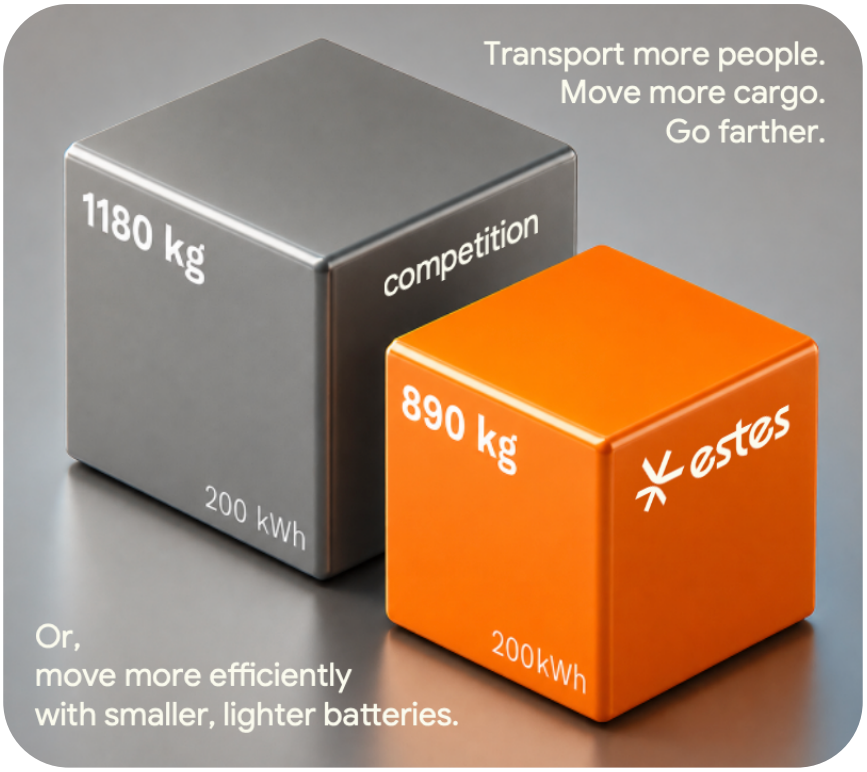
The Economic Value of Lightweighting
Across Electrified Mobility

Commercial · Rail · Marine · Aerospace · Defense · Passenger

EXECUTIVE SUMMARY

Vehicle lightweighting is one of the most consistently validated methods for improving transportation economics. Research from the U.S. National Academies, the Department of Energy, and the National Renewable Energy Lab demonstrates that mass reduction generates lifetime economic benefits that substantially exceed implementation cost across virtually every mobility segment [1][2][3].

The established industry valuation of $10–30/kg represents conservative trucking-centric analysis. Across higher-value segments like rail, marine, aerospace, and defense, the economic return per kilogram removed is considerably higher, driven by energy cost, payload premiums, certification complexity, and mission-critical performance requirements.



Estes' Magnus™ platform delivers 225+ Wh/kg and 375 Wh/L at the system level. This yields a ~30% weight and space advantage over current state-of-the-art with cell equivalence, which yields mass reduction of hundreds to thousands of kilograms per vehicle, depending on application.

BATTERY WEIGHT: A CENTRAL CONSTRAINT OF ELECTRIFICATION

Conventional battery pack architecture has reached a practical ceiling. While cell chemistry has improved substantially, the non-cell mass of structural, thermal management, power transmission, and safety components has held pack-level energy density from making the advancements that tomorrow's applications demand.

Today, batteries are often the single heaviest component on any electrified platform.

Battery weight directly governs:	Each kilogram removed from the battery creates:
· Payload capacity and revenue potential	· Direct mass reduction in the system
· Energy consumption and range	· Secondary 'decompounding' mass savings in chassis
· Suspension, braking, and chassis loading	· Reduced energy consumption per trip
· Total cost of ownership across asset life	· Potentially smaller battery for same range target
· Regulatory compliance with axle weight limits	· Compounding economic return across vehicle life

THE MAGNUS™ ADVANTAGE ACROSS SEGMENTS

The table below illustrates Magnus™ mass savings relative to a **170 Wh/kg commercial baseline** across representative applications in each mobility segment. Savings scale directly with pack size, making the Magnus™ advantage most decisive in the highest-energy applications where weight is a critical constraint.

Segment	Pack (kWh)	Competitor (kg)	Magnus™ (kg)	Mass Saved
Heavy Commercial	500	2,940 kg	2,220 kg	720 kg
Class 8 Truck	850	5,000 kg	3,780 kg	1,220 kg
Passenger Automotive	80	470 kg	355 kg	115 kg
Light Passenger Rail	3,500	20,600 kg	15,600 kg	5,000 kg
Marine	200	1,180 kg	890 kg	290 kg
Aerospace	300	1,765 kg	1,333 kg	432 kg
Defense / Autonomous	100	590 kg	440 kg	150 kg

Note: Competitor baseline of ~170 Wh/kg reflects published commercial pack-level energy densities across the high-performance competitive landscape (Cummins, BorgWarner, Harbinger, American Battery Solutions, etc.), all of which employ NMC battery cells with similar energy density equivalence. Battery packs below 200Wh/kg are generally not useful for propulsion in aerospace applications, comparison to 170Wh/kg shown here for consistency.

SEGMENT ANALYSIS: WHERE LIGHTWEIGHTING CREATES VALUE

Commercial & Heavy-Duty Trucking

Federal gross vehicle weight regulations make every kilogram of battery mass directly contiguous with payload capacity. On Interstate highways, the federal maximum gross vehicle weight for battery electric trucks is 82,000 lbs (37,195 kg), a hard ceiling that applies regardless of trailer size or cargo type. For a Class 8 long-haul operator running dense freight (e.g. bulk commodities, steel, food products, fluids), a truck routinely hits that ceiling before

the trailer is full. In these weight-limited applications, every kilogram of battery mass reduction translates directly into a kilogram of additional revenue freight [4][5].

Tesla has publicly disclosed structural battery integration as a mechanism for reducing Semi mass, eliminating redundant support structures and directly converting mass savings into payload capacity and range; independent engineering analysis of the approach has been widely reported in industry trade press [6].

The Magnus™ platform delivers a 1,220 kg battery mass advantage over baseline at 850 kWh. For a weight-limited operator, that recovery represents roughly 6% of usable payload capacity on a standard five-axle configuration. At current long-haul dry van rates of approximately $2.25–$2.44 per mile, a typical 500-mile run generates $1,125–$1,220 per load. Six percent of that load revenue, attributable directly to the recovered payload, is $67–$73 per run. Across 250 operating days at one load per day, that compounds to approximately $17,000–$18,000 in annual incremental freight revenue per truck, without changing routes, drivers, or operating patterns [7].

Over a conservative 10-year vehicle life, the cumulative payload earning power of the Magnus™ mass advantage reaches up to $180,000 per truck for weight-limited operators, a figure that is both meaningful at the fleet level and grounded in published freight rate data.

Marine

Vessel displacement is the governing parameter in commercial and military marine design. Every kilogram of battery mass removed improves stability, reduces freeboard requirements, and enables either additional cargo tonnage or a smaller, lighter hull. For commercial ferries and workboats, hull weight savings translate to fuel savings, reduced port fees (often assessed on displacement), and extended maintenance intervals. For defense vessels, displacement reduction has direct implications for speed, stealth, and survivability. Marine lightweighting values of $20–50/kg reflect published shipbuilding and naval program data.

Electric hydrofoil vessels represent the most mass-sensitive application in the marine segment, and arguably across all surface-bound mobility categories. The physics of hydrofoiling create a compounding mass penalty categorically different from displacement vessel economics: a heavier battery simultaneously raises the speed required to achieve foiling, increases the power required to reach that threshold, and reduces the energy available for sustained foiling-mode operation. Below the foiling threshold, the vessel operates in displacement mode, where energy consumption is 5–8x higher per nautical mile. Battery mass is not merely dead weight in this context; it is the variable that determines whether the vessel can foil at all.

Candela's P-12, the world's first electric hydrofoil ferry in scheduled commuter service, has been operating across Stockholm, Gothenburg, Oslo, and Trondheim since 2024 and was recognized by TIME as one of 2025's most important inventions [8]. Its computer-controlled submerged hydrofoils lift the vessel above the water at speeds exceeding 20 knots, cutting energy consumption by approximately 80% compared to conventional vessels [8]. In February 2026, a P-12 completed the longest journey ever recorded by an electric passenger ship, 160 nautical miles from Gothenburg to Oslo, demonstrating that hydrofoil range and reliability now extend well past demonstration-scale routes [9]. But that efficiency is only accessible if the vessel achieves lift. Every kilogram removed from the battery pack lowers the foiling threshold speed, reduces the power draw during the energy-intensive takeoff phase, and extends foiling-mode range across every route cycle. Magnus™ packs at 225+ Wh/kg versus a 170 Wh/kg baseline reduce battery system mass by 24%, directly lowering the foiling threshold and improving the energy economics of every departure.

Larger-scale hydrofoil ferries are following the same trajectory. Artemis Technologies' 150-passenger EF-24 vessels were delivered to Belfast for outfitting in January 2026, with commercial service across UK routes anticipated later in 2026 pending sea trials [10]. As hydrofoil vessels scale toward this passenger capacity, the battery-mass sensitivity described above becomes even more consequential to route economics.

Note: Estes packs are not installed in the Candela or Artemis vessels referenced here; these are cited as industry analogues illustrating hydrofoil mass sensitivity, not as existing Magnus™ deployments.

Passenger Automotive

The passenger car lightweighting calculus is distinct from commercial applications, and it is better understood through the lens of battery cost reduction and range optimization than through simple payload economics. NREL's FASTSim analysis found that although lightweighting impacts BEV energy efficiency less than it impacts conventional vehicles, it reduces battery component cost and overall vehicle cost more [11]. The primary mechanism is not energy savings per mile, it is the ability to achieve the same range from a smaller, cheaper battery pack.

A representative 80 kWh midsize passenger EV pack at the 170 Wh/kg commercial baseline weighs approximately 470 kg. The same energy stored in a Magnus™ pack at 225 Wh/kg weighs approximately 355 kg, a reduction of 115 kg. Research published in Machines quantifies the Energy Reduction Value (ERV) for battery-electric passenger vehicles at 0.47–1.17 kWh per 100 km per 100 kg of mass reduction [12]. This range extension benefit is real, but the more compelling value for OEMs is battery resizing holding range constant and reducing pack size to lower bill-of-materials cost, which at $80–110/kWh current cell pricing can yield savings in the low thousands of dollars per vehicle at scale.

Tesla has demonstrated this logic deliberately across multiple platforms. When redesigning the Model S Plaid, Tesla reduced the battery module count from 16 to 5, producing a lighter, more energy-dense pack that contributed to both improved efficiency and a 10-14% range increase [13]. In both cases (passenger cars and Semi), Tesla's motivation was explicit: a lighter battery system enables a better vehicle without adding cells [6][13].

Lightweighting Benefits for Passenger Cars

Consumer Value: range extension	Platform Value: vehicle dynamics
At an ERV of 0.7 kWh/(100 km · 100 kg), a 115 kg reduction extends real-world range by approximately 6–9 km on a 400 km platform. For consumers where range anxiety influences purchase decisions, this is a relevant differentiator.	Beyond energy metrics, a lighter vehicle delivers measurably improved acceleration, braking, and handling. Tesla's own Plaid weight reduction was cited by Edmunds as a direct contributor to the car's efficiency leadership [14].
OEM Value: battery downsizing	**System Value: mass decompounding**
At constant range, a 115 kg mass reduction enables a smaller pack (e.g. fewer cells). At $80–110/kWh, a 10–15 kWh reduction in required pack size represents $800–$1,650 in per-vehicle BOM savings, compounding across millions of units on high-volume platforms.	Secondary weight reduction is especially pronounced in BEVs due to the high initial battery mass. A lighter primary pack enables lighter chassis, suspension, and brake components. NREL analysis confirms this multiplier effect is larger for electric vehicles than conventional ones [11].

Light Passenger Rail

Rail electrification presents a unique lightweighting opportunity: axle load limits govern maximum train length and speed on most North American rail infrastructure. A lighter battery-electric locomotive directly enables longer routes, higher throughput, and reduced track wear.

Peer-reviewed rail engineering analysis of axle lightweighting confirms reduced track access charges and infrastructure wear as direct benefits of unsprung and vehicle mass reduction [15]; published rail industry analyses value mass reduction at $10–30/kg for traction applications, reflecting both the energy savings over long operating cycles and the infrastructure savings from reduced axle loading. At 5,000 kg saved for a 3,500 kWh pack, Magnus™ delivers $50,000–$150,000 in segment-specific economic value per train over its lifetime.

Aerospace

Aerospace represents the highest-value lightweighting environment. Commercial aviation has historically valued structural mass reduction at $200–1,000/kg over aircraft lifecycle, driven by fuel burn reduction on routes measured in thousands of nautical miles; academic cost/weight optimization studies of aircraft structures support valuations in this range once lifecycle fuel and operating costs are capitalized [16].

Electric vertical take-off and landing (eVTOL) and other advanced airborne mobility platforms face an even more acute constraint than mass alone: rotor lift capacity scales unfavorably with gross weight, making energy density, not simply mass reduction, both a performance and a certification imperative. The 170 Wh/kg baseline used elsewhere in this paper for cross-segment consistency is, in practice, below what aerial propulsion requires to be viable at all: published eVTOL programs report pack-level energy densities in the 225–300 Wh/kg range as the entry point for a certifiable, revenue-capable aircraft, well above the density of a typical ground-vehicle commercial pack [17].

The chemistries capable of reaching aerial-grade energy density today, high-silicon-content anodes, near-solid-state designs, typically get there at the cost of cycle life. Current aviation-grade lithium-ion packs are commonly rated for less than 1,000 charge cycles before reaching the 80% state-of-health threshold at which aviation convention requires pack replacement, translating to a pack lifespan of roughly one to two years at the 10–15 flights per day a commercial air-taxi operation would need to fly to be economical. Every pack swap at that density class is a significant maintenance event levied against a business model that depends on high utilization.

Magnus™ is built around the opposite trade: heavy duty-cycle capable cells at aerial-relevant energy density. This is the same strategic bet Joby Aviation has already validated in its own FAA certification program, by qualifying automotive-supply-chain cells rather than exotic chemistries, Joby has publicly reported 235 Wh/kg at the module level (288 Wh/kg at the cell level) alongside more than 10,000 charge cycles demonstrated in lab testing, an order of magnitude beyond the ceiling of the silicon-rich and solid-state chemistries some competing programs are counting on [18]. Magnus™ targets this same category of outcome, at the full system level (pack): energy density competitive with exotic chemistries, without inheriting their cycle-life penalty.

A 432 kg reduction (equivalent to ~6 passengers) on a 300 kWh eVTOL pack, as illustrated here on the 170 Wh/kg baseline used consistently across this paper for cross-segment comparability, represents transformative value at aerospace valuation rates once translated to an aerial-appropriate density class [16]. The commercial argument is not that Magnus™ makes a non-viable 170 Wh/kg pack fly; it is that Magnus™ reaches the energy density aerial propulsion requires while retaining the duty-cycle durability that exotic chemistries have not yet solved for.

Defense & Autonomous Systems

Defense procurement places a premium on mission energy density for tactical, logistical, and autonomous applications. The reason runs deeper than any single vehicle's specifications: in a contested environment, moving energy itself is one of the most expensive and dangerous logistics tasks the U.S. military performs. The Pentagon's own “fully burdened cost of fuel” (FBCF) accounting, mandated by Congress for major weapons-system acquisition decisions, captures not the price of fuel alone but the total cost of procuring, transporting, and protecting it all the way to the point of use [19]. That burden scales sharply with how the fuel is delivered: the Army has estimated that fuel costing a few dollars a gallon at the depot can cost as much as $400 per gallon by the time it reaches a forward position by helicopter, often the only viable means of resupply in austere terrain, with Defense Science Board estimates for contested theaters running as high as $1,000 per gallon [20]. Every gallon that does not have to be moved into theater is one that does not have to be trucked through contested terrain, escorted, or flown in at a multiple of its base cost: in June 2008 alone, DOD reported 44 trucks and 220,000 gallons of fuel lost to attacks or other incidents while resupplying a single airfield in Afghanistan [19].

Battery mass follows the same logic even though it is not a consumable: the mass of the energy-storage system that must be transported, positioned, and protected in theater is functionally equivalent to the mass of fuel that would otherwise need to be delivered to power the same mission. A higher-energy-density pack does not just make a single vehicle lighter, it reduces the total mass of stored energy that must move through the logistics chain

to deliver a given mission capability, most acutely when that energy must go by air. For unmanned ground vehicles, lighter batteries extend operational range and enable air-transportability thresholds that heavier systems cannot meet. For autonomous drones and loitering munitions, battery mass directly governs endurance; government research programs targeting energy-consumption reduction in unmanned aerial systems, such as DARPA's Albatross program, reflect this same operational premium the defense sector places on weight and energy efficiency in unmanned platforms [21].

DOD cost-per-kilogram analyses for airborne systems range from $100 to over $1,000/kg saved, with ground systems typically valued at $100–300/kg. These figures are Estes' estimate, derived from aerospace-sector cost-per-kilogram analogues rather than a published DOD unit-cost schedule for batteries specifically. The fully burdened cost of fuel data above independently supports the underlying premise that any mass moved into a contested or airborne logistics chain carries a cost far above its intrinsic value. This range should be presented as an Estes estimate in any external-facing use.

ILLUSTRATIVE ECONOMIC VALUE BY SEGMENT

The following analysis quantifies lifetime economic value creation from Magnus™ mass savings across commercial segments. These figures apply conservative DOE and National Academies benchmarks of $10–30/kg for surface transportation segments [1][2][3]. Aerospace and defense premiums represent significant additional upside and are estimates as noted in the segment analysis above [16][19][20].

Segment	Magnus™ Mass Savings Per Vehicle	Mass Savings Economics	Magnus™ Economic Value Per Vehicle
Heavy Commercial	720 kg	$10-$30 / kg	**$7,200-$21,600**
Class 8 Truck	1,220 kg	$10-$30 / kg	**$12,200-$36,600**
Passenger Automotive	115 kg	$10-$30 / kg	**$1,150-$3,450**
Light Passenger Rail	5,000 kg	$10-$30 / kg	**$50,000-$150,000**
Marine	290 kg	$20-$50 / kg	**$5,800-$14,500**
Aerospace	432 kg	$200-1000 / kg	**$86,400-$432,000**
Defense / Autonomous	150 kg	$100-$1000 / kg	**$15,000-$150,000**

Note: Values above are per-vehicle over lifetime. Aerospace and defense ranges are estimates derived from analogue sectors, not published per-unit figures [16][19][20].

MASS DECOMPOUNDING: BATTERY LIGHTWEIGHTING MULTIPLIES

Traditional vehicle lightweighting is evaluated on a one-to-one basis. Battery lightweighting in electrified platforms triggers a compounding effect that multiplies the value of the initial mass savings. Mass savings in a battery system do not travel alone: a lighter battery enables a lighter vehicle, and structural reinforcement, chassis, suspension, and braking components can all be scaled down in turn once the dominant mass load is reduced.

This multiplier is more pronounced in electric vehicles than in conventional platforms precisely because battery mass represents such a disproportionately large share of total vehicle weight, larger than any single component in a conventional vehicle. A reduction to the battery therefore cascades further through the structural, suspension, and braking systems than an equivalent reduction to any one part of a conventional-vehicle architecture would, which is why NREL's analysis finds this multiplier consistently larger for EVs than for internal-combustion platforms [11].

- **First-order savings:** A lighter battery directly reduces system mass by the delta: hundreds to thousands of kilograms depending on pack size.
- **Second-order savings:** Lighter vehicles require less structural reinforcement. Chassis, suspension, brakes, and wheels can be downsized or respecified, adding further mass reduction.
- **Third-order savings:** A lighter vehicle consumes less energy per kilometer. This can enable the same range from a smaller battery, further reducing mass in a positive feedback loop.
- **System-level implication:** OEM programs that fully optimize around a higher-energy-density battery can realize total vehicle mass reductions that exceed the direct battery weight savings by **1.5–2x** [11].

STRATEGIC IMPLICATIONS FOR OEMS & FLEET OPERATORS

Battery lightweighting has moved from a technical differentiator to a vehicle-level commercial strategy. The implications are direct and quantifiable:

Payload	Every kilogram removed from a GVWR-constrained vehicle is a kilogram added to revenue-generating payload. For commercial operators, this is the most direct P&L lever available.
Range	Lighter vehicles consume less energy per kilometer. At equal battery capacity, Magnus™ packs extend range. At equal range targets, Magnus™ enables smaller, lighter, lower-cost battery systems.
TCO	Energy savings, reduced maintenance load on tires, brakes, and suspension, and longer vehicle life compound into total cost of ownership advantages that dwarf the initial purchase premium of higher-performance battery systems.
Compliance	Axle weight regulations, airworthiness limits, and vessel stability requirements cannot be negotiated. Battery lightweighting is often the only path to compliance without compromising energy capacity or mission performance.

CONCLUSION

Research from the National Academies, DOE, NREL, and commercial sector sources consistently demonstrates that vehicle lightweighting creates measurable, durable economic value across every segment that moves weight [1][2][3]. The $10–30/kg surface transportation benchmark is well-established and conservative. In aerospace, defense, and marine applications, the value per kilogram is multiples higher.

With 225+ Wh/kg pack-level energy density versus a 170 Wh/kg commercial baseline, Magnus™ delivers a ~30% energy density improvement across applications, translating directly to payload, efficiency, compliance, and total cost of ownership advantages. Mass decompounding amplifies these gains at the vehicle level. As electrification extends into heavier, higher-value mobility segments, battery lightweighting is no longer a component-level specification choice. It is a vehicle-level competitive advantage and a mission-critical system requirement.

Across every segment examined here, battery mass is the one input to vehicle economics that OEMs and operators can still act on. Magnus™ is the only platform built to act on it without forcing the trade-off, between energy density and duty-cycle durability, that every competing approach still requires.

REFERENCES

[1] National Research Council. Technologies and Approaches to Reducing the Fuel Consumption of Medium- and Heavy-Duty Vehicles. National Academies Press (2010). https://doi.org/10.17226/12845

[2] U.S. Department of Energy. Lightweight Materials for Cars and Trucks. https://www.energy.gov/eere/vehicles/lightweight-materials-cars-and-trucks

[3] National Academies. Costs and Benefits of Integrating Fuel Consumption Reduction Technologies into Medium- and Heavy-Duty Vehicles. https://www.nationalacademies.org/read/12845/chapter/8

[4] North American Council for Freight Efficiency (NACFE). Lightweighting Confidence Report. https://nacfe.org

[5] What is GVWR? Truck Weight Classes Explained and What They Mean for Truckers. https://www.tcsfuel.com/blog/truck-weight-classification/

[6] InsideEVs. Tesla Semi 4680 Battery Pack Engineering Analysis. July 2021. https://insideevs.com/news/521840/tesla-semi-480-battery-analysis/

[7] Uber Freight. A Guide to Freight Trucking Rates in 2025. https://www.uberfreight.com/en-US/blog/a-guide-to-freight-trucking-rates-in-2025

[8] Candela Technology AB. Flying Electric Vessel Maker Candela Raises €30M Amid Soaring Oil Prices. March 2026. https://www.mynewsdesk.com/candela-speedboat-ab/pressreleases/flying-electric-vessel-maker-candela-raises-eu30m-amid-soaring-oil-prices-3438277

[9] Candela Technology AB. Candela P-12 Completes World's Longest Electric Sea Journey. February 2026. https://candela.com/newsroom/candela-p-12-completes-worlds-longest-electric-sea-journey/

[10] Artemis Technologies. EF-24 Passenger Vessels Delivered to Belfast, Marking Major Milestone. January 2026. https://www.artemistechnologies.co.uk/news/artemis-ef-24-passenger-vessels-delivered-belfast/

[11] Brooker, A., Ward, J., Wang, L. Lightweighting Impacts on Fuel Economy, Cost, and Component Losses. NREL/CP-5400-57607. Presented at SAE World Congress, April 2013. https://docs.nrel.gov/docs/fy13osti/57607.pdf

[12] Del Pero, F., Berzi, L., Antonacci, A., Delogu, M. Automotive Lightweight Design: Simulation Modeling of Mass-Related Consumption for Electric Vehicles. Machines, 8(3), 51 (2020). https://doi.org/10.3390/machines8030051

[13] InsideEVs. Tesla Model S Plaid Battery Pack Is Modern Marvel of Engineering. December 2021. https://insideevs.com/news/557757/tesla-models-plaid-battery-magic

[14] Edmunds. 2021 Tesla Model S Plaid Real-World Range Test. September 2021. https://www.edmunds.com/car-news/2021-tesla-model-s-plaid-travels-345-miles

[15] Mistry, P.J., Johnson, M.S. Lightweighting of Railway Axles for the Reduction of Unsprung Mass and Track Access Charges. Proc. IMechE Part F: Journal of Rail and Rapid Transit (2020). https://doi.org/10.1177/0954409719877774

[16] Kaufmann, M. Cost/Weight Optimization of Aircraft Structures. Doctoral Thesis, KTH Royal Institute of Technology. https://www.diva-portal.org/smash/get/diva2:13224/FULLTEXT01.pdf

[17] eVTOL.Travel. eVTOL Battery Technology: Range, Charging & Future Breakthroughs. https://evtol.travel/evtol-battery-technology

[18] Joby Aviation. LinkedIn post confirming battery cell/pack performance: 288 Wh/kg cell-level, 235 Wh/kg pack-level, 10,000+ demonstrated flight cycles. https://www.linkedin.com/posts/jobyaviation_we-recently-confirmed-the-performance-of-activity-7085672425111121920-bNdU

[19] U.S. Government Accountability Office. Defense Management: Increased Attention on Fuel Demand Management at DOD's Forward-Deployed Locations Could Reduce Operational Risks and Costs. GAO-09-388T (2009). https://www.gao.gov/products/gao-09-388t

[20] U.S. Army. Driving Fuel Choices. Army.mil (2020). https://www.army.mil/article/241758/driving_fuel_choices

[21] DARPA. Albatross Program Solicitation (DARPA-PS-24-13): UAV Soaring for Reduced Onboard Energy Consumption. https://www.militaryaerospace.com/uncrewed/article/55143310/range-efficiency-unmanned