The Oil Drum
DISCUSSIONS ABOUT ENERGY AND OUR FUTURE

How Green Is Your Ride?

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Topic: Environment/Sustainability
Tags: transportation, transportation efficiencies [list all tags]

This is a guest post by Jeff Radtke. Jeff is an independent researcher holding BS degrees in Nuclear Engineering and Physics, and an MS in Nuclear Engineering and Engineering Physics. He is a member of the American Physical Society and The Institute of Electrical and Electronic Engineers. In addition to recent work with electric bicycles, for the past 27 years he has been designing and building nuclear instruments for materials studies, medical, physics and educational applications. He is a longtime lurker, and recent poster on TOD as CyclemotorEngineer.

This post is based on an article published in 2008 in the peer-reviewed "Open Fuels and Energy Science Journal" as The Energetic Performance of Vehicles. The article showed that the accepted vehicle performance metric known as the Gabrielli-von Karman Limit is the same as twice the maximum vehicle kinetic energy divided by maximum motor output power. This result was not found in an extensive literature search.

This type of analysis is useful because it is easy to factor in conversion efficiencies and payload versus tare weight. Rather than use motor output power, one can use the thermal power theoretically available in the flowing fuel. EROI may be factored in, as well as GHG emissions. Analysis may be completed at the level of individual trips, vehicles, or an entire system with resource extraction, infrastructure development, manufacturing and direct fuel use.

Kinetic energy divided by required power is considered a residence time for the input energy in the utilized form. This model may provide an intuitive understanding of energy use. Residence time for anything in a container is the quantity residing divided by the flow rate. This is as true for a vehicle containing kinetic energy as it is for a mountain lake holding melted glacier, or the CO2 present in our atmosphere.

Common Vehicle Performance Criteria

Payload Mass. In the US, the automobile is most commonly used to carry one person, even though it is capable of far greater payloads. In this analysis, automobiles are considered personal vehicles hauling a 70 kilogram payload mass. By including payload mass in a performance metric, it is possible to obtain an economically relevant comparison means. In this article, M_p denotes payload mass.

Speed. Vehicle speed may be the most obvious performance metric. The most fuel conservative choice may not be the best, since time is also a finite resource. For most automobile trips, speed is governed by safety considerations, especially in the presence of other vehicles. Congested urban roadways result in an average speed in US cities of only about 20 miles per hour [8.9

meters per second]. In this article, <**v**> denotes average speed.

Fuel Economy. Fuel economy is a complex performance metric. It depends on payload mass, speed, and host of vehicle characteristics. Payload density can effect fuel economy indirectly by changing vehicle displacement requirements, as reflected in shipping carrier dimensional weight charges. Variations in speed will decrease fuel economy, but the utility is dependent on average speed. For example, a trip via expressway is no more or less useful than a trip at same average speed through a series of stoplights. The most familiar unit used to express fuel economy is miles per gallon of gasoline. Since a gallon of gasoline typically contains 133 million Joules of thermal energy, fuel economy may be expressed in meters per Joule. Fuel economy is length traveled divided by thermal energy used, and is denoted below as $\mathbf{l}/E_{th}$.

Vehicle Energetic Performance

Definition. The above performance criteria are combined via multiplication. The result is a ratio of the benefits of vehicle use (payload mass, average speed and distance moved) to the cost, expressed in universal currency as thermal energy. Vehicle energetic performance (Q) is:

$$Q = M_p \; \langle \mathbf{v} \rangle \, \mathbf{l} \, / E_{th} \tag{1}$$

G-K Limit. Q is an economically meaningful refinement of a vehicle performance "limit" known as the G-K limit.[1] This limit was first described in 1950 by the former president of Fiat Motors, Guiseppi Gabrielli and the great aerodynamicist Theodore von Karman.[2]

Mode	Payload Mass	Average Speed		Energetic Economy		Emiss. Econ.	Q	Form	Avg Pth	Payload KE
	(kg)	(Mi/Hr)	(m/s)	(Person-MPG)	(kg-m/Jth)	(kg-km/gCO2e)	(s)		(Watts)	(J)
Airplane, 1 Person N99VE	70	169.5	75.8	51	0.043	0.53	3.26	E	123,325	200,870
NASA Puffin VTOL	70	147.7	66	125	0.106	1.31	7.00	E	43,585	152,460
Bicycle, Faired	70	75.0	33.5	1,149	0.973		32.62	C	2,411	39,328
Motorcycle	70	55.0	24.6	48	0.041	0.51	1.01	C	41,969	21,150
Elec Trike, Twike	70	53.0	23.7	91	0.077	1.10	1.82	C	21,535	19,639
Motorcycle, Completely Faired	70	50.1	22.4	470	0.398	4.93	8.91	E	3,938	17,549
Auto, Prius Hybrid Hwy	70	48.0	21.5	45	0.038	0.47	0.82	C	39,519	16,109
Electric Car, Tesla Hwy	70	48.0	21.5	37	0.031	0.44	0.66	C	48,482	16,109
Auto, Civic Nonhybrid Hwy	70	48.0	21.5	36	0.030	0.38	0.65	C	49,259	16,109
SUV, Escalade Hwy	70	48.0	21.5	18	0.015	0.19	0.33	C	98,519	16,109
Bicycle, Electric Cyclemotor	70	25.0	11.2	358	0.303	4.33	3.39	E	2,578	4,370
Bicycle, Racing	70	20.0	8.9	1,232	1.043		9.32	E	600	2,797
Bicycle, Touring	70	20.0	8.9	818	0.693		6.20	E	902	2,797
Moped, Unpedaled Gas	70	20.0	8.9	117	0.099	1.23	0.88	E	6,320	2,797
Auto, Prius Hybrid City	70	20.0	8.9	48	0.041	0.51	0.37	E	15,262	2,797
Electric Car, Tesla City	70	20.0	8.9	39	0.033	0.47	0.30	E	18,938	2,797
Auto, Civic Nonhybrid City	70	20.0	8.9	25	0.021	0.26	0.19	E	29,796	2,797
SUV, Escalade City	70	20.0	8.9	12	0.010	0.12	0.09	E	62,572	2,797
Bicycle, Touring	70	17.0	7.6	1,215	1.029		7.82	E	517	2,021
Bicycle, Electric Cyclemotor	70	17.0	7.6	716	0.606	7.51	4.60	E	878	2,021
Segway I2 (TM)	70	12.5	5.6	182	0.154	2.20	0.86	E	2,539	1,092
Bicycle, Touring	70	12.0	5.4	1,967	1.666		8.94	E	225	1,007
Human Walking	70	4.0	1.8	413	0.350		0.63	E	358	112
Airplane, 2 Person N99VE	140	169.5	75.8	102	0.086	1.07	6.52	E	123,325	401,739
Auto, Civic 2 Person	140	20.0	8.9	25	0.042	0.52	0.38	E	29,796	5,593
Auto, Prius 4 Person Hwy	280	48.0	21.5	45	0.152	1.89	3.27	C	39,407	64,434
Auto, Prius 4 Person City	280	20.0	8.9	48	0.163	2.02	1.45	E	15,394	11,187
Bus, Avg Load Urban	609	17.0	7.6	30	0.025	0.31	0.19	E	185,089	17,579
Spacecraft, Voyager 1	7.2E+02	3.80E+04	1.70E+04	7.32E+06	6.20E+03		1.00E+08	C	2.1E+03	1.0E+11
Train, Avg Load Amtrak	1.3E+03	45.0	20.1	46	0.039	0.48	0.78	E	6.5E+05	2.5E+05
Train, Avg Load Commuter	1.6E+03	35.0	15.6	48	0.041	0.51	0.64	E	6.0E+05	1.9E+05
Bus, Full Urban	2.5E+03	17.0	7.6	74	0.063	0.78	0.48	E	3.0E+05	7.3E+04
Airliner, Avg Passenger	6.3E+03	270.0	120.7	33	0.028	0.35	3.38	E	2.7E+07	4.6E+07
Airliner, Avg Passenger 2006	6.9E+03	93.0	41.6	64	0.054	0.67	2.24	E	5.3E+06	5.9E+06
Truck, Avg Intercity	1.3E+04	65.0	29.1	778	0.659	8.17	19.14	E	5.8E+05	5.6E+06
Train, High Speed Full Load	1.4E+04	110.0	49.2	602	0.510	7.29	25.09	C	1.3E+06	1.7E+07
Train, Full Load Intercity	1.8E+04	45.0	20.1	141	0.119	1.70	2.39	E	3.0E+06	3.5E+06
Airship, 1936	2.3E+04	66.0	29.5	224	0.190	2.36	5.60	C	3.5E+06	9.9E+06
Truck, Best	3.6E+04	55.0	24.6	2,531	2.143	26.57	52.68	C	4.2E+05	1.1E+07
Airliner 747-8, 467 Pass.	4.5E+04	650.0	290.5	117	0.099	1.23	28.76	C	1.3E+08	1.9E+09
Airliner, 747-8, 10 lb/ft3 Freight	1.3E+05	650.0	290.5	306	0.259	3.21	75.24	C	1.5E+08	5.6E+09
Airliner, 747-200-CCW Freight	1.3E+05	580.0	259.2	361	0.306	3.79	79.37	C	1.1E+08	4.5E+09
Train, Avg Freight	4.0E+06	60.0	26.8	2,480	2.100	26.04	56.32	E	5.1E+07	1.4E+09
Train, Dense Freight (Coal)	8.3E+06	60.0	26.8	4,416	3.740	46.37	100.29	E	6.0E+07	3.0E+09
Pipeline, 6 Inch Crude Oil	2.0E+07	7.4	3.3	2,964	2.510	31.12	8.26	C	2.6E+07	1.1E+08
Tanker, Valdez to Long Beach	1.2E+08	18.4	8.2	20,193	17.100	212.01	140.63	C	5.8E+07	4.1E+09
Tanker, VLCC Class	2.0E+08	18.0	8.0	15,664	13.265	164.46	106.70	C	1.2E+08	6.5E+09
Tanker, ULCC Class	3.2E+08	20.0	8.9	38,559	32.653	404.84	291.90	C	8.8E+07	1.3E+10
Oil, Prudhoe Bay to Long Beach	4.2E+08	15.4	6.9	12,517	10.600	131.42	73.14	C	2.7E+08	9.9E+09
Pipeline, 40 Inch Crude Oil	8.9E+08	7.4	3.3	9,069	7.680	95.22	25.27	C	3.8E+08	4.8E+09
Pipeline, 48 Inch Trans Alaska	1.3E+09	7.4	3.3	5,833	4.940	61.25	16.25	C	8.7E+08	7.0E+09

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Table 1. Table 1 lists the energetic performance of various vehicles. Some vehicles are listed more than once to indicate different speed or payload. Since greenhouse gas emissions are tied to thermal energy use and fuel choice, it is possible to compare emissions for various transport

means provided that primary fuel choice is known. Electric vehicles are thus compared by estimating thermal energy utilized in a matrix of powerplants fueled by various means to produce the electricity that charges vehicle batteries.

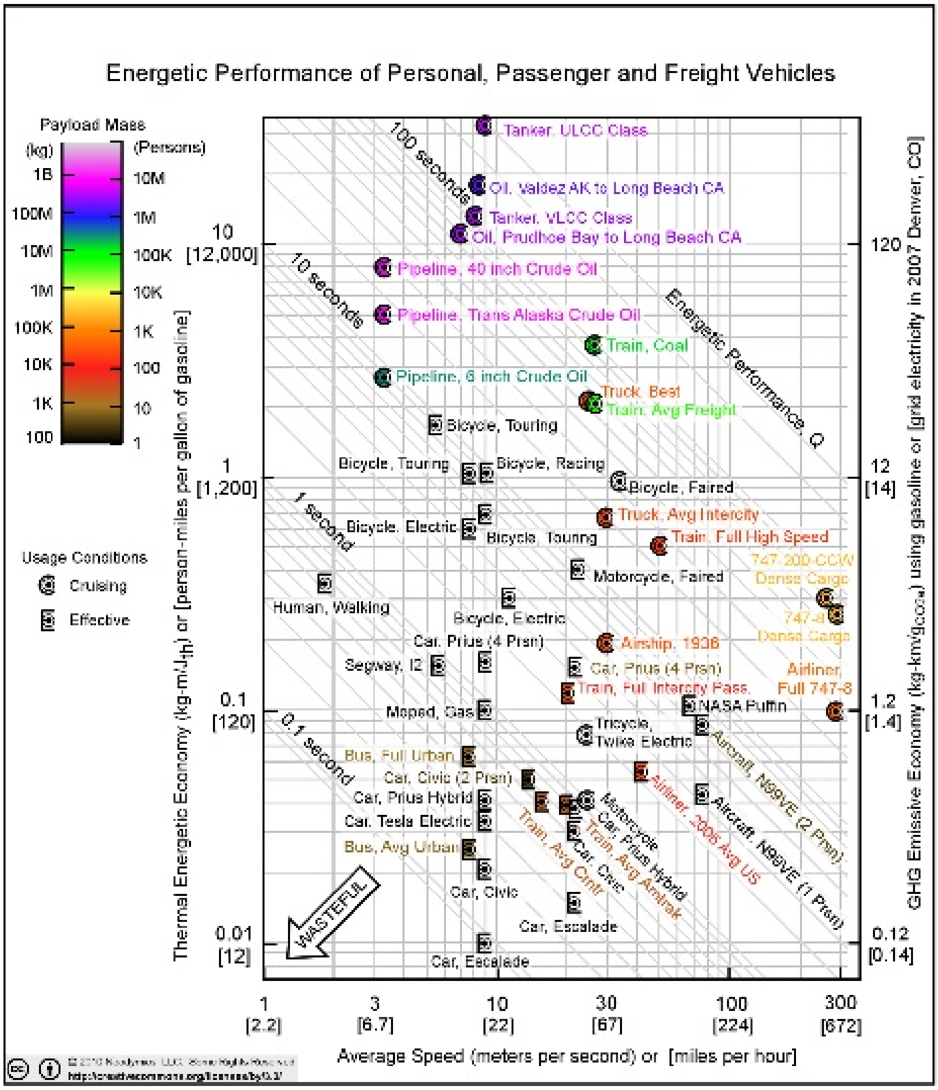

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Figure 1. Figure 1 graphically compares these vehicles. Logarithmic scales were chosen for both axes not to distort, but to fit the vastly differing numbers on a single screen. A factor of ten, for example, is the same length everywhere on this graph. Diagonal lines on this logarithmic graph represent the product of values from each axis, which is Q. Payload mass is indicated by another logarithmic scale using color. Notice that supertankers, bicycles and urban automobiles all travel at about 20 miles per hour, but fuel economy differs by a factor of 3000.

Energy Primer

Energy Forms. Energy may take many forms, but the most familiar are thermal and mechanical. Energy can be released in thermal form by burning a fuel to raise the temperature of something. An increase in temperature is another way of saying that the average speed of atoms increase in a random fashion. This thermal energy can be converted to mechanical or kinetic form, moving all of the atoms comprising something in a uniform manner by, for example, spinning it or sending it down a road. Thermal energy is less organized than mechanical energy, and is said to have a lower quality. Conversion of thermal energy to mechanical energy in modern large-scale powerplants is typically 30-40% efficient. Automobile engines exhibit considerably less efficiency. Mechanical energy can be converted to electrical energy very efficiency, often about 90%, since these two forms are both highly organized.

Rejection. When discussing energy use, it is important to be clear about which form of energy is being described. Powerplant engineers typically do this by adding a subscript or parenthetic (th), (m), or (e) to powerplant specifications. For example, a 1000 Megawatt(e) powerplant may also be described as a 3000 Megawatt(th) powerplant. The apparently lost 2000 Megawatts is said to be “rejected” power.

Waste. It is a theoretical impossibility to convert thermal energy to mechanical form without rejection loss, which increases as the temperature of a thermal energy source decreases. Energy rejected in conversion between forms is very different from energy wasted because of forgetfulness or oversight. Energy is rejected at the powerplant because of natural laws, but energy may be wasted at the point of use because a light is left on when nobody is there to see by it. Similar end-use waste occurs in driving a two ton car when a 60 pound electric bicycle would do the same job faster, and with much less energy.

Energy Measurement. Just as distance can be measured with various units, such as centimeters, feet or fathoms, energy may be measured in a number of ways. If a thing is heated or moved, a transfer of energy is involved. This energy may be inferred from measurements of the things mass and temperature or distance moved over a period of time time using instruments calibrated in whatever measurement system is convenient. Various academic disciplines or trades are accustomed to seeing energy measured in different units, resulting in some confusion. A physicist might use the Joule, or the electron-volt. A chemist may use the calorie. A nutritionist may use the Calorie, which is the same as 1000 chemist-style calories, or one kcal. A heating contractor may use the BTU. An electric utility may use the kiloWatt-hour. A motor manufacturer might use the horsepower-hour. A mechanical engineer might use the foot-pound. A nuclear engineer might use atomic mass units. An electrical engineer might use watt-seconds. An energy macro-economist might use the Quad, shorthand for a Quadrillion BTU. All of these units describe the same physical parameter, energy. The most standard international unit of energy is the Joule, which is the energy transferred when a single kilogram mass is dropped one 102 centimeters to the earth’s surface.

Power. Another source of confusion results from the terms power and energy. Power is the rate of energy use, or energy flow rate, in a system. Given the preceding plethora of energy units, and the variety of ways time is described, power units may appear confusing indeed. The most standard international unit of power is the Watt, which is one Joule flowing per second.

Power Measurement. Power may be measured over a long period of time, such as a year, in which case it is an average. Peak or instantaneous power is measured over a period which is comparable to the response time of the energy system. Peak power is often much higher than average power. A healthy adult, for example, is capable of producing 800 Watts of mechanical power for ten seconds, but a yearly average power of only about 33 Watts.

Physical Meaning of Energetic Performance

Kinetic Energy. The energetic performance, Q, may be calculated for steady state (cruising) conditions by multiplying numerator and denominator in equation 1 by the elapsed time. Since distance covered divided by elapsed time is speed, and energy transferred divided by elapsed time is power P_{th}, equation 1 becomes:

$$(2) \qquad Q = M_p \mathbf{v}^2 / P_{th}$$

Because conditions are steady state, the use of average values is redundant. The numerator may be recognized by any student of general physics as twice the kinetic energy of the payload.

Why Seconds? Q is expressed in seconds, and it is natural to ask what this might mean. It turns out that the average residence time of a physical substance flowing into a full container is routinely calculated as the container size divided by the flow rate. This concept of residence time can also be applied to the abstraction we call energy, since a moving mass is a container of energy. Steady-state Q is twice the time during which fuel thermal energy resides as payload kinetic energy.

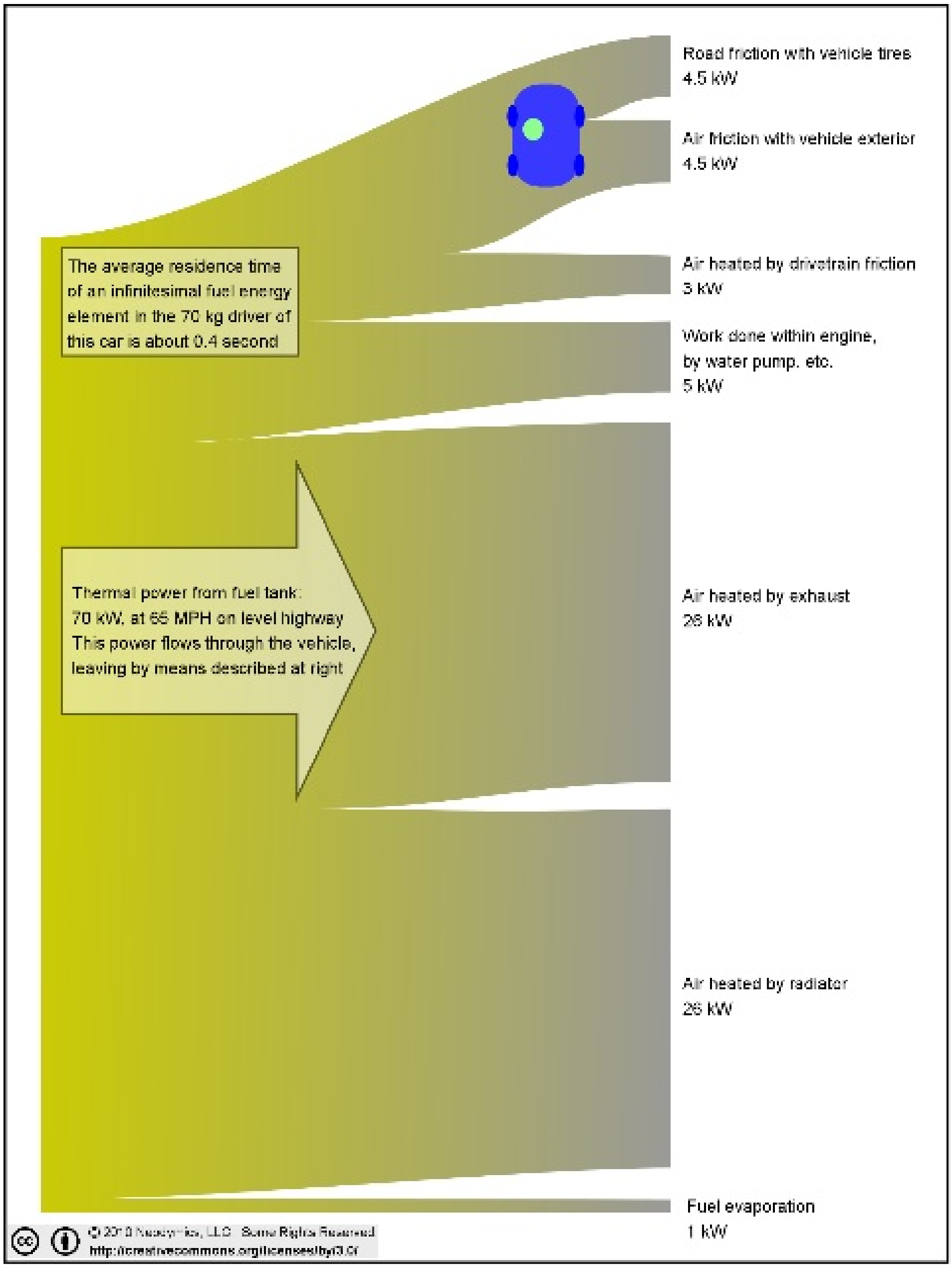

Figure 2. The complex flow of energy in an automobile traveling at highway speed is represented in figure 2. The kinetic energy of a vehicle and its payload is converted back to

thermal energy through friction, either with the surrounding environment or between moving parts on the vehicle. As a passenger in a conventional automobile, your body contains kinetic energy that was derived from burning gasoline. The length of time this energy stays in your body decreases if you choose to upgrade to a sporty model, which requires a higher fuel flow to maintain a given speed.

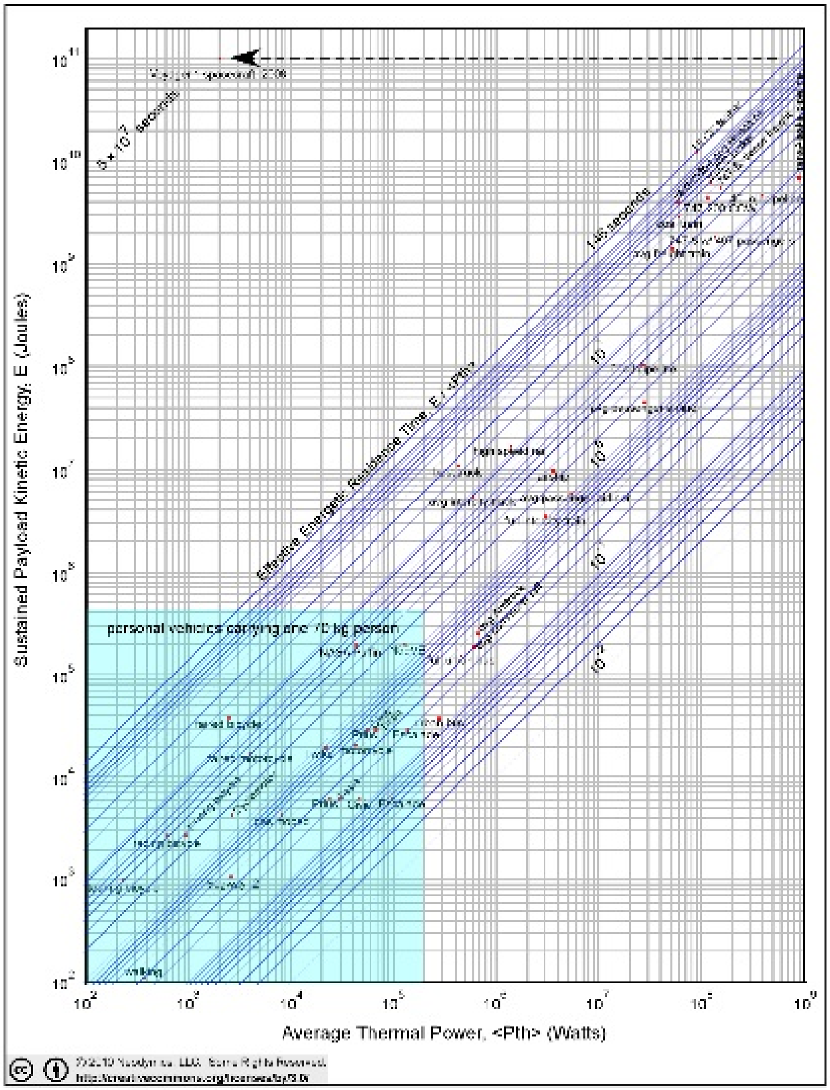

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Figure 3. Equation 2 suggests another way to depict data presented in table 1, organizing according to vehicle power and payload kinetic energy. Effective values for the residence time of energy were calculated from average speeds and plotted in figure 3. In this log-log plot, diagonals are drawn to represent the ratio of kinetic energy to thermal power. Economies of scale are evident as the high power and energy vehicles which lie in the upper right corner tend to have significantly longer residence times than the much smaller personal vehicles in the lower left.

Reversibility. The Voyager 1 spacecraft has been traveling in the essentially frictionless environment of deep space for decades. The average power used to move to its present distance from earth is the booster fuel energy content divided by this elapsed time. Residence time for this energy in this vehicle will only increase with time as the vehicle is in a state of perpetual motion. All of the other vehicles described lose their kinetic energy through friction with the surrounding environment. Kinetic energy returns to thermal form in these utilization processes, as quantified by the residence time. The most reversible processes change their state with the least transfer of energy, and energetic residence time is a measure of this reversibility.

Conclusions

Performance Incorporates Efficiency and More. Performance describes the utilization of energy, and efficiency describes the conversion of energy. Whether directly or indirectly, performance measurement includes efficiency measurements, but efficiency measurements do not include performance. Voyager 1 demonstrates that there is no limit to energetic performance. While efficiency is often used colloquially to describe performance, any true efficiency metric must lie between zero and one.

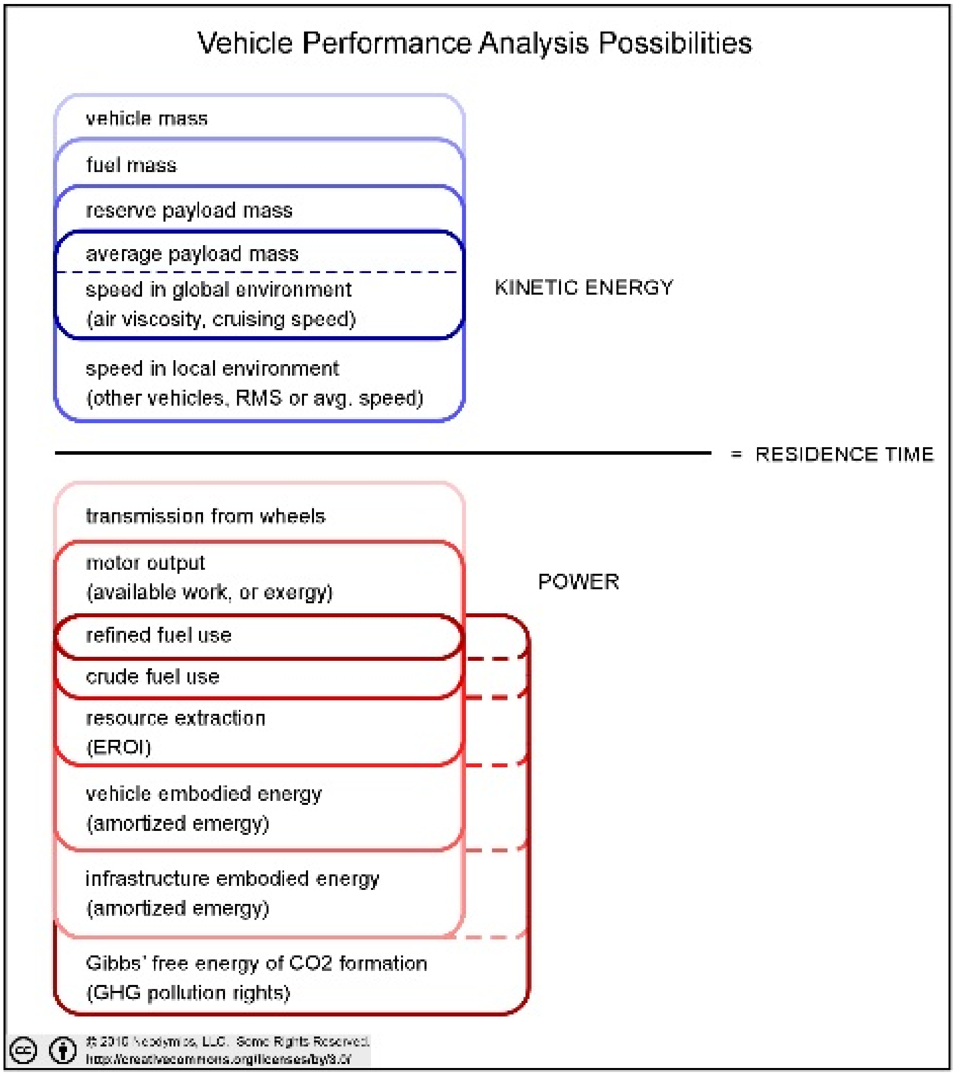

Figure 4. Energetic residence time measures the utilization effectiveness of an energy resource, and is the ratio of a sustained energy benefit to the corresponding rate of resource consumption.

Analysis bounds may be defined along various time scales, and with respect to many levels of resource use, so as include EROI, emissions, or other external cost considerations. Average values can be calculated for a vehicle, single trip, or an entire transportation system. Comprehensively applied, it would be useful in a long-term comparison of our existing transportation paradigm to a hypothetical, dominated by ultra-light personal vehicles and robotic couriers. In the most optimistic scenario, energetic performance may measure of how much more is accomplished with how much less.

Vehicle Characteristics. This analysis shows that light personal vehicles perform far better than heavy ones. Vehicle and infrastructure embodied energy were not considered, and such an inclusion would make light vehicles appear even more attractive. Since 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. High performance vehicles also tend to be compact and streamlined. Commercial airliners perform well because people are willing to crowd themselves in an aerodynamically optimized fuselage for fast, long distance travel. The greatest gains in performance may be obtained by redefining vehicle use mode, tare weight, shape and dimensions, rather than changes to vehicle motor or fuel system.

[1] Radtke, J.L. The Energetic Performance of Vehicles. *Open Fuels and Energy Science Journal* **1**, 11-18 (2008).

[2] Gabrielli, G., von Karman, T. What Price Speed? *Mechanical Engineering* **72**, 775-781 (1950).