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Energy Intensity and Human Mobility after the Anthropocene

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Abstract: After the Anthropocene, human settlements will likely have less available energy to move people and things. This paper considers the feasibility of five modes of transportation under two energy-constrained scenarios. It analyzes the effects transportation mode choice is likely to have on the size of post-Anthropocene human settlements, as well as the role speed and energy play in such considerations. I find that cars, including battery-electric cars, are not feasible under a highly energy-constrained scenario, that buses, metros, and walking are feasible but will limit human settlement size, and that cycling is likely the only mode of transportation that would make suburbs possible in an energy-constrained post-Anthropocene scenario.

Keywords: energy; transportation; mobility; energy intensity; Anthropocene; cities

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> Past a certain threshold of energy consumption, the transportation industry dictates the configuration of social space.
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> —Ivan Illich, *Energy and Equity*

1. Introduction

People living after the epoch of human dominance will likely control a smaller fraction of the Earth's surface area, its material resources, and the other animals on and in it than they do today [1,2]. As a result, they will have less control over the energy flows and stocks on and in Earth, and thus less available energy with which to move and make things. One characteristic of the current organization of life on Earth is that human beings, in large part because of their exclusive access to underground reserves of fossil fuels and their control of the Earth's surface area, material, and other animals, direct a large amount of the energy flows on and inside the planet. The primary energy supply of all human societies is about 585 exajoules per year. This is small compared to the amount of energy in the form of solar radiation striking the Earth every day (about 7680 exajoules), but enormous compared to what is harnessed by other life forms and past humans. Human use of fossil fuel reserves is likely to decline in most post-Anthropocene scenarios. The exigencies of climate change, resource depletion, the difficulty and mounting inefficiency of extracting harder-to-reach reserves, breakdowns in the large-scale organization needed for energy extraction, or a combination of these and other factors offer plausible reasons to think so. Human control of the planet's surface and other animals is also likely to decline, whether because of shrinking human populations, breakdowns in organization required to organize and control large amounts of surface area, or—as documented later—declines in energy availability that make motorized transportation over long distances increasingly difficult. As a result of declining fossil fuel use as part of a broader trend of decreased control of the planet's material resources, the amount of primary energy produced by and therefore available to people is likely to decline. What would an energy-constrained world be like? What would humans still be able to do in this world and which capabilities would they lose?

Past human societies, which had less available energy than today's societies, provide some useful evidence about how to function in low-energy environments, and so it is possible to read accounts of earlier societies for guidance on this question [3,4]. Consulting past societies as models for future ones remains necessary but insufficient, however, for making considered observations about the possible paths of existing societies because (i) our understandings of past civilizations are imperfect, as the tendency of historians to revise these understandings, often fundamentally, every generation or so demonstrates, because (ii) post-Anthropocene humans will have some form of access to and knowledge about technologies and schemes for organizing society, food and goods production, government, and so on that pre-Anthropocene societies did not, and because (iii) it is unlikely that present societies would simply revert to past forms upon the imposition of past constraints, not least because societies change irreversibly as they move forward. History is not a time-reversible process. There is little evidence in the historical record of straightforward reversion as compared to, say, reversion with modifications [4]. Other work focused on the Anthropocene proper has discussed ways of conceptualizing an exit from the epoch and the material realities that occasion and condition such an exit [5,6].

One way of making observations about future paths is to start from any physical or material limits that create boundary conditions for what future societies will look like [7]. This paper represents one such attempt to work out these boundary conditions with respect to primary energy production dedicated to transportation, especially daily commuting. I estimate the energy, in gigajoules per person, that will be available for transportation under two energy-constrained scenarios. I then examine five modes of transportation (cars [electric and combustion], metros, buses [electric and combustion], bicycles, and walking) and calculate how much distance each can reasonably cover given certain energy constraints. I discuss the implications of these estimates for the mode choice, speed, and physical size of human settlements in a world after human dominance.

2. How Much Energy and How Much Distance?

Current primary energy consumption per person in US is about 326 gigajoules (GJ). Worldwide, it is closer to 82 GJ per person [8,9]. This number captures the electricity consumed from power plants (including imported and domestic coal, nuclear, natural gas, hydroelectric, geothermal, solar [thermal, concentrated, and photovoltaic], wind, wood, biomass), from burning petroleum products like gasoline and diesel, and from burning ethanol and biodiesel, as well as "non-combustion" fossil fuel use, as in construction, feedstock, and manufacturing [9]. Primary energy consumption, therefore, offers a reasonably good measure of the energy required to sustain the lifestyle and activities of a given population. Its increase or decrease, therefore, is a matter of general concern.

Any future decline in the energy available to humans could follow a gentle slope downward along which optimistic predictions about the ability of economies to transition to carbon-neutral energy sources like wind and solar come true quickly and thoroughly. In this world, humans would be able to settle at a steady state in which available energy is lower, but still high by historical standards. The decrease in energy available to human societies could also come quickly. Given that humans' most current and most lucrative energy-production techniques (e.g., longwall mining, deepwater drilling, hydraulic fracturing) tend to rely on human dominance and complexity, failures in the support systems these techniques rely upon could lead to rapid, non-linear decreases in available energy. To quantify and explore the differences between these two possible futures, I model two scenarios that I call demi-Anthropocene and post-Anthropocene. The first, demi-Anthropocene (demi-A), represents a partial or optimistic exit from the human-dominated geological epoch. It is characterized by the sort of transition to entirely carbon-neutral energy presented by Jacobson et al. [10]. Jacobson et al. suggest that a reduction in total energy demand of around 57.1% is consistent with a transition to entirely carbon-neutral energy systems. Estimates of reductions in energy use vary among different analyses [11] but are generally within ten percentage points of each other and of Jacobson et al.'s estimate. I use the round figure of 45% of available energy per person in the United States (that is, a 55% reduction) in the demi-A scenario as it captures the median of such work and avoids clothing itself in a false precision. The demi-Anthropocene scenario represents the sort of world brought about by rapid shifts to renewable energy alongside the widespread electrification of transportation and industry. This is the sort of situation that would involve nation-states and companies aggressively investing in renewable energy in the next three decades, closing coal and gas power plants, and phasing out internal combustion vehicles quickly and completely by 2050 or earlier. These changes would be rapid and thorough but would not radically change the constituents of the global economy or the total amount of energy available to human societies. Note, for instance, that because the demi-Anthropocene is based on 45% of the current US energy primary energy supply per capita, it would actually involve an *increase* in world energy supply per capita (from about 82 GJ to about 147 GJ per person per year). The demi-A scenario, therefore, can accommodate visions of increasing global standards of living for all but the most energy-intensive populations, who would have to reduce their energy demand by more than half, either through efficiency improvements or straightforward reductions in goods, services, and travel. This scenario would also involve some cooperation from non-human factors: to arrive safely at a demi-A plateau, worst-case scenarios like runaway feedback loops from widespread Arctic methane release will probably have to not occur, as they are likely to frustrate the supply chains, social systems, and technological improvements that will make providing 147 GJ of energy per person per year possible.

The second scenario, post-Anthropocene (post-A), is harder to model. This scenario represents a severe decline in available energy. The post-A considers a clear transition out of the human-dominated geological epoch and into a world in which human control of the planet's energy has largely slipped away. In this scenario, societies can no longer harness the energy available on the planet as efficiently or at the scales they do today and are consequently limited in their ability to organize and operate societies that demand high concentrations of energy. In climatological terms, such a scenario might coincide with, to take one example, the hotter Earth scenario presented by Steffen et al. [7], in which humans live on in a world much warmer (perhaps four to five degrees Celsius above preindustrial levels) and less hospitable to them. Unlike the demi-A scenario, this is a world in which global levels of available energy would shrink from 82 GJ to fewer than 17 GJ. Standards of living would fall for most people on the planet, either slowly or quickly. Travel, the consumption of goods, and the provision of critical infrastructure services would become more difficult and less robust. There are fewer ways of estimating the energy available in such a situation, because these situations are more distant and more different from our own. No matter how many studies of the Eocene or a "hothouse Earth" are conducted, knowing the quantity of available energy in such scenarios remains out of reach. Thankfully, this analysis does not rely on precise knowledge about the future paths of extreme warming or social collapse. This paper focuses on understanding how human transportation systems are constrained under low-energy scenarios, however such scenarios are arrived at. For these purposes, I set a benchmark value of 5% of current available energy for the post-Anthropocene scenario (that is, a 95% reduction in available energy from 2018 levels in the United States).

I mostly rely on US data in this analysis (noted when otherwise) because the United States represents the largest, most carbon-intensive economy whose figures on vehicle miles driven, total primary energy production, and other metrics tend to be comprehensive and accessible. I also start the analysis from US numbers because the US has often served as a vanguard for the energy-intensive patterns of behavior (personal car use, high amounts of meat consumption, home ownership, large-scale suburban housing) and the infrastructure systems that realize those actions (industrial farming, national highway systems, fossil fuel extraction and delivery, financial support for home ownership, a large military distributed across the planet) that make the most difference in the energy-use figures of a society on a per capita and absolute basis.

In the demi-A scenario, total primary energy per US resident would decline to 146.7 GJ, down 55% from 326 GJ today. In the post-A scenario, it would be 16.3 GJ, down 95% from today. Of course, not all this energy is spent on travel. From 2016 to 2018, transportation consumed 28.4% of total energy usage in the US [12]. (This is up from 23% in 1965 and 26.5% in 1990.) This 28.4% transportation share leaves 41.616 GJ to each person per year in a soft-transition demi-A scenario and a scant 4.62 GJ per person per year in a post-A scenario. The task, then, is to see how feasible each mode of transportation is under these energy constraints. A table (Table 1) summarizing the results of this work appears after the following discussion of cars, buses, metros, bicycles, and walking.

Table 1. Energy intensity, distance, and predicted effective commute range by mode.

	Energy Intensity (MJ per Passenger-km)	Distance/Year (km)	Distance/Year (km)	Effective Commute Limit (km)	Effective Commute Limit (km)
		Demi-A	Post-A	One-Way, Demi-A	One-Way, Post-A
Cars (ICE)	1.3	25,610	2896	35	3.97
Cars (BEV)	0.67	49,691	5516	68	7.6
Metros	0.1584	210,181	23,353	287.5	32
Buses (ICE)	0.54	77,067	6844	105.5	9.3
Buses (BEV)	0.29	114,803	12,744	157	17.5
Bicycles	0.105	317,074	35,200	434.3	48.2
Walking	0.218	152,719	16,954	209	23

3. Cars

The average American drives 21,688 km (13,476 miles) per year [13]. This represents an energy expenditure of 77.53 GJ [14]. Using a conversion factor of 34.34 MJ per liter of gasoline and an average fuel efficiency of 10.4 L per 100 km, as in Prokopiak (2012)'s work, but adjusting for unit conversion and distance. This figure, divided by the 92.58 GJ that is used per person for transportation in the US today, indicates that ~83.7% of the energy budget for transportation in the US goes toward car travel, which is broadly in line with US commuters' current modal share (76.6% of commuters drive themselves to work and another 9% carpool) [15,16]. The energy expenditure of a car that is driven 21,688 km per year outstrips the demi-Anthropocene energy budget by 86% and the post-Anthropocene energy budget by 1677%, or sixteen times over. Note that 6 GJ roughly represents the chemical energy of combusting 1 barrel (159 L) of crude oil.

Even if cars dropped to zero percent of the US modal share, the energy spent on all remaining forms of transportation (14.95 GJ) still far exceeds the travel energy budget in a post-A scenario (roughly tripling it). This implies that further reductions among modes of transit seen as low-carbon transit, like commuter rail and buses, will be necessary after the Anthropocene. It is possible that, under scenarios in which the calories available to human beings in the form of food are limited, strategies like reducing walking in favor of biking (biking is somewhere between two to four times as efficient as walking, and has around 30% lower carbon intensity per km, depending on diet) [17], reducing walking and biking together by, e.g., reducing the size of human settlements and increasing density, or some combination of these and other strategies will be necessary.

Under the demi-A scenario, distance driven would run up against a hard cap of about 32,012 km/year. This assumes a highly efficient internal combustion car, the most efficient of which can move one person one kilometer at a cost of about 1.3 MJ. Even this is likely impossible, as it requires directing every last joule of energy spent on travel into cars. A less unrealistic "soft cap" would fall around 25,610 km/year. (This number assumes the current balance of energy shifts modestly toward non-car travel, with car travel commanding a reduced, but still high, 80% of the travel energy budget.) This would limit most drivers to a bit over 70 km of total driving per day, effectively limiting the distance between workplace, school, and home to under 35 km (~22 miles), or from White Plains, New York, to the southern tip of Manhattan, or a little less than the driving distance from Machakos, Kenya, to downtown Nairobi. This would put downward pressure on American car use, but is unlikely to impose hard limits: the average round trip car commute is currently about 51 km. Much of Europe would come in under this limit, albeit not by much: drivers in the UK, for example, covered 34.8 km per day in 2013, consuming about half of what the demi-A scenario would allow [18]. (Chinese driving numbers are harder to come by, but data from Cox and Liu et al. indicate that kilometers driven in China remain ~42% lower than the US but are climbing rapidly [19,20].) However, these figures remain within the quite optimistic demi-A scenario. The numbers become formidable when considering the post-Anthropocene scenario.

In a post-Anthropocene scenario, the hard cap for driving would be about 2896 km per person per year. Again, this comes from redirecting 100% of the 4.62 GJ energy budget for travel toward car travel and is therefore almost certainly an overestimate. The soft cap for driving would be, using the optimistic 1.3 MJ per person per kilometer energy intensity figure, about 1035 km. As before, this assumes a reduction in the energy budget directed toward driving down to 80%. (In absolute terms, this is still quite high.) This scenario limits drivers to just 7935 m of driving per day, limiting the distance between home and commuter destinations to 3900 m or so. This is the distance from Manhattan's 1st Street to its southern tip, or the length of one large airport runway. These distances are more readily covered by foot, bicycle, scooter, or another form of low-energy intensity travel. This, obviously, leaves little room for car commuting in a post-Anthropocene scenario. Even electric cars, which are more efficient than internal combustion engine (ICE) cars, are too constrained under a low-energy scenario to provide travel beyond a few kilometers.

Battery-electric vehicles (BEVs) vary widely in their efficiency, as do internal combustion engine vehicles. A stringently efficient ICE car like the Volkswagen Polo expends about 1.3 MJ to move one kilometer. An efficient BEV, like the Nissan Leaf, expends about 0.67 MJ to move the same distance [21]. Using these efficiency numbers, if 100% of the light-duty fleet were converted to electric vehicles, the post-Anthropocene soft cap for one-way feasible commute distance would rise to a still-modest 7556 m per person per day. (Keep in mind that these numbers do not incorporate the energy costs or material demands of manufacturing cars.) A rough approximation of materials and energy expended can be gleaned by simply looking at the weights of the relevant vehicles: most light-duty BEVs weigh between 1600 and 2500 kg, ICE cars between 1100 and 2500 kg, bicycles 7–16 kg, and walking shoes 0.2–1 kg. The manufacturing energy required roughly scales with the total weight of each vehicle. Cars take around 73 GJ to manufacture per unit [22,23]. A bicycle, based on weight alone, should take about 0.47 GJ to manufacture. Note that, when spread over a ~12 year lifespan, the per-year amounts are relatively modest for both vehicles. Energy consumption from use is about ten times more important than energy consumption from manufacturing. Note, however, that if manufacture energy is included as part of the energy budget, one car, BEV or not, consumes five years of the post-Anthropocene energy budget via the energy demands of its manufacture alone, without being driven a meter. Note further that this energy-only analysis does not touch on the availability of rare earth metals and other materials needed to produce the amounts of BEVs needed for mass electrification, material in little demand by bicycles and walking shoes.) Hydrogen cars fare worse than BEVs on energy intensity metrics, falling somewhere between BEVs and ICE vehicles [24,25]. In anything approaching a post-Anthropocene world, cars will require commutes so short that other uses of transportation are better suited even if one considers factors other than energy intensity.

If cars have little use where they are not impossible, how do other forms of transportation, like metros, fare?

4. Mass Rapid Transit

I will examine mass rapid transit systems, or metros, next. Catling (1966) found that the London Underground expends 0.1584 MJ to move one passenger one kilometer, and (the physics of moving trains having changed little in the intervening years) contemporary sources do not disagree with him, generally finding between 0.09 and 0.35 MJ per passenger-km [26]. This is about one order of magnitude less than a very efficient ICE car and one-fifth of the energy required by a BEV. It falls about halfway between walking, which is less efficient, and cycling, which is more efficient. Under the demi-Anthropocene scenario of 41.616 GJ available per person per year for transport, distance traveled via metro would be subject to a soft cap of around 210,181 km/year. (This number, as with the soft cap calculation for cars, assumes that rapid transit consumes 80% of the travel energy budget.) This is a hugely generous travel allowance, allowing each user to circle the globe several times per year, or to cover 575 km per day. From an energy standpoint, rapid transit can accommodate arbitrarily long commutes. Travel distances would be limited by constraints other than energy, like time and geography. Note that these numbers remain within the optimistic demi-A scenario and become more constrained in a post-Anthropocene world.

The post-Anthropocene scenario allows for 23,353 km per year of travel using mass rapid transit, or 64 km of total riding per day, with 20% of the travel budget left over for other modes (which, in a system dominated by metro use, will be necessary to cover 'last-mile' scenarios and other gaps in the network. Note, too, that intercity rail transit is usually slightly more efficient than metros, allowing for moderate travel between cities under this scenario.) This travel limit is no longer arbitrarily high, and this has real-world consequences: commuters will not have the energy budget to commute by rail between Washington, D.C., and Baltimore (about 125 km roundtrip via MARC, which as intercity rail requires similar energy per km to metro systems) five days per week, for example, or from Potsdam to central Berlin (about 120 km roundtrip via S-Bahn), or between Shanghai and its outlying suburbs, or between Tokyo and its outlying suburbs.

Metros, unlike cars, consume sufficiently low levels of energy in a post-A scenario to be feasible for daily commuting within human settlements no wider than about 30 km, or between settlements no further apart than 30 km. Their consumption of energy in a demi-A scenario allows for arbitrarily long commutes (over 285 km each way).

5. Buses

I examine buses, both diesel and electric, next. Cushman-Roisin and Tanaka Cremonini find that standard diesel-powered urban buses use 0.4 MJ to move one passenger one kilometer if the bus carries 20 passengers, and 0.6 MJ if it carries ten [27]. New York City, Los Angeles, and San Francisco report an average passenger load per bus of about 17 [28]. Plugging an average passenger load of 17 into the above estimates yields an energy intensity of 0.54 MJ per passenger per km. This is very close to US Department of Transportation statistics (on which Cushman-Roisin and Tanaka partially rely), which, converted appropriately, yield 0.53 MJ per passenger per km [16]. This is about 20% more efficient than a BEV and 58% more efficient than an ICE car. Diesel buses carrying an average passenger load consume about two and a half times the energy consumed by walking and about five times that consumed by cycling the same distance.

Diesel buses would, under a demi-Anthropocene scenario with a travel energy budget of 41.616 GJ per person, be able to cover about 77,067 km per person per year, assuming, as before, that conventional buses would be consume 80% of the energy for travel. This is 211 km per person per day, allowing for a fairly generous maximum commute distance of 105 km or so. Under a post-Anthropocene scenario, the yearly limit would be 6844 km per person, or 18.75 km per person per day, for a maximum commute of about 9 km each way. This is a fairly restrictive scenario, falling somewhere between mass rapid transit and BEVs. Commuters would be unable to traverse the length of Manhattan or the width of Paris. Electric buses, however, are said to demand less energy per passenger-km than do diesel buses. Do they offer a workable transportation solution under energy constraint?

Electric buses employ a battery-electric drivetrain with regenerative braking. The efficiency advantages of battery-electric systems relative to combustion engines (like the diesel or clean diesel systems used by most buses) are compounded by the effectiveness of regenerative braking, which is able to recapture significant energy otherwise lost to brake heat in the start-and-stop use cases common to urban bus routes. Full electric buses remain more expensive than their diesel predecessors, but their adoption is widespread in China, where about 90% of new bus sales are electric, and major cities like Shenzhen only use electric buses. Uptake has been slower outside of China, though a variety of major cities have committed to electric-only bus fleets by dates like 2035 (San Francisco), 2037 (London), and 2040 (New York City).

Electric buses are indeed less energy-intensive than diesel buses. Electric urban transit buses consume between 0.18 and 0.4 MJ per passenger per km, depending on the analysis used [24,29]. I will use an average figure of 0.29 MJ per passenger per km. Under this assumption, distance traveled via electric bus would have a soft cap of around 114,803 km/year under a demi-A scenario. (This number, as with the soft cap calculation used for other modes, assumes that electric urban buses receive 80% of the travel energy budget.) In an electric bus system, commuters would be able to cover 314 km per day without exceeding the energy budget for transportation. While not limitless, this distance covers virtually all commute scenarios. Travel distance, for electric buses, would be constrained by factors other than energy.

A post-Anthropocene scenario allows for 12,744 km/year of travel using battery-electric buses, or 35 km of travel per day, with 20% of the travel budget remaining over for other modes (which, as before, will be necessary to cover 'last-mile' scenarios and other gaps). This travel limit allows for most travel within cities, few of which are wider than 17.5 km, but remains somewhat restrictive for most other scenarios. Travel between Flushing, Queens, and lower Manhattan five days per week would exceed the energy available for transportation in such a model. Nor could anyone commute between, say, Cairo and New Cairo under these constraints. In fact, commuters would be hard pressed to commute from the suburbs of all but the most compact major cities into their central business districts.

6. Bicycles

Other than some electric kick scooters and solar-powered vehicles built for specific contests, like Solar Impulse 2 or the Nuna series, the bicycle is the most energy efficient means of transportation known. This includes the animal kingdom, human-developed means of transportation, and every form of transportation under consideration in this study. (Bicycles also demand less manufacture energy than every form of transportation considered in this study aside from walking.) A person on a bicycle, moving at 16 km per hour, consumes between 0.095 and 0.115 MJ per kilometer per person, depending on the weight of the rider, bicycle, and the rider's position (upright positions are less aerodynamic than lower positions and therefore require more energy at the same speed) [30,31]. I will use a figure of 0.105 MJ, because this is the best estimate for a human of global average adult weight (about 62.3 kg).

The soft cap for bicycle travel (using the same 80% allocation as before) under a demi-A scenario is 317,074 km. This is high. Currently, the world record for most kilometers traveled in a year on a bicycle is 122,432, which was accomplished by biking twelve or more hours per day for a year. A bicycle commuter would have the energy budget to travel 867 km per day. This limit is mathematically impossible to exhaust: 16 km per hour for 24 h is only 384 km. Even much faster cyclists, consuming energy and distance at a faster rate, would be hard pressed to exceed this limit: the world record for cycling for 24 h straight was set at 896 km in near-perfect conditions at an airport in Berlin. So, the distance limits for bicycle commuting are unconstrained by available energy under a demi-Anthropocene scenario. A great deal of the energy saved by bicycle commuting could eventually be reallocated to other uses, like manufacturing, medicine, or agriculture.

The soft cap for bicycle travel under a post-Anthropocene scenario, allocating 80% of energy to cycling, would be 35,200 km per person per year. This allows for 96.4 km of travel per person per day, or an effective commute distance of 48 km on the high end. This is the most generous allowance of any post-Anthropocene mode. Commutes between Texcoco and Mexico City, or Plano and Dallas, would remain possible seven days per week. Commutes between downtown Dallas and downtown Fort-Worth would remain possible five days per week, as would travel between famously sprawl-friendly Houston and virtually all of its outlying suburbs. The few examples that would be energy limited are already limited by simple practicality. Cycling from Irvine to downtown Los Angeles passes beyond the edge of the energy frontier but takes between four and five hours anyway—hardly a practical commute.

In all but the most extreme cases, the bicycle keeps the suburbs within reach of the central business districts to which they are nominally attached. Ironically, given the historical intertwining of the car and the suburbs, the bicycle is the only mode of transportation yet studied that would make something like true suburbs possible in a post-Anthropocene world.

7. Walking

Walking, because it does not take advantage of a wheel and ball bearing system to conserve forward momentum, is less efficient than riding a bicycle. Because it does not require any external weight or complication, it is more efficient than almost all forms of motorized transportation (electric kick scooters are, under the right circumstances, a possible exception). Combining the global average adult weight (62.3 kg) with evidence from McArdle (2000) on the energy demanded by walking, running, and cycling yields an energy consumption rate of 0.218 MJ per pedestrian per km [31].

A demi-Anthropocene society in which 80% of the transportation energy budget is allocated to walking can supply the energy for each of its members to cover about 152,719 km on foot per person per year. This is 418 km per day, or more than most humans can walk in several days. As expected, energy is not a significant constraint for walking under a demi-A scenario. Practical limitations remain more important than considerations of energy expenditure.

Under a post-A scenario, members of the same walking-dominant society would be able to cover 16,954 km per year, or about 46 km per day. This at the limit of what an experienced walker can cover in one hard day of hiking. Walking is unlikely to be constrained by energy after the Anthropocene. Instead, it will be constrained by the usual things that hamper walking long distances in any situation: walking is slow (about 3–7 km/h), and so it takes a long time to get anywhere further than a few thousand meters away, you are exposed to the elements while you do it, it is tiring, sensitive to terrain, and a burdensome means of transporting cargo.

8. Motorized Versus Non-Motorized Transportation

Note that cars, metros, and buses draw from energy stores external to themselves, either via electricity or the pumping of liquid fuels like diesel and gasoline. Human-powered transportation, like biking and walking, draws on the metabolic processes of human beings and, therefore, from the food humans eat and stored energy in the form of fat. The unit we have been using so far, the megajoule, is equal to about 239 kilocalories. A cyclist who uses 0.1 MJ to travel one kilometer will require about 24 kilocalories of food, or a bit less than one walnut, to do so. This means that, unlike the motorized forms of transit, the diet of the person walking or cycling matters for the energy efficiency and environmental effects of these forms of transit. A cyclist who mostly consumed beans, wheat, and corn, for example, could have an environmental impact as low as one-twentieth that of a beef-fed cyclist [32,33].

Please note that the transportation budgets used in this paper are derived from primary energy production in the United States. These numbers carry more or less straight over to motor vehicles, which use primary energy sources like gasoline, diesel, and electricity. However, primary energy production does not directly include kilocalories consumed per person per day or some equivalent measure. The overall numbers for food energy are not too hard to calculate (e.g., US residents eat about 3300 kilocalories per person per day, which is about 5 GJ of food energy per person per year), but for consistency, this paper assumes that for societies in which large-scale conversions to non-motorized forms of transportation occur, the pool of primary energy currently used for transportation will, in some form, still be drawn on by non-motorized forms of transportation. This may involve, as a practical matter, transferring material and power from centralized electricity production or fossil fuel extraction toward increased kilocalorie production, but the underlying energy budget will remain similar.

There are, finally, several reasons for preferring mechanically simpler and physically lighter forms of transportation in a post-Anthropocene scenario aside from energy intensity. Cars, buses, and trains, whether combustion or battery-electric, require extensive infrastructure in the form of electrical grids, power plants, substations, mining, machining, and so forth. Bicycles and shoes require no fueling infrastructure beyond potential increases in kilocalorie supply (i.e. growing and transporting slightly more food). They also require lighter and fewer manufacturing, supply chain, and raw material components for their production and maintenance. These economies can be Fermi-estimated by looking at the curb weight of bicycles and shoes against the curb weight of motorized vehicles. Bicycles weigh between two or three orders of magnitude less than cars, buses, and metros do (even when divided by the average passenger load of each). Shoes weigh about four orders of magnitude less than those vehicles. We should expect, at a rough cut, a bicycle to demand about 1/500th the materials and complexity that a car, bus, or train would (on a per passenger basis). Similarly, we should expect to be able to produce thousands of pairs of shoes with the materials and manufacturing required for one car. In a post-Anthropocene scenario in which materials and supply chains are limited or damaged, these material economies are likely to matter a great deal.

Considerations of equity also offer reasons to prefer simpler, lighter means of transportation. Because cars, buses, and trains are more expensive to produce and use than bicycles and shoes (by orders of magnitude similar to their weight differences), they are more expensive for people to use. This is likely to translate preexisting inequalities into the transportation system, as is currently common. Fewer people can afford a car than can afford a bicycle. Whether the costs for complicated, resource-intensive transportation are paid upfront, financed via debt, or amortized via ticket sales, road taxes, and insurance, they fall heaviest on those least able to pay. The only exception to this fact would be a society that used some form of progressive taxation to subsidize motorized travel (either via public transit or, say, by subsidizing private car ownership). (This same tax-and-subsidy scheme, however, could be used to make cycling or walking more affordable, likely to greater effect.)

9. Implications and Findings

Changing a mode of travel's speed modifies the relationship this form of travel establishes between energy consumption and distance. At higher levels of speed, more energy is expended resisting the movement of air. As a result, running the same modes of transportation more slowly is one way of eking more distance out of a limited energy budget. Hastening a mode of transit is, conversely, a way of trading energy for time. A cyclist traveling at 15 km/h requires 30 watts (or 30 joules per second), less than half of which is spent on air resistance [30]. A bicycle traveling at 30 km/h demands 148 watts. More than two-thirds of this power goes to moving air out of the way. (This assumes that the rider and bicycle have a combined weight of 75 kg and an average-sized frontal area.)

Pedestrians experience similar costs associated with speed, as do motor vehicles. A rough application of the drag equation indicates that an intercity bus moving at 30 km/h demands 1875 watts (joules per second) to push through the air (assuming a fairly typical drag coefficient of 0.6). ($F_d = \frac{1}{2}pu^2C_dA$, where p is the density of air, u is flow velocity, C_d is the drag coefficient of the vehicle, and A is its frontal area. Drag force (F_d) can be used to calculate the power needed to overcome drag at a given velocity using $P_d = \mathrm{F}_d{\cdot}\mathrm{v} = \frac{1}{2}pv^3AC_d$, where v is velocity, p is again air density, v is velocity relative to Mach 1, A frontal area, and C_d drag coefficient. Note that the power needed to resist drag increases with the cube of velocity.) The same bus moving at 60 km/h loses 15,000 watts to air resistance, or 15 KJ per second. Decreases in energy efficiency via higher speed reduce the effective range for all mode types under constrained-energy scenarios, with the exception of walking, which is still mostly limited by factors like time and fatigue. If air resistance accounts for, say, 40% of the energy expended by an intercity bus running its route, and the energy spent overcoming air resistance increases eightfold when speed doubles from 30 km/h, something like a 35% reduction in range can be expected from running buses closer to 60 km/h as opposed to 30 km/h. Combining the range numbers from the post-A scenario with the increased air resistance estimates means that diesel buses would have a new effective commuting range below six kilometers each way and electric buses would be unable to cover commuting distances more than 11 or 12 km each way. Because the energy required to overcome air resistance increases non-linearly, further speed increases shrink this range to a pinprick. In an energy-constrained system, speed is ruinously dear.

Illich (1974) identifies the severe demands that speed makes on energy as a structuring feature of societies, especially those that provide means of transportation that go faster than about 24 km/h [34]. Illich points out that "[i]n traffic, energy used over a specific period of time (power) translates into speed," because of which certain levels of speed will demand sufficiently high concentrations of energy and physical separation from other people and machinery as to change the physical and social organization of a human settlement. He argues that "the critical quantum" of speed is about 15 mph, or a bit over 24 km/h, and that "[w]herever this limit has been passed [a] basic pattern of social degradation by high energy quanta" can be observed [34]. After this limit was breached by public or private vehicles, "equity declined and the scarcity of both time and space increased. Motorized transportation monopolized traffic and blocked self-powered transit" [34]. As we have seen, something important inheres in the relationship between speed and energy intensity, but a more detailed exploration of these claims is needed. This paper has attempted to analyze the specific energy intensity of different modes of transportation in a way that prices in their average velocities but also takes into account their various efficiencies and energy demands as really-existing systems of movement. This information allows for a reevaluation of Illich's observation. We do see some correlation between the modes of transportation with high energy intensities and high speed (Table 2).

Table 2. Energy intensity and typical effective speed.

	Energy Intensity (MJ per Passenger km)	Speed Range Usually Achieved in Cities
Cars	0.67–5	30–95 km/h [35]
Metros	0.1584	25–85 km/h
Buses	0.29–0.54	13–85 km/h
Cycling	0.105	13–32 km/h
Walking	0.218	3–7 km/h

This correlation is somewhat jagged, however, with buses fairly inefficient for speed traveled, and metros and bicycles fairly efficient. Cars remain much less efficient (even for their speed) than other ways of getting around. Illich's dictum captures an important insight about the relationship between speed, energy, and the physical and social organization of cities, but probably remains too simple. A cyclist or metro train at 30 km/h commands a different amount of power, and therefore a different organization of energy, than does a car traveling at that same speed. Both are over Illich's speed limit. But under the energy-constrained scenarios I have considered, a car cannot be sustained at that speed for the length of an average commute, while a train or bicycle can. Moreover, the amount of infrastructure and space that must be dedicated to cars traveling at 30 km/h through a city is much higher, on a per-passenger basis, than what must be dedicated to make it possible for subway cars and bicycles to travel 30 km/h through the same city. The reorganization of space to allow for increased energy-intensity travel has certain social effects that urbanists, historians, environmental scientists, and others have documented: neighborhoods delimbed by controlled-access highways, city centers sheared by surface parking, pedestrians pushed back by road widening, playgrounds dusted with $PM_{2.5}$, those without cars separated from job centers and schools by roads, those with cars tethered to the fueling and maintenance of cars, and so forth. All of this is to say nothing of atmospheric carbon at 412 ppm and rising, ocean pH >8.1 and falling, and September Arctic ice extent <4 million km^2 and shrinking [36–39].

Under future conditions of energy constraint, Illich's posited relationship between energy intensity and the organization of cities may begin to work in reverse. Higher levels of speed will not drive increased extraction and the reordering of social and physical space. Instead, decreased extraction will put downward pressure on speed and will in its own way change social space. As concrete examples, I have listed certain commuting routes that will be difficult or impossible for simple energy-expenditure reasons in a post-Anthropocene scenario. No more Flushing to Manhattan, no more Machakos to Nairobi, and so on. One observation remains common to every scenario and mode of transportation under discussion: because humans will be restricted to distances that are smaller and will have to cover these distances more slowly, human communities will experience pressure to become geographically smaller. This means that these communities will have fewer people, those people will be more densely packed, or some combination of the two. If humans are reluctant to give up the economic, social, and cultural benefits that come with living in organized settlements with many other people [40], they will have to choose density, probably with effective commuting distances shorter than 17 km or so if using electric buses, 30 km using rapid transit, and 48 km using bicycles. The shape and extent of communities may conform to something of a weighted average of these figures, dependent on how much of a role the various modes of transportation play and how much energy is allotted to each.

(There is another set of scenarios, of course, in which humans do give up on the agglomerative effects of living together and live in relatively isolated semi-rural communities with no complex system of transportation to speak of because no one has any commuting to do beyond walking in the immediate vicinity of one's own settlement. I do not model this future, although I can say from the work here that, while bicycles are likely to be effective in these futures, it is hard to produce bicycles without some degree of agglomeration, trade, and design.)

The analysis in this paper suggests one motivating factor for policy change and about six concrete normative implications. The motivating factor comes from the fact that a demi-A scenario is probably not that bad and a post-A scenario is quite bad. A lot of useful transportation technology (to say nothing of other socially useful goods not considered here) will be useless or severely limited in a world where the total energy available per human being is under 17 gigajoules. Human societies should make every effort to land on a higher energy plateau, around demi-A, than on a lower one. This objective remains possible, but it will require aggressive efforts to lower emissions and some degree of luck. The more rapid and effective the effort, the less luck will be needed. The first normative implication is that societies ought to plan for lower-energy states in ways that are far-reaching and detailed. Transportation is an obvious area, and one severely affected by energy constraints, but still only represents about 28% of total energy expenditure. Other areas, like manufacturing, healthcare, and communication technology, will be affected in much the same way as transportation, and will have to move toward less total consumption and more efficient machines and system design. How many data centers can society maintain in a demi- or post-Anthropocene scenario? How many hospital ventilators per 100,000 people? Further research and planning in this area remains essential. A second recommendation is to model the intentional slowing of transportation systems and to build the possibility of slower, lower energy-expenditure operation into system design. A third recommendation is to plan for and construct the infrastructure needed for low-energy forms of transportation. A fourth recommendation is to take resources and physical space from high-energy systems of transportation to do so. (Several of these recommendations will be familiar to city planners and urbanists.) A fifth recommendation is to plan for and construct denser human settlements. In addition to sparing energy and carbon emissions, density may be demanded by energy constraints in transportation. How would your city change if no one could commute more than ten kilometers in any direction? A final normative implication regards the necessity of planning for and investing in simpler, physically lighter systems to replace or supplement existing systems of transportation. These systems require less energy to manufacture, maintain, run, and repair, and are less likely to suffer breakdowns in the first place. They are therefore more suited to an energy-constrained world.

It is too much to expect that the downward pressure on transportation speed exerted by decreased energy availability will *reverse* the changes set into physical space by two centuries of faster and more energy-intensive transportation. Future human settlements are unlikely to resemble village idylls, because (i) history is not a time-reversible process and (ii) low-power technologies (e.g., information technology, ball bearings, pneumatic tires) that were limited or non-existent in the pre-velocity age will coexist with lower-energy forms of transportation in the post-velocity age. If the systems for knowledge transmission are more resistant to change and retrenchment than the systems for energy production (which is not certain), humans may pass into a state of relatively high knowledge paired with relatively low energy availability. Technologies that demand a moderate level of knowledge to design and build but a low level of energy to run, like the bicycle, are likely to play an increased role in such societies. The technologies that remain viable in a low-energy world can be expected to create new configurations of social and physical space. And, as documented by Kidder (2009), Oldenziel and de la Bruhèze (2011), and others, new configurations of space loop back into the people who traverse that space, transforming attitudes and behaviors which further alter the built environment [41,42]. One can imagine, for example, suburbs centered on bicycle transportation, because no other mode can effectively reach city centers from outlying residential communities. Just as the car, combined with American urban planning, developed and spread specific forms of human settlement and arrangements of energy across the planet in the twentieth century, the modes of transportation demanded by an energy-constrained system are likely to grow their own topologies of movement and exchange.

10. Conclusions

It is impossible to know the specific effects, challenges, and constraints that will accompany any exit from the human-dominated geological epoch. Most plausible post-Anthropocene scenarios, however, envision a decline (slowly or not) in human control of the material and surface area, and therefore the energy stocks and flows, of Earth. This potential reduction in the total amount of energy available to human societies will constrain the ability of these societies to move people through physical space, a task whose scale and complexity in existing societies remains significant.

This article finds that the choice among different modes of transportation turns out to be non-trivial in energy-constrained scenarios. Energy-efficient means of transportation allow for physically larger human settlements, for example, that can (holding density constant) fit more people than can settlements that rely on less-efficient means of transportation. Bicycles allow for quite large coverage areas, rapid transit for moderately large ones, buses for smaller areas, and cars for coverage areas so small they would be better served by other modes of transportation to begin with. Walking is not meaningfully energy constrained but is constrained by considerations of time, terrain, fatigue, and cargo. Because any post-Anthropocene scenario is likely to involve changes in the structures that preserve and communicate knowledge as well as those that produce and distribute energy, the transportation modes available to future societies will be different, the choices among them will be influenced by new incentives, and their development may rely on previously-developed knowledge more suited to a low-energy world. Finally, transportation after the loss of current levels of energy availability is likely to be slower than existing transportation, even holding mode choice constant, because of the cubic relationship between velocity and the power needed to overcome drag.

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