

Freight density, carbon footprint, and fuel cost

Light weight but bulky items cost more to ship than denser items – they burn more fuel, and emit more greenhouse gas, than items that weigh the same but take up less space. In 2015, the major U. S. carriers began to apply a surcharge to packages that occupy more than a certain maximum amount of space allowed for their weight.

This page provides a method for calculating the actual cost of shipping items which fill up a vehicle or vessel's volume capacity before the total weight of the cargo reaches its weight capacity. This method can be applied to cargo transported in any specified vehicle or vessel, and is the only consistent way to define a density-specific emission factor for freight transport, as explained below.

Note that the cost and impact amounts provided by these calculations do not necessarily reflect what shippers may expect to pay. In practice, the density surcharges that carriers apply to a particular shipment are based on a variety of factors (see for example pp. 39-42 of UPS's [Rules and Charges for Less-Than-Truckload \(LTL\) Service](#)). The calculation method provided here looks specifically at actual fuel consumption and greenhouse gas impacts, and does not depend on how carriers set rates.

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The Cost of Shipping Air

Vehicles carrying less than their maximum weight capacity burn extra fuel and create extra emissions per ton of cargo transported. A lighter vehicle will burn less fuel per mile, but not enough less to make up for the fact that the energy cost of moving the non-cargo portion of the gross weight is now being shared among fewer tons of freight.

Carriers have begun to pass the additional cost on to their customers. According to one current standard (originally used for air transport, but now also being applied by many land-based carriers), any package whose volume (in cubic inches) per pound is greater than 166 is charged as if its weight were actually a quantity called the "[dimensional weight](#)" of the package. This quantity is always more than the actual weight of the package, and the shipper is billed accordingly. Numerically, the "[dim weight](#)" is simply the item's volume in cubic inches, divided by 166. It is what the package would weigh if it had the same density as a one pound package occupying 166 cubic inches. (In more familiar terms, that threshold number of 166 cubic inches per pound is equivalent to a density of 10.4 pounds per cubic foot, or about one-sixth the density of water. It is about the same density as a pile of blankets.)

Setting a threshold is a good start, giving shippers an incentive to avoid unnecessary bulk in packaging, and consequently reducing emissions. But thresholds are arbitrary, and subject to change. In addition, once a threshold has been met, it provides no further incentive for improvement.

The next section provides a formula for allocating the total amount of fuel consumed in a shipment to the individual items in the shipment, such that items taking up excess space per pound are held responsible for a greater share of the consumption, that share being in proportion to the actual cost and

impact. In the following section, some numerical examples indicate how costly excess bulk can be. The final section shows that the method is not arbitrary – the formula provided is the only consistent way to allocate fuel cost and carbon emission impact based on density.

The Allocation Formula

In addition to knowing the volume and the weight of the item, we need to specify three other pieces of information about the vehicle or vessel used to transport the item:

- the total weight capacity for cargo (i. e. the maximum load), denoted M_{max}
- the total volume capacity for cargo, denoted V_{max}
- the average fuel consumption rate, as a function of load (see below for notation)

The weight and volume capacities for various vehicle types are generally easy to find, and will typically be included in any tabulation of vehicle specifications. As far as fuel consumption is concerned, carriers will have access to detailed information about specific vehicles, and so can supply accurate input data. If specific vehicle data are not available, industry averages for various vehicle types may be accurate enough (see next section for some examples).

For use in the formula, it will be convenient to express the load dependence of the fuel consumption as a relative quantity, specifically as the percentage by which the fuel consumption rate increases when a given amount of weight is added to the load. It will be designated in the formula as “R%”. If the fuel consumption rate of the vehicle (say in gallons per mile) is known for two different loadings (ideally representing the high end and low end of what the vehicle normally carries), then R% is given by

$$R\% = \frac{(G_{heavy} - G_{light})}{G_{heavy} * (M_{heavy} - M_{light})} * 100\%$$

where G_{heavy} and M_{heavy} are the fuel consumption rate and load at the heavy end, and G_{light} and M_{light} the corresponding quantities at the light end. For a relative rate expressed in this form, the units used to measure G are irrelevant. If M is measured in tons, then R% will have units of “percent per ton”. (This assumes that fuel demand is linearly proportional to weight, which is an approximation, but it is accurate enough for this calculation.) For future reference, we will designate the vehicle’s fuel consumption rate when it is loaded to its weight capacity as $G_{baseline}$. It represents the vehicle operating at its most efficient (in terms of least fuel consumption per ton transported), and will serve as a baseline value in the formula.

Denoting the weight and volume of the item as M_{item} and V_{item} , we have all the input variables necessary for the allocation formula. But it will be convenient to combine some of the variables we have on hand already into a few new ones, to make the formula more readable. First we define a “baseline density” for the vehicle as

$$D_{baseline} = M_{max}/V_{max}$$

The vehicle would be carrying its maximum load if it were filled to volume capacity with cargo of the baseline density. We can also define the item density: the density of any item is by definition given by

$$D_{item} = M_{item} / V_{item}$$

Finally, we define the “shortfall weight” M_{short} as

$$M_{short} = M_{max} * (V_{item} / V_{max}) - M_{item}$$

It equals the difference in weight between the item and the weight of an identically sized item having the baseline density. For light packages the item weight will be less than that of its baseline-density imaginary twin, so M_{short} as defined above will be positive (a positive shortfall) for light items.

We can express the effect of density on emissions by defining an [emission factor](#) that applies to all items with density D_{item} . An emission factor for freight transportation specifies how much of a pollutant is emitted when a given weight of cargo is moved a given distance. Emission factors are generally applied as averages across all cargo without regard to density. But we can define a **density-specific emission factor** by the following formula:

$$E_{item} = G_{baseline} / M_{max} * [(D_{baseline} / D_{item}) - R\% * M_{short} * (M_{max} / M_{item})]$$

Written in terms of these variables, the formula is not hard to interpret. The factor outside the square brackets, $G_{baseline} / M_{max}$, is the emission factor when the vehicle is carrying its maximum load. This is multiplied by the quantity inside the square brackets, a difference of two terms, which act in opposite directions. The first term, $D_{baseline} / D_{item}$, is greater than one whenever the item density is less than the baseline density, and thus tends to raise the value of the emission factor (more of the fuel demand is allocated to less dense items, in proportion to their densities). This is partially offset by the second term, which measures the decrease in fuel demand in proportion to the shortfall mass. $R\%$ is always small enough that the effect of the first term outweighs that of the second, so the net result of the two counteracting terms is always greater than one, and the emission factor attributed to lighter items is always greater than that for items at the baseline density.

The formula still works numerically for items above the baseline density – the first term in square brackets, the density ratio, is now less than one, still partially counteracted by the second term (M_{short} becomes negative, so the fuel demand is increased by the added weight), but again the first term wins, and the calculated emission factor is now smaller than for a baseline load. An actual decrease in emissions per ton of cargo for a vehicle full of such heavier-than-baseline items could not be realized in practice, since it would involve loading the vehicle beyond M_{max} (a situation that would never occur in Michigan, though there is no telling what might be going on in Ohio or Indiana), so the potential savings from increasing package density is limited by the vehicle’s capacity. Still, a case could be made for awarding “credit” to heavier items, in the sense that they allow room for lighter items in the same load, so that the total load can still fill the vehicle to its weight capacity without overflowing the available space. For purposes of calculation, the formula must be applied to all items, regardless of density, in order for the results to remain consistent.

In the case of carbon dioxide emissions from vehicles, the emission rate is proportional to the fuel consumption rate, so the same factor applies to both quantities. In other words, the density-specific emission factor for a freight transport vehicle can also serve as a density-specific “consumption factor”. Instead of measuring $G_{baseline}$ in terms of **emissions** per mile per ton transported, the formula can just as well represent **gallons of fuel consumed** per mile per ton transported – and, since fuel is sold by the gallon, it provides an absolute measure of **fuel cost** per mile per ton transported as a function of density, when the goods are transported in that vehicle.

Examples

Detailed information on fuel economy as a function of speed, weight, and terrain for Class 8 trucks is available in a 2011 [report](#) from Oak Ridge National Laboratories (ORNL). Data presented in the report (p. 27) show plots of fuel efficiency (in miles per gallon) as a function of gross vehicle weight for trucks traveling in four different speed ranges on flat terrain. The average mileage for trucks traveling 65-70 miles per hour ranged from an average of 9.5 miles per gallon (0.105 gallons per mile) for vehicles with gross weights of 20,000 lb (10 tons, i.e. presumably with no payload) to 7.5 MPG (0.133 GPM) for vehicle weight 70,000 lb (35 tons). That implies a consumption rate increase per ton which works out to

$$(0.133 - 0.105) / (35 - 10) = 0.0011$$

additional gallons of fuel consumed per mile for every ton added to the load.

As noted above, it will be convenient to express this number as a percent. Dividing by the fuel consumption rate when the vehicle is carrying its maximum load, we find a relative consumption rate change per unit of vehicle weight change that equals $0.0011/0.103 = 0.84\%$ per ton. In other words, we can say that, for a vehicle that is carrying less than its maximum weight, its fuel consumption rate decreases by 0.84% for every ton that the load falls short of the maximum.

A fraction of a percent per ton is a relatively small change – it is a reflection of the fact that the mileage of an unloaded vehicle, 9.5 MPG, is not all that much better than a fully loaded one, at 7.5. The fuel savings from lightening the load are relatively modest. But the logistic consequences of carrying less than full weight are dramatic. Suppose a truck is carrying a payload of 15 tons, 10 tons below its maximum of 25. To cover the same distance as a fully loaded truck, one carrying the lighter load will consume 8.4% less fuel. But only 15, rather than 25 tons will have been transported. In other words, compared to a trip with a full load, 91.6% of the fuel has been used to transport 60% of the load. Put another way, cargo that could be transported in six fully loaded trucks would require four additional trucks carrying the lighter loads to do the same job. Bulk matters.

In addition to this value, $R\% = 0.84\%$ per ton, we need values for the payload weight and volume capacity of a typical Class 8 truck. Typical values for a standard 53 foot trailer are $M_{max} = 25$ tons and $V_{max} = 3,650$ cubic feet, respectively. This implies a baseline density for these vehicles of

$$25 \text{ tons} * 2000 \text{ lb/ton} / 3,650 \text{ CF} = 13.7 \text{ lb/CF}$$

Note that those carriers who are currently adhering to the “166 cubic inch/lb” threshold, equivalent 10.4 lb/CF, are actually giving shippers something of a break for packages being transported in large trailers, since items with density between the 10.4 lb/CF threshold and the 13.7 lb/CF baseline density are displacing heavier items and raising per pound costs, but aren’t being charged a premium.

This is all the input data we need to find the allocation factor for any item of a specified density. The table below lists a range of typical item types, together with the carbon emission and fuel cost per mile for each ton of that item transported by large truck. The table follows the [National Motor Freight Classification](#)[®] (NMFC) system, a proprietary standard used extensively by carriers to set rates. The examples of items in each freight class have been compiled from lists appearing on various websites. (Note that not every carrier will classify freight the same way – these examples should be used for illustration only. See More Resources below for references). The dollar amounts in the table assume a diesel fuel price of \$1.85 / gallon.

Density range (lb/CF)	NMFC Class	Examples	Density (lb/CF)	Fuel use factor (gal/ton-mi)	Emission factor (kg/ton-mi)	Fuel cost per ton (\$/ton-mi)
50 +	50	Stone, sheet steel				
			50	0.120	1.300	\$ 0.24
35 – 50	55	Bricks, cement, mortar, hardwood flooring				
			35	0.156	1.582	\$ 0.29
30 – 35	60	Food				
			30	0.171	1.739	\$ 0.32
22.5 – 30	65	Books, periodicals				
			22.5	0.207	2.105	\$ 0.38
15 – 22.5	70	Automobile engines				
			15	0.279	2.836	\$ 0.52
13.5 – 15	77.5	Tires				
			13.5	0.303	3.080	\$ 0.56
12 – 13.5	85	Crated machinery, palletized engines or transmissions				
			12	0.334	3.385	\$ 0.62
10.5 – 12	92.5	Computers, refrigerators				
			10.5	0.372	3.777	\$ 0.69
9 – 10.5	100	Furniture, wine cases, caskets, canvas				
			9	0.424	4.300	\$ 0.78
8 – 9	110	Lathes, table saws, tools				
			8	0.469	4.757	\$ 0.87
7 – 8	125	Small household appliances				
			7	0.527	5.345	\$ 0.97
6 – 7	150	Automotive sheet metal parts, bookcases				
			6	0.604	6.130	\$ 1.12
5 – 6	175	Clothing, stuffed furniture				
			5	0.712	7.227	\$ 1.32
4 – 5	200	Aircraft parts, mattresses				
			4	0.874	8.874	\$ 1.62
3 – 4	250	Light furniture (bamboo, wicker), flat screen TV				
			3	1.145	11.618	\$ 2.12
2 – 4	300	Assembled furniture, empty wooden cabinets				
			2	1.685	17.106	\$ 3.12
1 – 2	400	Assembled cages, empty crates				
			1	3.308	33.572	\$ 6.12
< 1	500	Low density (ping pong balls) or high value (gold dust bags)				

The same calculations can be applied to any vehicle or vessel for which data are available. TERC provides a [downloadable spreadsheet](#) allowing users to enter their own vehicle, fuel, and fuel cost data. The spreadsheet will then take any list of items, along with their corresponding weights and dimensions,

and will provide a breakdown by item of per pound carbon dioxide emissions and fuel costs, along with load totals.

Under the Hood

The allocation formula given above is certainly one possible way to split the total cost of fuel into item-by-item components. But does it allocate the costs consistently? And wouldn't some other breakdown do just as well?

One way to see how the formula works is to watch what happens as the pieces are put back together. Imagine a load made up of a number of items of different densities. The allocation formula assigns to each item a different emission factor, depending on its density.

Now there are two different ways to calculate how much fuel the vehicle will consume per mile when pulling that load. We can either:

1. multiply each item's emission factor times its weight, and add up the total, or
2. start with the total weight of the load, and use the vehicle's value for R% to calculate the fuel consumption rate directly, without using an emission factor

The point is that the answers have to agree, no matter what combination of items makes up the load. That is the condition that allows us to assign carbon footprint and fuel cost values to an item unambiguously, based solely on the density of the item and the fuel economy of the vehicle transporting it, without regard to whatever else the vehicle may be carrying.

The easiest way to see what is happening is to rewrite the allocation formula by pulling a factor of M_{max}/M_{item} out of the square brackets and combining it with the factor of $G_{baseline}/M_{max}$. The formula now looks like this:

$$E_{item} = G_{baseline} / M_{item} * [(V_{item} / V_{max}) - R\% * M_{short}]$$

Aside from looking simpler, the main advantage of this form is that all the quantities in the square brackets that are specific to the item appear in the numerator, rather than the denominator. (The disadvantage is that, whereas the factor of $G_{baseline}/M_{max}$ in the old form can be described simply as the fuel consumption rate at maximum load, the factor of $G_{baseline}/M_{item}$ in the new form is harder to interpret.)

To verify that all item terms are indeed upstairs, here is the same formula with M_{short} written out:

$$E_{item} = G_{baseline} / M_{item} * [(V_{item} / V_{max}) - R\% * (M_{max} * V_{item} / V_{max} - M_{item})]$$

Now we can verify that if we apply these emission factors as intended, we will calculate the correct fuel consumption rate for an arbitrary collection of individual items.

First of all, knowing the total weight of the load, what is the number we are shooting for? The fuel consumption rate G_{load} when the vehicle is pulling a load with the total weight M_{load} can be given, using $G_{baseline}$ as a baseline, by:

$$G_{load} = G_{baseline} * [1 - R\% * (M_{max} - M_{load})]$$

We have to compare this with the result of multiplying each item's emission factor times its weight, and summing the results. The sum can be written as:

$$G_{load} = E_{item1} * M_{item1} + \dots + E_{itemN} * M_{itemN}$$

where the sum is taken over all N items in the load.

We can also write:

$$M_{item1} + \dots + M_{itemN} = M_{load}$$

(the total weight of the load equals the sum of the item weights), and

$$V_{item1} + \dots + V_{itemN} = V_{max}$$

(the sum of the item volumes equals the volume capacity of the vehicle). For partially empty trucks, we can include an additional "item" with density equal to zero in the total, to make up for the unused space. The calculation still works, and the total of the item volumes, including the "air item", always equals V_{max} .

Now we reap the benefit of clearing the item-dependent quantities out of the denominators in the square brackets. We calculate G_{load} as the sum of emission factors times item weights, using the equation written above. The factor of $G_{baseline}/M_{item}$ in each emission factor, times the factor of M_{item} multiplying each emission factor, simplifies to a factor outside the brackets of $G_{baseline}$ for each term. Using the above equation for G_{load} as a sum over items, and collecting common factors, we have:

$$\begin{aligned} G_{load} = & G_{baseline} * [(V_{item1} / V_{max}) - R\% * (M_{max} * V_{item1} / V_{max} - M_{item1})] \\ & + \dots + \\ & G_{baseline} * [(V_{itemN} / V_{max}) - R\% * (M_{max} * V_{itemN} / V_{max} - M_{itemN})] \end{aligned}$$

or

$$G_{load} = G_{baseline} * [(1 - R\% * M_{max}) * (V_{item1} + \dots + V_{itemN}) / V_{max} - R\% * (M_{item1} + \dots + M_{itemN})]$$

which simplifies to

$$G_{load} = G_{baseline} * [(1 - R\% * (M_{max} - M_{load}))]$$

as required.

The fact that this agreement must be true for **any** combination of items implies that the allocation formula provided here is the only one that will work. (Consider what happens when the load is one big item with density D_{item1} and volume V_{max} . Now apply that argument to each item density in turn.) Details are provided in the "notes" tab in the downloadable spreadsheet.

[More resources](#)

Detailed information on fuel economy for large trucks is available from two different studies. One, carried out at Oak Ridge National Laboratories and released in 2011, is available at http://cta.ornl.gov/cta/Publications/Reports/ORNL_TM_2011_471.pdf. Another, published in 2010, is

available from the National Academies Press (as a no-cost download, but you need to register) at <http://www.nap.edu/catalog/12845>.

The list of examples of freight classifications according to the NMFC system was compiled from several websites, including <http://www.fmlfreight.com/freight-101/freight-classes/> and <http://shiptms.com/shipping-tips/what-is-a-freight-class/>.