Appendices to
Would the Proposed Baltimore-Washington Maglev Increase Greenhouse Gas Emission?

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Appendix A: CO_2 from Constructing the Maglev

The following equation estimates the amount of carbon dioxide $m_{construct}$ (kg) that would be emitted to construct 40 miles of tunnel and elevated track for the proposed maglev:

$$m_{construct} = d\ (\ f_{tunnel}\ m_{tunnel} + f_{elevate}\ m_{elevate}\ )$$

The values used to evaluate this equation are stated in Table A. Two values for $m_{construct}$ are produced because two methods are used to estimate the CO_2 emission rate per kilometer of tunnel or elevated track, m_{tunnel} and $m_{elevate}$ (kg km^{-1}). The two methods give an $m_{construct}$ value of either 316 or 815 million kilograms of CO_2 released to construct the maglev's track.

Method 1 derives values for m_{tunnel} and $m_{elevate}$ from the quantities in Table A and the following equations:

$$m_{tunnel} = e_{concrete}\ r_{concrete,tunnel} + e_{steel}\ r_{steel,tunnel}$$

$$m_{elevate} = e_{concrete}\ r_{concrete,elevate} + e_{steel}\ r_{steel,elevate}$$

In method 1, the equations for m_{tunnel}, $m_{elevate}$, and $m_{construct}$ evaluate as follows:

$$13.08\times10^6 \text{ kg km}^{-1} = 300 \text{ kg m}^{-3} \cdot 30{,}000 \text{ m}^3 \text{ km}^{-1} + 1.7 \text{ kg kg}^{-1} \cdot 2.4\times10^6 \text{ kg km}^{-1}$$

$$11.44\times10^6 \text{ kg km}^{-1} = 300 \text{ kg m}^{-3} \cdot 20{,}000 \text{ m}^3 \text{ km}^{-1} + 1.7 \text{ kg kg}^{-1} \cdot 3.2\times10^6 \text{ kg km}^{-1}$$

$$815\times10^6 \text{ kg} = 64.36 \text{ km } (\ 0.75 \cdot 13.08\times10^6 \text{ kg km}^{-1} + 0.25 \cdot 11.44\times10^6 \text{ kg km}^{-1}\ )$$

Method 2 uses the values for m_{tunnel} and $m_{elevate}$ published in Kato and Shibahara (2005). Using their values, the equation for $m_{construct}$ is evaluated as follows:

$$316\times10^6 \text{ kg} = 64.36 \text{ km } (\ 0.75 \cdot 5.31\times10^6 \text{ kg km}^{-1} + 0.25 \cdot 3.68\times10^6 \text{ kg km}^{-1}\ )$$

Table A: Parameters used in Appendix A to estimate the carbon-dioxide emission to construct the track of the proposed Baltimore-Washington maglev

Variable	Quantity	Notes
d	64.36 km	The 40-mile-long track that would connect Baltimore & Washington
f_{tunnel}	0.75	The fraction of the track that would be in a tunnel or along an elevated track. The route would be 67% to 80% in a tunnel and the rest would be elevated (FRA 2018, pg. 9,12).
$f_{elevate}$	1 - f_{tunnel}	
	Method 1: m_{tunnel} and $m_{elevate}$ derived from the concrete and steel to build the track	
$e_{concrete}$	300 kg m^{-3}	Fantilli et al. (2019) and Gursel (2014, Fig. 5.32) report 200 to 400 kg of CO_2 are emitted to manufacture 1 m^3 of concrete.
e_{steel}	1.7 kg kg^{-1}	Fantilli el al. (2019) and Liu et al. (2019) report 1.38 to 2.0 kg of CO_2 are emitted to manufacture 1 kg of steel.
$r_{concrete,tunnel}$	30,000 m^3 km^{-1}	The amount of concrete or steel required to build 1 km of tunnel or elevated track (IEA 2019, pg. 57).
$r_{concrete,elevate}$	20,000 m^3 km^{-1}	
$r_{steel,tunnel}$	2.4×10^6 kg km^{-1}	
$r_{steel,elevate}$	3.2×10^6 kg km^{-1}	
	Method 2: published values used for m_{tunnel} and $m_{elevate}$	
m_{tunnel}	5.31×10^6 kg km^{-1}	The amount of CO_2 that would be emitted to build 1 km of tunnel or elevated track (Kato and Shibahara 2005).
$m_{elevate}$	3.68×10^6 kg km^{-1}	

Appendix B: CO_2 from Operating the Maglev

The following equation estimates the net amount of carbon dioxide (moperate, kg y-1) that would be emitted each year from generating the electricity to run the maglev trains and from the hypothesized reduction in car travel because of people switching from driving cars to riding the maglev:

$$m_{operate} = d_{maglev} f_{maglev} - d_{car} f_{car}$$

The values used to evaluate this equation are stated in Table B. A range for $m_{operate}$ is calculated because BWRR gives a range for the maglev ridership, d_{maglev}. Two methods are used to estimate the maglev's CO_2 emission rate per passenger-kilometer, f_{maglev} (kg km^{-1}). Method 1 derives f_{maglev} from the electricity that the maglev would use. The result is a range for $m_{operate}$ of 2 to 33 million kilograms per year of increased CO_2

Table B: Parameters used in Appendices B and C.

Variable	Quantity	Notes
d_{maglev}	656.5×10^6 to 991.1×10^6 km y^{-1}	Maglev ridership in passenger-kilometers per year. BWRR projects that 10.2 to 15.4 million trips annually would be made on the proposed Baltimore-Washington maglev (Rogers 2015, pg. 17). To simplify the calculation, assume that these trips go the full length of the 64.36 km (40 mile) track.
d_{car}	451.3×10^6 km y^{-1}	Reduction in car ridership in passenger-kilometers per year. BWRR projects that there would be a reduction in gas-powered car travel of 165 million annual vehicle-miles because of people switched from riding a car to riding the maglev (Rogers 2015, pg. 18). Convert from vehicle-miles to passenger-kilometers and use 1.7 people per car (FHA 2018).
e_{gallon}	8.9 kg gallon^{-1}	CO_2 emission per gallon of gas burned.
P_{car}	40.4 km gallon^{-1} vehicle^{-1}	Kilometers traveled by a car per gallon of gas. The EPA (2019) reports that gas-powered cars sold in the US currently average 25.1 miles per gallon.
$n_{passenger}$	1.7 vehicle^{-1}	Number of people in a car on average (Federal Highway Administration 2018).
		Method 1: Derive f_{maglev} *from the electricity to run the train*
$e_{electricity}$	0.576 kg kWh^{-1}	CO_2 emitted to generate a kilowatt-hour at the on-peak marginal emission rate (PJM 2019). Maryland is unable to generate all of its power, so a new load, such as the maglev, would be serviced by the PJM regional electric grid. Most maglev trips would occur during rush hour, which means primarily "on peak" hours for the power industry.
$P_{maglev,full}$	0.100 kWh km^{-1} seat^{-1}	The electricity that the maglev would use per seat on the train when it travels at 300 mph (Fritz et al. 2018).
s_{maglev}	0.625 seat^{-1}	The fraction of maglev seats occupied by a passenger, on average. See Appendix B for an explanation.
		Method 2: Derive f_{maglev} *from a Japan Railroad report*
f_{maglev}	0.067 kg km^{-1}	CO_2 emitted per passenger-kilometer on the maglev. Japan Railroad (2019) states that a maglev emits 1/3 as much CO_2 as an airplane and an airplane emits 50 kg per seat during a 400-km trip. These values imply that the airplane and maglev emit 0.125 and 0.0417 kg of CO_2 per seat-kilometer, respectively. Convert the maglev value from per seat-kilometer to per passenger-kilometer by dividing by s_{maglev}.

emission. Method 2 derives f_{maglev} from a Japan Railway report. The result is $m_{operate}$ ranging from a decrease of 15 million to an increase of 8 million, in units of kilograms per year of CO_2 emission. The details of this calculation are below.

In these calculations, a single value is used for the CO_2 emission rate f_{car} (kg km^{-1}) for 1 person to travel 1 kilometer in a gas-powered car:

$$f_{car} = e_{gallon} \div (P_{car}\ n_{passenger})$$
$$0.1296 \text{ kg km}^{-1} = 8.9 \text{ kg gallon}^{-1} \div (40.4 \text{ km gallon}^{-1} \text{ vehicle}^{-1} \cdot 1.7 \text{ vehicle}^{-1})$$

Method 1 derives a value for the maglev emission rate f_{maglev} (kg km^{-1}) from the electricity to run the maglev:

$$f_{maglev} = e_{electricity}\ P_{maglev,full} \div s_{maglev}$$
$$0.09216 \text{ kg km}^{-1} = 0.576 \text{ kg kWh}^{-1} \cdot 0.100 \text{ kWh km}^{-1} \text{ seat}^{-1} \div 0.625 \text{ seat}^{-1}$$

In this derivation of f_{maglev}, the value for s_{maglev} was chosen based on Baltimore-Washington commuter demographics. According to the US Census Bureau (2015), most of the morning commute is toward Washington: 4,765 people southbound vs. 1,234 people northbound. Approximately the same number of maglev train trips must occur in each direction, so if the southbound morning maglev trains were 100% full, then the northbound morning maglev trains would be only 25% full. Averaging the two directions gives 62.5%, i.e., the fraction s_{maglev} of maglev seats occupied by a passenger would average 0.625. This value for s_{maglev} applies equally well when the commute reverses in the evening.

With the above-derived emission rate f_{maglev}, the equation for $m_{operate}$ evaluates to a range of a 2-to-33-million-kilogram increase in annual CO_2 emission:

$$[2.0\times10^6 , 32.8\times10^6] \text{ kg y}^{-1} = [656.5\times10^6 , 991.1\times10^6] \text{ km y}^{-1} \cdot 0.09216 \text{ kg km}^{-1} - 451.3\times10^6 \text{ km y}^{-1} \cdot 0.1296 \text{ kg km}^{-1}$$

Method 2 derives a value for the emission rate f_{maglev} from Japan Railroad's 2019 annual report, as described in Table B of the present article. Calculating $m_{operate}$ from this value for f_{maglev} results in a change in CO_2 annual emission that ranging from a decrease of 14.5 million kilograms to an increase of 7.9 million kilogram.

In the most optimistic scenario, maglev operations would cause a 14.5-million-kilogram reduction in CO_2 emission. At that rate, it would take 22 to 56 years to make up for the 316 to 815 million kilograms of CO_2 emitted to build the maglev track, as estimated Appendix A.

Appendix C: BWRR's CO_2 Estimate

BWRR claims that operating the maglev would reduce greenhouse gas emission by 2 million short tons and reduce car travel by 165 million vehicle-miles annually (Rogers 2015). One way to arrive at such a large emission reduction would be to operate the maglev for several decades and to ignore the CO_2 emitted to construct the maglev's track or to generate the electricity to run the maglev.

To verify this statement, first convert the stated tonnage and mileage to metric units: the goal is to avoid a total of 1,814 million kilograms of CO_2 emission (m_{BWRR}) by avoiding 265 million vehicle-kilometers of driving per year ($d_{car,vehicle}$). Then, use the following equation to estimate that it would take 31 years to achieve the desired emission reduction:

$$t = m_{BWRR}\ (P_{car} \div e_{gallon}) \div d_{car,vehicle}$$
$$31 \text{ y} = 1{,}814\times10^6 \text{ kg} (40.4 \text{ km gallon}^{-1} \div 8.9 \text{ kg gallon}^{-1}) \div 265\times10^6 \text{ km y}^{-1}$$

To evaluate this equation, use two values from Table B: e_{gallon} and P_{car}.

Another quantity mentioned in the text is the cost for gas to drive the 80-mile round-trip distance instead of taking the maglev. If gas cost $2.50 per gallon and with a car that averaged 25.1 miles per gallon, then the gas cost would be $7.97 for the round trip.

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