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Energy use per hour is key determinant of future transport energy consumption

Majdi Hunter-Batal[1], William Fajzel[1], Kevin Manaugh[2,3], A Ross Otto[4] and Eric D Galbraith[1,5,6,*]

[1] Department of Earth and Planetary Science, McGill University, Montreal, Canada
[2] Department of Geography, McGill University, Montreal, Canada
[3] Bieler School of the Environment, McGill University, Montreal, Canada
[4] Department of Psychology, McGill University, Montreal, Canada
[5] ICTA-UAB, Universitat Autònoma de Barcelona, Barcelona, Spain
[6] ICREA, Pg. Lluís Companys 23, 08010 Barcelona, Spain
[*] Author to whom any correspondence should be addressed.

E-mail: eric.galbraith@mcgill.ca

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Abstract

Transportation is a growing component of global energy consumption. Improvements in efficiency over time have reduced the energy used per kilometre travelled, but so far this has not reversed the increasing energy consumption per person. Instead, due to a complex interplay of factors—including changes in the built environment, shifts in transport modes, and human behaviour—average travel distances have increased, effectively negating efficiency gains. These adaptive dynamics have made it difficult to predict future energy consumption in travel. Here, we present data on remunerated and personal travel covering over half the global population, which supports a simple predictive heuristic based on energy use per unit of travel time, rather than distance. We find that total travel time among 43 countries converges to 1.3 ± 0.2 h d^{-1} and is invariant with per capita income across two orders of magnitude. This implies that psychological, social, and economic factors lead people to travel for similar daily durations, regardless of wealth, culture, geography, or transport technology, and that built environments and lifestyles co-evolve with economic and technological development to preserve stable travel times despite increasing travel speeds. Therefore, significant decreases in future energy consumption can only be achieved by reducing the average energy used per hour of human travel.

1. Introduction

Reducing the emissions of CO_2 from transportation is an essential component of strategies to mitigate anthropogenic climate change (Jaramillo *et al* 2022). Currently, transportation is responsible for more than 20% of end-use CO_2 emissions, and is growing more rapidly than other sectors (IEA 2024). The demand for both freight and passenger transport is typically projected to increase over the coming decades, linked to increasing material wealth, and could feasibly double by 2050 (Khalili *et al* 2019). This growth in energy demand could potentially undermine efforts to reduce emissions (Creutzig *et al* 2015).

Many efforts to reduce the energy consumption related to transport have focused on increasing distance-based efficiency (Banister 2008). Distance-based efficiency refers to the amount of energy required to travel a given distance, such as the number of Joules (or litres of gasoline, or kWh) consumed per 100 km by a passenger road vehicle. Improved fuel economy in internal combustion vehicles has contributed to substantial gains in distance-based efficiency in the past few decades. The ongoing transition to battery electric vehicles is leading to further improvements in distance-based energy efficiencies in passenger road vehicles, with electric and hybrid cars expected to exceed 20% of world vehicle sales in 2024 (IEA 2024). However, despite continual gains in distance-based efficiency, transportation emissions increased at almost twice the rate of world population between 1990 and 2023 (Lamb *et al* 2021, IEA 2024), which can be linked to shifts in the mode of transportation and changing mobility behaviour. Essentially, the total distance travelled by humans has increased significantly faster than the rate at which distance-based efficiency has improved (Munyon *et al* 2018).

Understanding how travel distances could continue to change in the future requires an understanding of how future patterns of mobility could evolve. However, mobility is a complex emergent process, shaped by both technological and lifestyle factors that include interactions between society and the built environment, making it difficult to predict (Thomas *et al* 2024). The average distances traveled by populations in different parts of the world vary widely, from less than 10 km per person per day to more than 150 km per person per day (figure 1(a)). Travel is often understood as a 'derived' demand, undertaken to satisfy other aims, rather than an activity of intrinsic utility, and is often imbricated with economic activities (Thomas *et al* 2024). The complex interplay of social, cultural and economic factors is challenging to capture in predictive models, such that existing modelling approaches are heterogeneous and incomplete (Andreou *et al* 2022). As a result, future scenarios, such as those generated by Integrated Assessment Models, have tended to focus on the emissions reduction potential of fuel switching rather than delving into complex behavioural changes, leaving the role of travel behaviour in future energy consumption relatively underexplored (Creutzig 2016).

One potentially simplifying aspect of travel behaviour that can help with future projections is the concept of a constant travel time budget. Research in the 1970's revealed that humans living in different parts of the world travel for surprisingly similar amounts of time (Zahavi 1977). This finding has been supported through subsequent comparisons of multiple contemporary countries, cities, and villages (Schafer and Victor 2000, Metz 2008) and historical analysis has suggested that urban forms co-evolved with travel speed to maintain a constant travel time across centuries (Marchetti 1994). If true, the maintenance of a constant travel time would require that any increase in the speed of travel, caused by innovation in transportation technology or the development of new infrastructure, be perfectly balanced by an increase in the distance traveled (Hupkes 1982). To put this in mathematical terms, given that $d = vt$, where d is distance traveled, v is velocity and t is travel time, the ratio d/v must remain constant for t to remain constant. A constant travel time could provide a powerful predictive relationship unifying complex changes in technology, the built environment, and travel behaviour (Zahavi and Ryan 1978).

Yet, the proposed 'constancy' of travel time has been a subject of controversy (Goodwin 1981, Gunn 1981, Supernak 1982, Mokhtarian and Chen 2004, Ahmed and Stopher 2014). Survey results have shown that travel time varies widely between individuals within a population, as well as from day to day for a given individual. As an example of this, figure 1(B) shows the self-reported time spent travelling in the 2022 American Time Use Survey (Bureau of Labor Statistics 2022), revealing that most participants traveled very little on the day for which they were surveyed, while a few respondents traveled for many hours. Such differences have been shown to depend on age, gender, household size and occupation (Mokhtarian and Chen 2004). In addition, prior work has shown strong evidence that travel time is not truly constant across time and space at the population level, but is affected by many variables that include the level of urbanization, congestion and cultural features (Feng *et al* 2013, Kung *et al* 2014, Gallotti *et al* 2015). Furthermore, travel time is often viewed as a cost to be minimized, in order to allow time for leisure or other desired activities (Becker 1965, Mokhtarian and Salomon 2001), which would lead to the expectation that societies will tend to reduce their travel time when enabled by improvements of technology or infrastructure. The controversy has undermined widespread acceptance of the idea of constant travel time, and even though travel time budgets have been incorporated in some models as an upper limit on travel (Daly *et al* 2014), the potentially unifying predictive role of travel time is obscured by other factors. Importantly, if the constant travel budget idea is wrong, then developing rapid transportation with high distance-based efficiency may indeed be expected to consistently reduce the energy use in personal transport.

Here, we show evidence to the contrary, that supports the idea of a strong central tendency in population-averaged travel time that holds across diverse societies with very different levels of technology and infrastructure. We base our conclusions on a holistic new analysis of travel times, compiled from nationally-representative surveys collected between 2000 and 2019. Unlike prior works that have focused exclusively on personal travel time, we also include estimates of travel as an economically-remunerated activity. We interpret the observed travel times not as reflecting a constant budget, but as an emergent result of the psychological factors that influence individual behaviours, leading to the convergence of travel times toward a strong central tendency despite very different circumstances. We conclude that, because of the convergence, time-based energy consumption (*i.e.* the rate of energy consumption per hour of travel, e.g. Joules per hour), is a much better predictor of energy consumption than distance-based efficiency (e.g. Joules per km), and we discuss how this factor depends primarily on the transport mode.

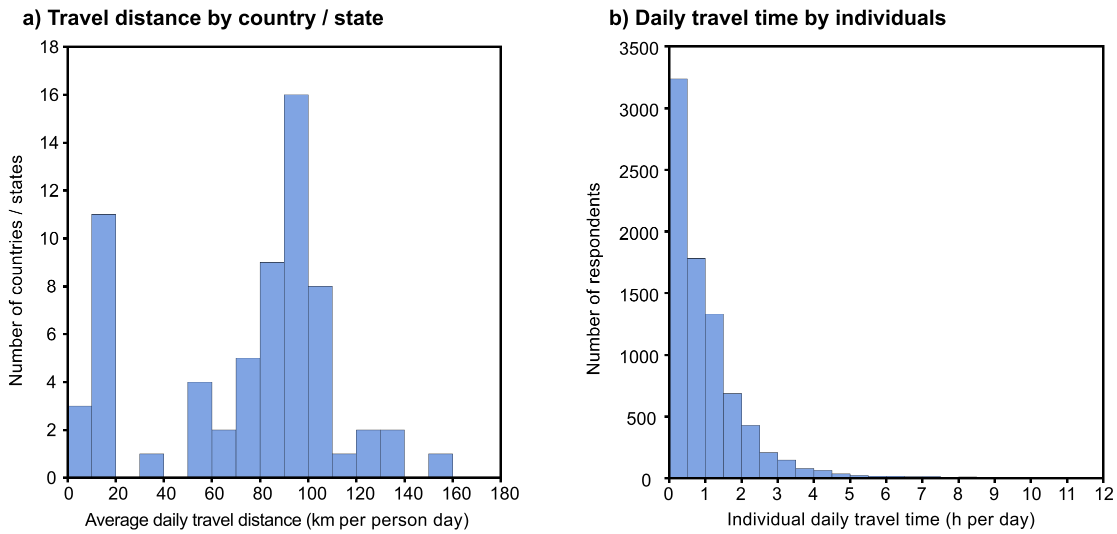

Figure 1. Observed heterogeneity of daily travel distance and individual travel time. (a) Histogram of daily population-average travel distances, from surveys of EU countries (eurostat 2021) and USA states (Replica 2024), showing the very wide range that exists among populations. (b) Histogram of daily travel time reported by individual respondents in the 2022 American Time Use Survey (Bureau of Labor Statistics 2022).

2. Methods

We draw travel time data from Fajzel *et al* (2023). 'Remunerated' travel time (carried out for pay or profit) is estimated from labour force surveys, while 'personal' travel time is self-reported in time-use surveys. Time use surveys (TUS) are conducted by national statistical agencies and are designed to be nationally representative (Cornwell *et al* 2019). While all activity categorizations in a TUS are mutually exclusive and exhaustive, some countries report highly aggregated data that does not include a travel category. As such, of the 58 countries included in the original dataset, we use the 43 countries that explicitly list one or more 'travel' categories. These countries represent a combined population of 4.4 billion people across North America, South America, Europe, Africa, Asia, and Oceania. Because certain countries include children as young as 6, while others only include those over 15 years, we use the demographically consistent youth model of Fajzel *et al* (2023) to standardize across ages. The influence of the age sample correction is small, as shown in supplementary figure 1. The time spent in travel as a remunerated activity was derived from employment and mean hours worked by economic activity provided by ILOSTAT, the online data repository of the International Labour Organization, supplemented with the labour force surveys of three additional countries (Canada, China, Japan). National energy consumption by the transportation sector is provided by the International Energy Agency's Energy Balance Sheets, which reports energy consumption according to standard sectors (domestic, industry, transportation). For each country we calculate the energy consumption per person-hour by dividing the total national energy consumption (J/d) by the population (persons) and by the hours of travel per day. The country-level data can be downloaded from Fajzel and Galbraith (2025). All r^2 and *P*-values were calculated in python using the statsmodels library, OLS function (www.statsmodels.org/stable, v.0.14.0).

For each selected mode of transport, the efficiency per distance or per time was obtained using performance data for common vehicles for each mode of transport (supplementary table S1). For walking and cycling, we used the metabolic equivalent of task (MET) from Herrmann *et al* (2024). For personal vehicles, an average occupancy of 1.5 passengers per vehicle was used (Wolfram *et al* 2020). To convert from efficiency per distance to efficiency per time, an average speed on the low end of cruising speed range was used to account for starting and stopping. Where independently available, data on efficiency per time and per distance were compared to ensure consistency.

3. Results

3.1. Global evidence for convergent travel time

Our estimates of daily travel time, combining country-level time use surveys and labour force surveys, are summarized in figure 2(A). These data represent the daily activities of approximately 4.4 billion people from 43 countries and sample all six inhabited continents. In contrast to the long-tailed distribution of individual respondent daily travel times (figure 1(B)), the population average travel times are normally distributed, whether considering remunerated, personal, or total travel time (supplementary figure 2). The total travel time has a mean of 1.27 h d^{-1} ($\pm$0.21 h d^{-1}, 1-sigma), close to the

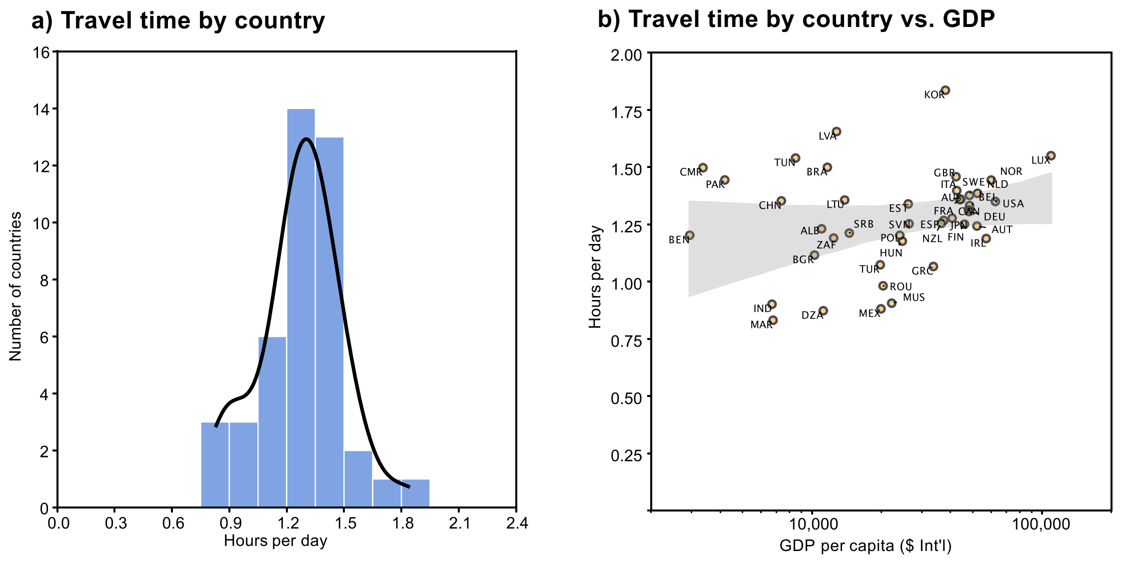

Figure 2. Convergence of average travel time and its invariance with material wealth among 43 countries representing more than half the global population. (a) Histogram of national average total daily travel time (the sum of persona l and remunerated travel time). (b) National average total daily travel time vs. GDP per capita (International dollars per year). Grey area shows the 95% confidence range for a linear regression, for which the trend is not significantly different than zero ($P = .179$, $r^2 = 0.04$, Pearson's r).

1.2 h d^{-1} (± ±0.2 h d^{-1}, 1-sigma) total travel time estimated for the entire human population by Fajzel *et al* (2023), which used interpolation to gap-fill countries without available survey data, suggesting that the incomplete sampling does not introduce a large bias. As shown in supplementary figure 2, the majority of travel time is allocated to personal mobility with no remuneration (mean $= 1.11 \pm 0.20$ h d^{-1}, 1-sigma), while 15% of the total time is for transportation activities undertaken directly for pay, e.g. the working time of bus, taxi or truck drivers, sailors, pilots, etc (mean $= 0.16 \pm 0.05$ h d^{-1}, 1-sigma). Although our estimate covers a larger geographic range than prior works on travel time and includes remunerated travel time, the average personal travel time is not distinguishable from that found previously, with an average near 70 min per day (Ahmed and Stopher 2014). For the subset of countries in which multiple surveys are available, trends over time are not significant (P-value = .1, supplementary figure 3). Note that all travel times here are self-reported, a method which is generally reliable (Gershuny *et al* 2020) but may tend to generate slight overestimates as suggested by direct comparisons with GPS travel observations (Kelly *et al* 2013).

The broad range of travel time among countries (relative standard deviation of 17%) supports the critiques of the 'constant' travel time hypothesis. The observed range spans from 0.8 h d^{-1} (Morocco) to 1.8 h d^{-1} (South Korea) and shows that—even averaged across millions of people—entire countries can have travel times that differ by a factor of two. However, this total range is much smaller than the possible range of daily travel, which could feasibly range from minutes to many hours per day. What's more, as shown in figure 2(B), travel time is invariant in a critical way: it does not systematically change with differences in GDP per capita. The total travel time has a very weak positive trend with GDP per capita, but it is not statistically significant (P-value = .179). This absence of trend also holds for personal (P-value = .156) and remunerated (P-value = .968) travel times, when examined separately (supplementary figure 4). The lack of trend shows that improvements of transportation technology and infrastructure, both of which tend to accompany higher GDP per capita, do not lead to significant changes of travel time. Instead, travel times converge to similar values under a wide range of conditions.

4. Discussion

Our results show that daily travel time is a highly predictable aspect of human behaviour. While not a universal constant, it consistently converges to 1.11 ± 0.20 h d^{-1} for personal travel and 0.16 ± 0.05 h d^{-1} for remunerated travel, despite wide differences in transportation modes, climate, culture, economy, and urban form. The convergence of travel time provides a powerful rule of thumb for understanding how other aspects of travel behaviour can feasibly coevolve in future: whatever changes occur, future human populations are likely to engage in travel for, on average, a total of 1.3 ± 0.2 h d^{-1} (95% range 0.9–1.7 h d^{-1}).

The lack of trend in travel time vs. GDP per capita is not consistent with the idea that travel is simply a cost to be minimized. Even though greater material wealth allows large improvements of transportation infrastructure and vehicle technology in high-income societies, which could theoretically allow people to spend less time traveling, the data show no significant relationship. Instead, people in high-income countries spend just as much time traveling as those in low-income countries, even if they are traveling by car and high-speed train instead of by foot, bicycle, or city bus. This invariance is in stark contrast with activities such as agriculture, which shrinks with mechanization from $\sim$1.5 h d^{-1} in low-income countries to just a couple of minutes per day in the wealthiest countries (Fajzel *et al* 2023).

The contrast between the remarkable global convergence of travel time and individual travel times, which range from a few minutes to >5 h d^{-1} (figure 1(B)), demands some kind of explanation. Prior work has offered explanations for a constant travel time that conceptualize a 'derived' demand, undertaken to reach destinations (Mokhtarian and Salomon 2001) while others have suggested an innate desire of humans to survey the surrounding territory on a regular basis (Marchetti 1994). Both ideas have been combined in economic models positing both an 'intrinsic utility' (an evolved desire to travel) and a 'derived utility' (travel as a means to access goods) which are balanced against the cost of travel to produce a rationally optimal travel time (Hupkes 1982, Susilo and Avineri 2014).

We suggest that it is more accurate to consider the convergent travel time as a central tendency, motivated by multiple interacting and opposing psychological factors, rather than as a fixed rational optimum. As such, the convergence of population average travel times on a relatively narrow range reflects fairly universal upper and lower bounds, between which the motivations to travel for specific ends (i.e. commuting, shopping, entertainment, etc) vary strongly among societies and with urban form. These psychological motivations act at the individual level, but are coupled to socially-aggregated feedbacks via cultural, political and economic mechanisms. One obvious psychological motivation is fatigue, which will produce a growing aversion to travel that intensifies as travel times grow larger (Morris and Guerra 2015). Similarly, frustration with long travel times that detract from other activities (i.e. opportunity costs) will compel people to reconfigure their lifestyles. The psychological mechanisms governing the lower bound of travel times are perhaps less evident, but are nonetheless familiar as the desire to get out of the house, stretch one's legs, or go for a ride—the desire to explore. These individual psychological motivations can be socially linked, and connected to the built environment, through economic processes such as changes in real estate prices, investment in transportation infrastructure, or relocation of residential and service buildings in response to psychological pressures (e.g. Levinson and Kumar 1994). Thus, travel times converge on a narrow range, given that the exploratory motivation always maintains a significant amount of travel—even if technology could potentially enable very rapid satisfaction of specific goals—while very long travel times are averted by fatigue and frustration.

The predictability of travel time enables robust estimates of the energy consumption for an arbitrary future society, whether at the scale of a city or the globe. Since daily travel time ($\boldsymbol{t}$) varies consistently about a mean of 1.3 $\pm$ 0.2 h d^{-1}, the total energy consumption $\boldsymbol{E}$ (MJ d^{-1}) of a population of size $\boldsymbol{N}$ (persons, p) can be predicted within $\pm$30% using average per capita energy use per unit time, $\boldsymbol{e_t}$ (MJ p^{-1} h^{-1}):

$$\boldsymbol{E} = 1.3\, h\, d^{-1} \boldsymbol{N}\, \boldsymbol{e_t}.$$

In contrast, to calculate $\boldsymbol{E}$ using energy efficiency per distance, $\boldsymbol{e_d}$, requires knowledge of the daily travel distance $\boldsymbol{d}$, which varies significantly between populations based on urban form and behaviour (figure 1(a)) and is therefore hard to predict for an arbitrary future society. For example, the energy efficiency of European passenger cars improved from 1975 to 2005, decreasing the value of $\boldsymbol{e_d}$ by roughly 40% (Zachariadis 2006) which might be expected to have reduced energy consumption in, say, Germany. However, due to shifts in transportation mode and behaviour, the distance travelled per person over this period in Germany increased from 25 to 38 km d^{-1} (Scheiner 2010), a 50% increase that more than eliminated the efficiency gains. Instead, the absence of a benefit would have been accurately predicted from the energy efficiency per unit time, $\boldsymbol{e_t}$, given that panel data have shown that German travel times have tended to be very stable at 1.35 $\pm$ 0.03 h d^{-1} (Chikaraishi *et al* 2011).

Furthermore, because $\boldsymbol{d} = \boldsymbol{vt}$, the convergence of travel time requires that $\boldsymbol{d/v}$ remain within a narrow range. This implies that a doubling of average travel speed, due to new infrastructure or vehicle technology, will tend to occur along with a doubling of travel distance, as the built environment and/or lifestyles coevolve with the change in speed. Thus, at a societal level, increasing the speed of travel will not result in savings of travel time on average, but will only increase travel distance (Metz 2008). Our results show that this holds for both personal and remunerated travel.

The critical importance of energy use per unit time, $\boldsymbol{e_t}$, is in fact even greater because travel modes differ in energy use per time ($\boldsymbol{e_t}$) by far more than per distance ($\boldsymbol{e_d}$), as shown in figure 3. For example, an SUV on a highway (single occupancy) consumes about 10-fold more energy per km as walking, which could lead one to conclude that a country that transitions from walking to single occupancy SUV travel would increase its travel energy consumption by a factor of 10. But in fact, the

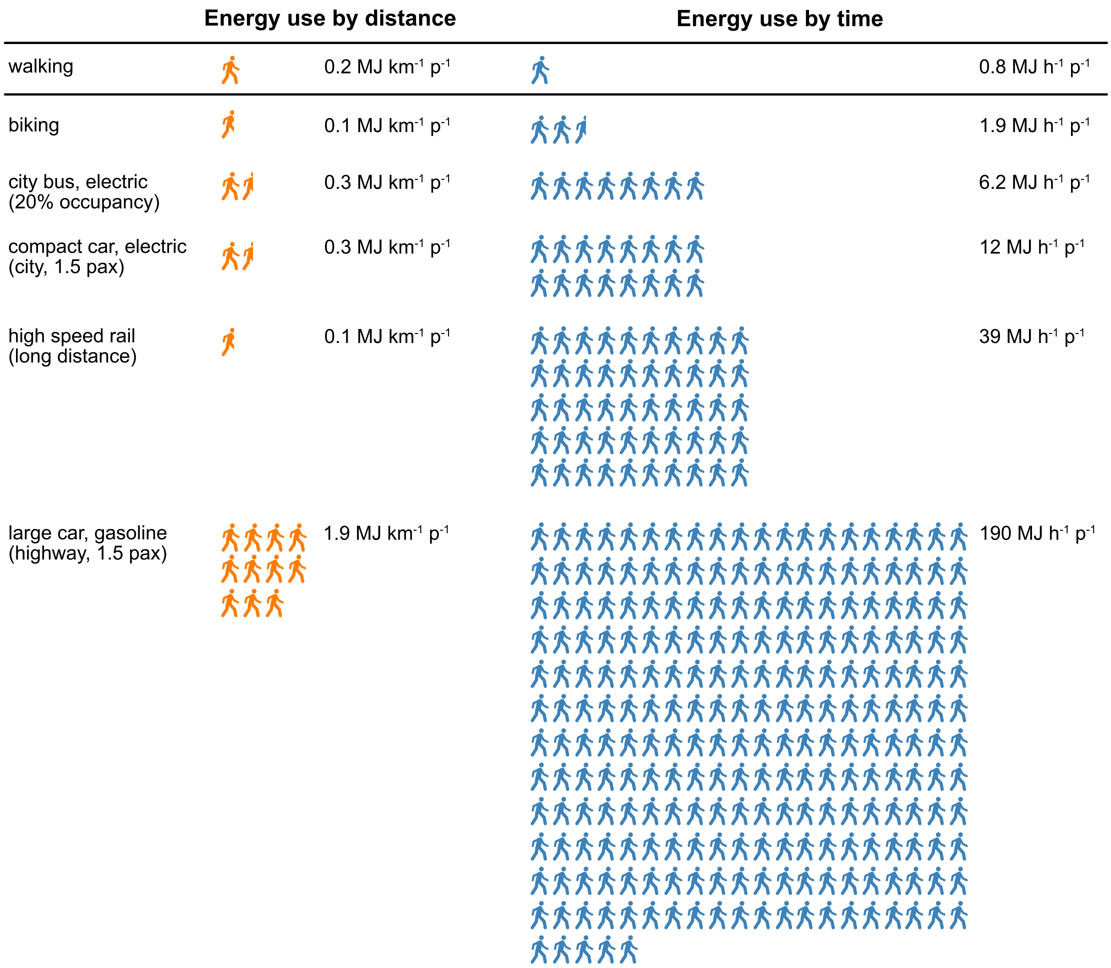

Figure 3. Representative values of energy use per distance and per time for different modes of mobility. Energy use is shown numerically, as well as graphically by human icons, where one human represents the marginal cost of metabolic energy (i.e. energy derived from food, in Joules) for an adult human to walk one kilometre (left side) or to walk for one hour (right side). Note all values are approximate, calculated using typical speeds for each mode, and in reality would be expected to vary with details of the vehicle and travel conditions. Since travel time converges towards a central value, whereas travel distances vary widely, the energy use by time is a much better indicator of the energy consumed. See table S1 for details and additional travel modes (supplementary materials).

energy per unit time increases by almost 300-fold (95% C.I. 210- to 430-fold). Thus, a society reliant on single-occupancy SUVs for personal travel will use almost 300-fold more energy than an equivalent population that carries out its personal mobility on foot, since both societies will converge on ∼1.1 h of personal travel per day. This massive difference reflects the highly predictable tendency for populations to travel farther when using transport modes that operate at high speeds, a tendency that is mechanistically achieved through changes in urban form (Hankey and Marshall 2010).

Our travel time estimates allow us to contextualize country-level transport energy consumption rates, revealing the large impact of transportation modes. Figure 4 shows the average energy consumption per hour of travel for all citizens in a country, vs GDP per capita. At the low end of the wealth spectrum, the hourly energy consumption of total transport, including both personal and economic motivations, is approximately that of cycling (e.g. Pakistan at ∼2 MJ h^{-1}), reflecting the dominance of active transport and high-occupancy, low speed vehicle transport. At the opposite extreme, the hourly energy consumption is that of a car at highway speeds (140 MJ h^{-1}, e.g. USA, Canada), consistent with the widespread use of high speed automobile travel in these countries. The two order of magnitude range among countries is driven entirely by the mode-specific energy consumption per unit time ($\boldsymbol{e}_t$), not by differences in travel time.

Despite the strong convergence of travel time towards 1.3 h d^{-1}, there is scope for the average global travel time to shift up or down in the future. Psychological research has suggested that environmental diversity and exposure to complex environments generate positive affect through daily travel (Schooler 1984, Crowe *et al* 2008, Poranen-Clark *et al* 2017, Heller *et al* 2020, Reneau *et al* 2023), which vary with travel mode and location (St-Louis *et al* 2014), thereby influencing the satiation of the exploratory motivation. Similarly, economic research

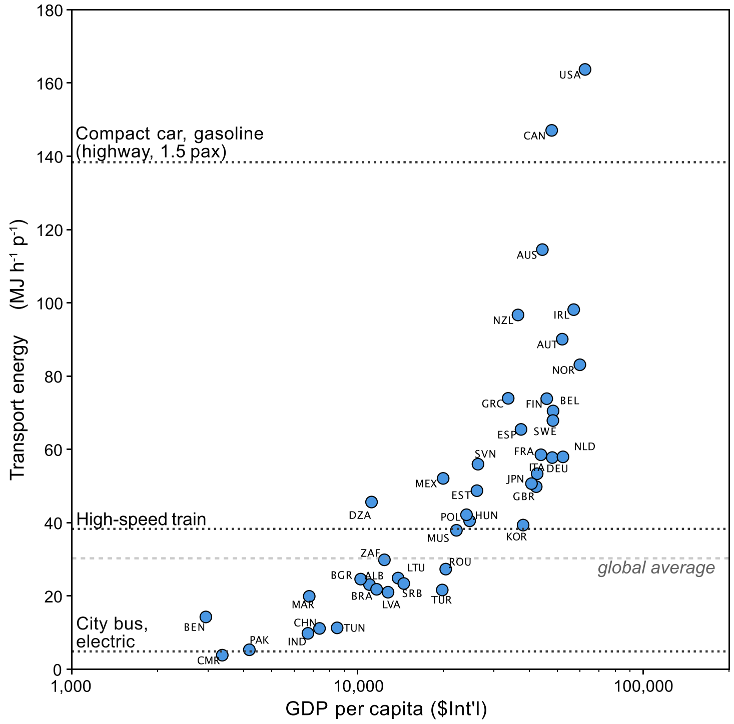

Figure 4. Rate of energy consumption in the transport sector vs. GDP. The average transport energy per hour of travel, per person, is estimated from the country-level energy consumption per capita divided by the total daily time spent traveling, plotted vs. GDP per capita (International dollars per year). Also shown are energy consumption rates representative of different modes of transport (black horizontal dotted lines) and the global average (total consumption divided by global population and average travel time, grey dashed line). Wealthier countries tend to use more energy per hour of travel, but there is substantial variation among the wealthiest countries, reflecting differences in predominant travel modes.

has shown that the revealed cost of travel varies with factors such as mode of transport (Wardman *et al* 2016), reliability (Gim 2017) and quality of infrastructure (Flugel *et al* 2022), suggesting variation in the rate at which fatigue and frustration accumulate. Conceivably, the accumulation of satisfaction and fatigue could both be slower for forms of travel in which the passenger is unaware of the passing landscape, such as inside a comfortable commuter train when engaged in other activities such as using personal electronics or reading. Consistent with this, South Korea, the country with the highest average travel times among our sample, has a high modal share of train travel (Fountas *et al* 2020). Travel can also simultaneously meet other goals, such as exercise obtained through active transit, or passive relaxation during train rides, which may tend to further motivate longer travel times.

These findings have implications for incipient changes in transport that will be enabled by self-driving vehicles. It has been suggested that travel by self-driving cars may be less prone to fatigue than other forms of travel (Childress *et al* 2015, Rashidi *et al* 2020), which could push travel times upwards. Although the global convergence of travel times suggests that such differences between modes of travel are not large, a significant upward creep in travel times could occur with self-driving cars, in the absence of policy intervention (Meyer *et al* 2017). For example, an increase of global average travel from 1.3 to 1.6 h d^{-1} would, all else being equal, drive a 23% increase in transport energy consumption, equal to 5% of total global energy consumption. Still, this change would be dwarfed by the roughly 5-fold increase in transport energy (from 90 EJ y^{-1} to 450 EJ y^{-1}) if the majority of the world's passenger travel were to occur by low-occupancy gasoline cars. This hypothetical change would—on its own—roughly double the total global energy consumption.

5. Conclusion

Our findings suggest that convergent travel time provides a very robust tool for predicting how societies will respond to transportation technology and policy changes in future, with major implications for energy consumption. Although travel times do not adhere to a universally constant budget, they do fall within a relatively small range at a population level, and are normally distributed about a mean of 1.3 ± 0.2 h d^{-1}. Alterations of transportation infrastructure are unlikely to significantly change the $\sim$1.3 h d^{-1} of average total travel, but they will change how that time is distributed across different modes of transport and, consequently, the distance travelled (Miotti *et al* 2023).

The convergence of travel times to a narrow range means that energy use per hour will determine the energy consumption for a given transport mode, without the need to know any other details of urban form or societal behaviour. For example, urban development centred around a rail system that is used, on average, for 40 min per person per day (with the remainder spent walking) will reliably use roughly 5-fold as much energy as a design that allows the same population to achieve all their travel by foot, even if the energy efficiency per km is the same for both modes of travel. Alternatively, a city where all transportation takes place by combustion automobile will evolve to use more than 100-fold as much energy per person as a pedestrian-only city, even if the automobiles only consume a few times more energy per km, because the energy use per hour of driving is two orders of magnitude larger than walking. Infrastructure and urban form are well-known to shape residents' choice of transportation mode (McIntosh *et al* 2014, Rode *et al* 2017, Hymel 2019, Miotti *et al* 2023, Althoff *et al* 2025), placing policymakers in a powerful position. Because of the convergence of travel time, policies that enable modes of transport with low rates of energy consumption per hour will be most effective at reducing energy use in the transportation sector, regardless of what other changes occur.

Data availability statement

IEA energy data are publicly available at www.iea.org/data-and-statistics/data-tools/.

The data that support the findings of this study are openly available at the following URL/DOI: https://doi.org/10.5281/zenodo.17312321.

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Conflict of interest

The authors declare no conflict of interest.

Author contributions

Majdi Hunter-Batal
Investigation (lead), Methodology (equal), Writing – original draft (equal), Writing – review & editing (equal)

William Fajzel 0009-0009-5821-0450
Data curation (lead), Formal analysis (equal), Writing – review & editing (equal)

Kevin Manaugh 0000-0003-2975-030X
Writing – review & editing (equal)

A Ross Otto 0000-0002-9997-1901
Writing – review & editing (equal)

Eric D Galbraith 0000-0003-4476-4232
Conceptualization (equal), Formal analysis (equal), Supervision (lead), Writing – original draft (equal), Writing – review & editing (equal)

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