THE ENVIRONMENTAL PARADOX OF BICYCLING

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Abstract

Substituting bicycling for driving is frequently promoted as a means of reducing energy consumption and the associated degradation of the environment. This paper estimates the magnitude of this effect. The analysis takes account of the first-order effects due to the dramatically lower energy requirements of transportation by bicycle relative to automobiles. The environmental benefits of human power are, however, strongly coupled to the environmental costs of increased population, due to increased longevity of those who engage in physical activity. Paradoxically, increased use of human power for transportation is unlikely to reduce substantially the use of energy because of this second-order effect. Human-powered transportation is therefore less an environmental issue and more an issue of public health. The interplay between longevity and environmental impact is a central feature of the conflicting societal objectives of improving human health and increasing environmental sustainability.

Illustration: Alex Eben Meyer

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Introduction

Two interesting articles on human-powered transportation have appeared in *Energy Policy* in recent years. Coley (2001) argued that the energy efficiency of human-powered transportation is typically overestimated because of a failure to account for the latent energy associated with the production, processing, and distribution of the food that provides the energy for human power. Higgins and Higgins (2005) argued that the body fat of the overweight population is actually a significant and environmentally beneficial potential source of energy for transportation. As with most environmental issues, assessment of the net benefits of human-powered transportation is complex. This article explores a highly relevant factor in this assessment— the interplay among human-powered transportation, longevity, and environmental costs.

It is axiomatic among environmentalists that substitution of human-powered transportation for single-occupant automobile trips provides environmental benefits. Yet, given the current state of the automobile-driving population, particularly in the United States, first-order environmental benefits can result in high second-order environmental costs due to increased longevity of those engaging in increased physical activity. That is, the energy savings due to the use of human power for transportation may be offset by the increased energy used by living longer due to better health. On first reflection, this is a bizarre Swiftian argument. However, I believe that the argument correctly places human-powered transportation, and physical activity generally, at the center of a basic societal tension between the quest for longevity and the environmental costs of increased population.

The basic logic of my argument is:

- Human-powered transportation can substitute for trips by single-occupant automobiles. This substitution has a direct and immediate benefit of reducing energy consumption, even accounting for the latent energy content of the food required for human power.
- A substantial increase in the use of human-powered transportation would engage a substantial number of currently sedentary people in physical activity.
- Physical activity by previously sedentary individuals increases their longevity, and therefore their overall energy consumption.

- Depending on the characteristics of the population that adopts human-powered transportation, there may be little net environmental benefit associated with an increase in human-powered transportation.

In this article, I first lay out the evidence for these arguments, then engage the relationship between human-powered transportation and health policy, and finally argue that human-powered transportation remains a sound policy objective, given the most prevalent notions of social welfare.

My analysis focuses on the use of the bicycle as a substitute for the single-occupant vehicle, but a similar analysis produces essentially similar results for other forms of human-powered transportation, including walking, scooting, and skating. I focus on energy consumption as a proxy for environmental impact. The arguments are most salient for societies in which a sedentary lifestyle exists in combination with widespread use of the automobile for personal transportation. In most such societies, the primary source of energy is fossil fuels; and fossil fuel extraction, processing, transport, and combustion account for a large fraction of the environmental cost of modern life.

Bicycling reduces the energy costs of transportation

The average automobile in the U.S. achieves fuel economy of 11.6 km/kg (Davis and Diegel, 2004), which is equivalent to an energy consumption rate, at the vehicle's fuel tank, of 3.8 MJ/km. For the OECD countries, this figure is 2.5 MJ/km (Schipper 2004). Extraction, refining, and transportation of automotive fuel requires approximately 20 percent of the energy in the crude oil (Brinkman et al. 2005), so the fossil fuel costs "at the well" are 1.25 times greater than these figures. I assume that an individual owns an automobile whether using a bicycle for transportation or not, and so the automotive energy consumption does not account for the energy required to manufacture the vehicle, which is typically about 10 percent of the energy consumed over the life of the vehicle.

The average utility cyclist pedals at a speed of approximately 20 km/hr, which requires human power input on a conventional "roadster" style bicycle of 17 kJ/km (Wilson 2004) over and above resting energy requirements. The ratio of work done to food energy consumed for a cyclist at commuting power levels is approximately 22 percent (McDaniel et al. 2002), and so in dietary equilibrium, the cyclist consumes 77 kJ/km of fuel in the form of food to fuel this activity. The energy required to produce, process, and transform food is approximately 5.75 times greater than the energy content of the food itself (Coley 1998), and so the total energy cost of cycling is approximately 443 kJ/km. Of

course this energy cost for a specific individual would vary based on diet, origin of food, bicycle technology, riding style, terrain, body mass, and metabolic efficiency. Despite the inefficiencies in the energy conversion processes to generate human power, the bicycle remains about 6-9 times more efficient per km traveled than the single-occupant automobile.

Human-powered transportation engages sedentary people in physical activity

In many developed countries, including the U.S., more than half of the population is sedentary (Dishman et al. 2004). Although there is certainly likely to be a positive correlation between fitness and willingness to engage in human-powered transportation, widespread use of human power sufficient to have a significant environmental impact must involve previously sedentary people.

In my analysis I consider a base case of a sedentary individual. I then consider two scenarios in which an individual (a) substitutes bicycling for 2600 km of automotive transport, requiring 4200 kJ/wk of energy expenditure or (b) engages in an equivalent non-transportation "workout" also expending 4200 kJ/wk. The level of bicycling in the first scenario corresponds to an average of 10 km per day, 5 days per week.

Physical activity increases longevity

Warburton et al. (2006) and Lee and Skerrett (2001) review the literature on the dose-response relation between volume of physical activity and all-cause mortality. Several dozen studies provide clear evidence that energy expenditure of about 4200 kJ/wk (1000 kcal/wk) is associated with a 20-35 percent reduction in risk of all-cause mortality. The greatest relative benefit appears to be associated with the transition from a sedentary lifestyle to a modest level of physical activity, although mortality risk appears to decrease monotonically with physical activity over gross expenditure rates from 2100 kJ/wk to 13,000 kJ/wk. (4200 kJ/wk corresponds to approximately 2600 km/yr of bicycling.) This result appears to hold for men and women of all ages. Although the evidence is from observational studies, the basic findings hold even when controlling for sex, smoking, economic status, disease status, and other lifestyle factors.

Fatalities due to accidents while bicycling present mortality risks relative to automobile use. Pucher and Dijkstra (2003) estimate that the fatality rate for bicycling in the U.S. is 72 fatalities per billion kilometers, whereas for automobile travel it is just 6 fatalities per billion kilometers. There is some evidence that fatality rates decrease with an increase in overall bicycle use in a region. However, for

the purposes of this analysis, I assume that the fatality rate for cycling is 12 times higher per km traveled than for automobile use and that this rate is 7.2E-8 1/km.

Using the U.S. Center for Disease Control (CDC) 2002 life tables (Arias 2004), which are representative of mortality patterns for development countries, I estimate the change in average longevity that would result from a *decrease* in mortality due to increased physical activity and an *increase* in mortality due to the increased accident risk from bicycling. I do this by adjusting the mortality rate in each one-year age period in which the bicycling behavior is present (a) downward by 27.5% to account for increased physical activity and (b) upward by 0.00017 for the increased risk of death due to a fatal accident. I performed this analysis over the age brackets 45-55, 40-60, 35-65, 30-70, 25-75, and 20-80 (Appendix A). Based on this analysis, the relationship between the period of activity and change in longevity is nearly linear over periods lasting 10-50 years; with each year of bicycling increasing longevity by an average of 0.029 years (10.6 days), and a year of physical exercise without the accident risk of bicycling increasing longevity by 0.034 years (12.4 days).

The energy cost of increased longevity offsets the energy savings of human-powered transportation

Spillman and Lubitz (2000) find that increasing longevity does not change fundamentally the pattern of end-of-life healthcare requirements. Instead, an increase in longevity tends to extend the healthy "middle years" of life. I infer from this finding that increasing longevity due to physical activity would not change fundamentally the pattern of energy use at the end of life, but essentially also extend the middle years of energy use. The average per-capita energy use in the U.S. is 334 GJ/yr and in the OECD countries is 195 GJ/yr and I use these average values to estimate the energy cost of increased longevity (International Energy Administration 2004).

Table 1 integrates each element of the analysis to estimate the net effect of displacing driving with bicycling. These figures are computed *per year* of bicycling or physical activity. In sum, a year of bicycling reduces energy use for transportation substantially, -11 GJ for the US context and -7 GJ for the OECD context. However, for each year of bicycling, longevity is increased by 0.029 years (10.6 days) which corresponds to an increase in lifetime energy use of 10 GJ for the US and 6 GJ for the OECD.

Table 1. Results of analysis of impact of physical activity on net energy use for two scenarios compared to a sedentary base case. Scenario A is for an individual substituting 2600 km/yr of bicycling for single-occupant vehicle transportation. Scenario B is for an individual engaging in 4200 kJ/wk of physical exercise that does not substitute for automotive transport. These calculations are shown for the United States context of automotive and energy use and for the OECD context.

	Base Case: sedentary lifestyle		**Scenario A: bicycling for transportation (4200 kJ/wk)**		**Scenario B: non-transport exercise (4200 kJ/wk)**	
United States Context						
transport distance by bicycle instead of automobile	0	*km/yr*	2600	*km/yr*	0	*km/yr*
change in automobile energy use ("at well")	0	*MJ/yr*	-12350	*MJ/yr*	0	*MJ/yr*
change in energy used in physical activity (energy in food "at well")	0	*MJ/yr*	1151	*MJ/yr*	1151	*MJ/yr*
net change in energy used in transportation and physical activity	0		-11199	*MJ/yr*	1151	*MJ/yr*
relative all-cause mortality due to physical activity	1		0.725		0.725	
change in risk of accidental death due to bicycling	0	*1/yr*	1.7E-04	*1/yr*	0	*1/yr*
net change in longevity	0	*yr/yr*	0.029	*yr/yr*	0.034	*yr/yr*
change in energy used due to change in longevity	0	*MJ/yr*	9686	*MJ/yr*	11356	*MJ/yr*
net change in energy use relative to sedentary base case			-1513	*MJ/yr*	12507	*MJ/yr*
net change as fraction of total per capita energy use			-0.005		0.037	
OECD Context						
transport distance by bicycle instead of automobile	0	*km/yr*	2600	*km/yr*	0	*km/yr*
change in automobile energy ("at well")	0	*MJ/yr*	-8125	*MJ/yr*	0	*MJ/yr*
change in energy used in physical activity (energy in food "at well")	0	*MJ/yr*	1151	*MJ/yr*	1151	*MJ/yr*
change in energy used in transportation and physical activity	0		-6974	*MJ/yr*	1151	*MJ/yr*
relative all-cause mortality due to physical activity	1		0.725		0.725	
change in risk of accidental death due to bicycling	0	*1/yr*	1.7E-04	*1/yr*	0	*1/yr*
change in longevity	0	*yr/yr*	0.029	*yr/yr*	0.034	*yr/yr*
change in energy used due to change in longevity	0	*MJ/yr*	5684	*MJ/yr*	6664	*MJ/yr*
net change in energy use relative to sedentary base case			-1290	*MJ/yr*	7815	*MJ/yr*
net change as fraction of total per capita energy use			-0.007		0.040	

Model Parameters		
energy use of automobile (US)	3.8	*MJ/km*
energy use of automobile (OECD)	2.5	*MJ/km*
conversion factor from tank to well	1.25	
energy use of bicycling	0.077	*MJ/km*
conversion factor from food to well	5.75	
fatality risk for automobile transport	6.00E-09	*1/km*
fatality risk for bicycle transport	7.20E-08	*1/km*
human energy consumption per capita (U.S.)	334	*GJ/yr*
human energy consumption per capita (OECD)	196	*GJ/yr*

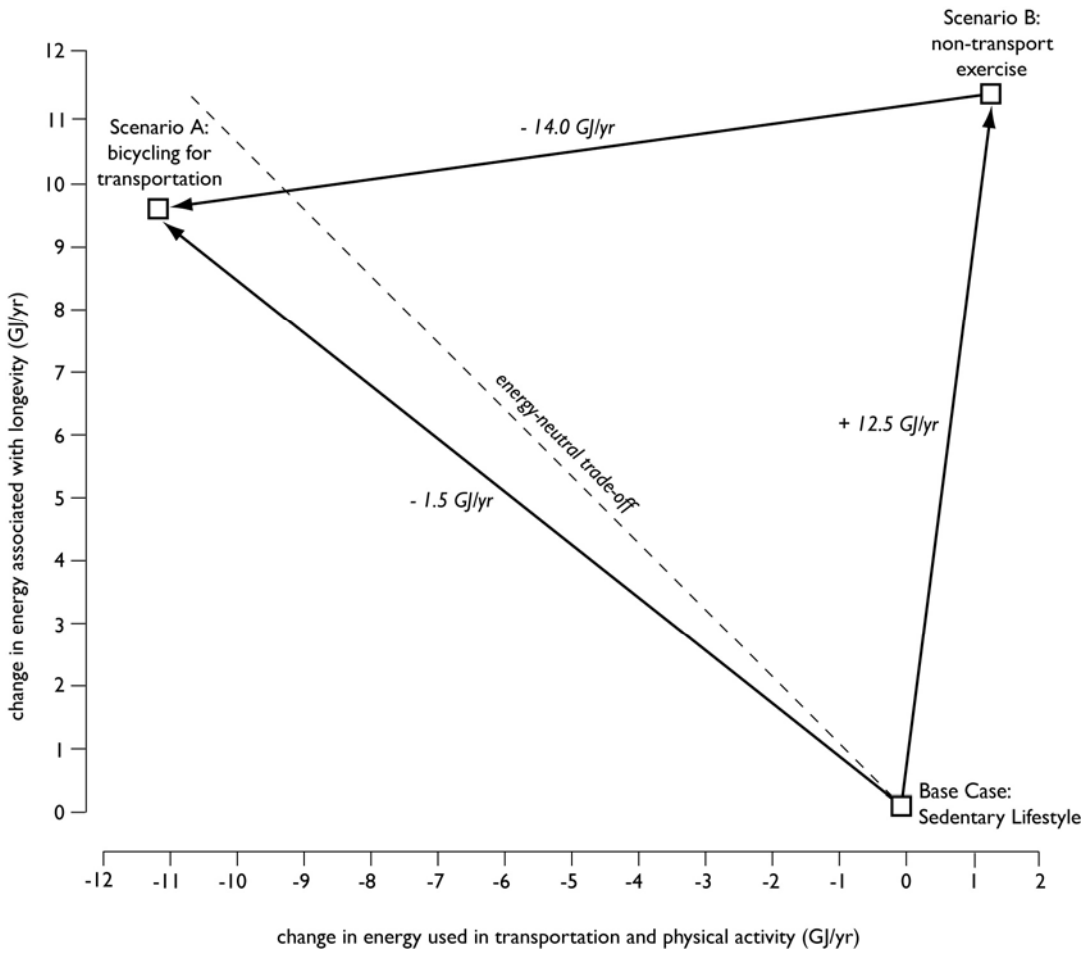

Figure 1. The trade-off between energy used in transportation and physical activity and the energy associated with increased longevity. The numerical values shown are for the US context shown in Table 1. However the diagram is substantially similar in shape for the OECD context.

For the assumed parameters the net savings from bicycling are 1.3-1.5 GJ/yr. This savings is 0.5-0.7 percent of total annual energy use, so small as to be well within the likely error in the estimate. However, by this same analysis, engaging in physical activity *without* the benefit of offsetting the use of the automobile results in a dramatic and significant increase in energy use. This is a result of both the increase in longevity and the increase in energy required to provide additional food. For the assumptions in Table 1, non-transportation physical activity in a previously sedentary individual increases total energy use by 8-13 GJ/yr or by about 4 percent.

Figure 1 is a graphical illustration of the trade-off between energy used in transportation and physical activity and that associated with longevity. As illustrated in Figure 1, the displacing of driving by bicycling is almost a neutral trade-off. Of course, the largest benefit to bicycling is for an individual who is highly fit because of non-transportation exercise to substitute bicycling for the other form of physical activity.

Human-powered transportation and public health

As a society, we value longevity more than long-term environmental impact. If we did not, we might provide incentives for risky behaviors such as smoking, drug abuse, and driving without seat belts. Thus, even if human-powered transportation does not provide a significant net environmental benefit, it provides other benefits we seem to value even more. Economically developed societies spend a substantial fraction of their resources to increase longevity through their health care systems. In the U.S., interventions that cost less than 60,000 USD per quality-adjusted life year (QALY) are considered economically efficient (Owens 1998). Of course, many interventions that are widely used are much more costly than this, and some that we fail to use are less costly. For instance, the cost of hepatitis vaccination among college students is estimated to be only 8,000 USD/QALY (Jacobs 2003).

Given that each person-year of human-powered transportation by a previously sedentary individual offers an average increase in longevity of 0.029 years, we might ask how efficient human-powered transportation could be as a public health instrument. At a value of 60,000 USD/QALY, 0.029 years of additional longevity should be worth 1740 USD. Could individuals be converted from a sedentary lifestyle to the use of bicycles for transportation at a cost of less than 1740 USD/yr? To my knowledge, a careful analysis has not been done of the efficiency of incentives and infrastructure improvements as a way to encourage physical activity. (Given that the longevity benefits of physical activity are enjoyed by the individual who incurs the costs of the physical activity, in theory each individual should be able to make an informed decision about engaging in physical activity as a health-related intervention. However, the fact that more than a quarter of the global population smokes cigarettes raises doubts about this framing of the individual decision process as a benefit-cost analysis.)

In theory, any surplus economic value of the longevity benefits of human-powered transportation could be used to offset the environmental costs of the increase in longevity. Market mechanisms to offset environmental impact are now widely available. That is, money paid by one party can be used to buy reductions in emissions by another party. Two examples of such mechanisms are the cap-and-trade

market for sulfur dioxide emissions implemented in the U.S. and the Kyoto Protocol for trading carbon dioxide emissions among nations. In the U.S., renewable energy credits are purchased by utility companies in order to meet energy portfolio requirements legislated by state governments. The wholesale price of renewable energy credits provided by wind power producers currently sell for less than 1.0 USD/GJ in regions of the country in which electricity is largely provided by coal (e.g., the state of Minnesota). In economic terms, the longevity benefits of physical activity are quite large, and only a small portion of this surplus would be required to purchase offsets for the environmental costs.

Concluding remarks

There are likely to be many additional implications and effects associated with a shift from driving to bicycling. I list a few of them as starting points for those interested in further analysis.

- For trips of more than 10 km outside of cities, the automobile may require less transportation time than the bicycle. There may therefore be an economic cost in lost productivity due to longer transit times by bicycle for those who would not otherwise spend time on physical activity.
- Those who adopt the bicycle as a means of transportation could potentially develop an increased awareness of the environmental impact of their actions and may over their lifetimes reduce energy consumption substantially in their other, non-transportation activities.
- Sedentary individuals are likely to have higher levels of body fat than fit individuals. When a sedentary person engages in cycling and reduces fat stores, there will be a one-time recovery of the energy value of the fat (Higgins and Higgins, 2005).
- Analyses of gasoline taxes typically focus on the reduction in energy use that might result from shifting to more efficient vehicles and to reductions in driving. However, to the extent that a reduction in driving corresponds to an increase in human-powered transportation, these analyses may omit a significant longevity effect of the tax policy.
- The overall system energy consumption of a personal electric vehicle such as an electric scooter or electric bicycle is very similar to that of a human-powered bicycle (Ulrich 2006), and yet the personal electric vehicle does not increase longevity. In fact, an open vehicle like an electric bicycle is likely to increase fatality risk without providing offsetting health benefits. As a result,

transportation by personal electric vehicle offers substantial environmental benefits, but not the health benefits of human-powered transportation.

The bicycle is a remarkable machine, allowing humans to transport themselves much more efficiently than by most other means. At the same time, physical activity, fitness, and health are almost axiomatically worthy objectives. And yet, the steady improvements in human health and longevity have a tremendous impact on the energy use and environmental impact of the human population. Indeed the greatest environmental peril society may face is the looming prospect of slowing the aging process. In this article, I use the focused example of human-powered transportation, longevity, and environmental impact to illuminate this basic conflict. My hope is to open a dialogue about the interplay among population, individual energy consumption, and environmental impact.

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Appendix

There is near scientific consensus that physical activity extends life. However, despite several dozen studies of the effect of physical activity on mortality, the precise relationship between dose and response has not been established. Controlling for major known factors, the effect of moderate physical activity on mortality appears to be a reduction of 20 to 35 percent in all-cause mortality during the period in which the physical activity occurs. To estimate how a reduction in mortality rate translates to an increase in longevity, I performed an analysis based on U.S. Center for Disease Control data on current mortality rates (Arias 2004). The analysis is the basis for Figure A1. I start with the 2002 CDC life tables, which provide, for each age cohort from birth to 100+ years old, the average mortality rate over the next year; i.e., the fraction of each age cohort that dies within a year. For each year in which assumed physical activity occurs, I adjust the CDC mortality rate downward by 20, 27.5 and 35 percent (to represent three reasonable scenarios based on the empirical evidence) and upward by the estimated increased risk of accidental death associated with substituting 2600 km of bicycling for 2600 km of automobile driving. Based on the resulting changes in the death rates for each age cohort, I calculate the change in average age at death, i.e., the change in longevity. I do this for several alternative durations of the period of physical activity up to a length of 60 years. I center the period of physical activity on 50 years of age, so that 10 years of activity is assumed to be years 45-55, and 20 years of physical activity is years 40-60, etc. Based on these assumptions, the effect of physical activity on increased longevity is nearly linear in the length of the period of activity over an individual's life, largely because mortality rates are nearly constant over the middle years of life. I use

the average slope of these curves in the middle scenario (corresponding to 27.5 percent reduction in mortality) to derive the estimate of a 0.029 yr increase in longevity for each year an individual engages in bicycling 2600 km.

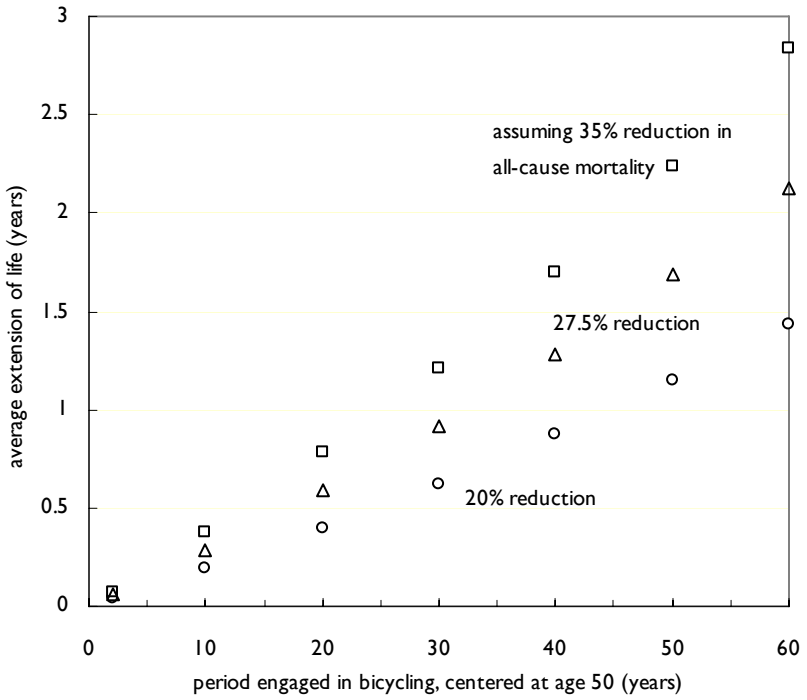

Figure A1: Estimated change in length of life associated with duration of the period of bicycling. The period of bicycling is assumed to be centered at 50 years of age. Based on calculations from CDC life tables assuming physical activity reduces all cause mortality by (a) 20 percent, (b) 27.5 percent and (c) 35 percent, and assuming that bicycling 2600 km/yr instead of driving increases the risk of accidental death in a one year period by 1.7E-4. Based on the assumption of a 27.5 percent reduction in all-cause mortality, each year of bicycling 2600 km increases average longevity by 0.029 years (11 days).