The Energetic Performance of Vehicles

J. L. Radtke

Published by Neodymics™ on January 18, 2008

Abstract - **Various methods of determining the energetic performance of vehicles were described and compared. Earlier work emphasized maximum vehicle power and theoretical performance limits, and characterized the vehicle or payload in terms of weight. Energetic efficiency was calculated here as the payload mass times distance moved divided by thermal energy used. This efficiency was multiplied by average speed to yield an energetic performance parameter that was expressed in seconds, using SI units. The differential form of this parameter was twice the useful payload kinetic energy divided by thermal power expenditure. A transportation matrix was developed, describing how vehicles are most commonly used in terms of speed, efficiency, GHG emissions, payload mass and energetic performance. Vehicles with the highest level of energetic performance have efficient powerplants, high payload to gross mass ratios, or reduced friction with the surrounding environment.**

Background

In evaluating transportation choices, efficiency is an important and well-characterized consideration. Average speed is also important, since people are paid by the hour and "time is money." Others have considered this interplay between vehicle speed and efficiency.

Gabrielli and von Karman [1] defined the specific resistance of a vehicle, ε, as maximum motor output power P, divided by total vehicle weight W multiplied by maximum speed V_M.

(1) $$\varepsilon = P / W V_M$$

Specific resistance was determined for various vehicles operating at a range of speeds. An empirical limit for the minimum specific resistance as a function of maximum speed was found for any isolated vehicle. This was described by Eq. 2, where A is 0.000175 hours per mile. This relationship is depicted by the diagonal line in Fig. 1, which has become known as the Gabrielli-von Karman limit line of vehicular performance.

(2) $$(\varepsilon)_{min} = A V_M$$

Gabrielli and von Karman used gross vehicle rather than payload weight because, "exact information regarding the useful load of vehicles was not available to the authors." Their analysis was reconsidered with regard to payload weight and fuel consumption by Stamper [2]. This latter treatment was more relevant to the economical application of energy resources. Here, "useful transport work" was defined as the product of payload weight and distance traveled. "Transport efficiency" was defined as the ratio of useful transport work to thermal energy expended.

In a subsequent analysis by Teitler and Proodan [3], a quantity was defined as the specific fuel expenditure ε_F, where ζ is the energy per unit volume of fuel, η is the distance traveled per unit volume of fuel, and W_P is the weight of the vehicle payload.

(3) $$\varepsilon_F = \zeta / \eta W_P$$

The reciprocal of ε_F was defined as the fuel transport effectiveness, and related to vehicle cruising speed V_C by Eq. 4. Following Stamper's definition, the reciprocal of ε_F was referred to as, "the dimensionless ratio of useful work output to energy input." C_F was referred to as a "factor of proportionality." As shown in Fig. 2, C_F was applied as a limit to what is technologically possible, rather than as a performance parameter to be applied generally to individual vehicles. The dashed diagonal line was referred to as, "the next level of fuel transport effectiveness to be used as a future standard." [3]

(4) $$(\varepsilon_F^{-1})_{max} = C_F^{-1} V_C^{-1}$$

Other writers referencing [1] have also applied A or C_F as a factor describing an experiential performance limit, while treating ε or ε_F^{-1} as a general performance parameter [4-7].

There is another vehicle performance parameter that is expressed in units of time or velocity. Specific impulse, I_S, is a universally accepted parameter used to describe rocket motor performance. It is defined as shown in Eq. 5, where F is the motor thrust force, m dot is the propellant mass flow rate, and w dot is the propellant weight flow under constant thrust conditions [8].

(5) $$I_S = F / (\dot{m} g_o) = F / \dot{w}$$

Force divided by propellant mass flow is also used to describe rocket motor performance. This is known as the effective exhaust velocity, and has units of speed. Ascribing mass to propellant gives a physical insight into this performance parameter; it is proportional to rocket motor exhaust velocity [8].

Analysis

In combining speed and energy expenditure to yield an energetic performance parameter, ε_F is more economically informative than ε. The specific fuel expenditure ε_F takes payload weight and motor efficiency into account under cruising conditions, and is more representative of actual use and indicative of resultant benefit. C_F^{-1} is convenient because an increase corresponds to a performance improvement.

Defining useful transport work as the product of travel distance and payload weight is misleading, since mechanical work is conventionally defined by the vector dot product of force and spatial displacement. For horizontal displacement near the earth‘s surface, payload weight is a force perpendicular to the direction of motion, so that the work done in this fashion is zero. The dot product of the payload weight and distance traveled is vertical displacement multiplied by the force exerted by the payload mass. This dot product divided by thermal energy expenditure is a true measure of lifting efficiency, and is always less than unity.

Treating the payload as a mass (denoted M_P) rather than a weight yields a performance parameter Q with units of time. For cruising conditions, Q_C is defined by Eq. 6, where g_o is the acceleration due to gravity.

$$Q_C = g_o / C_F = V_C M_P \, \eta / \zeta \tag{6}$$

An analogous fuel transport effectiveness is defined by Eq. 7, with E_{th} representing the thermal energy expended to travel a path length, denoted as l. The parameter ε_{Qc}^{-1} is also referred to as the thermal transportation efficiency, and it has been used by others to compare various modes of transport [9].

$$\varepsilon_{Qc}^{-1} = Q_C / V_C = [l \, M_P / E_{th}]_C \tag{7}$$

As shown in Eq. 8, the differential form of the travel distance to thermal energy ratio becomes the ratio of cruising speed to thermal power expenditure (P_{th}). Eq. 9 thus provides a physical interpretation of Q_C as the time during which a total fuel energy release equals twice the payload kinetic energy (E_{pk}).

$$\eta / \zeta = [l / E_{th}]_C = [V / P_{th}]_C \tag{8}$$

$$Q_C = [M_P V^2 / P_{th}]_C = [2E_{pk} / P_{th}]_C \tag{9}$$

Propellant weight is the quantity a rocket designer would like to minimize while obtaining the same result. Since fuel (energy) consumption is the quantity most other vehicle designers endeavor to minimize, and Q_C is an energy divided by an energy flow, Q_C is analogous to I_S. Ascribing mass rather than weight to matter provides a physical insight into both vehicle performance parameters.

Using mass rather than weight to describe energetic performance yields a result which can be consistently applied in any environment, as illustrated by considering an extraterrestrial vehicle. Due to differences in gravitational acceleration and atmospheric density, a vehicle should travel further on Mars (for example) than on earth, using the same quantity of energy. Defining performance with C_F^{-1} gives a result that decreases because of the atmospheric density difference, and does not change because of the difference in gravitational acceleration. On the other hand, Q_C increases due to both influences, and is more indicative of the change in conditions. Whether moving a payload mass through a gravitational field or head wind, Q consistently reflects changes in conditions. A pedagogically inferior treatment of this discrepancy is to introduce the concept of "standard weight," which is a measure of mass expressed in units of weight.

Transportation modes are often compared in terms of fuel economy, or distance traveled per unit volume of fuel, and Q_C can be defined as a related quantity. Q_C can readily be determined from vehicle speed, and automobile person-miles per gallon of gasoline or freight carrier BTUs per ton-mile. Given that a gallon of gasoline contains about 133 MJ of thermal energy [9], one can readily determine Q_C for a given number of persons in an automobile from the cruising fuel economy rating. Cruise conditions are similar to those encountered on a long distance highway trip, and it is tempting to use the automobile "highway" miles per gallon rating to determine l/E_{th}.

The EPA fuel economy ratings are intended to represent how vehicles are actually used. The highway rating is meant to model free flow traffic at highway speeds. This is measured with a dynamometer system over a simulated distance of only ten miles, with no stops and a maximum speed of 60 miles per hour (27 m/s). Average speed during test is 48 miles per hour (21 m/s). City driving conditions are simulated over a distance of 11 miles (18 km), with 23 stops and a maximum speed of 56 miles per hour (25 m/s). Average speed during city driving simulation is only 20 miles per hour (8.9 m/s). Fuel consumption is measured over these short simulated distances by collecting and analyzing exhaust gas.

By using the EPA fuel economy ratings $[l/E_{th}]_E$, measured at an average speed, V_E, we can calculate an effective energetic performance, Q_E, for transporting given number of persons through the EPA driving routine. This is shown in Eq. 10 below. Since the mass of the human payload is typically much less than the mass of the car, it is assumed that $[l/E_{th}]_E$ does not change based on how many persons are in the automobile.

$$Q_E = M_P l V_E / E_{th} = M_P V_E^2 / P_{th} \tag{10}$$

The physical meaning of Q changes when the average speed is used instead of the steady state cruising speed. The numerator in Eq. 9 becomes twice the useful payload kinetic energy, which is evaluated at the average speed. This differs from the average payload kinetic energy, which is determined from the root mean square (rms) speed. Because rms speed is always greater than or equal to average speed, the payload kinetic energy evaluated at the average speed is the minimum possible average kinetic energy for any speed profile. It may be difficult to obtain rms speeds, and these higher values would not represent an improvement in the utility of the trip. A vehicle traveling at constant speed on an elevated express lane is assumed to be no more or less useful than a vehicle traveling at the same average speed through a series of stops. To use rms speed would inflate the value of Q_E in the latter case. The denominator in Eq. 9 is still the average thermal power expenditure, which is measured directly. Using the average speed to determine performance thus takes the effectiveness of the speed profile into account. The parameter Q_E is applicable to intermodal comparisons of transportation energy use.

For some modes of mass transit, a passenger may spend a considerable amount of time captive within the system, perhaps while not even being present on the vehicle or while the vehicle itself waits for other vehicles. This describes air travel in particular. For this situation, V_E is determined by dividing the distance between airports by the average time between passengers entering the departure airport and leaving the arrival airport.

Table 1 gives efficiency, greenhouse gas emissions, payload mass, speed and energetic performance for various modes of human transportation. Since thermal energetic efficiency is directly proportional to person-miles per gallon of gasoline (or carbon dioxide emission) these columns were easily added. Table 2 gives assumptions and conversion factors used in creating Table 1. Efficiency is determined by estimating the number of passenger-kilometers obtained per unit of thermal energy present in the fuel consumed. Typical human mass is assumed to be 70 kg. The human body is assumed to be 25% efficient in converting the caloric content of food into mechanical work [10]. Moped vehicles are assumed to be ridden without pedaling. Table 1 was sorted first by payload mass, then by energetic performance. This indicates a trend for personal vehicles travelling at low speeds, where vehicles with highest payload to vehicle mass ratios tend to perform better. At high speeds, aerodynamic effects predominate. Fig. 3 is a logarithmic representation of the data from Table 1.

The most complex efficiency determinations were those of electric vehicles. Since electrical energy is a more organized form than thermal energy, it is important to determine how much thermal energy was expended in creating the electricity used to charge the vehicle batteries. By measuring charger energy input, the battery charge, storage, and discharge efficiencies are accounted for. Electrical powerline transmission efficiency was assumed to be 96%. Net efficiency of the generating facility at the other end of the powerline is typically 33% [11]. The range of the prototype Neodymics Cyclemotor electric bicycle is 17.7 km at 11.2 m/s. Fully charging the four DeWalt lithium iron phosphate battery packs (model DC9360) required 360 Whr of 110 VAC power into the battery chargers. So, one may travel 17.7 km on an electric bicycle using 4.1 megajoules of thermal energy released at a modern electrical powerplant.

In a similar manner, efficiency of the Segway™ I2™ personal transporter was determined from the manufacturer's specifications [12]. This device uses the same battery chemistry as the Neodymics Cyclemotor, so battery efficiency was assumed to be the same. It is suspected that much of the energy consumed by the I2™ is used to keep it upright.

Fig. 3 also compares efficiency in the movement of petroleum and people. Most petroleum is transported by ship or pipeline. These means are about 1000 times more efficient than a single occupant SUV.

Discussion

This analysis shows that light personal vehicles perform far better than heavy ones. Energy used to produce vehicles and transportation infrastructure was not considered here, and such an analysis would make light vehicles appear even more attractive. For all payload weight classes, the payload to vehicle mass ratio of the best performers is between three and four. Since most people tend to travel individually when possible, and energy resources are becoming increasingly scarce with respect to demand, it would appear that personal vehicles of the future will be very light by today's standards. A challenge in the development of urban transportation infrastructure will be to allow for safe use of these personal vehicles amidst heavier cargo and mass transit vehicles. There is a related challenge to improving efficiency ratings for personal vehicles in developed countries. Here, people tend to view a light vehicle as impractical because of it lacks the crumple zone they have become accustomed to. A light personal vehicle such as bicycle is often seen as an exercise toy to be carried on top of a car. Future changes in environmental and economic considerations may induce a sea change in this attitude.

Energetic performance was determined for widely different modes of transportation. Streamlined human powered vehicles excel in personal vehicle energetic performance because of the relatively efficient human engine and the designer‘s careful attention to aerodynamics. Commercial airliners also perform well because people are willing to crowd themselves into an aerodynamically optimized fuselage for fast, long distance travel. By terrestrial standards, a one-way trip into the void of interstellar space can be extremely fast and efficient. Using the chemical energy release of the launch vehicle, and the present displacement from earth, Q_E for the Voyager 1 spacecraft is on the order of 10^8 seconds. The gravitational assist in propelling Voyager 1 is acknowledged as free, since it was not paid for with chemical combustion. Various means of capturing and using solar energy for earthly transport without terrestrial combustion are in a similar sense free.

Acknowledgments

The author gratefully acknowledges receiving encouragement, helpful comments or suggestions as a result of text review from A. Babson, Dr. A. Hobson, Dr. D. Faber, Dr. G. Oldfield, Dr. F. Wilczek, and Dr. J. Zorn; graphics review from D. Bahr, Dr. W. Connors, L. Dore, H. Noeldner, P. Nonn, Dr. G. Penn and Dr. C. Sprott; mathematical review from T. Schmidt and T. Snyder; and data refinement from Dr. A. Bartlett, R. Finley, G. Hertzler, T. Millett, R. Parker, Dr. R. Steeves, M. Weaver, C. Vetter and R. Zitarosa.

References

1 Gabrielli G, von Karman T (1950) What price speed? Mechanical Engineering 72: 775-781.

2 Stamper J (1975) Time is Energy. Aeronautical Journal 79: 169-178.

3 Teitler S, Proodian, R (1980) What Price Speed, Revisted. J Energy 4: 46-48.

4 Minetti A, Pinkerton J, Zamparo P (2001) From Bipedalism to Bicyclism, Evolution in Energetics and Biomechanics of Historic Bicycles. Proc Royal Soc London B 268: 1351-1360.

5 Young J, Smith R, Hillmansen S (2005) What Price Speed - Revisited. Ingenia 22: 46-51.

6 Greenewalt C (1977) The Energetics of Locomotion - Is Small Size Really Disadvantageous? Proc Am Phil Soc 121: 100-106.

7 Carson B (1982) Fuel Efficiency of Small Aircraft. J Aircraft 19: 473-479.

8 Sutton G (1986) Rocket Propulsion Elements. New York: John Wiley and Sons. pp. 21-34.

9 Hobson A (2003) Physics literacy, energy and the environment. Physics Education 38: 109-114.

10 DeLong F (1974) DeLong‘s Guide to Bicycles and Bicycling. Radnor Pennsylvania: Chilton Book Company. pp. 186-192.

11 El-Wakil M (1984) Powerplant Technology. New York: McGraw-Hill. pp. 30-78.

12 Segway, Inc. (2007) Segway I2 Specifications. Available: http://www.segway.com/downloads/pdfs/i2-specs.pdf. Accessed 2007 Oct 19.

13 Weaver M (2001) Fastest Human Pure Muscle Speeds Illustrated. Available: http://www.speed101.com/sprint/2001sprints.htm. Accessed 2007 Aug 28.

14 Verucci Gas Scooters (2007) Gekgo Worldwide. Available: http://www.gekgo.com/verucci-gas-scooters.htm. Accessed 2007 Sep 27.

15 US Department of Energy (2007) MPG Ratings, 2007 Model Year. Available: http://www.fueleconomy.govfeg/fe_test_schedules.shtml. Accessed 2007 Dec 29.

16 NASA (2007) Voyager Weekly Report. Available: http://www.voyager.jpl.nasa.gov/mission/weekly-reports/index.htm. Accessed 2007 Aug 28.

17 Wade, M. (2007) Titan 3E. Available: http://www.astronautix.com/lvs/titan3e.htm. Accessed 2007 Aug 28.

18 Simpson A (2007) Where the Rubber Meets the Road. Available: http://www.teslamotors.com/blog4/?p=60. Accessed 2007 Oct 19.

19 Vetter C (1985) Craig Vetter Fuel Economy Contest. Available: http://www.craigvetter.com/pages/470MPG/470MPG%20Main.htm. Accessed 2007 Oct 17.

20 Twike (2007) Twike Specifications. Available: http://www.twike.com/twike_con.htm. Accessed 2008 Jan 1.

21 Google RechargeIT.org (2007) Vehicle Calculator. Available: http://www.google.org/recharge/dashboard/calculator#notes. Accessed 2007 Oct 19.

22 City of Denver (2007) Climate Action Plan. Available: http://www.greenprintdenver.org/docs/Greenprint_Council_Report.pdf. Accessed 2007 Oct 19.

23 Fallows J (2001) Freedom of the Skies. Available: http://www.theatlantic.com/doc/200106/fallows. Accessed 2007 Oct 19.

24 Holmes B (2004) Life After Airliners_VII, Slide 25. Available: http://www.airtraveler.com/Airtraveler/NASA/Bruce/default.aspx. Accessed 2007 Nov 3.

25 Air Transport Association (2007) Fuel Efficiency: US Airlines. Available: http://www.airlines.org/economics/energy/fuel+efficiency.htm. Accessed 2007 Nov 1.

26 US Bureau of Transportation Statistics (2004) Domestic Flight Availability and Distance. Available: http://www.bts.gov/publications/white_house_economic_statistics_briefing_room/january_2004/html/domestic_flight_availability_and_distance.htm. Accessed 2007 Nov 1.

27 Dick H (1985) The Golden Age of Passenger Airships: Graf Zeppelin and Hindenburg. Washington, DC: Smithsonian Institution Press. pp. 111-123.

28 Seeley B (1994) The World's Most Efficient Aircraft! Available: http://www.cafefoundation.org/v2/pdf_apr/WMEA.pdf. Accessed 2007 Nov 1.

29 Boeing Corporation (2007) Preliminary 747-8 Airport Compatibility. Available: http://www.boeing.com/commercial/airports/acaps/7478brochure.pdf. Accessed 2007 Nov 1.

30 Elert G (2003) The Physics Factbook, Energy Density of Aviation Fuel. Accessed: http://hypertextbook.com/facts/2003/EvelynGofman.shtm. Accessed 2007 Nov 1.

31 US Federal Aviation Administration (2007) Federal Aviation Regulation 121.645. Available: http://www.flightsimaviation.com/data/FARS/part_121-645.htm. Accessed 2007 Nov 4.

32 Airline Industry Information (2005) New Regulations Result in Increased Average Weight of Passengers and Luggage on US Airlines. Available: http://findarticles.com/p/articles/mi_m0CWU/is_2005_August_12/ai_n14892484. Accessed 2007 Nov 1.

33 Maxim L (2001) Trans Alaska Pipeline System Renewal Environmental Impact Statement: 4.9 Energy Requirements and Conservation Potential. Available: http://www.tapseis.anl.gov/documents/docs/Section_4_9_May2.pdf. Accessed 2007 Dec 1.

34 US Congressional Budget Office (1982) Energy Use in Transportation. Available: http://www.cbo.gov/ftpdocs/53xx/doc5330/doc02b-Entire.pdf, Table 1. Accessed 2007 Dec 1.

35 Davis S, Diegel S (2007) Transportation Energy Data Book: Edition 26. ORNL-6978. Available: http://cta.ornl.gov/data/index.shtml. Accessed 2007 Dec 8.

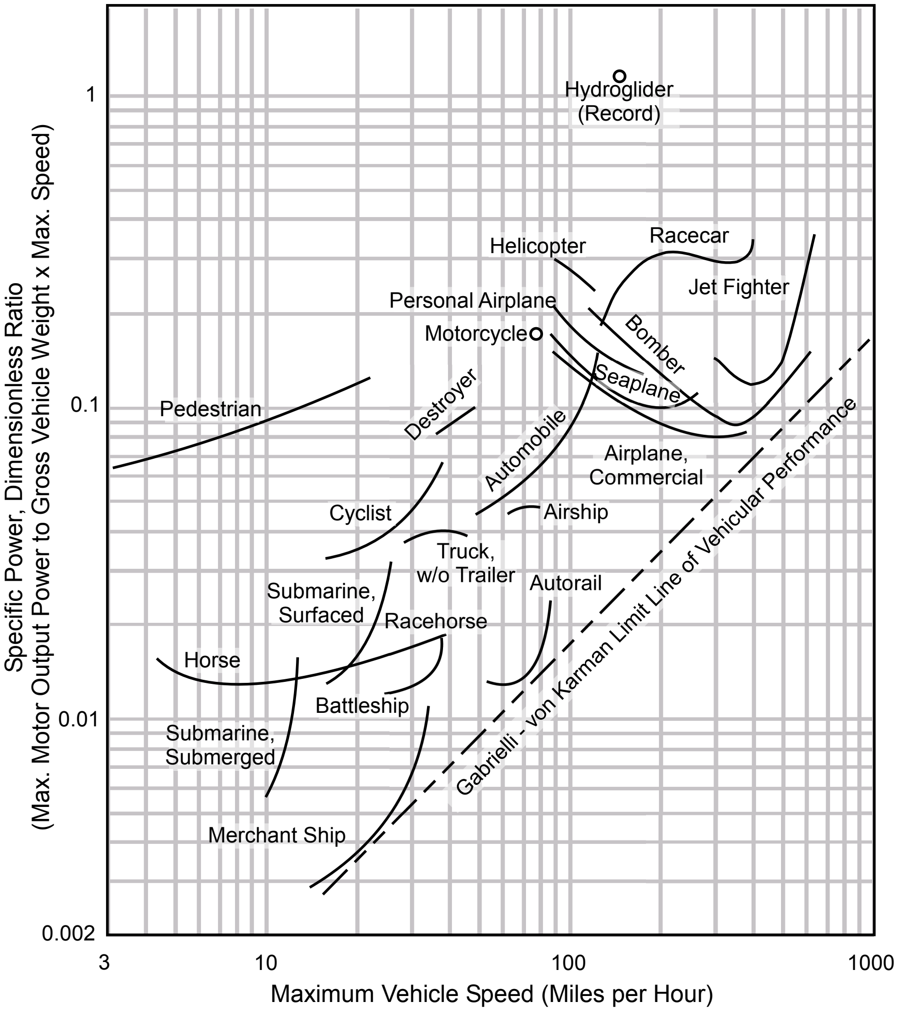

Figure 1. Specific resistance of single vehicles. Diagonal is G-K limit line of vehicular performance. Adapted from Gabrielli and von Karman [1].

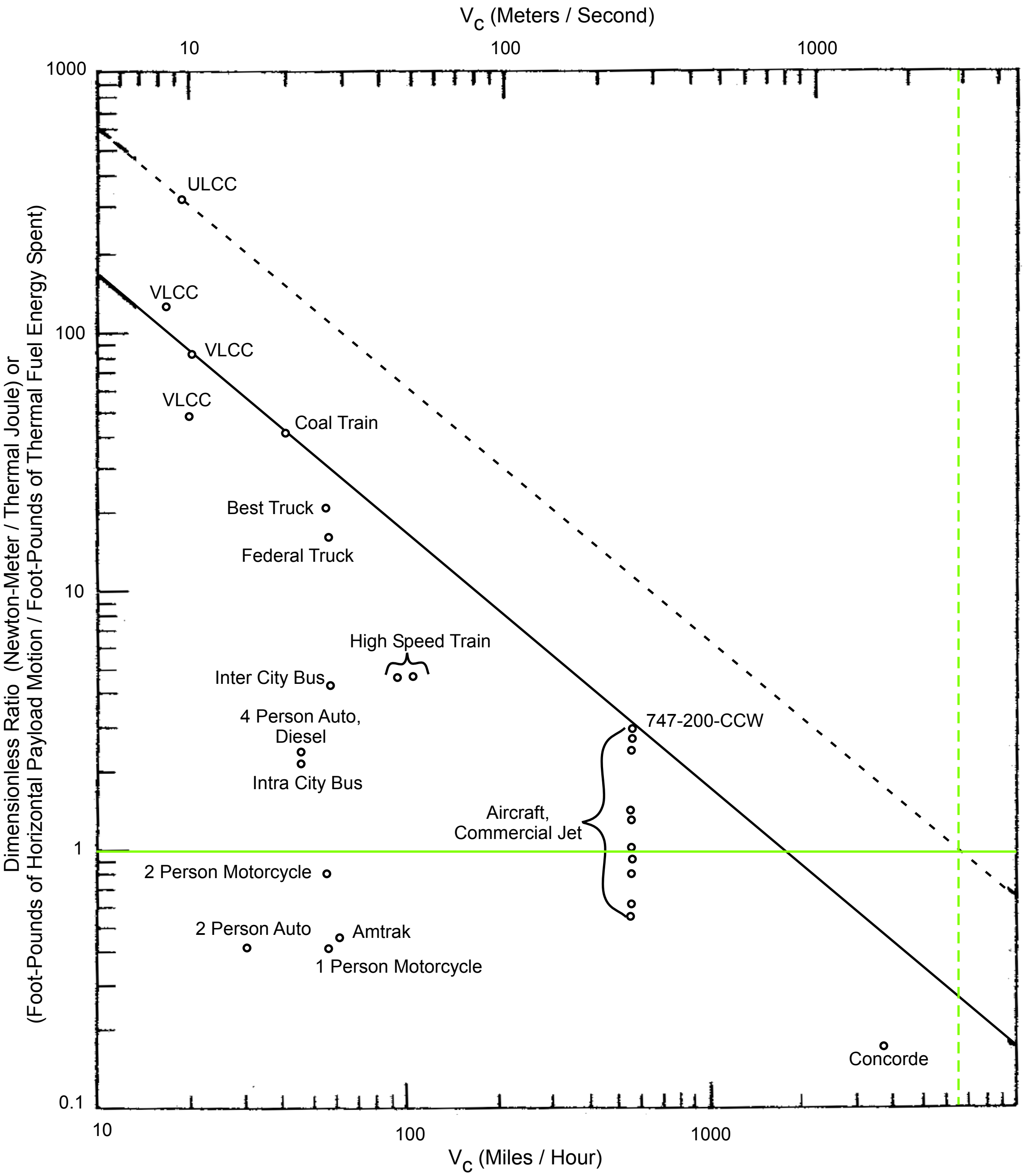

Figure 2. Dimensionless fuel transport effectiveness ($\mathcal{E}_F^{-1}$) plotted as a function of cruise speed. Adapted from Teitler and Proodian [2]. Green lines added here to demonstrate nomographical technique. C_F^{-1} can be read from graph for ULCC by seeking intersection of diagonal with horizontal green line, and reading position vertical green line on the V_C scale. For the ULCC, C_F^{-1} is about 2800 meters per second. Technique may be extended to determine C_F^{-1} for other vehicles by drawing parallel diagonals through other points on this graph.

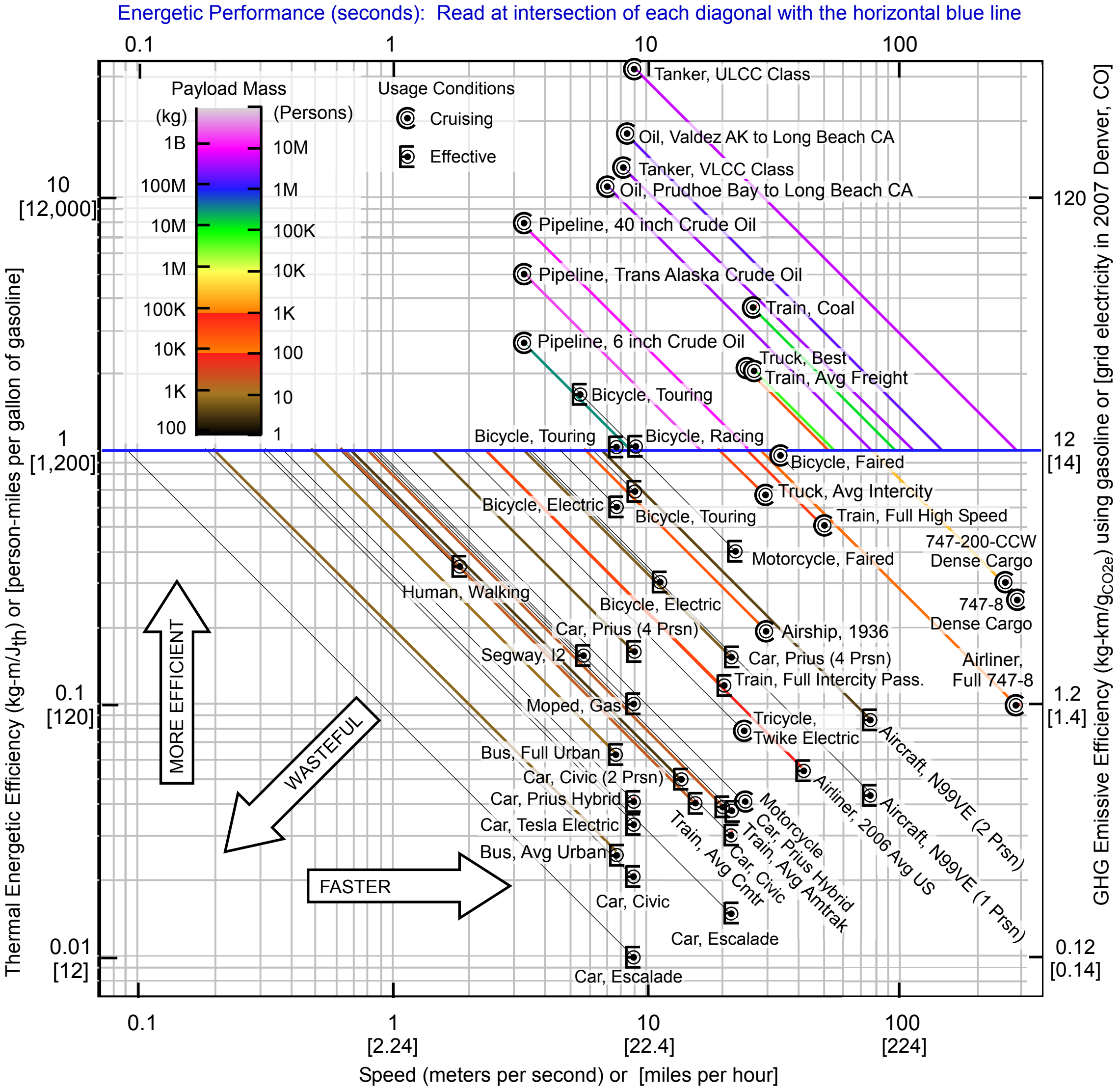

Figure 3. Transportation matrix indicating thermal energetic efficiency ($\mathcal{E}_Q^{-1}$) and energetic performance (Q) for various modes at typical loads and usage speeds. Since Q is the product of thermal efficiency and speed, it is read by following the diagonal (constant Q) lines to the point where thermal efficiency is unity. Effective values for mass transit take wait time into account and are strongly influenced by utilization, delays and terminal pedestrian flow. Steady state cruising conditions are denoted by "C" data point icons. Average conditions which include velocity changes in crowded environments are represented by "E" icons. The price for convenience of personal transit is evident when compared to mass transit.

Table 1. Thermal Efficiency & Energetic Performance of Various Transportation Modes.

Mode	Fuel Econ. (Person-MPG)	Emissive Eff. (kg-km/gCO2e)	Payload Mass (kg)	1/ef	1/eq (kg-m/Jth)	Speed (Mi/Hr)	Speed (m/s)	Q (s)	Conditions	Source
Bicycle, Faired	1,149.0		70	9.54	0.973	75.0	33.5	32.62	Qc	[13]
Bicycle, Racing	1,231.6		70	10.23	1.043	20.0	8.9	9.32	Qe	[10]
Bicycle, Touring	1,967.3		70	16.34	1.666	12.0	5.4	8.94	Qe	[10]
Motorcycle, Completely Faired	470.0	4.93	70	3.90	0.398	50.1	22.4	8.91	Qe	[19]
Bicycle, Touring	1,215.2	12.76	70	10.09	1.029	17.0	7.6	7.82	Qe	[10]
Bicycle, Touring	818.3		70	6.80	0.693	20.0	8.9	6.20	Qe	[10]
Bicycle, Electric Cyclemotor	715.6	7.51	70	5.94	0.606	17.0	7.6	4.60	Qe	
Bicycle, Electric Cyclemotor	357.9	4.33	70	2.97	0.303	25.0	11.2	3.39	Qe	
Airplane, 1 Person N99VE	50.8	0.53	70	0.42	0.043	169.5	75.8	3.26	Qe	[28]
Elec Trike, Twike	90.9	1.10	70	0.76	0.077	53.0	23.7	1.82	Qc	[20]
Motorcycle	48.4	0.51	70	0.40	0.041	55.0	24.6	1.01	Qc	[3]
Moped, Unpedaled Gas	117.0	1.23	70	0.97	0.099	20.0	8.9	0.88	Qe*	[14]
Segway I2 (TM)	181.9	2.20	70	1.51	0.154	12.5	5.6	0.86	Qe	[11,12]
Auto, Prius Hybrid Hwy	45.0	0.47	70	0.37	0.038	48.0	21.5	0.82	Qc	[15]
Electric Car, Tesla Hwy	36.6	0.44	70	0.30	0.031	48.0	21.5	0.66	Qc	[18]
Auto, Civic Nonhybrid Hwy	36.0	0.38	70	0.30	0.030	48.0	21.5	0.65	Qc	[15]
Human Walking	413.3		70	3.43	0.350	4.0	1.8	0.63	Qe*	[9]
Auto, Prius Hybrid City	48.0	0.51	70	0.40	0.041	20.0	8.9	0.37	Qe	[15]
SUV, Escalade Hwy	18.0	0.19	70	0.15	0.015	48.0	21.5	0.33	Qc	[15]
Electric Car, Tesla City	39.0	0.47	70	0.32	0.033	20.0	8.9	0.30	Qe	[18]
Auto, Civic Nonhybrid City	25.0	0.26	70	0.21	0.021	20.0	8.9	0.19	Qe	[15]
SUV, Escalade City	12.0	0.12	70	0.10	0.010	20.0	8.9	0.09	Qe	[15]
Airplane, 2 Person N99VE	101.6	1.07	140	0.84	0.086	169.5	75.8	6.52	Qe	[28]
Auto, Civic 2 Person	25.0	0.52	140	0.41	0.042	20.0	8.9	0.38	Qe	[15]
Auto, Prius 4 Person Hwy	45.0	1.89	280	1.49	0.152	48.0	21.5	3.27	Qc	[15]
Auto, Prius 4 Person City	48.0	2.02	280	1.59	0.163	20.0	8.9	1.45	Qe	[15]
Bus, Avg Load Urban	29.5	0.31	609	0.25	0.025	17.0	7.6	0.19	Qe*	[35]
Spacecraft, Voyager 1	7.3E+06		7.2E+02	6.1E+04	6.2E+03	3.8E+04	1.7E+04	1.0E+08	Qe	[8,16,17]
Train, Avg Load Amtrak	46.1	0.48	1.26E+03	0.38	0.039	45.0	20.1	0.78	Qe*	[35]
Train, Avg Load Commuter	48.4	0.51	1.57E+03	0.40	0.041	35.0	15.6	0.64	Qe*	[35]
Bus, Full Urban	74.4	0.78	2.52E+03	0.62	0.063	17.0	7.6	0.48	Qe*	[9]
Airliner, Avg Passenger	33.1	0.35	6.30E+03	0.27	0.028	270.0	120.7	3.38	Qe*	[9]
Airliner, Avg Passenger 2006	63.8	0.67	6.85E+03	0.53	0.054	93.0	41.6	2.24	Qe	[23-26]
Truck, Avg Intercity	778.2	8.17	1.32E+04	6.46	0.659	65.0	29.1	19.14	Qe*	[34]
Train, High Speed Full Load	602.2	7.29	1.40E+04	5.00	0.510	110.0	49.2	25.09	Qc	[3]
Train, Full Load Intercity	140.5	1.70	1.75E+04	1.17	0.119	45.0	20.1	2.39	Qe*	[9]
Airship, 1936	224.4	2.36	2.27E+04	1.86	0.190	66.0	29.5	5.60	Qc	[27]
Truck, Best	2,530.6	26.57	3.64E+04	21.00	2.143	55.0	24.6	52.68	Qc	[3]
Airliner 747-8, 467 Pass.	116.9	1.23	4.46E+04	0.97	0.099	650.0	290.5	28.76	Qc	[29,30]
Airliner, 747-200-CCW Freight	361.3	3.79	1.33E+05	3.00	0.306	580.0	259.2	79.37	Qc	[3]
Airliner, 747-8, 10 lb/ft3 Freight	305.8	3.21	1.33E+05	2.54	0.259	650.0	290.5	75.24	Qc	[29,30]
Train, Avg Freight	2,479.8	26.04	4.00E+06	20.59	2.100	60.0	26.8	56.32	Qe*	[34]
Train, Dense Freight (Coal)	4,416.4	46.37	8.30E+06	36.68	3.740	60.0	26.8	100.29	Qe*	[34]
Pipeline, 6 Inch Crude Oil	2,964.0	31.12	2.00E+07	24.61	2.510	7.4	3.3	8.26	Qe*	[33]
Tanker, Valdez to Long Beach	20,192.7	212.01	1.20E+08	167.69	17.100	18.4	8.2	140.63	Qc	[33]
Tanker, VLCC Class	15,664.1	164.46	2.00E+08	130.00	13.265	18.0	8.0	106.70	Qc	[3]
Tanker, ULCC Class	38,558.5	404.84	3.20E+08	320.00	32.653	20.0	8.9	291.90	Qc	[3]
Oil, Prudhoe Bay to Long Beach	12,517.1	131.42	4.16E+08	103.95	10.600	15.4	6.9	73.14	Qc	[33]
Pipeline, 40 Inch Crude Oil	9,069.0	95.22	8.87E+08	75.32	7.680	7.4	3.3	25.27	Qe*	[33]
Pipeline, 48 Inch Trans Alaska	5,833.4	61.25	1.30E+09	48.44	4.940	7.4	3.3	16.25	Qc	[33]

* From estimated speed

Table 2. Assumptions and Conversion Factors.

Parameter	Value	Source
Fuel energy content (MJth/Gal)	133.000	[9]
Person weight (kg)	70.000	
MPG to effectiveness	1.210E-02	
Effectiveness to 1/eq	0.070	
MPH to m/s	0.447	
Electrical grid efficiency	0.960	
Power station thermal efficiency	0.330	[11]
Human thermal efficiency	0.250	[10]
Miles per kWhr to effectiveness	0.142	
CO2e per gallon gasoline (kg)	10.727	[20]
CO2e per Jth (kg)	8.066E-08	
1/eq to GHG em. Eff. (gasoline)	12.398	
CO2e per kWhr - electric (kg)	0.796	[21]
1/eq to GHG em. Eff. (electric)	14.285	
Reserve Aircraft Fuel %	15.000	[30]
Jet fuel energy density MJ/kg	43.000	[29]
Avg airliner flight length (mi)	689.000	[25]
Avg airliner eff. speed (MPH)	93.000	[22,23]
Avg airline pass+bags wt. (lb)	190.000	[31]
1/ef to 1/eq	0.102	