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Energy intensity of human transportation

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Abstract

Humans are a mobile species, and transportation technology has been one of the primary enablers of our current shared, globally-connected society. Transportation is also one of the largest categories of human energy use, and this energy use correlates with a diverse range of environmental impacts. Different modes of transportation have different energy intensities, with increasing speed being associated with greater energy intensity. This study reviews the fundamental relationships and energy requirements of human-powered and wheeled ground transportation. Relevant data for modeling energy efficiency of walked, running and wheeled transport in the context of engineering design are compiled and presented. It is shown that increasing energy intensity facilitates greater speed and movement of more people. In general, people are able to travel anywhere at any speed, if they are willing and able to pay the energy price. At the same time, a willingness to accept reduced speeds would greatly reduce the energy intensity and environmental impact of transportation. Finally, several design implications for low energy ground transportation are examined in the context of energy efficiency.

1. Introduction

Transportation accounts for a significant proportion of energy usage in developed countries. In Canada in 2018, 29% of secondary energy usage was for transportation (Natural Resources Canada, 2019). In our modern technological society, it has been said "one can travel from any place to any other place, at any speed, as long as one is willing to pay the price." That price can be interpreted to mean financial cost, but it can also refer to energy use or environmental impact.

The aim of this paper is to review the energy intensity of moving humans across the landscape. There are many different transportation technologies, each with a different energy intensity, as well as other benefits and limitations. This paper will examine human transportation over land by foot and wheeled vehicles using the common measure of energy intensity, although the relationships and ideas explored here will be applicable to air and sea transport in some measure.

This study attempts to compare a series of different data sets on transportation energy use. There are myriad sources of data on the energy use of different transportation technologies and applications. Here, attempts have been made to utilize reliable sources that use accepted standards that are transparent (i.e. information on methods and assumptions for the data are available). Two primary approaches will be taken. First, models of energy intensity for different transportation modes will be presented from the literature. These will generally take the form of equations that predict energy intensity based on relevant input variables which will typically include common variables such as speed and mass, as well as additional technology-specific variables. Common models that are accepted in the relevant field are utilized. Importantly, these may not be the most recent versions of a model, nor the most accurate for a specific case. (For this study, the interest is in representative energy intensity, rather than special cases.) The second approach will be to collect reliable samples of "real world" energy intensity for specific technologies in specific cases, most of which will have been directly measured. Both approaches will be used to build comparisons between the energy intensity of different transportation technologies and options.

The primary measure of interest in this study will be the amount of energy required to move a person or vehicle a specific distance. Generally, the discussion will be limited to steady state, constant velocity travel, ignoring the start and end of trips. There are many units of energy: this study will measure all forms of energy (including electrical, thermal and chemical potential as appropriate) in kWh/km, kilowatt hours of energy per kilometer traveled. One kilowatt-hour is 1000 Joules per second for one hour, or 3.6 MJ. Energy economy of vehicles that carry large numbers of passengers are typically reported in terms of energy intensity per distance, per passenger (i.e. kWh / passenger-km). For cargo transport, it is common to normalize energy intensity per ton (1000 kg) of cargo transported (i.e. kWh / ton-km).

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2. Walking and running

A human at rest has a base metabolic energy usage on the order of 100 W. For walking, running or bicycling, the power intensity of interest is the "power cost", the additional amount of energy that exceeds this base metabolic usage and is used to travel. After all, when considering the energy needed for automobile travel, we do not include the metabolic energy used by the driver.

Energy utilized by humans is commonly measured using units of calories. Importantly, there are two units of the calorie. One Calorie (commonly called a "food calorie" or sometimes a kilocalorie) is 1000 calories. It is kcal (i.e. Calories) that are used to provide the metabolic energy content of foods, and in which human energy use is normally (but not always) reported. One Calorie equals 4184 J of energy. In terms of power, 1.0 kcal/h is 1.16 W.

Humans naturally assume a walking gait (one foot always in contact with the ground) at low speeds. The most energy efficient walking speed, for level smooth ground carrying no additional load, based on a treadmill study of eight fit 19-25 year old males, was experimentally determined to be about 1.3 m/s or 4.68 km/h (Abe et al., 2004). This speed was confirmed as optimal for backpack loads ranging from none to 75% of body mass (for healthy young adult males) by Bastien et al. (2005). In this case, slower is not better: at lower-than-optimum speeds, power use only decreases slightly (most energy is used to physically move the limbs), but distance covered is much less, increasing the energy used per unit distance relative to the optimum speed. The maximum speed for practical walking is about 8.5 km/h. At higher speeds, running (feet periodically contacting the ground) becomes more efficient than walking (Pandolf et al., 1977).

It should be noted that while human feet are excellent for low speed travel in rough terrain, if a smooth surface is available, rolling on wheels such as those of a bicycle can be much more energy efficient than walking or running. On a smooth flat surface with no wind, the power cost of travel can be an order of magnitude less if a person rides a bicycle instead of walking (Whitt and Wilson, 1974). Bicycles will be examined further later in this paper.

Pandolf et al. (1997) developed an equation for metabolic energy expenditure while walking, with or without a loaded backpack, over a range of slopes and terrain types. Based on experimental data, Pandolf et al. (1977) modeled the metabolic power usage while loaded walking as four metabolic power components: standing without load (M_1), supporting an additional load while standing (M_2), walking on the level (M_3), and climbing a grade (M_4):

$$M_1 = 1.5m_B \tag{1}$$
$$M_2 = 2.0(m_B + m_L)(m_L/m_B)^2 \tag{2}$$
$$M_3 = 1.5C_T(m_B + m_L)V^2 \tag{3}$$
$$M_4 = 0.35C_T VS(m_B + m_L) \tag{4}$$

These are non-homogenous equations, and so must be used only with the following specified units. All power costs (M) are units of Watts. The body mass m_B and additional load mass m_L have units of kg. Velocity V is in m/s and slope S is in units of % (e.g. use the value of "1" for a 1% grade, which would be the slope associated with a rise of 1 m over a horizontal distance of 100 m). The terrain constant C_T is unitless, with values of 1.0 for smooth pavement or a treadmill, 1.1 for dirt roads, 2.1 for loose sand and 4.1 for 35 cm of soft snow. The total metabolic power use while walking (M_W) is the sum of these components. For the purposes of this study, we are interested in the "power cost" of walking (P_W), that is, the additional power that must be expended beyond that used by the body when at rest which is on the order of 100 W, and would be used regardless of whether they were walking or not. This will be approximated by removing M_1 from the sum:

$$M_W = M_1 + M_2 + M_3 + M_4 \tag{5}$$
$$P_W = M_2 + M_3 + M_4 \tag{6}$$

This model is valid for walking speeds up to 2.2 m/s (Epstein et al., 1987). Pandolf et al.'s (1977) studies were based on measured respiration data from soldiers (e.g. slow loaded walking data is from six males, all age 20±0.8 years, weight 78±1.6 kg, in good physical condition) and greater uncertainty should be allowed if applying this equation to different populations.

The maximum speed for practical walking is about 8.5 km/h. At higher speeds, running becomes more efficient than walking (Pandolf et al., 1977). Epstein et al. (1987) extended the walking model of Pandolf et al. (1977) to include running at speeds of 2.2 m/s to 3.2 m/s (7.9 km/h to 11.5 km/h), with and without loads, again in the context of soldiers carrying backpacks:

$$M_R = M_W + 0.5(1 - 0.01m_L)(850 + 15m_L - M_W) \quad (7)$$

$$P_R = M_R - M_1 \quad (8)$$

where M_R is the metabolic power used while running, and again we estimate the power cost of running (P_R) by subtracting M_1. This model is also based on data from fit soldiers (all males age 20.6±0.6 years, weight 68.7±1.6 kg).

Figure 1 shows the "energy cost" of walking and running, based on Eqns. 1-8, assuming level, smooth ground (C_T = 1.0, S = 0, body mass m_B = 70 kg with no additional load (m_L = 0). In this case, energy cost is obtained by dividing P_W or P_R by velocity V and converting units from J/m to a more practical kWh/km. It is notable that these models predict slower walking (if unloaded) is a more efficient means of covering ground than faster walking, and running is (slightly) more costly than walking, although the distance is covered much faster owing to higher speeds. It should be noted that at low walking speeds (below about 2 km/h) the no load energy cost model of Eqn. 1-8 goes to zero energy cost at zero velocity. This is different from the loaded case in Fig. 1, and also from the optimum no load velocity of 4.68 km/h observed experimentally by Abe et al. (2004), and seemingly may not be correct at low speed. These differences suggest significant uncertainty remains in the energy cost of walking at low speeds.

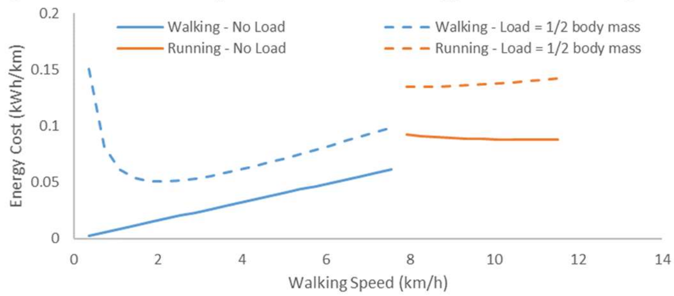

Fig. 1. Energy cost of walking and running (C_T = 1.0, m_B = 70 kg, m_L = 0, S = 0).

3. Wheeled Vehicles

The range of transportation technologies that can be considered to be wheeled vehicles is large, including bicycles, motorcycles, automobiles, buses, trucks (lorries, or heavy goods vehicles; HGVs) and trains. All but the smallest of these (bicycles or related human powered devices) are motorized vehicles propelled by internal combustion engines fueled by gasoline (petrol) or diesel fuel, although a range of alternative fuels (natural gas, propane, ethanol, biodiesel) are sometimes utilized. Alternatively, electric motors are sometimes used. Other options, such as compressed air or wound spring motors are infrequently used.

3.1 Theoretical Energy Intensity of Wheeled Vehicles

At higher speeds, overcoming aerodynamic drag can account for over 90% of power needs in vehicles carefully designed for maximum speed, such as racing bicycles (Kyle and Weaver, 2004).

The power use of a wheeled vehicle (P_V) traveling on a consistent plane surface at steady speed V can be modeled as (Kyle and Weaver, 2004):

$$P_V = mgV\sin\theta + C_{rr}mgV\cos\theta + \frac{1}{2}\rho C_d A_f V^3 \quad (9)$$

where m is vehicle mass, g is the gravitational constant (9.81 m/s^2), C_{rr} is a dimensionless rolling resistance coefficient, ρ is air density, C_d is dimensionless drag coefficient, and A_f is projected frontal area of the vehicle. The variable θ is the angle of the ground plane from horizontal ($\tan\theta = S$) in the direction of travel. The terms on the right hand side each represent a specific mode of power loss. The first term accounts for power needed to lift the vehicle when traveling up a slope, the second term accounts for the rolling resistance of wheels on the ground surface, and the last term estimates power needed to overcome aerodynamic drag.

If the entire equation is divided by velocity V, the result is an expression for the energy per distance that would be expended by the vehicle:

$$E_V = mg\sin\theta + C_{rr}mg\cos\theta + \frac{1}{2}\rho C_d A_f V^2 \quad (10)$$

where E_V is the energy per distance that would be expended by the vehicle. (If all variables are in SI units, the units of E_V would be J/m.) The power or energy per distance predicted by these equations should be interpreted as the amount of power or energy delivered to the point where the vehicle wheels meet the ground surface. They do not include energy losses within the vehicle (such as engine thermodynamics or bearing and powertrain losses).

Variations of these equations have been widely applied to model vehicle energy usage. The forward direction of the vehicle is taken as positive, so speed V is always positive. The air density ρ typically has a value of about 1.20 kg/m^3 (at standard temperature of 20 °C and 101.3 kPa pressure). The slope angle θ is zero for flat ground, is positive if the vehicle is traveling uphill, and is negative for downhill travel.

This model defines any vehicle based on four variables: total mass (m), frontal area (A_f), drag coefficient (C_d) and rolling resistance coefficient (C_{rr}). Rolling resistance depends on vehicle mass and C_{rr} which in turn depends on both tire and road/surface properties. Generally, C_{rr} increases with softer, lower pressure tires or increasing road surface roughness. Table 1 shows some representative values of rolling resistance for different vehicles and ground surfaces. Characteristics of low rolling resistance conditions include smooth ground surfaces and large diameter wheels with high rigidity. For rubber tires, higher inflation pressures and harder rubbers generally give higher C_{rr} values. Table 2 shows typical drag coefficient values for a range of vehicles. The drag coefficient quantifies the effects of streamlining and surface qualities on resistance to passing flow. Lower drag coefficients are associated with more streamlined shapes that require less power to move through the air than blunt shapes with the same frontal area. Like rolling resistance, drag coefficients are generally determined experimentally.

Table 1. Typical values for C_{rr}.

Conditions	Value	Source
Train – steel wheel on steel track	0.00011	Bernsteen et al., 1983
Bicycle – Sport Hybrid	0.008	Pease, 2005
Mountain bike tire – average all surfaces – 26 inch diameter	0.013	Warnich and Steyn, 2014
Mountain bike tire – average all surfaces – 29 inch diameter	0.010	Warnich and Steyn, 2014
Car tires (lab tests 50+ tire models)	0.006 – 0.012	Ejsmont et al., 2017
Car tire – low rolling resistance for EVs	0.005	Larminie and Lowry, 2012
Car tire – radial ply	0.015	Larminie and Lowry, 2012
Car tire on concrete or asphalt	0.013	Wong, 2008
Car tire on unpaved road	0.05	Wong. 2008
Truck tire on concrete or asphalt	0.006 – 0.01	Wong, 2008

Table 2 shows typical drag coefficient values for a range of vehicles. The drag coefficient quantifies the effects of streamlining and surface qualities on resistance to passing flow. Lower drag coefficients are associated with more streamlined shapes that require less power to move through the air than blunt shapes with the same frontal area. Like rolling resistance, drag coefficients are generally determined experimentally. Note that C_d and A_f are sometimes reported as a single combined value, particularly if the variables were determined experimentally. Since these two variables occur together in Eqns. 9 and 10, this is not a significant concern.

Table 2. Typical values of aerodynamic drag coefficient C_d. (Adapted from Wong, 2008)

Vehicle Class	Typical C_d Values
Streamlined wheeled vehicle theoretical minimum	0.15 (White, 2016)
Passenger cars	0.3 – 0.50
Vans	0.4 – 0.58
Buses	0.5 – 0.8
Tractor-semitrailers	0.64 – 1.1
Truck-trailers	0.74 – 1.0

Examining Eqn. 10, it is apparent that rolling resistance energy per distance is proportional to vehicle mass, and is independent of velocity. In practice this is usually not completely true, and some amount of additional energy loss can become apparent during high speed travel, particularly for rubber tires at very high rotational speeds. However, velocity independence of rolling resistance is a reasonable assumption for general analysis. On the other hand, energy per distance required to overcome aerodynamic drag is dependent on the velocity squared. This means that a doubling of velocity will result in a quadrupling of the energy required to travel a given distance. The energy cost of additional speed is considerable. Slower velocity travel will be more energy efficient.

Table 3 gives values of the mass, rolling resistance and drag variables for a range of different wheeled vehicles. Additionally, a typical speed is also given. Finally, Table 3 also provides the corresponding calculated power to needed for steady travel on a flat surface at the specified speed using Eqn. 9, and the energy per distance that would need to be supplied at the wheels using Eqn. 10.

The range of required power and energy intensity varies drammaticaly between the example vehicles. It is apparent that to travel at a given velocity, minimizing mass and size are important, as is reducing C_d as much as possible through attention to vehicle form. Minimizing rolling resistance by selecting low rolling resistance tires, and traveling on smoother, lower friction surfaces, is also important. Taken all together, it is apparent that no matter the powertrain, fuel type or other details, the most energy efficient wheeled vehicles are smaller (which reduces both mass and frontal area), streamlined and low rolling resistance. Put another way, the ideal values of C_{rr}, C_d, m and A_f are all zero, or more practically, as close to zero as can be reasonably attained.

3.2 Observed Energy Economy of Automobiles

Equation 10 provides a theoretical basis for steady state vehicle operation in ideal conditions. In practice, most road vehicles are operated under varying driving, load and weather conditions, and which impacts actual energy efficiency.

All US passenger vehicle models (cars and light trucks) are required to complete a set of standardized fuel efficiency tests. Vehicles are operated through prescribed distances and speeds (which includes accelerating and decelerating, use of air conditioners, and other secondary systems. See (www.fueleconomy.gov) for complete information. These tests provide a consistent test case across which the energy intensity of American vehicles can be compared. Figure 1 shows fuel economy of a range of American cars and light trucks, plotted against vehicle curb weight. Curb weight is the mass of the vehicle read to operate, including lubricants, fuels, safety equipment but without passengers or cargo. All data for automotive energy use is based on the combined city and highway fuel economy ratings from the United States government (www.fueleconomy.gov). The data was sourced from the website www.edmunds.com, a private company that aggregates and provides publicly available data, including both US government fuel economy data and reported vehicle curb weights (defined as empty weight of the vehicle plus fuel, lubricants and any required on-board equipment) on individual models and years of motor vehicles sold in the United States.

Figure 2 shows the Combined (highway and city driving cycles) energy economy of 37 gasoline-fueled internal combustion engine US vehicles, ranging from sub-compact cars to full-size four-wheel drive extended cab pick up

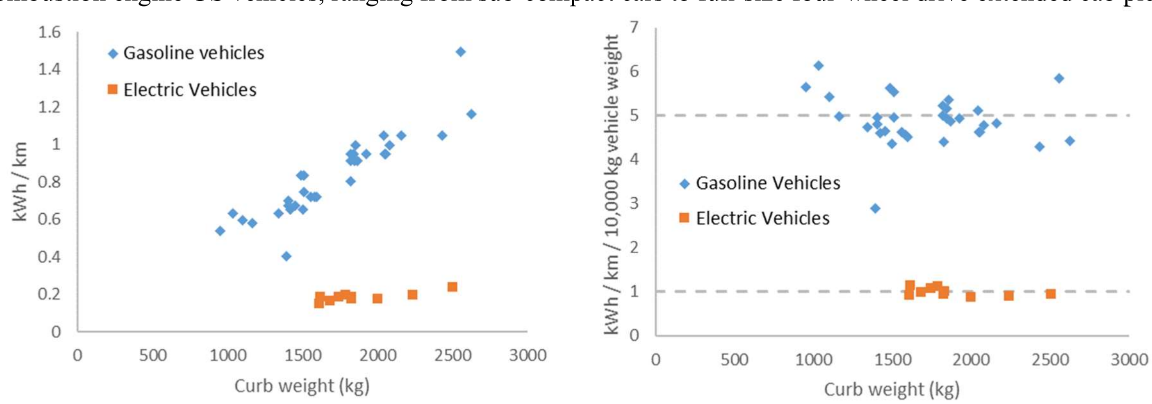

Figure 2. EPA Combined energy economy of example US vehicles.

Table 3. Data for a range of example wheeled vehicles. Sources as indicated.

Vehicle	m (kg)	C_{rr} (-)	C_d (-)	A_f (m^2)	C_dA (m^2)	V (km/h)	V (m/s)	P_V (W)	E_V (J/m)	E_V (kWh/km)	Source
Bicycle – Sport Hybrid	81.5	0.008	C_dA_f = 0.517 m^2		*0.517*	20	6	89	16	0.004	Pease, 2005
Bicycle – UCI Drop Bar Racer	76.8	0.004	C_dA_f = 0.294 m^2		*0.294*	50	14	514	37	0.010	Pease, 2005
Bicycle – Full Faired Recumbent Performance – Lightning F90	83.6	0.006	C_dA_f = 0.144 m^2		*0.144*	50	14	300	22	0.006	Pease, 2005
Bicycle – Upright position. Tubeless 22 mm tire, linoleum surface.	76.8	0.004	C_dA_f = 0.299 m^2		*0.299*	50	14	523	38	0.010	Grappe et al., 1997
Bicycle – Dropped position. Tubeless 22 mm tire, linoleum surface.	76.8	0.004	C_dA_f = 0.276 m^2		*0.276*	50	14	486	35	0.010	Grappe et al., 1997
Bicycle – Aero position. Tubeless 22 mm tire, linoleum surface.	76.8	0.004	C_dA_f = 0.262 m^2		*0.262*	50	14	463	33	0.009	Grappe et al., 1997
Bicycle – Obree's position. Tubeless 22 mm tire, linoleum surface.	76.8	0.004	C_dA_f = 0.216 m^2		*0.216*	50	14	389	28	0.008	Grappe et al., 1997
HPV – Streamlined, world speed record holder – Varna Diablo	97.2	0.005	C_dA_f = 0.01853 m^2		*0.01853*	50	14	96	7	0.002	Pease, 2005
Motorcycle – 2013 Honda Verza 150	220	0.02	0.5	0.8	0.4	100	28	6343	228	0.063	Pance et al., 2019
Car – 2014 Chevrolet Volt	1708	0.01	0.28	2.2	0.616	100	28	12576	453	0.126	Sherman, 2014
Car – 2014 Mercedes-Benz CLA 250	1530	0.01	0.3	2.16	0.648	100	28	12503	450	0.125	Sherman, 2014
Car – 2012 Nissan LEAF SL	1521	0.01	0.32	2.28	0.7296	100	28	13527	487	0.135	Sherman, 2014
Car – 2012 Tesla Model S P85	2170	0.01	0.24	2.34	0.5616	100	28	13135	473	0.131	Sherman, 2014
Car – 2014 Toyota Prius	1442	0.01	0.26	2.22	0.5772	100	28	11352	409	0.114	Sherman, 2014
Minivan – 2017 Chrysler Pacifica Hybrid	2262	0.01	C_dA_f = 0.92 m^2		*0.92*	100	28	17995	648	0.180	C_dA_f: Brooke, 2016
Truck – Full size pickup – 2019 Ram 1500	2224	0.01	C_dA_f = 1.21 m^2		*1.21*	100	28	21621	778	0.216	Mass: https://www.edmunds.com/ram/1500/2019/features-specs/
Bus – Electric bus – Typical city bus	12565	0.008	C_dA_f = 6.12 m^2		*6.12*	100	28	106095	3819	1.061	Kivekäs et al., 2019
Truck – 2011 Freightliner M2-106	14000	0.007	C_dA_f = 2.61 m^2		*2.61*	100	28	60270	2170	0.603	Zhang et al., 2015
HGV – Tractor w/ one semitrailer (6 axles|)	40000	0.008	C_dA_f = 6.0 m^2		*6*	100	28	164360	5917	1.644	Lajunen, 2014
HGV – Full trailer	60000	0.008	C_dA_f = 6.4 m^2		*6.4*	100	28	213105	7672	2.131	Lajunen, 2014
HGV – Swap body + link + semitrailer	76000	0.008	C_dA_f = 6.7 m^2		*6.7*	100	28	251843	9066	2.518	Lajunen, 2014
HGV – Semitrailer + dolly + semitrailer	90000	0.008	C_dA_f = 7.0 m^2		*7*	100	28	286221	10304	2.862	Lajunen, 2014
HGV – DAF XF95 type Space-cab with 3-axle trailer	26000	0.0072	0.43	10.34	4.4462	100	28	108190	3895	1.082	Aero. Data: Van Raemdonck and van Tooren, 2009. Masses: https://www.truck1.eu/tractor-units/daf-xf95-430-space-cab-a585450.html

Table notes: Underlined values are assumed. Pease, 2005 reported bicycle masses only: an additional 70 kg mass of a typical rider is added here. Grappe et al, 1997 experimentally measured C_dA_f but did not report bicycle mass. A UCI minimum 6.8 kg bicycle and 70 kg rider is assumed.

trucks. Figure 2 also includes 10 battery electric vehicles, all compact to midsize sedan or hatchback cars (since at the time of writing, these are the only class of passenger vehicle available in the United States with an electric-only drive train). The data for this plot, including vehicle makes and models, is available in an accompanying spreadsheet file.

Figure 2 suggests that energy intensity is proportional to vehicle mass. Normalizing energy intensity by vehicle mass (i.e. plotting vehicle mass, in the form of curb weight, against the amount of energy needed to travel one kilometer for each 10,000 kg of vehicle mass) makes this relationship clear. At this point, it is worth noting that vehicle frontal area usually increases with vehicle mass – vehicles with more mass are typically physically larger. So while mass only appears in the rolling resistance term in Eqn. 9, it also is an indicator of the frontal area in the aerodynamic resistance term.

For the gasoline-engined vehicles, the average energy intensity is 5 kWh/km per 10,000 kg of vehicle mass. The corresponding value for the battery electric vehicles is 1 kWh/km per 10,000 kg. There is less scatter in the electric vehicles because this set of vehicles is much less diverse than the gasoline-engined vehicles. All of the example electric vehicles are five passenger sedan or hatchback cars, with similar (but not identical) aerodynamic characteristics. There is greater diversity in the gasoline engine vehicles: the data set includes small sub-compact hatchbacks, sedans, sport utility vehicles, vans and pick up trucks. Some vehicles, particularly the pickup trucks and sub-compact cars, generally have higher drag coefficients and so have higher aerodynamic resistance for their size than other types leading to higher energy intensity.

The vehicle power train can greatly impact the energy intensity. The electric vehicles are on average five times more efficient than similar gasoline engine vehicles. It must be remembered these two classes of vehicle use different forms of energy. The electric vehicles utilize electricity. The efficiency of battery charging and discharging, and the electric motor, are all quite high, giving an overall expected plug-to-wheels efficiency of 80% for typical electric vehicles in normal operation (Hjelkrem et al., 2020). However, the efficiency numbers plotted here to do not include upstream processes required to generate the electricity (whether from burning a fossil fuel, fissioning atoms or from renewable generation such as hydropower). The gasoline vehicles are utilizing a chemical potential form of energy, which has thermodynamic limits on efficient conversion of thermal energy to mechanical work in a heat engine. Energy losses in the gasoline engine vehicles using internal combustion engines include thermal losses, pump losses and mechanical losses. The thermal losses are the main reason why the energy intensity of the gasoline engine vehicles is so much higher: most of the available energy in the fuel is lost (indeed, must be lost according to the laws of thermodynamics) as heat for the engine to do mechanical work. Hjelkrem et al. (2020) report that the tank-to-wheel efficiency of gasoline fueled internal combustion engined vehicles is about 16% – 20% for typical driving cycles, with higher efficiencies achieved in steady highway driving (28% efficient) than during urban driving cycles (about 10% – 13% efficient). This same overall five-fold efficiency difference between the electric and gasoline engine vehicles is apparent in the US vehicle data shown in Figure 2 which plots energy intensity for combined highway and urban driving cycles.

Significant efficiency variation is possible even with the same energy source. The one gasoline-engined vehicle with a hybrid power train in Figure 2, the Toyota Prius, has a lower energy intensity than any other gasoline vehicle in the plot. This is expected because hybrid vehicles generally perform much better in the combined energy economy test than conventional internal combustion only engine power trains. While gasoline is the only energy source for a non-plug in hybrid vehicle like the Prius, the power train includes an internal combustion engine, an electric motor and a battery for short term energy storage. This allows the internal combustion engine to operate at more efficient operating points (no lugging or overspeeding) and regenerative braking allows energy recovery that is not possible in the conventional gasoline engine vehicles. Since fuel efficiency was a significant marketing strength of the Prius, it is also likely that the engineers put more emphasis than normal on power train efficiency, rather than other goals such as acceleration or handling.

Comparing the values in Fig. 2 with those in Table 3, it must be noted that the energy intensity predicted using Eqn. 10 is "energy intensity at the wheels", and does not include internal inefficiencies within engines and drive trains. This is why the energy intensities calculated using Eqn. 10 and shown in Table 3 are so much lower than the energy intensity values for similar vehicles in Fig. 2 or reported by Hjelkrem et al. (2020).

4. Discussion

4.1 Energy Intensity of Vehicles

Equation 10 and the data in Tables 1-3 provide a good model for exploring the potential impacts of different design decisions on transportation energy intensity. Aerodynamic drag is the most important consideration at higher speeds. The different examples of bicycles in Table 3 provide a good case study in the effects of optimizing for aerodynamic drag. Fig. 3 shows the energy intensity (energy per distance in kWh/km) of four different bicycles from Table 3 as a function of velocity. The Varna Diablo was custom designed and built solely for setting speed records and reached 133.28 km/h piloted by Sam Whittington during the 2009 World Human Powered Speed Challenge at Battle Mountain, Nevada, USA (IHPVA, 2022). It is not a practical bicycle, although the Lightning F90 included in Fig. 3 is at least commercially available and is reasonably comfortable and practical (https://www.lightningbikes.com/f90/index.html).

Mass is similar across all bicycle examples (with the more streamlined bicycles being somewhat higher mass), but aerodynamic drag varies significantly. The "sport hybrid" bike (representing a "normal person using a normal bike for transportation") has $C_dA_f = 0.517\ m^2$, while the world record setting Varna Diablo has C_dA_f less than 4% of that value ($0.01853\ m^2$). Notably, at high speeds, the energy cost of covering one kilometer in the Varna Diablo at high speeds is only 5% of that of the sport bike. Propelling the sport bike at 100 km/h would require a humanly impossible 6800 W, about 9 hp.

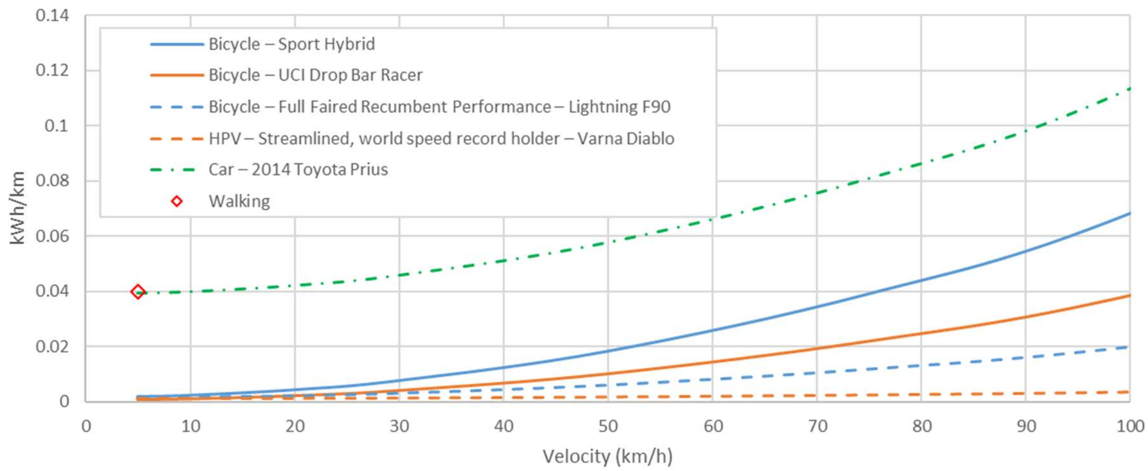

Figure 3. Energy per distance of four different bicycles as a function of speed.

Fig. 3 also includes the energy intensity of a representative reasonably efficient automobile (Toyota Prius, details in Table 3). At low speeds, the energy intensity is dominated by rolling resistance (which is proportional to vehicle mass) and moving the car is much more energy intensive. At highway speeds (on order of 100 km/h), however, the energy cost to move the "sport hybrid" bicycle at 100 km/h would be over half that of the car (which it should be noted can carry up to five people plus some baggage in weather-protected comfort).

Finally, the energy intensity of walking at 5 km/h is also shown in Fig. 3. It is notable that the 0.04 kWh/km predicted by Eqn. 6 for walking is coincidentally the same energy intensity required "at the wheels" to move the car at 5 km/h, and much more energy required than any of the bicycles at 5 km/h. (It is worth reminding ourselves that Eqn. 10 is an idealized prediction of energy required at the wheels of the car, not the total energy available in the vehicle's fuel.)

Nonetheless, this discussion has served to illustrate the point that to travel in an energy efficient manner, attention must be given to both rolling resistance and aerodynamic drag, which are in turn dependent on vehicle aerodynamics (i.e., C_dA) and vehicle size (which impacts mass m and frontal area A). Additionally, energy intensity in kWh/km increases for all methods of travel as speed increases, and this increase becomes particularly pronounced at higher speeds. The faster you want to travel, and the more vehicle you want to take with you, the more it will cost in terms of energy. While it was shown that choice of energy supply and powertrain (i.e. energy conversions within the vehicle system) can significantly impact vehicle energy efficiency, the dynamics above apply to all types of vehicles propelled by all energy systems. For example, Fig. 2 demonstrated that an electric powertrain in a car is much more energy efficient than a gasoline-based powertrain. However both electric and gasoline-powered vehicles will become more energy efficient if mass or aerodynamic drag are reduced.

4.2 Design Implications

The prior discussion leads to some relevant insights. For example, it has been shown (Fig. 3) that a bicycle designed to set speed records must be extremely streamlined and have the minimum possible aerodynamic drag. However, Eqn. 10 suggests an additional way to reach even faster speeds by human power. Examining the other term of the equation, energy intensity could be further reduced by reduced energy losses due to rolling resistance. Practically, there are probably limited opportunities to further reduce mass, however, Table 1 suggests that switching from rubber tires on a paved road to steel wheels on a smooth steel track (like a train) could significantly reduce rolling resistance. At the high speeds of record setting bicycles, this would provide a relatively small (but significant for record-setting purposes) advantage.

Since the aerodynamic drag term in Eqn. 10 is the most significant term when speeds are high, other things can be done to reduce this effect. The (former) world speed record of Sam Whittington in the Varna Diablo was mentioned previously. However, the record speed for a self-propelled human on a bicycle is actually much higher than the 130+ km/h reached by human powered vehicles like the Diablo at recent competitions in Battle Mountain. In 2018 Denise Mueller-Korenek set a record for fastest self-propelled person at 296.01 km/h (Yeager, 2018). This was accomplished by intentionally riding in the wake of a larger, customized, motorized vehicle. This approach greatly reduces the relative air velocity at the bicycle, allowing a much higher speed to be attained. However, it is extremely dangerous and perhaps an even less practical exercise than the design and racing of vehicles like the Varna Diablo.

However, there are potentially practical applications of the wake effect exploited by Denise Mueller-Korenek. So-called platooning of vehicles in which two or more vehicles travel in close formation in a tightly spaced line has been shown to significantly reduce the overall energy use of the set of vehicles, compared to having each vehicle travel independently. There have been a number of experiments involving automated vehicle operation and control to overcome the significant safety concerns of having vehicles travel in such close proximity to each other at high speeds. Of course, efficiencies can also be gained by connecting multiple trailers together where feasible (as in the case of the famous Australian "road trains" in which up to four full size truck trailers are pulled by a single tractor). A similar effect also occurs in long trains. A trailer or car following closely in the immediate wake of a similar trailer or car experiences an order of magnitude reduction in aerodynamic drag. (In some cases, it is theoretically possible for the following vehicle to experience negative drag – which was likely the case in Denise Mueller-Korenek's record, where she travelled in the wake of specially designed car with an integrated, wake-producing fairing.) Since each train car follows in the wake of the car immediately preceding it, Eqn. 10 would have to be modified for extremely long composite vehicles like trains to account for the fact that the aerodynamic drag becomes primarily a function of (composite) vehicle length rather than vehicle frontal area.

Reducing vehicle mass is also an important approach to improving vehicle efficiency. It is theoretically possible to build very light weight motor vehicles, and examples of these are very efficient. Shell Eco-marathon (www.makethefuture.shell) high mileage vehicles achieve significant efficiency gains relative to conventional automobiles by reducing both aerodynamic drag and also vehicle mass. It is also notable that the Eco-marathon competition requires an average speed of 23 km/h during the competition. This minimum speed would seem to be an essential rule, since Eqn. 10 suggests that even slower is likely to be better in vehicles optimized for the competition. But barely moving cars do make for a compelling competition.

In 2019, the Eta Eco-marathon class car by Duke Electric Vehicles (Fig. 4) set the Guinness World Record for most efficient electric vehicle at 1283 km/kWh, or 0.000779 kWh/km. The Eta has a race ready mass of m = 20 kg (excluding driver) and a measured C_dA_f of 0.0328 m^2 (Duke, 2019). Also noteworthy is that the these figures represent extreme values of all variables for a vehicle, illustrating what is possible if a vehicle is optimized for a single goal of efficiency. Nominal power use is listed as 18.8 W at 24.1 km/h. It is notable that maximum efficiency can only be achieved by attending to both the aerodynamic and friction terms in Eqn. 10. Otherwise, the term that is not optimized will dominate the energy use of the resulting vehicle.

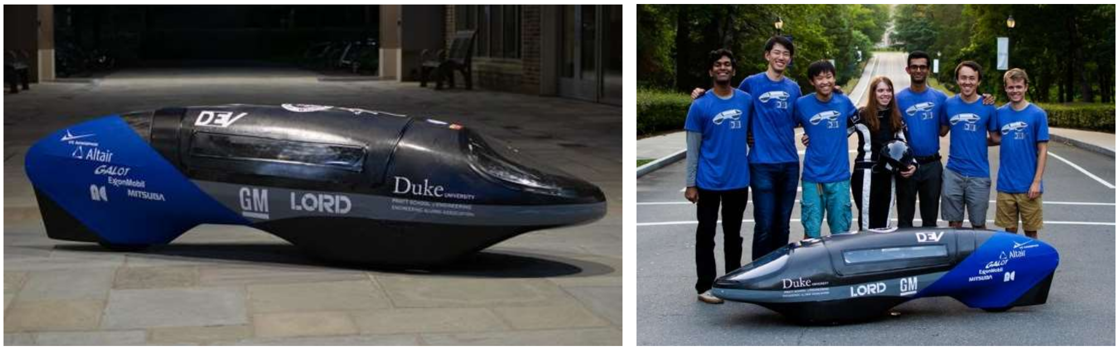

Figure 4. Duke Electric Vehicles supermileage vehicle Eta. (Duke, 2019)

One lesson from the Eco-marathon vehicles is that vehicle efficiency can be improved by removing unnecessary mass from the vehicle. It is notable that the energy to propel a vehicle also has associated mass. There is an efficiency cost in carrying additional energy to allow the vehicle to travel a longer distance before it needs to take on additional energy. In gasoline-powered vehicles, each liter of gasoline carried adds approximately 0.75 kg of mass, while in electric vehicles like those in Table 3, the batteries needed to provide 24 to 80 kWh of electrical energy contribute significant mass to the vehicle. In the case of electric vehicles, such as the example electric cars in Table 3, batteries add hundreds of kilograms to the vehicle mass. The amount of energy stored is proportional to the mass of the battery, or the mass of the liquid fuel. An efficient vehicle should carry as little onboard energy in the form of liquid fuel or batteries as possible. Electrified vehicles can be supplied with energy from overhead wires with pantographs, eliminating the need for a large and expensive battery pack. This is a widely-used, proven method to power trolleybuses and electric trains. Electrifying trucks (or heavy goods vehicles; HGVs) by adding large battery packs has been proceeding slowly – more slowly than proponents have suggested it would proceed – limited by the added vehicle costs and high battery weight (which also reduces useful load in a truck). Alternatively, trials with pantograph equipped trucks and overhead wires on frequently traveled highways have so far proven promising (Fig. 5).


Figure 5. Heavy goods vehicle using electrified highway near Sandviken, Sweden (Alaküla and Márquez-Fernández, 2017.)

4.3 Other Factors in Transportation Energy Efficiency

This discussion has focused on the energy use of a range of individual vehicles mostly in the context of moving one or a small number of people. When comparing the energy efficiency of transportation systems, infrastructure requirements must also be considered. The costs (financial, environmental, material and energy) of building and maintaining of roads, tracks, pipes or airports can be significant. Higher quality roads and tracks, with smoother surfaces, more direct routing and reduced grades, generally have higher costs (and embodied energy) but result in reduced vehicle energy use.

It is notable that regular production cars are much less energy efficient than is achievable. There are good reasons why commercially-available cars (and other vehicles) are so massive. Our prior example of the Toyota Prius, a relatively efficient commercially available vehicle, has a mass of 1440 kg in order to transport a few people. Most of that mass provides value in areas other than energy efficient movement. Vehicle occupants are fully weather-protected in comfortable seating, with sound deadening insulation, and a wide range of safety equipment that adds mass in the form of air bags, lighting, redundant braking systems, and structural stiffness as well as equipment for social benefit such as a pollution reducing catalytic converter. The vehicle components are durable: doors can be slammed, the body can be struck or leaned on, and the car can be expected to be durable and reliable when stored outside exposed to all forms of weather for many years. The vehicle can accommodate drivers and passengers ranging from small children to people much larger and heavier than 70 kg person assumed in some of the previous calculations. All of this in a package that can cruise reliably at highway speeds exceeding 100 km/h in almost all weather conditions. As in most practical engineering applications, cars are an example of optimization of many, often competing variables, to provide a range of services to the user.

This combination of services is achievable because energy has historically been relatively inexpensive in our modern societies. One kWh of electricity is on the order of $0.10, while one liter of gasoline is on the order of $1. (The US EPA assumes the energy content of one liter of gasoline is 8.90 kWh, for vehicle efficiency comparisons.) Worldwide road and rail systems are built assuming vehicles of specific typical sizes and capabilities, traveling at particular speeds. For example, regular cars have a mass on the order of 1 ton (1000 kg) and travel at speeds on the order of 100 km/h. It would be an interesting exercise (although outside the scope of this paper) to predict the typical mass and speed of vehicles that would have evolved if energy costs had historically remained one, two or more orders of magnitude higher than actually occurred over the past century.

So far, the data and models presented here have suggested that slower travel is more energy efficient travel. However, slower travel also means lower utilization of roads, tracks and paths. Generally, a road or track can accommodate a particular number of vehicles if all travel at particular speed. If the travel speed is doubled, it becomes possible for many more vehicles (theoretically up to twice as many, although this is not usually reached in practice) to use the same infrastructure. For this larger number of vehicles to travel at the original, slower speed, it would be necessary to build another parallel road or track to accommodate the traffic, with all the embodied energy and costs related to that additional infrastructure. In practice, this is one reason why traveling at extremely low speeds is generally not the most efficient at a system level (even if it is most efficient for the individual vehicle.) Other reasons include that (to varying degrees) people value their time and place a low value on time spent in transit. Additionally, most real vehicles have some energy uses or losses that are proportional to time, rather than a function of mass or velocity as in Eqn. 10. This includes auxiliary systems that operate continuously (lights, climate control, control systems, accessory pumps etc.) and in vehicles with internal combustion engines, minimum fuel use in engines operating at any speed just to keep the combustion engine operating. This means that in practice, most automobiles become less efficient in terms of energy use per distance at low speeds. The author found through on-road driving experiments that the most energy efficient steady operating speed of a Chevrolet Metro compact car was approximately 60 km/h, although this optimum speed will vary in different vehicles and can also depend on driver practices.

Infrastructure is particularly important when comparing the full range of possible transportation modes. Cars, trucks and trains require tracks and roads that are not needed by aircraft or ships, while a pipeline is a somewhat different form of "track" for moving bulk gases or liquids. The lack of infrastructure required between ports or airports represent an additional system efficiency for sea or air travel over wheeled surface transport. But sea and air transport have different characteristic energy use. In aircraft energy intensity is relatively high, and the optimum travel speed is a function of vehicle design (and even at a theoretical level, traveling slower than the optimum for an aircraft design can be less energy efficient). Similarly, while "slow steaming" has been advocated and used as a way to reduce costs associated with energy use in ships, these gains can be countered by lower utilization of the ship. (If a trip takes twice as long, the ship only delivers half as much cargo, and makes half as much revenue in a certain amount of time.) Most ships also have an optimum hull speed, which is a function of ship design, so the relationship between energy intensity and travel speed is not as straightforward as with wheeled land vehicles.

5. Conclusion

This paper has reviewed the energy intensity of ground transportation from a theoretical perspective using accepted model of vehicle energy use supplemented with data and examples from actual experience. The overall conclusions of this exercise are perhaps not too surprising. Regardless of details like energy source (e.g. fossil fuels, electricity, or others) or vehicle power train,

- Traveling costs energy,
- Traveling faster, or in a larger vehicle, costs more energy,
- Additional vehicle capabilities (such as comfort, safety, flexibility, maximum speed or range), cost yet more energy

Transportation energy efficiency can be improved by optimizing vehicle design and operation for this specific goal, but it will come at the expense of reducing performance of other aspects of the vehicle or travel process, including but not limited to comfort, flexibility, safety and utilization of common infrastructure. As we seek more sustainable methods of moving people and cargo in an energy-constrained and environmentally challenged world, we would do well to keep in mind that any "new" method of transportation will be governed by the same fundamentals as those we currently use.

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