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# A Data Set for Exploring Allometric Relations of Mass, Speed, and Power in Terrestrial Locomotion

by Alexander Kott, Sean Gart, and Jason Pusey

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# **A Data Set for Exploring Allometric Relations of Mass, Speed, and Power in Terrestrial Locomotion**

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<b>14. ABSTRACT</b> This report offers a data set that we prepared to explore the allometric relations among mechanical power, speed, and mass of systems—animals and manmade systems—that move themselves via terrestrial locomotion. The data were extracted from widely available open sources. The types of systems include animals of widely different scales (such as cockroaches, crabs, quail, humans, dogs, and horses), and artificial, manmade systems such as all-terrain vehicles, trucks, tanks, and robots. The records in the data sets cover the systems’ mass, speed, and mechanical motive power. The report includes the data, notes on the sources of the data, and a brief example of possible uses of the data.					
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## 1. Introduction and Motivation

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Remarkable regularities are observed with respect to the relations among speed, mass, and energy expenditures of biological organisms. Most of these relations are allometric in nature (i.e., they describe how a function or attribute of organisms changes with their scale, for example, mass). Although the accuracy of the relations tends to be limited to the order of magnitude, they hold over very large ranges of values and over multiple orders of magnitude.

For example, one allometric law refers to the metabolic cost of transport (CoT<sub>m</sub>), which is the metabolic energy consumption that an organism requires to move a unit of mass of its body over a unit of distance. Equivalently, it is the amount of metabolic energy per unit time P<sub>m</sub> required of the organism to move with speed V per unit of its mass M: CoT<sub>m</sub> = P<sub>m</sub>/(M×V). For all biological organisms, CoT<sub>m</sub> diminishes approximately as mass to the power of  $-1/3$ :  $P/(M \times V) \sim M^{-1/3}$  (Heglund et al. 1982a; Full and Tu 1991; Alexander 2005; Bale et al. 2014). Metabolic energy is the energy that an organism obtains from its food, measured typically via the organism's consumption of oxygen (Kramer and Sylvester 2011).

Unlike metabolic energy, the mechanical energy of an organism P is the mechanical energy produced by the organism's muscles to deliver the forces by which it propels itself relative to the terrain and surrounding media, and moves its limbs with respect to the rest of its body. It has been observed that unlike the metabolic CoT<sub>m</sub>, the mechanical CoT—CoT = P/(M×V)—remains approximately constant, or at least within the same order of magnitude, over a very wide range of M (Alexander 1977, 2005; Heglund et al. 1982b; Blickhan and Full 1987; Full and Tu 1991; Biancardi et al. 2011; Lee and Biewener 2011).

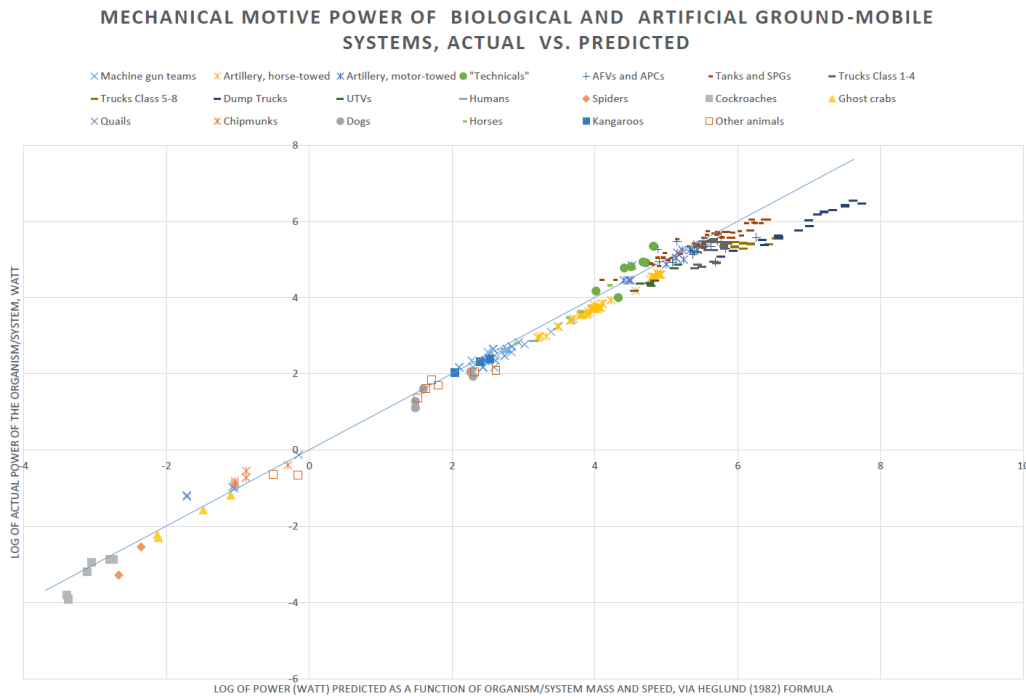
Elaborating on the latter observation, Heglund proposed a formula for estimating the mechanical power P expended by an organism of mass M in order to move itself at speed V (Heglund et al. 1982b):

$$P = M*(0.478 \times V^{1.53} + 0.685 \times V + 0.072) \quad (1)$$

Do similar regularities apply to artificial, manmade systems? If so, how do they differ from those that apply to biological systems?

Our motivation in asking these questions combines foundational and applied interests. In particular, with growing interest in bio-inspired approaches to robotics, we seek opportunities to learn about tradeoffs in the speed, mass, and power of biological systems, as they may apply to the design of robotic systems.

The data set we have assembled in this report is a step toward answering these questions. Based on the data set, our preliminary findings are that artificial ground-mobile systems of multiple types and of a great range of scale comply with the same power-mass-speed relation—the Heglund formula—that was proposed nearly 40 years ago for biological organisms (Fig. 1). To the best of our knowledge, this finding has never been reported before. We anticipate discussing this and other related findings in upcoming publications, as well.



**Fig. 1** The Heglund formula, originally developed for animals, also applies for a broad range of manmade vehicles

This report is organized as follows. Section 2 presents the data. Section 3 contains the notes on the sources of the data. Finally, Section 4 offers a few conclusions and describes potential future work.

To the best of our knowledge, the data set presented in this report is the first of its kind and is not directly available elsewhere.

## 2. Data

With respect to the power-speed-mass relations of biological organisms, data from experimental research studies generally refer to two types of energy expenditures: metabolic and mechanical (Kramer and Sylvester 2011).

Mechanical energy expenditures by an animal are derived using a number of approaches (Kramer and Sylvester 2011). Most of them assess the changes in the body's potential and kinetic energy. The movement of the body's center of mass can be determined either using a recording of the movement based on a marker placed near the center of mass or from the force that the body exerts against the ground (i.e., the ground reaction force). Examples include Heglund et al. (1982a, 1982b), Blickhan and Full (1987), Full and Tu (1991), and Biancardi et al. (2011).

In this report, we limit the scope to mechanical energy only. We obtained the data on the relation of mechanical energy expenditure among biological organisms via a rigorous review of experimental literature, which we believe to be exhaustive, to the best of our knowledge.

Data pertaining to artificial ground-mobile systems primarily represent diverse classes of defense-related systems along with civilian transportation, construction, mining, and outdoor recreational vehicles (see sources specified later in Sections 2 and 3). The approaches to obtaining or estimating the power, mass, and speed of such systems differed.

In the case of modern vehicles, for example, the mechanical horsepower of a system was taken as the maximum horsepower specified by the manufacturer or other authority for the engines or other movers of the system (e.g., for a heavy dump truck a database of specifications [Randall-Reilly 2020] provides the horsepower of the engine for each truck). The mass of the dump truck is the sum of the vehicle's empty weight plus the weight of its specified maximum load. Similarly, speed is the specified maximum speed. In many of the systems considered in this study, both offroad and on-road speed are specified. In such cases, we preferred to use the offroad speed because it is more relevant to our interests in defense-related systems (which typically operate in offroad environments) and perhaps more consistent with the locomotion of animals, who generally do not move on hard, smooth surfaces like a paved road.

The following systems are included in our data set:

- Machine-gun teams comprise machine guns and pertinent equipment, sometimes with wheeled or sled-like carriages, operated and carried by teams of human Soldiers, and sometimes pulled by teams of horses. The systems were designed and operated at various times between the years 1868 and 2015. Because machine-gun teams and horse-towed artillery (described later) are powered by biological movers (humans and horses), these data can be seen as a useful bridge as intermediate cases between strictly biological and strictly artificial systems.

- Utility task vehicles (UTVs) are small 2- to 6-person, four-wheel offroad vehicles used for recreation, farming, and other purposes.
- Horse-towed artillery are various artillery systems used between the 16th century and early 20th century; each system typically includes a cannon along with its carriage, limber, sometimes a caisson, a team of horses, and a team of soldiers.
- Motor-towed artillery are artillery systems appearing between the 1920s and early 2000s; each system typically includes a cannon along with its carriage, a truck, or a tractor that pulls the cannon and a team of soldiers.
- “Technicals” are systems that appeared between 1970s and 2000s, typically consisting of a civilian truck with heavy machine guns or automatic cannons installed in the bed of the truck.
- Trucks Class 1–4 in our data set are modern (2010 and beyond) commercial civilian trucks that belong to classes 1 through 4 of the US vehicle classification system. Examples include light pickup trucks, cargo vans, heavy-duty pickups, and city delivery trucks. No vehicles can exceed a gross weight (i.e., the weight of the loaded vehicle) of 16,000 lb.
- Trucks Class 5–8 in our data set are modern (2010 and beyond) commercial civilian trucks that belong to classes 5 through 8 of the US vehicle classification system. Examples include beverage trucks, furniture trucks, tractor-trailer combinations, cement trucks, and dump trucks. The vehicles of up to class 7 are limited to a gross weight of 33,000 lb. Class 8 includes vehicles with a gross weight over 33,000 lb.
- Armored fighting vehicles (AFVs) and armored personnel carriers (APCs) are military vehicles intended mainly for transportation of soldiers to and around the battlefield. Examples in our data set appeared in the 1920s through early 2000s, and typically include a machine gun or an automatic cannon, and armor that can defend against relatively light weapons.
- Tanks and self-propelled guns (SPGs) are military vehicles armed with heavy guns and often with heavy armor suitable for protecting against powerful weapons. Examples in our data set appeared between 1916 and 2015.
- Dump trucks in our data set are modern (post-2010) vehicles used in mining and constructions for carrying large loads of bulk materials. Their gross weight can be far in excess of any other types of vehicles.

Table 1 constitutes the data set.

**Table 1 All data**

System type	Description	Notes	System mass (kg)	System HP (hp)	Speed (kph)
Animals (continued)	American cockroach	RTL16	0.00081	0.000000163	1.62
	American cockroach	RTL16	0.00081	0.000000869	2.88
	American cockroach	RTL16	0.00081	0.00000152	3.24
	American cockroach	RTL16	0.00081	0.00000184	5.4
	Cockroach	RTL23	0.0026	0.000000209	0.36
	Cockroach	RTL23	0.0026	0.00000177	2.16
	Ghost crabs	RTL17	0.03	0.00000805	0.72
	Ghost crabs	RTL17	0.03	0.0000362	3.24
	Ghost crabs	RTL17	0.05	0.00000671	0.36
	Ghost crabs	RTL17	0.05	0.0000872	4.5
	Spider <i>Grammostola mollicoma</i>	RTL20	0.0185	0.000000705	0.201
	Spider <i>Grammostola mollicoma</i>	RTL20	0.0185	0.00000386	0.68
	Humans	RTL19	60	0.178	8
	Humans	RTL19	170	0.507	8
	Human	RTL22	70	0.994	32
	Human	RTL24	70	0.594	16.2
	Painted quail	RTL18	0.044	0.0000872	1.36
	Painted quail	RTL18	0.044	0.0000805	1.36
	Painted quail	RTL18	0.044	0.000155	5.47
	Painted quail	RTL18	0.044	0.000134	5.47
	King quail	RTL22	0.04	0.000141	5.65
	Bobwhite quail	RTL22	0.18	0.000997	9.46
	Chipmunk	RTL18	0.061	0.000202	4.24
	Chipmunk	RTL18	0.061	0.000175	4.24
	Chipmunk	RTL18	0.061	0.000379	5.76
	Chipmunk	RTL18	0.061	0.000252	5.76
	Eastern chipmunk	RTL22	0.1	0.00054	11.4
	Dog	RTL18	5	0.0252	13.3
	Dog	RTL18	5	0.0171	13.3
	Dog	RTL22	11	0.115	29.9
	Dog	RTL24	20	0.0536	5.4
	Dog	RTL24	20	0.15	18
	Kangaroo rat	RTL22	0.07	0.000307	10.4
	Ground squirrel	RTL22	0.19	0.000293	8.82
	Springhare	RTL22	2.5	0.0315	24
	Wild turkey	RTL22	7	0.0671	18
	Stump-tailed monkey	RTL22	3.6	0.0546	21.9
	Greater rhea	RTL22	22.5	0.151	18
	Red kangaroo	RTL22	20.5	0.338	28
	Red kangaroo	RTL24	18	0.284	24.8
Red kangaroo	RTL24	9	0.144	22.3	
Tammar wallaby	RTL24	4.5	0.0939	21.6	
Sheep	RTL22	73	0.166	12.4	
Horse	RTL24	280	0.856	7.2	
Horse	RTL24	280	3.98	25.2	

**Table 1 All data (continued)**

System type	Description	Notes	System mass (kg)	System HP (hp)	Speed (kph)
Animals (continued)	Horse	RTL25	515	0.967	7.2
	Horse	RTL25	515	5.8	21.6
	Horse	RTL25	515	28.2	43.2
Tanks (continued)	Mark IV	RTL04	32000	105	5
	Mark V Male, 1917	RTL26	29000	150	7.4
	Whippet, 1917	RTL26	12700	90	12.9
	FT tank	RTL04	6500	39	5
	FT-17	RTL26	6000	39	7.7
	A7V	RTL04	33000	200	7
	Vickers 6-ton tank	RTL04	7300	98	17
	T-26 tank	RTL04	9600	90	16
	Char B1 bis	RTL04	28000	272	21
	SOMUA S35	RTL04	19200	190	16
	Panzer 38(t)	RTL26	9900	150	15
	Mk III Valentine, 1939	RTL26	16960	131	12.9
	Panzer III Ausf F, 1940	RTL26	23000	300	20
	KV-1 tank	RTL04	45000	600	16
	T-34 of 1941	RTL04	29200	500	40
	Mk VI Crusader I, 1941	RTL26	19730	340	24
	Churchill Mk IV, 1941	RTL26	39000	350	13
	M4 Sherman	RTL04	30300	350	20
	Tiger I	RTL04	57000	700	20
	T-34/85	RTL04	32000	500	20
	Panzer IV	RTL04	25000	296	16
	IS-2 tank	RTL04	46000	600	20
	Sherman Firefly	RTL04	35300	425	20
	Panther	RTL04	44800	690	30
	Tiger II	RTL04	68500	700	15
	M26 Pershing	RTL04	41700	450	8
	Centurion tank	RTL04	52000	650	17
	T-54	RTL04	36000	500	35
	M48 Patton	RTL04	45000	650	21
	M60	RTL04	46000	750	16
	T-62	RTL26	40000	580	40
	T-64	RTL04	38000	700	30
	Chieftain tank	RTL04	56000	750	30
Strv 103B (aka S-tank)	RTL04	39700	490	30	
T-72 tank	RTL04	42500	780	45	
T-80	RTL04	46000	1250	48	
M1 Abrams	RTL04	54000	1500	40	
Challenger 1	RTL04	70000	1200	30	
M1A1 Abrams	RTL04	67600	1500	48	
Challenger 2	RTL04	75000	1200	40	
Challenger 2, 1998	RTL26	62500	1200	40	

**Table 1 All data (continued)**

System type	Description	Notes	System mass (kg)	System HP (hp)	Speed (kph)
Tanks (continued)	Leopard 2A6	RTL04	62300	1479	48
	Leopard 2A6, v2	RTL04	62300	1479	48
	Leopard 2A6, v3	RTL04	62300	1479	48
	M1A2 Abrams, 1996	RTL26	62000	1500	54.7
	T-14 Armata	RTL04	48000	1500	45
	T-14 Armata v2	RTL04	48000	1500	45
	T-14 Armata v3	RTL04	48000	1500	45
Self-propelled guns	Marder III	RTL04	10670	148	20
	Sturmgeschütz III	RTL04	23900	296	20
	Jagdpanzer IV	RTL04	25800	296	20
	M36 Tank Destroyer	RTL04	28600	450	25
	SU-85	RTL04	29600	493	20
	SU-100	RTL04	31600	500	20
	BMPT Terminator	RTL04	47000	780	45
	2S25 Sprut-SD	RTL04	18000	510	45
AFVs and APCs	Panhard 178, 1937 (wheeled)	RTL26	8300	180	42
	AAV-7, 1972 (tracked)	RTL26	22800	400	13.5
	Ratel, 1976 (wheeled)	RTL26	18500	282	30
	BVS 10, 2005 (tracked)	RTL26	10600	250	15
	BRM-1K (tracked)	RTL27	13300	300	40
	HJ-62C (tracked)	RTL27	13600	320	40
	Marder 1A3 (tracked)	RTL27	35000	500	65
	BMP-1P (tracked)	RTL27	13400	300	45
	BMP-2 (tracked)	RTL27	14300	400	50
	BMP-3M (tracked)	RTL27	18700	500	45
	Type 63 APC (tracked)	RTL27	12600	320	40
	BTR-60 (wheeled)	RTL27	10300	115	60
	BTR-80A (wheeled)	RTL27	14600	260	60
	BTR-82A (wheeled)	RTL27	16000	300	40
	M113A1 (tracked)	RTL27	11200	215	35
	MT-LB APC (tracked)	RTL27	11900	235	30
	S55 Mk1 car (wheeled)	RTL27	3600	114	48
1V13 (tracked)	RTL27	15700	240	26	
1V110 (wheeled)	RTL27	3600	115	35	
Towed artillery	Culverin Moyane 2-(pounder) pdr	RTL04	3402	4.6	5
	Falcon 1-pdr	RTL04	2451	3.3	5
	Falconet 3/4-pdr	RTL04	1701	2.3	5
	early-to-mid-1600s saker	RTL04	7140	9.2	5
	early-to-mid-1600s minion	RTL04	5180	7	5
	early-to-mid-1600s falcon	RTL04	3540	4.6	5
	Saker in Battle of Cheriton	RTL04	5700	7	5
Culverin 15-pdr	RTL04	7005	9.5	5	

**Table 1 All data (continued)**

System type	Description	Notes	System mass (kg)	System HP (hp)	Speed (kph)
Towed artillery (continued)	Demi-culverin 9-pdr	RTL04	5371	7.3	5
	Saker 5-pdr	RTL04	3670	5	5
	Minion 4-pdr	RTL04	2786	3.8	5
	Falcon 2-pdr	RTL04	951	1.3	5
	Falconet 1-pdr	RTL04	884	1.2	5
	Robinet 3/4-pdr	RTL04	884	1.2	5
	Saker	RTL04	4420	6	5
	Minion	RTL04	2786	3.8	5
	Falcon	RTL04	1701	2.3	5
	Falconet	RTL04	884	1.2	5
	Robinet	RTL04	884	1.2	5
	Regimental Gun of mid-1600s	RTL04	1150	1.3	5
	French Saker	RTL04	3670	5	5
	French Sixteenth	RTL04	2518	3.4	5
	French Thirty-second	RTL04	1701	2.3	5
	pre-Gribeauval, Austrian 12-pdr	RTL04	9350	11.5	5
	pre-Gribeauval, Austrian 12-pdr v2	RTL04	9350	11.5	5
	Prussian 6-pdr (HA)	RTL29	5237	20.1	15
	Canon de 8 Gribeauval	RTL04	4731	5.3	5
	Light 6-pdr	RTL04	3555	5	5
	Canon de 8 Gribeauval (HA)	RTL29	9911	46.9	15
	Canon de 12 Gribeauval	RTL04	6323	7.5	5
	Canon de 12 Gribeauval (HA)	RTL29	11503	53.6	15
	Canon de 4 Gribeauval	RTL04	3684	4.8	5
	Canon de 4 Gribeauval (HA)	RTL29	8864	46.9	15
	British 1790 12-pdr	RTL04	6714	7.3	5
	British 1790 12-pdr (HA)	RTL29	11894	53.6	15
	British 1805 9-pdr	RTL04	6200	7.2	5
	British 1805 9-pdr (HA)	RTL29	11380	53.6	15
	French AnXI 12-pdr	RTL04	6337	7.3	5
	French AnXI 12-pdr (HA)	RTL29	11510	53.6	15
	French AnXI 6-pdr	RTL04	4400	5	5
	French AnXI 6-pdr (HA)	RTL29	9580	46.9	15
	Griffen 3-inch Ordnance Rifle	RTL04	4236	4.8	5
	Griffen 3-inch Ordnance Rifle (HA)	RTL29	9416	46.9	15
	Napoleon 1857 gun	RTL04	5550	6.8	5
	Napoleon 1857 gun (HA)	RTL29	10730	53.6	15
	Prussian C/61	RTL04	5500	6.8	5
	Prussian C/61 (HA)	RTL29	10680	53.6	15

**Table 1 All data (continued)**

System type	Description	Notes	System mass (kg)	System HP (hp)	Speed (kph)
Towed artillery (continued)	RBL 12-pounder 8 cwt Armstrong gun	RTL04	3610	4.8	5
	RBL 12-pounder 8 cwt Armstrong gun (HA)	RTL29	8790	46.9	15
	Parrott 10-pdr rifle	RTL04	5400	8.8	5
	Parrott 10-pdr rifle (HA)	RTL29	10580	60.3	15
	German 96 m/A 77mm	RTL04	4920	6.6	5
	Canon de 75 modèle 1897	RTL04	5444	6.6	5
	British QF 13-pdr, horse artil.	RTL29	8428	40.2	15
	British QF 13-pdr, field artil.	RTL04	6000	6.6	5
	3.7 cm Pak 36 antitank gun	RTL04	3567	38	15
	47mm APX antitank gun	RTL04	4450	38	15
	5 cm Pak 38 (L/60) antitank gun	RTL04	4170	38	15
	6-pdr antitank towed gun	RTL04	4640	92	15
	7.5 cm Pak 40 antitank gun	RTL04	9625	100	20
	17-pdr antitank towed gun	RTL04	13120	147	20
	17-pdr antitank towed gun, v.2	RTL04	13120	147	20
	8.8 cm Pak 43	RTL04	16850	133	20
	2A17 D-30 in anti-tank role	RTL04	13700	200	20
	100mm antitank gun T-12	RTL04	15650	240	25
	2A36 "Giatzint-B" in anti-tank role	RTL04	26000	330	20
	2A65 Msta-B	RTL04	16100	240	20
2A45M Sprut-B smoothbore 125mm antitank towed gun	RTL04	19600	240	25	
Machine gun teams	Gatling gun 1870, 1.0 caliber	RTL04	5014	6.8	5
	Gatling gun 1870, 0.50 caliber	RTL04	2605	3.5	5
	Gatling gun 1870, 0.45 caliber	RTL04	1687	2.4	5
	Hotchkiss Mle 1897	RTL04	682.5	0.7	3
	pre-1900 Maxim 0.45 caliber on artillery-like carriage	RTL04	1338	1.7	5
	Skoda 1893	RTL04	682.5	0.7	3
	Hotchkiss 0.303 Mk I	RTL04	487.5	0.5	4
	Madsen 1904	RTL04	390	0.4	4
	Schwarzlose 1907	RTL04	682.5	0.7	3
	German Maxim MG08, crew 9	RTL04	849	0.9	3
	German Maxim MG08, crew 4	RTL04	394	0.4	3
	Hotchkiss Portative Mle1909	RTL04	292.5	0.3	4
	Russian PM1910	RTL04	749	0.8	4
	Vickers Mk1, crew 3	RTL04	293	0.3	3
	Vickers Mk1, crew 6	RTL04	586	0.6	3
	Lewis Mk1	RTL04	195	0.2	4
	German Maxim MG08/15, crew 4	RTL04	394	0.4	4
	Browning M1917 crew 6	RTL04	585	0.6	3
Vickers-Berthier	RTL04	292.5	0.3	3	

**Table 1 All data (continued)**

System type	Description	Notes	System mass (kg)	System HP (hp)	Speed (kph)
Machine gun teams (continued)	Browning Automatic Rifle M1918A2	RTL04	195	0.2	4
	Chatellerault Mle 24/29	RTL04	292.5	0.3	3
	Bren Mark 1	RTL04	292.5	0.3	4
	Fiat 12mm	RTL04	585	0.6	2
	Vickers 12.7mm	RTL04	585	0.6	2
	Hotchkiss 13.2mm or Breda 31	RTL04	585	0.6	2
	M2HB of 1930s	RTL04	585	0.6	2
	German MG34 w/tripod	RTL04	585	0.6	3
	German MG34 w/bipod	RTL04	292.5	0.3	3
	DShK38	RTL04	487.5	0.5	2
	German MG42 w/tripod	RTL04	585	0.6	3
	German MG42 w/bipod	RTL04	292.5	0.3	3
	Browning M1917 crew 3	RTL04	292.5	0.3	3
	Goryunov SG43	RTL04	487.5	0.5	3
	Degtiarev RPD M1927	RTL04	195	0.2	4
	FN MAG	RTL04	292.5	0.3	3
	MG3 - bipod	RTL04	195	0.2	4
	MG3 - tripod	RTL04	390	0.2	3
	US M60	RTL04	292.5	0.3	3
	HK21	RTL04	195	0.2	3
	Soviet PK	RTL04	195	0.2	4
	M2HB of 1970s	RTL04	292.5	0.3	2
	Soviet NSV-12.7	RTL04	195	0.2	2
	STK 50MG	RTL04	195	0.2	2
Kord	RTL04	195	0.2	2	
PKP Pecheneg	RTL04	195	0.2	4	
Technicals	Ford T w/Lewis MG	RTL04	996	20	20
	Tachanka w/PM1910	RTL29	2975	13.4	15
	Chevrolet C-20 w/ZPU-4	RTL28	4536	115	20
	Land Rover w/DShK	RTL28	3095	86	20
	Land Cruiser BJ45 w/ZPU-2	RTL04	2480	80	20
	Unimog 404 w/ZPU-4	RTL04	5000	110	20
	Unimog 404 w/ZU-23-2	RTL04	5000	110	20
	Ford F-350 Super Duty w/ZPU-4	RTL28	6342	300	20
Dump trucks	BELAZ 75710	RTL32	810000	4600	64
	Caterpillar 797F	RTL33	980000	4000	68
	Liebherr T 282	RTL33	620000	3650	64
	John Deere 260E ADT	RTL34	46700	321	64
	John Deere 460E ADT	RTL34	74040	481	64
	Mack M917A3	RTL35	42800	440	64
	Komatsu 980E-5	RTL33	626000	3346	64
	Caterpillar 789D	RTL33	304000	2000	57
Caterpillar 777G	RTL33	185000	1025	67	

**Table 1 All data (continued)**

System type	Description	Notes	System mass (kg)	System HP (hp)	Speed (kph)
Dump trucks (continued)	Rhino RT50	RTL33	81000	525	60
	Bell B60E	RTL33	97000	577	51.5
	Bell B20E LGP	RTL33	26400	228	46.7
	Bergmann ADT-150	RTL33	22000	162	40
	Caterpillar 775G	RTL33	128000	768	68
	Caterpillar 785D	RTL33	241000	1450	55
	Hitachi EH4000AC-3	RTL33	383000	2370	56
	Hitachi EH5000AC-3	RTL33	500000	2640	56
Class 1–4 trucks	Ford T	RTL04	996.6	20	50
	Land Rover	RTL28	3095	86	104
	Land Cruiser BJ45	RTL04	2480	80	104
	Unimog 404	RTL04	5000	110	104
	Ford F-350 Super Duty	RTL28	6342	300	104
	US Class 1 truck, light duty	RTL37	2722	100	104
	US Class 1 truck, heavy duty	RTL37	2722	210	104
	Chevrolet Colorado ZR2	RTL36	2763	308	104
	Ford F-150 Platinum	RTL36	3171	395	104
	US Class 2a truck, light duty	RTL37	3856	236	104
	US Class 2a truck, heavy duty	RTL37	3856	381	104
	US Class 2b truck, light duty	RTL37	4536	235	104
	Chevrolet C-20	RTL28	4536	115	104
	GMC Sierra 2500HD Denali	RTL36	4530	445	104
	US Class 2b truck, heavy duty	RTL37	4536	390	104
	Ram 3500 Limited	RTL36	5571	385	104
	US Class 3 truck, light duty	RTL37	6350	255	104
	US Class 3 truck, heavy duty	RTL37	6350	362	104
	US Class 4 truck, light duty	RTL37	7257	350	104
	US Class 4 truck, heavy duty	RTL37	7257	383	104
Class 5–8 trucks	US Class 5 truck, light duty	RTL37	8845	288	104
	US Class 5 truck, heavy duty	RTL37	8845	385	104
	US Class 6 truck, light duty	RTL37	11793	260	104
	US Class 6 truck, heavy duty	RTL37	11793	362	104
	US Class 7 truck, light duty	RTL37	14969	330	104
	US Class 7 truck, heavy duty	RTL37	14969	350	104
	US Class 8 truck, light duty	RTL37	27000	330	104
	US Class 8 truck, heavy duty	RTL37	34000	475	104
	Cascadia tractor-trailer w/DD15 engine	RTL38	36000	500	104
UTV	Cub Cadet Challenger 550	RTL31	1169	27	65.6
	Honda Pioneer 500	RTL31	870	31	62.4
	Can-Am Defender HD5	RTL31	1135	38	72
	Polaris Ranger 500	RTL31	940	32	73.6
	Textron OffRoad	RTL31	1310	80	102
	Polaris General 100 EPS	RTL31	1220	100	116

**Table 1 All data (continued)**

System type	Description	Notes	System mass (kg)	System HP (hp)	Speed (kph)
UGV systems, fielded and/or commercially available	Boston Dynamics RHex	RTL39	12.5	0.0643	9.72
	Uran-9	RTL40	10000	300	34.92
	Recon Throwbot 2	RTL41	2.4	0.00442	2.16
	iRobot 710 Warrior	RTL42	316	0.455	15.12
	Taifun-M	RTL43	10886	300	100.8
	Clearpath Warthog	RTL44	862	2.14	18
	Clearpath Husky	RTL45	125	0.536	3.6
	Clearpath Jackal	RTL46	37	0.0911	7.2
	Agility Robotics Digit	RTL47	45	0.67	5.4
	Agility Robotics Cassie	RTL47	32	0.201	5.4
	Spot Mini	RTL48	80	0.201	5.76
	Talon	RTL49	170	0.297	9.656064
UGV systems, experimental	NASA Valkyrie	RTL50	129	1.61	0.9
	Legged micro robot (UMd)	RTL51	0.0001	1.62E-08	0.1332
	Boston Dynamics Atlas	RTL52	155	4.96	1.8
	HAMR (Harvard)	RTL53	0.00143	0.0000522	1.368
	John Deere Walking Tractor	RTL54	2700	67.1	13

### 3. Notes on the Sources of the Data

The numbering of following notes corresponds to the column “Notes” in Table 1. The numbers are not necessarily contiguous—there are gaps in the numbers.

RTL4.

Data are from Kott (2020).

RTL16.

Data adapted from Full and Tu (1991), Fig. 5.

RTL17.

Data adapted from Blickhan and Full (1987), Fig. 7.

RTL18.

Data adapted from Heglund et al. (1982a), Table I.

RTL19.

Data adapted from Taboga et al. (2012), Fig. 2. The paper mentions speeds of 7–9 kph; we assume 8 kph.

RTL20.

Data adapted from Biancardi et al. (2011), Table 1.

- Mass = 18.5 g; speed = 5.6 cm/s; total mechanical work (internal plus external;  $J/(kg \cdot m)$ ) = 0.507; from this, we calculate  $Power[W] = 0.507 \cdot 0.0185[kg] \cdot 0.056[m/s]$ .
- Speed = 18.9 cm/s; mechanical work = 0.823; power calculated as above.

RTL22.

Data for mass and  $J/(m \cdot kg)$  were taken from Nudds et al. (2009), Table 1, who in turn obtained them from Heglund et al. (1982a) with corrections. Data for speed were taken directly from Heglund et al. (1982a), Table I, max speed.

RTL23.

Data adapted from Full and Tu (1990), Fig. 8. Mass: 2.6 g.

RTL24.

Data from Biewener (1998), Table 3.

RTL25.

Data adapted from Minetti et al. (1999), Fig. 4. Mass of the horses was stated as 515 kg on average.

RTL26.

Data from McNab (2019).

RTL27.

Data from Training and Doctrine Command's (TRADOC's) *Worldwide Equipment Guide*, Vol. 1 (2016).

RTL28.

Data obtained largely from Kott (2020), but the mass of the system was corrected by changing it to the highest specified gross vehicle weight rating (GVWR).

RTL29.

Data taken from Kott (2020), except that the horsepower of all horse artillery data points were adjusted by using the horsepower of trotting horses from Minetti et al. (1999). The Kott 2020 data assume that the speed of horse artillery was 15 kph or 4.16 m/s. Per Minetti et al. (1999), Fig. 4, this corresponds to 1.2  $[J/(kg \cdot m)]$  or

1.2 [W/(kg\*m/s)]. For a 500-kg horse (which Kott [2020] assumes), the power in watts is  $1.2*500*4.16 = 2496$  [W] = 3.35 [hp].

RTL31.

UTV speed data were actual tests reported in *Outdoor Life* (Hansen 2019). Mass and horsepower were taken from ATV.com (2020).

RTL32.

Data were taken from BelAZ manufacturer's specifications datasheet for the BelAZ-75710 (BelAZ Australia 2020).

RTL33.

From Equipment World's Spec Guide, an online database (Randall-Reilly 2020).

RTL34.

From the John Deere website (2020).

RTL35.

From the Mack Defense website (2020).

RTL36.

From *Truck Trend's* "2018 Pickup Truck of the Year Specs: Specifications as Tested" (2017).

RTL37.

The US truck classification and corresponding GVWR were taken from the National Research Council (2000).

Examples of trucks in each class were taken from Wikipedia (2020).

In each class, we provided net horsepower of the engines specified by the manufacturer of the examples; the lowest value of horsepower we designated as "light duty" and the highest value as "heavy duty".

RTL38.

From Freightliner's website (Daimler 2020).

RTL39.

Data from *IEEE Spectrum* (2020); power estimated from the RHex robot's two 144-Wh batteries and 6-h estimated run time.

RTL40.

Data from European Security & Defense (2019); the power reported in that source is vehicle horsepower.

RTL41.

Power estimated from a 110-min battery life (battery 11.1 V, 550 mAh); speed and payload also reported in the user's manual (ReconRobotics 2018).

RTL42.

Data from the user's manual (ArchiExpo 2020). This source reported an 8-h average battery life using twelve 225-Wh batteries. Power was estimated from these data.

RTL43.

Data from Military-Today.com (2020). Power reported in this source is engine horsepower.

RTL44.

Data from Clearpath Robots Inc. (2016). Power estimated from one 200-Ah battery at 48 V and a 6-h estimated run time.

RTL45.

Data from Clearpath Robots Inc. (2013). Power reported is average power. This system is an overpowered research platform with speed limited by constraints other than power.

RTL46.

Data from a Clearpath Robots Inc. brochure (n.d.). Power reported is based on a 270-Wh battery and estimated 4-h run time.

RTL47.

Data acquired through personal communication with Steve DiAntonio of Agility Robotics (2020).

RTL48.

Data from Boston Dynamics (2020).

RTL49.

Data from the Army Technology website (2020). Power estimated from two 300-Wh batteries and a 3-h estimated run time.

RTL50.

Data from personal communication with Joshua Mehling of the NASA Johnson Space Center (2020) and also from Radford et al. (2015).

RTL51.

Data from St Pierre et al. (2018).

RTL52.

Data acquired during the 2014 Defense Advanced Research Projects Agency Robotics Challenge as reported in Faraji et al. (2014).

RTL53.

Data from Goldberg et al. (2017).

RTL54.

The John Deere Walking Tractor is an experimental vehicle (Futuristic News 2020). The vehicle was originally designed and developed by Ohio State University researchers Waldron and McGee (1986).

#### **4. Conclusions and Future Work**

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To our knowledge, the data set presented in this report is the first of its kind and is not directly available elsewhere.

Much future work can be recommended with respect to this data set. Additional classes of manmade systems should be added. Greater completeness of coverage should be pursued, even for those classes that are already considered in the data set. Additional sources should be sought to improve the accuracy and credibility of the data. Researchers who use this data set should proceed with caution; recognize that individual data points could be inaccurate and cross-validate the results.

Nevertheless, although limited and imperfect in many respects, this data set can be useful in studies of allometric relations among power, mass, and speed of terrestrial mobile systems, across a remarkably broad range of systems.

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## List of Symbols, Abbreviations, and Acronyms

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AFV	armored fighting vehicle
APC	armored personnel carrier
CoT	cost of transport
CoT <sub>m</sub>	metabolic cost of transport
pdr	pounder
SPG	self-propelled guns
UTV	utility task vehicle

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