often aided by integral fan	Principally conductive heat transfer directly to motor housing
Typical efficient operating speeds	5000–20,000 rpm	1500–6000 rpm
Typical power densities	1000 W/kg @ 10,000 rpm	2000 W/kg @ 2500 rpm
Required transmission ratio to achieve 500 rpm drive wheel speed	20:1 @ 10,000 rpm typically a two-stage transmission	5:1 @ 2500 rpm typically a single-stage transmission
Controller configuration	Single-phase FET drive	Three-phase FET drive with microprocessor
Typical costs of motor, transmission, and controller for 1000 W drive	US$80.00	US$120.00
Typical total drive system efficiency	0.60	0.75

Table 5
Summary of technology choices for analytical model

Wheels	Batteries	Drive system	Structure
200 mm soft-urethane	SLA	Brushed motor/2-stage transmission	Steel tubular frame
250 mm pneumatic	NiMH		Aluminum tubular frame
250 mm urethane	LiIon	Brushless motor/single-stage transmission	"Bicycle-like" weight reduction techniques
400 mm pneumatic			
550 mm pneumatic			

a steel to an aluminum frame. Given the similarities between personal electric vehicle design and bicycle design, some analogies are instructive. Bicycle design is highly evolved. Because the available power for a bicycle is limited by human physiology, a principal objective of bicycle design is to minimize vehicle weight. Analysis of the relationship between cost and weight for bicycle structural components informs the question of the extent to which weight reductions in personal electric vehicle structures are possible and at what cost. Appendix 1 is an analysis of the shadow price of weight for high-performance bicycle structural components (such as seat posts and handlebars). Based on an analogy to bicycles we can infer that structure mass can be reduced at a cost of about 277 US$/kg once the obvious material and geometry optimization has been done.

3.5. Summary of technology choices

Although in some instances technology choices are possible across a continuous parameter space (e.g., wheel diameter), I have selected a set of discrete choices representing reasonable possibilities and spanning the space of what are likely to be commercially acceptable ranges. These choices are shown in Table 5. These choices to a large extent reflect the design space for personal electric vehicles.

4. Analysis

Using the analytical model of vehicle power developed in Section 2 and the technology alternatives and their relative costs developed in Section 3, I can estimate the mass and cost of a set of vehicle design possibilities. Using these point estimates, I can then estimate the efficient frontier for vehicles satisfying the requirements of the market segments identified in Section 1.

I do this analysis for each market segment by beginning with a baseline design, usually comprised of an SLA battery, a brushed motor, a steel frame, and small, low-cost wheels. Based on a given set of range and speed requirements for a market segment, I use the power model to estimate how much battery will be required. Once the battery mass is estimated, I can estimate the overall vehicle mass and cost. Because power and mass are jointly determined by a system of equations, I solve for the vehicle mass iteratively by first guessing the vehicle mass, solving for the power requirements and then the battery mass. Using this value of battery mass, I can estimate the overall vehicle mass. I then update the original guess of vehicle mass and iteratively refine the solution.

Additional feasible points in the design space are developed by incrementally considering the substitution of higher-cost but higher-performing technologies selected from those developed in Section 3. I apply these technologies in a rational sequence, applying first a technology that decreases mass at the lowest cost penalty. This sequence of technologies can differ across the three market segments. This is because, for example, rolling resistance is more significant in a mobility scooter than in a sit-on scooter.

The results of this analysis are shown in Figs. 5–7. Cost, weight, and range are the principal performance metrics given a particular set of terrain and speed requirements. All three variables can be traded off against one another. To represent these trade-offs, I compute a cost–weight trade-off for three different values of assumed range: the baseline range, twice the baseline range, and half the baseline range. The exception is mobility scooters, for which I compute only the baseline range and double that range. (Half the range of the baseline for a mobility scooter is not remotely commercially viable.)

These results, when plotted, give a sense of the efficient frontier relating cost and mass for a given range requirement, and assuming technologies available today.

For the purposes of calibrating against actual industrial practice, I also plot the performance of several products that have been manufactured and sold commercially. In order to do this, I must adjust the performance specifications for these existing products to reflect range targets that are equivalent to those used in the analytical model. I do this by adding or subtracting an estimate of battery mass and cost to adjust the actual range of the commercial products to a hypothetical range appropriate for comparison with the analytical model. Of course, there are significant differences in features among competitive products. For example, the Segway P Series scooter is "off the chart" as being extremely heavy for its cost. However it is marketed in large measure on the basis of its innovative balancing mechanism and ability to move with agility in tight spaces. Nevertheless, these competitive benchmarks are useful to ensure that the estimate of the efficient frontier is realistic.

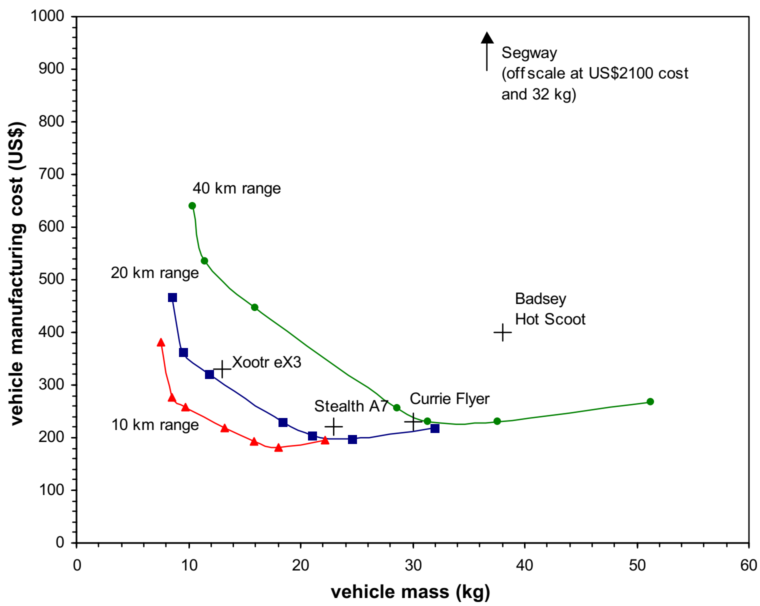

Fig. 5. Relationship between manufacturing cost and vehicle mass for stand-on scooters. Estimates for several commercial products are shown, adjusted for 20 km range at 25 km/h.

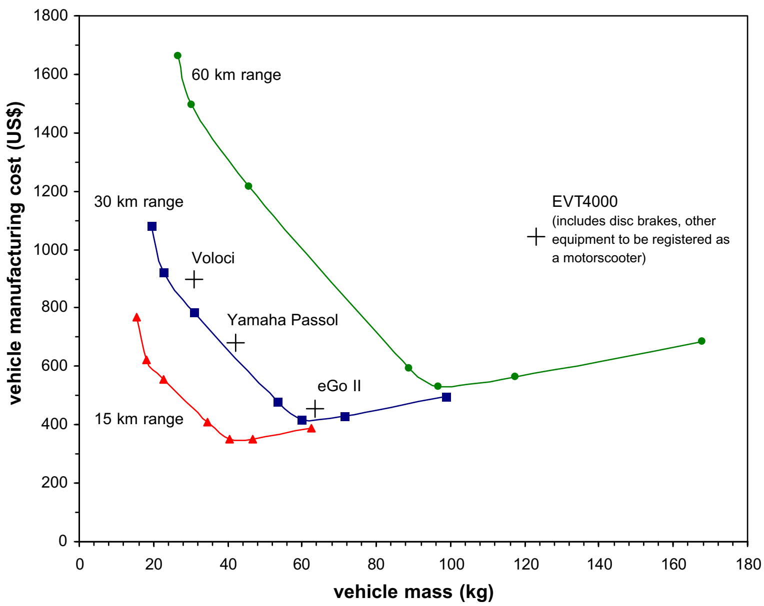

Fig. 6. Relationship between manufacturing cost and vehicle mass for sit-on cycles. Estimates for several commercial products are shown, adjusted for 30 km range at 35 km/h.

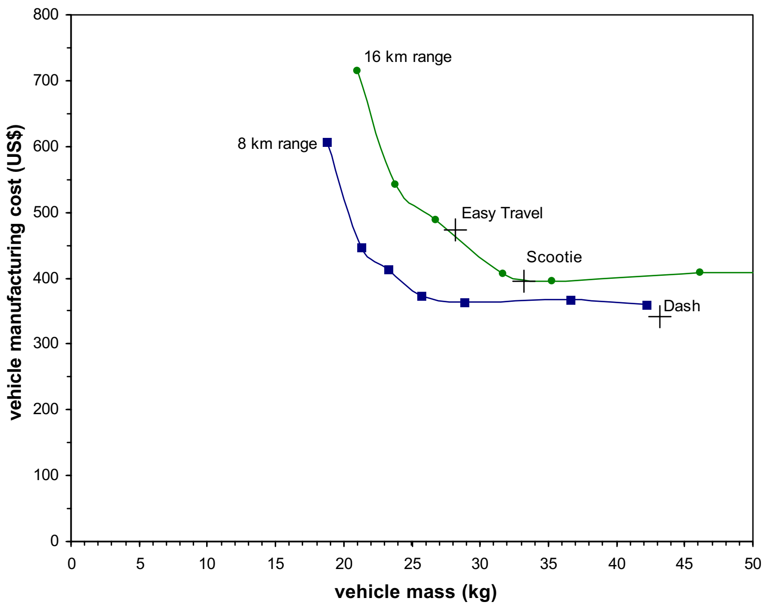

Fig. 7. Relationship between manufacturing cost and vehicle mass for mobility scooters. Estimates for several commercial products are shown, adjusted for 8 km range at 6 km/h.

Note that the cost analysis is done in terms of *manufacturing cost*, not price to the consumer. Currently personal electric vehicles typically go through a two-stage supply chain. The "manufacturer" usually sources the vehicle from a supplier (currently most frequently in Taiwan) and sells the vehicle to a retailer who sells to the consumer. For stand-one scooters, the retailer's gross margin is typically 35 percent and the manufacturer's gross margin is typically 35 percent. As a result, retail price is typically 237 percent of manufacturing cost (the price the manufacturer pays its supplier). Therefore a vehicle with an estimated cost of US$300, is likely to have a retail price of about $711. The multiple of manufacturing cost is approximately 220 percent for sit-on scooters and approximately 380 percent for mobility scooters. I do not know the exact manufacturing costs for all of the existing products and so I use this logic in reverse to estimate the manufacturing cost from the retail price. Of course this is an approximation, but it allows a rough normalization of prices for the purposes of comparison.

These results allow a product designer, market researcher, or company strategist to estimate which combinations of cost, mass, and range are likely to be technically feasible, and where existing products fall relative to what is technically possible.

5. Discussion

5.1. The right measures?

My analysis focuses on mass, range, and cost for given speed and terrain requirements. However, I essentially ignore many other performance characteristics such as comfort, cargo carrying capacity, and ease of handling and control. I believe that speed and terrain requirements arise from the fundamental nature of the transportation problem. Given such a problem, mass, range, and cost are of paramount importance. This is not to say that other requirements are not relevant, nor that these requirements might not be dominant in some applications. I believe that my estimates reflect the "minimal possible vehicle" and that additional features or performance requirements will incur additional cost and/or mass, or reduce the effective range of the vehicle.

5.2. How light can vehicles be?

The results of my analysis suggest that the lightest personal electric vehicles employing available technology will be stand-on scooters and are likely to be no lighter than 6–7 kg for a vehicle with modest range and speed (e.g., 10 km at 25 km/h). A book bag or briefcase containing a portable computer has a mass of 5–10 kg, and so an ultra-portable scooter is of comparable heft. Such a scooter would be about half of the mass of a bicycle, and could fold to be substantially smaller. My personal discussions with many commuters who use kick scooters (i.e., human-powered scooters) suggest that 5 kg devices are perceived as light and easy to carry, especially with a carry strap. Taken together, the evidence suggests that the vision of a portable scooter that can be carried on public transportation or in an automobile is highly feasible technically, and with substantial consumer demand could be feasible economically.

5.3. Technology trajectories and opportunities for shifting the frontier

The estimated technological frontier developed in Section 4 is based on the current state of PEV technology. Some of the technologies may get substantially better, while others are unlikely to see substantial improvements in cost or performance. The best motors are already nearly 90 percent efficient. Gear drives can be 85 percent or more efficient. Controllers are typically 95 percent efficient. Even pushing the efficiencies of these elements to close to 100 percent will not substantially alter the technology frontier. Similarly, structural technologies will get better, but not dramatically so.

The substantial opportunities for improvement are in battery energy density and production economics. Specifically, lithium polymer cells offer the prospect of improvements in energy density of 60 percent or more over current lithium-ion cells (Vyas et al., 1997) to levels of 720 kJ/kg. Perhaps more important is that the cost structure of lithium polymer cells is likely to improve substantially, to the point where they are competitive with NiMH cells in terms of cost per unit of energy. In the event of these improvements, PEVs with mass 20 percent or more lower than today's lithium-ion systems may be available at the cost of today's NiMH vehicles.

At the margin, some additional improvements are possible. Some of these possibilities include the use of ultracapacitors in combination with batteries to provide peak power during acceleration and hill climbing. Such a system may allow the average rate of discharge of the batteries to be reduced, thus increasing the energy than can be extracted in practice.

One improvement that I believe is worthy of exploration is the aerodynamic performance of scooters and cycles. At speeds of greater than 30 km/h, most of the power to move the vehicle is dedicated to overcoming air drag. Currently most scooters and cycles position the rider in possibly the worst orientation for both frontal area and coefficient of drag. The challenge would be to find comfortable riding positions, possibly in combination with the use of lightweight farings, all of which could reduce the effective frontal area by half. For example, if the effective frontal area of a sit-on scooter could be reduced from 0.50 to 0.25, perhaps through the use of a faring to reduce the drag coefficient from about 1.0 to 0.5, then the vehicle could achieve 25–35 percent greater range for the same battery mass. Some detailed ideas for reducing drag, derived from bicycle racing, can be found in (Abbott and Wilson, 1995).

5.4. Human power

Human-powered vehicles such as bicycles and kick scooters have proven to be highly reliable and useful personal transportation devices since the 19th Century (Sharp, 1977). In many parts of the world, the bicycle is the dominant means of mechanized transportation. Cyclists can achieve range of more than 100 km at speeds of 30 km/h using a bicycle with mass of less than 10 kg and costing less than US$1000. These performance characteristics dominate any personal electric vehicle that can be designed with today's technology. However, such performance requires a high level of fitness and a willingness to expend 20–30 kcal of human energy per km. And for most people, practical speeds are limited to about 25 km/h for bicycles and kick scooters. Fewer than one percent of people in the United States appear willing to use human-powered vehicles for daily personal transportation (USDOT, 2001). Although, in some countries like The Netherlands, with well developed infrastructure and flat terrain, these rates are much higher.

5.5. Other technologies

My analysis focuses on battery-powered electric vehicles and I suggested that other technologies are not likely to be practical in the near future. The most likely alternative means of energy storage are (1) hydrogen gas, which would be converted to electricity with a fuel cell, and (2) fossil fuel converted to electricity with an internal combustion engine and generator. Both of these technologies offer a great deal of promise for next-generation automobiles. This is because commercially viable automobiles probably require range of at least 400 km and speeds of at least 100 km/h. The energy required to deliver this performance can simply not practically be stored with current batteries at reasonable cost. Because of the energy density of hydrogen and other fuels such as gasoline, these energy sources are much more practical in high-energy applications. However, for personal electric vehicles, the energy requirements are more modest. In these applications, the "overhead" associated with storing and converting hydrogen or gasoline to electricity is greater than the net cost and mass benefits that such technologies can offer. For gasoline-powered hybrids, the noise, smell, and dirt associated with an internal combustion engine results in further drawbacks.

5.6. Weather and safety

Inclement weather is a problem for users of PEVs, both because of degradation of traction and because of personal comfort. In this area, analogies to bicycles are useful. In most Northern locations, bicycle use is substantially reduced in winter and on rainy days. Use of light, wheeled vehicles is technically possible in cold and snowy weather, as evidenced by the persistent use of bicycles, by more than a few riders, all winter in cities in Scandinavia. However, most people perceive winter use of open vehicles as uncomfortable and are likely to choose alternatives, such as walking or personal automobiles.

There have been some attempts at providing weather protection for light electric vehicles, bicycles, and motorcycles. Although any such protection is likely to add cost and mass to the vehicle, the benefits may outweigh these drawbacks.

Safety is a concern for any lightweight and/or open vehicle that shares the roadways with automobiles and trucks. There are opportunities for vehicle technologies to improve safety (e.g., protective cages, air bags, vehicle avoidance systems, etc.). There may also be opportunities for the design of infrastructure to minimize the incidence and consequences of collisions.

Protection from weather and collisions may be addressed simultaneously in some cases. The BMW C1 was a motorcycle with limited weather and crash protection, which offers some promise as an approach for larger personal electric vehicles.

5.7. Assessing consumer preference

My analysis attempts to estimate what is possible, but not what consumers want. Different consumers with different needs are likely to have very different preferences for the relative importance of weight, range, cost, and other features. However, the notion of an efficient frontier informs the market research that might be employed to answer the question of which alternatives consumers prefer. In a study of consumer needs, one might poll consumers about their relative preferences, perhaps using conjoint analysis, across the entire space of possibilities. However, the results of this analysis allow the market researcher to narrow the range of product concepts to be tested by focusing on alternatives at the frontier (Ulrich and Eppinger, 2004).

5.8. Concluding remarks

Personal electric vehicles are technically feasible now. However, suppliers have not yet arrived at a set of practical vehicles that best match technical feasibility and consumer demand. Part of the challenge is to understand the relative trade-offs among cost, weight, range and other dimensions of vehicle performance. This article estimates the technological frontier defined by these trade-offs. This frontier illustrates what is likely to be technically possible. The question of what is commercially feasible remains. However this question will be answered by suppliers and consumers in the marketplace in the coming years.

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Appendix 1. Bicycle structural component mass-cost analysis

Racing bicycles are highly evolved vehicles for which mass is an extremely important performance specification. Extreme efforts have been applied to their design (Züger et al., 1997). By examining the ‘‘cost of mass reduction’’ for racing bicycles, we can estimate what the cost of mass reduction would be for personal electric vehicle structures after the obvious weight reduction techniques have been applied. This analysis assumes that bicycle structures employ similar material and process technologies as PEV structures. Furthermore, the analysis assumes that production quantities for high-performance bicycle components are similar to those that might be anticipated for high-performance PEVs.

Figure A1 is a scatter plot of retail price versus mass for seat posts, a key structural component in a bicycle. I chose seat posts because their function is almost entirely structural and because their function is unambiguous and consistent across a wide range of manufacturers' offerings.

Ordinary least squares regression analysis results in a slope of −770 US$/kg. As is evident from the scatter plot, this relationship is highly significant and mass explains almost all of the variance in retail price (adjusted $R^2 = 81$ percent).

Margins for high-end bicycle components sold in the aftermarket are approximately 40 percent for both retailers and manufacturers, so we can estimate that retail prices are approximately 2.8 times manufacturing cost. Assuming these margins, 770 US$/kg in retail price is equivalent to 277 US$/kg in manufacturing cost. Of course, this estimate of the cost of mass reduction applies only to the marginal design choices made after obvious mass reduction strategies (such as switching from steel to aluminum tubing) have been applied.

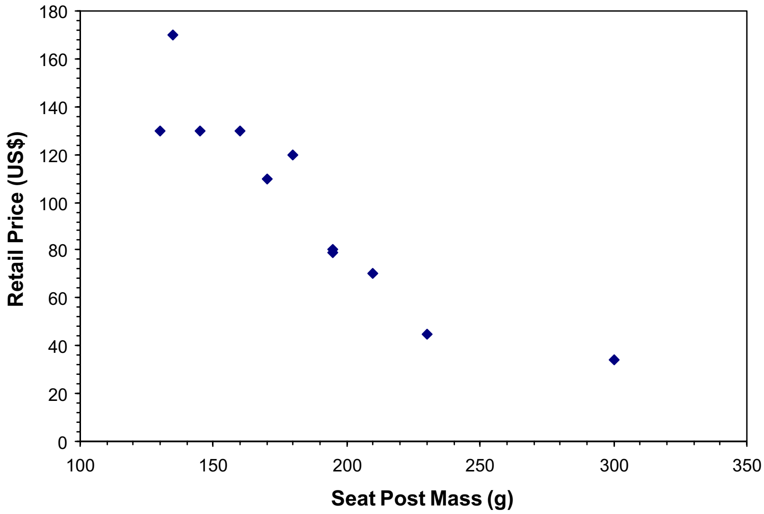

Fig. A1. Retail price versus mass for high-performance seat posts, a structural component for racing bicycles. Data from Colorado Cyclist, September 2003.

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