Locomotive Energetic Performance and Other Transportation Parameters

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***Abstract*—Locomotive energetic performance is defined as the product of energetic efficiency and average speed. For steady state conditions, this parameter becomes twice the payload kinetic energy divided by thermal power expenditure. This parameter is described using notation defined by others for similar parameters. Locomotive energetic performance is determined for various mechanical and biological modes of human locomotion, providing an informative basis of comparison. A transportation matrix is presented which includes vehicle speed, efficiency, and locomotive energetic performance on a single graph. Vehicles with the highest level of locomotive energetic performance have efficient powerplants, high payload to gross mass ratios, or reduced friction with the surrounding environment.**

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." For a payload object that begins at rest, follows a trajectory and returns to rest, we can determine object mass, distance traveled, thermal energy expended and transit time. From these values, the energetic efficiency and average speed may also be determined. Multiplying thermal energetic efficiency and speed yields a parameter that is expressed in seconds, which is called locomotive energetic performance [1].

Others have considered the interplay between vehicle speed and efficiency. Gabrielli and von Karman [2] determined the specific power (motor output power per gross vehicle weight) for various forms of biological and mechanical conveyance. Teitler and Proodian [3] considered payload weight and thermal energy expenditure in a similar fashion, thus taking vehicle utilization and motor thermodynamic efficiency into account. They described a "factor of proportionality," expressed in inverse units of speed. This factor is similar to locomotive energetic performance. However, it was not used to compare individual vehicle performance, but rather as an empirically determined limit to the performance of all vehicles.

The purpose of this work is to describe the locomotive energetic performance parameter in terms of work completed by others. The parameter will be applied to various vehicles for comparison. It will be shown that using payload mass rather than weight yields a convenient and intuitively understandable parameter, linking payload kinetic energy with thermal power expenditure.

Gabrielli and von Karman [2] 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: An empirical limit was described for any isolated vehicle by Eq. 2, where A is 0.000175 miles per hour.

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

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

Eq. 2 was rewritten by Teitler and Proodan [3] as Eq. 3, where $(P_S)_{\min}$ is the minimum specific power:

(3) $$(P_S)_{\min} = P_{\min} / W = A V_M^2$$

A quantity similar to specific resistance was defined as 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].

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

The reciprocal of ε_F was defined as the fuel transport effectiveness, and related to vehicle cruising speed V_C by Eq. 5. C_F was referred to as a "factor of proportionality," and applied as a limit to what is technologically possible, rather than as a general performance parameter [3].

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

(6) $$C_F^{-1} = V_C \eta_{\max} W_P / \zeta$$

Other writers referencing [2] have also applied A or C_F as a limiting factor, while treating ε or ε_F^{-1} as a general performance parameter [4-6].

If we are to combine speed and specific resistance and use the result as a performance parameter, using ε_F is more informative than ε. The specific fuel expenditure ε_F takes payload weight and motor efficiency into account under cruising conditions, which is more representative of actual use and resultant benefit. C_F^{-1} is convenient because an increase corresponds to a performance improvement. As will be described later, it is preferable to treat the payload as a mass (denoted M_P) rather than a weight. This yields a parameter with units of time, which we call energetic performance, or Q. For cruising conditions, Q_C is defined by Eq. (7), where g_o is the acceleration due to gravity.

(7) $$Q_C = g_o / C_F = V_C \eta M_P / \zeta$$

An analogous fuel transport effectiveness is defined by Eq. (8), with E_{th} representing the thermal energy expended to travel a distance (d): This is the thermal transportation efficiency, and it has been used by others to compare various modes of transport [7].

$$\varepsilon_Q^{-1} = Q_C / V_C = d(M_P / E_{th})_C \quad (8)$$

Noting the relationship between cruising speed and thermal power expenditure (P_{TH}) in Eq. 9, results in Eq. (10). This provides an intuitive interpretation of Q_C as being the number of seconds during which a total fuel energy release equals twice the payload kinetic energy (E_k), for constant velocity (cruising) conditions.

$$\eta / \zeta = (d / E_{th})_C = V_C / P_{th} \quad (9)$$

$$Q_C = M_p V_C^{\,2} / P_{th} = 2(E_k / P_{th})_C \quad (10)$$

Expressing Q_C in seconds is convenient not only because it results in Eq. (10). Rocket engineers are accustomed to seeing performance expressed in seconds. Specific impulse, I_S, is a universally accepted parameter used to describe rocket motor performance. It is defined as shown in Eq. (11), 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].

$$I_s = F / (\dot{m} g_o) = F / \dot{w} \quad (11)$$

Note that a weight flow has the same units as a force flow. 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. 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 [8].

Using mass rather than weight to describe locomotive energetic performance yields a more universal result, as can be illustrated by considering an extraterrestrial vehicle. Due to differences in g_o 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 g_o. On the other hand, Q_C increases due to both influences, and is more indicative of the change 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. Given that a gallon of gasoline contains about 133 MJ of thermal energy [7], one can readily determine Q_C for a given number of passengers in an automobile from the fuel economy rating. Cruise conditions are similar to those encountered on a long distance highway trip, so d/E_{th} is evaluated using the "highway" miles per gallon rating.

$$Q_C = M_P V_C (d / E_{th})_C \quad (12)$$

In city driving conditions, a vehicle stops frequently and travels at a much slower average speed, V_A. By using the "city" fuel economy rating $(d/E_{TH})_A$, we can calculate an average energetic performance, Q_A.

$$Q_A = M_P V_A (d / E_{th})_A \quad (13)$$

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, we define an effective energetic performance, Q_E , where V_E is determined by dividing the distance between airports by the average passenger temporal experience. This experience is quantified as the average time between entering the departure airport and leaving the arrival airport.

$$Q_E = M_P V_E (d / E_{th})_A \quad (14)$$

Table I gives efficiency, speed and energetic performance for various modes of human transportation [3,7-15]. Unless noted, all vehicles are assumed to be utilized by a single occupant. 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 [9]. Moped vehicles are assumed to be ridden without pedaling. Effective speeds were estimated from the author's personal experiences.

The most complex efficiency determinations were those of electric vehicles. The range of the prototype Neodymics Cyclemotor electric moped 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. 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% [10]. Thus, one may travel 17.7 km on an electric moped 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 [11]. 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.

Figure 1 includes values for efficiency and various forms of locomotive energetic performance and a variety of vehicle types.

Locomotive energetic performance was used to compare widely different modes of transportation. Streamlined human powered vehicles excel in locomotive energetic performance because of the relatively efficient human engine and the designer's careful attention to aerodynamics. The electric moped has the best locomotive energetic performance of all motor assisted personal vehicles considered. Commercial airliners also perform well because people are willing to crowd themselves into an aerodynamically optimized fuselage for fast, long distance travel. A one-way trip into the void of space can be both very fast and efficient. Treating the gravitational assist as free, Q_c for the Voyager 1 spacecraft is presently on the order of 10^8 seconds.

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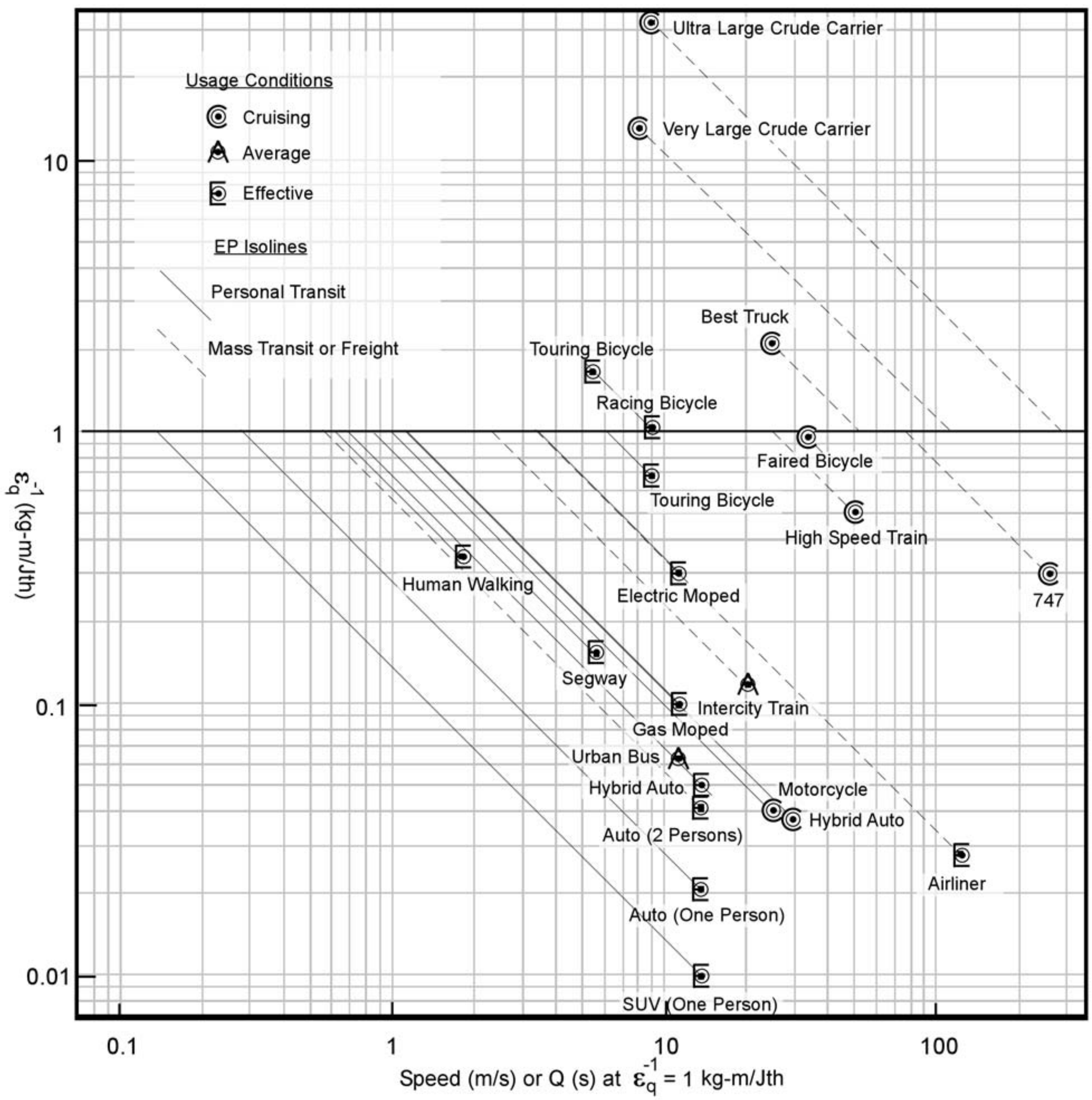
TABLE I. LOCOMOTIVE ENERGETIC PERFORMANCE OF VARIOUS TRANSPORTATION MODES.

Mode	Fuel Econ. (Mi/Gallon)	1/ef	Effectiveness (pass-km/MJth)	Speed (Mi/Hr)	Speed (m/s)	1/eq (kg-m/Jth)	Q (s)	Conditions	Source
Faired Bicycle			13.90	75	33.5	0.973	32.62	Qc	[12]
Racing Bicycle			14.90	20	8.9	1.043	9.32	Qe	[9]
Touring Bicycle			23.80	12	5.4	1.666	8.94	Qe	[9]
Touring Bicycle			9.90	20	8.9	0.693	6.20	Qe	[9]
Electric Moped, Unpedaled			4.33	25	11.2	0.303	3.39	Qe	[10]
Commercial Airplane (full)			0.40	270	120.7	0.028	3.38	Qe	[7]
Intercity Train (full)			1.70	45	20.1	0.119	2.39	Qa	[7]
Gas Moped, Unpedaled	117		1.42	25	11.2	0.099	1.11	Qe	[13]
Prius Hybrid Auto, Hwy	45		0.54	65	29.1	0.038	1.109	Qc	[14]
Urban Bus (full)			0.90	25	11.2	0.063	0.70	Qa	[7]
Prius Hybrid Auto, City	48		0.58	30	13.4	0.041	0.54	Qe	[14]
Human Walking			5.00	4	1.8	0.350	0.63	Qe	[7]
Segway I2 (TM)			2.20	12.5	5.6	0.154	0.856	Qe	[10,11]
Civic Auto, City	25		0.30	30	13.4	0.021	0.28	Qe	[14]
Escalade SUV, City	12		0.15	30	13.4	0.01	0.14	Qe	[14]
Ultra Large Crude Carrier		320		20	8.9	32.653	291.9	Qc	[3]
Very Large Crude Carrier		130		18	8.0	13.265	106.7	Qc	[3]
Best Truck		21		55	24.6	2.143	52.68	Qc	[3]
High Sp. Train		5		110	49.2	0.510	25.09	Qc	[3]
2 Pass. Civic Auto	25		0.61	30	13.4	0.042	0.57	Qe	[14]
1 Pass. Motorcycle		0.4		55	24.6	0.041	1.00	Qc	[3]
747-200-CCW		3		580	259.3	0.306	79.37	Qc	[3]
Voyager 1 Spacecraft					17000	6200	1E+08	Qc	[8,15,16]

Figure 1. Transportation matrix indicating thermal efficiency (ε_Q^{-1}) and locomotive energetic performance (Q) for various modes at typical 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 are strongly influenced by utilization, delays and terminal pedestrian flow. Steady state cruising conditions are denoted, along with average conditions which include velocity changes in crowded environments. The price for convenience of personal transit is evident when compared to mass transit.



Top: A GE Transportation plant in Fort Worth, Texas. Above: Over the last decade, GE Transportation has upgraded more than 2,000 locomotives for close to 40 customers around the world, and the company has strong orders for modernization from railroad operators like Norfolk Southern and Canadian Pacific. Images credit: Tomas Kellner for GE Reports. As we previously reported, GE Transportation has a long history of innovation, stretching from the first electric locomotives to the first freight locomotive that meets the U.S. governmentâ€™s strict Tier 4 emission standards. The company unveiled the