1. In Table VM-1 of the Highway Statistics 2020[1, p. 1], the Federal Highway Administration reports the total miles travelled, fuel consumed, and fuel economy (miles per gallon) for six vehicle types in 2019 and 2020.

To calculate the CO2 per gallon, you can assume that light-duty vehicles are primarily fueled with gasoline, and heavy-duty vehicles are primarily fueled with diesel fuel[2], and use the CO2 per gallon values in the table below provided by US EPA.[3]

|  |  |
| --- | --- |
|  | Grams of CO2/gallon |
| gasoline | 8,887 |
| diesel | 10,180 |

* 1. Calculate the average fuel economy (mile/gallon) in 2019 and 2020 for a new category that classifies all heavy-duty vehicles together (buses + single-unit truck + combination trucks).

2019: 6.61 mpg

2020: 6.77 mpg

If you have the total sum over sum, that is the easiest.

If you want to use the average fuel economy of each category, you can use the harmonic mean with weighting with miles traveled:

But essentially, you are just calculating the same as above, total miles divided by total gallons.

* 1. Calculate the average CO2 emission rate (g CO2/mile) for the new all heavy-duty vehicle category.

2019: 1,539 g CO2/mile

2020: 1,503 g CO2/mile

* 1. Calculate the total CO2 emissions (in million metric tons) for both the light-duty gasoline and heavy-duty diesel vehicles. What percentage contribution do heavy-duty diesel emissions make to total CO2 on-road emissions in 2019 and 2020?

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
|  | All light-duty + motorcycles | All heavy-duty | Total | Percentage |
| 2019 | 1,168.2 | 489.6 | 1,657.8 | 30% |
| 2020 | 994.7 | 477.0 | 1,471.7 | 32% |

* 1. Compare the total light-duty vehicle and heavy-duty CO2 emissions to the Greenhouse gas emissions inventory for transportation sector from the U.S. EPA’s Greenhouse Gas Emissions Inventory[4]. Does your answer make sense?

|  |  |
| --- | --- |
|  | EPA GHG Emissions Inventory (MMT CO2 equivalent) |
| 2019 | 1,874 |
| 2020 | 1,628 |

The CO2 equivalent emissions from transportation from the EPA GHG and sinks report is ~13% higher than what we estimated from the onroad transportation fuel consumed.

This makes sense because the transportation sector from the US EPA GHG Emissions inventory also includes other sources of transportation such as aircraft and rail.

In addition, the EPA estimate includes other GHG, such as methane, and fluorinated gases, contribute to ~3% of the CO2 equivalent GHG emissions. Whereas, our calculations from fuel only considered CO2 emissions.

Diagram

Description automatically generated

To calculate CO2 equivalent, we convert other greenhouse gases to CO2, based on their global warming potential. For example, using a 100 year horizon, methane has a global warming potential, 25 times higher than CO2.

Table

Description automatically generated

1. The National Renewable Energy Laboratory (NREL) developed a DriveCAT website that provides drive cycle data.[5] The DriveCAT website includes both regulatory drive cycles, such as the US EPA Federal Test Procedure (FTP). In addition, the DriveCAT includes drive cycles that are developed to be from NREL’s own instrumented truck data by NREL. NREL develops drive cycles that are representative of fuel economy and other performance statistics (e.g. grade, acceleration) from a large data set of vehicle data collected from multiple vehicles for many days of operation.[6], [7]

Drayage trucks ship goods over short distances, and operate at ports, rail yards, inter-modal freight facilities and distribution centers. Drayage trucks are typically Class 8 heavy-duty diesel trucks. In general, trucks used for drayage are older trucks, which previously were used for other vocations such as long-haul trucking.

Because drayage trucks typically operate in urban areas, and are older trucks, they are an important source of emissions.[8] In addition, because they operate on short-trips they are they a good candidate for electrification.[9]

In this question, evaluate the road loads needed to power a typical drayage vehicle on the Fleet DNA Drayage Representative cycle.

Use the following assumed vehicle weight and road load coefficients, obtained from the default values for drayage trucks in NREL’s FASTSIM tool [10] :

|  |  |  |
| --- | --- | --- |
| Drag coefficient | 0.6 |  |
| Frontal area (m^2) | 8.5 | m^2 |
| Empty Vehicle weight (kg) | 11,000 | kg |
| Cargo weight (kg) | 9,000 | kg |
| Rolling resistance coefficient | 0.006 |  |
| density of air = | 1.17 | kg/m^3 |
| acceleration of gravity = | 9.81 | m/s^2 |

Answer the following questions:

* 1. Calculate and graph the power (kW) using the road-load equation for each second of the NREL drayage drive cycle (or at least a section of the cycle). Considering aerodynamic drag, rolling resistance, acceleration resistance, and gravitational resistance, but not including the energy losses internal to the vehicle

Assume the vehicle is not a hybrid-electric vehicle (i.e. no regenerative brakes). The vehicle cannot capture any of the energy expended when the tractive power is negative (due to power from deceleration or going downhill being greater than the other power demands).

Tips: Using the road-load equation, calculate the Tractive Power for each second of operation, and then define Positive Tractive Power to be max(0,Tractive Power).

There are some unrealistic accelerations due to speed gaps in the NREL drive cycle. These can lead to very high power for a few data points (e.g. going from 0 to 80 km/hr in one second). I recommend setting limits on the acceleration. I estimated that the range of acceleration with non-zero speeds ranged from -3.5 and 2.5 m/s^2).

Use the road-load equation

*I recommend for this problem splitting it up into the power to overcome the following forces: (drag resistance, rolling resistance, gravitational resistance, and acceleration resistance)*

*Power to overcome gravitational resistance , can be calculated from the grade:*

*Make sure all your units are converted to SI*

*Figure is below*

*20 pts*

* 1. The NREL drayage drive cycle provides the engine speed (rpm), torque (Nm), and engine power (kW) for a representative vehicle.

Graph at least a subsection of the second-by-second tractive power and the engine power along with the calculated tractive power from 2.1.

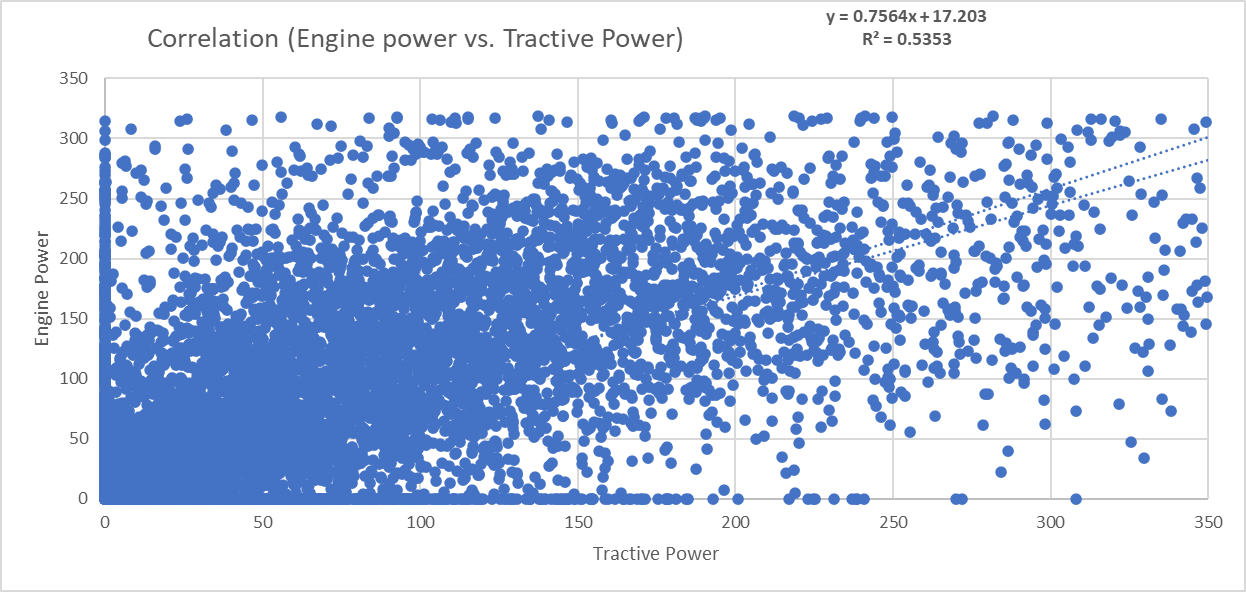
How do the second-by-second data compare? Does it make sense?

(original time)

Chart, histogram

Description automatically generated

(time by filling in missing time)



The vehicle tractive power and the engine power are correlated with one another. This makes sense, since the primary function of the engine is to provide power to move the vehicle. As the power demand increases, then the engine power also needs to increase to provide power for that load.

The engine power needs to be larger than the tractive power, so that the engine can provides energy to move the vehicle (vehicle power), and provides additional losses and loads within the vehicle drive train. The sum of the tractive power (tractive energy) over the entire cycle is 192 kw-hr and the positive engine energy is 245 kw-hr. This makes sense that on average, engine power > tractive power.

However, there are many instances where the calculated tractive power exceeds the engine power. For a conventional vehicle, the engine power needs to be greater than the tractive power. For a hybrid electric, the internal combustion engine can provide less than the required tractive power and vehicle losses, with the battery and electric motor providing remaining power.

The reason we are estimating lower engine power than tractive power for many seconds is due to the approximation of estimating the tractive power from aggregated second-by-second data and assumed road load coefficients. Using finer speed and acceleration data, and using road load coefficients that match the vehicle from which the engine power was measured, would improve the comparison.

10 pts

* 1. How much energy in units of kW-hr are required to move the vehicle at the wheels over the Drayage Representative Cycle?

Tip: Sum the Positive Tractive Power over the cycle to obtain kW-seconds. Note that there can be seconds where the acceleration resistance and/or the gravitational resistance power are negative, yet the total tractive power is positive.

For each second, calculate the positive power

Max(0,P)

Sum all the power across all seconds (units of kW-seconds)

10 pts

* 1. What percentage (%) of the power demand of a drayage truck operating is due to aerodynamic drag, rolling resistance, acceleration resistance, and gravitational demand?

Tip: For this question, only consider when the individual contributions to the power are positive. Define positive acceleration resistance power as max(0,acceleration resistance power), and the gravitational resistance power as max(0,gravitational resistance power).

Define the total positive tractive power for this sub-question, as the sum of the aerodynamic drag, the rolling resistance, the positive acceleration resistance, and the positive gravitational resistance power.

For this question we want to only look at the positive power. For the power to overcome acceleration and gravitational resistance contribution, the power can be both positive (going uphill, accelerating), or negative (going downhill, or decelerating). When the gravitational resistance or acceleration is negative, the power can often be used to off-set other power demands (such as the aerodynamic drag or rolling resistance), or the excess power is wasted as braking. If we just looked at the sum of all the gravitational power (positive and negative), we would underestimate the power requirements that we need to power the acceleration and gravitational components. For this question we only look at the positive power from each component.

|  |  |  |  |
| --- | --- | --- | --- |
|  | Sum (kw-hr) | Sum of Positive Power (kw-hr) | Percent Contribution of Positive Power |
| Aerodynamic Drag | 53 | 53 | 21% |
| Rolling Resistance | 51 | 51 | 20% |
| Acceleration | 10 | 118 | 47% |
| Gravitational Resistance | -0.3 | 29 | 12% |
| Total = | 114 | 251 | 100% |

10 pts

* 1. How much braking energy (in kW-hr) is available for regenerative power? What would be the tractive power needed to drive the drayage cycle be if 50%[11]–[13][[1]](#footnote-1) of the braking tractive power was re-captured? How much would the tractive power be reduced in percentage (%) compared to the total tractive power estimated in 2.1?

Here we sum the negative power from the road-load equation. This is the power needed to brake the vehicle

Assume we can recapture 50% of the braking energy

10 pts

* 1. Assuming the recorded engine power is representative of the drayage vehicle, and the average auxiliary load power is 7 kW (cooling fan, air conditioner, engine accessories, alternator, air compressor), what is the average efficiency of the driveline over the drive cycle?

Assume, is the maximum of the 7 kW or . In other words, cannot be greater than the for any second of operation.

Note:

10 pts

* 1. Using the engine power from the Fleet DNA drive cycle, the energy content of low-sulfur diesel fuel (the lower heating value) [14], and assuming , what is the fuel economy (mpg) of the drayage truck over the drayage cycle and the average fuel consumption per 1000 miles (gallons/1000 miles)? Show the equation you used.

From reference [14]:

10 pts

* 1. What would the fuel economy (mpg) and fuel consumption per 1000 miles of the drayage truck be if the truck is hybrid-electric, and 50% of the braking energy is captured through regenerative braking? (From Question 2.5) How many gallons of fuel and money would be saved assuming the miles driven on the Fleet DNA drayage is representative of the daily mileage a drayage truck travels, and that drayage trucks travel 5 days per week, 52 weeks per year and using the current national price of diesel fuel[15]

Hint: As a first step, re-organize the equation given in 2.5, to calculate the under the regenerative braking scenario.

The total power over the cycle is energy. Change equation to energy, to use the average driveline efficiency over the entire cycle.

Assume the same auxiliary loses using Equation 2.5

Assume the engine has the same efficiency (30%). However, as we learned in class, hybrid electric vehicles can operate their internal combustion engine at a higher efficiency (by downsizing the engine and running the ICE in its most efficient range).

10 pts

|  |  |
| --- | --- |
| miles per day | 96.9 |
| working days per year (5 days x 52 weeks) | 260 |
| miles per year (miles per day x work days per year) | 25204 |

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
|  | gallons per 1000 miles | Miles per year (thousands) | Gallons per year | Dollars ($5/gallon) |
| Conventional drayage truck | 224 | 25.2 | 5,644 | $ 28,222 |
| Hybrid drayage truck | 184 | 25.2 | 4,633 | $ 23,167 |
|  |  | Saved = | 1,011 | $ 5,056 |

10 pts

* 1. You just demonstrated there are potentially large efficiency gains in using hybrid technology in heavy-duty drayage trucks. Read the article by Jim Stinson “Why hybrid diesel trucks never quite caught on”[16]. What are some reasons listed in the article, or other reasons you think could be why hybrid technology has not been widely adopted by heavy-duty drayage trucks?
* Truck fleet owners don’t own the vehicle long enough to recoup the price of the fuel
* New trucks are typically purchased for long-haul operation, not drayage operation.
  + Long-haul trucks are not good candidates for hybrid technology because they spend most of their time at high speeds on the freeway
* Drayage trucks are good candidates with their frequent starts and stops, but are typically old long-haul trucks.
* Drayage trucks travel less miles than long-haul trucks, which takes longer for them to recoup the costs on upfront fuel consumption saving technology
* Hybrid power trains are more complex, and still have maintenance costs
  + Truck manufacturers have kept 100% diesel, or moved to all electric, which reduces complexity and maintenance costs

10 pts

1. Compare the grams of CO2/mile from the electricity or gasoline needed to fuel three vehicle technologies in model year 2021:

* conventional gasoline internal combustion vehicles
* electric-gasoline hybrid
* fully electric vehicles (200 mile range) using coal power generation and natural gas.

You can obtain the light-duty fuel economy from the different classes from the Annual Energy Outlook 2022.[17]

As we discussed in class, the miles per gallon equivalent for electric vehicles accounts for the energy equivalent in gasoline. You can use the conversion from the US DOE, that 1 kW-hr equals 0.030 gasoline gallon equivalent.[14]

You can obtain the CO2 emissions per kW-hr produced from coal and natural gas from this webpage from the EIA.[18]

* 1. Which of the three vehicle types has the lowest CO2/mile? Which one has the worst grams CO2/mile? Does it depend on the source of electricity for the electric vehicles?

From the EIA FAQs [18], calculate the average CO2 g/kwh for coal and natural gas in the US. Note the natural gas is for independent electric generation and does not include the improved efficiencies from co-generated heat and electricity like BYU’s co-generation plant.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
|  | Electricity generation million kWh | CO2 million metric tons | CO2 metric tons/kwh | CO2 g/kw-hr |
| coal | 757,763 | 767.00 | 0.00101219 | 1012.19 |
| natural gas | 1,402,438 | 576.00 | 0.000410713 | 410.7133 |

Using the CO2 g/kw-hr numbers, and the 1 kw-hr = 0.03 gallons of gasoline, we can calculate the CO2/mile.

For ICE and hybrid vehicles, use the CO2/gallon provided in Question 1 for gasoline:

|  |  |
| --- | --- |
|  | Grams of CO2/gallon |
| gasoline | 8,887 |
| diesel | 10,180 |

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
|  | mpge | gallon/mile | kw-hr/mile | source | g CO2/mile |
| Gasoline ICE Vehicles (Actual) | 25.4 | 0.039 | 1.312 | fuel | 349.9 |
| Gasoline ICE Vehicles (2021 Predicted) | 42.94 | 0.023 | 0.776 | fuel | 207.0 |
| Electric-Gasoline | 62.51 | 0.016 | 0.533 | fuel | 142.2 |
| 200 Mile Electric Vehicle | 101.9 | 0.010 | 0.327 | Coal | 331 |
|  |  |  |  | Natural Gas | 134 |

Emission rates of g CO2/mile smallest to largest:

1. 200 mile electric vehicle powered by natural gas
2. The electric-gasoline hybrid
3. Gasoline ICE vehicle (AEO 2022 predicted)
4. 200 mile electric powered by coal

10 pts

* 1. Note that the EIA values are significantly higher than real-world values reported by the US EPA Trends report[19], and FHWA[1]. The FHWA values are based on fuel consumption and measured and estimated VMT. The EIA values appear to be higher because they are using an older laboratory method for measuring fuel economy, called the two-cycle test. EPA now uses a five cycle test[20]. In addition, another AEO table for historic fuel economy provides fuel economy consistent with EPA and FHWA for model year 2020.[21]

How does your comparison change if you use the 2020 average (25.5 mpg and 350 g CO2/mile) to represent conventional internal combustion gasoline vehicles as reported in the EPA Trends Report?[19]

Revised list:

1. 200 mile electric vehicle powered by natural gas
2. The electric-gasoline hybrid
3. 200 mile electric powered by coal
4. Gasoline ICE vehicle (Actual)

10 pts

* 1. What sources of CO2 emissions from providing fuel, electricity, and vehicles are not included in your calculation?

* Does not include the benefits of co-generation heating and electricity generation natural gas plants, like BYU’s plant
* Does not include the emissions produced from mining, refining, and transportation the fuels for electricity generation or for use in motor vehicles
* Does not include the upstream CO2 emissions needed to build vehicles, electric vehicle batteries, and power-plant infrastructure.
* Does not include other greenhouse gases emisisons, such as methane (natural gas is primarily methane), and the leaks and losses of methane in mining, refining, and transporting natural gas

10 pts

[1] FHWA, “Table VM1 - Highway Statistics 2020 - Policy | Federal Highway Administration.” https://www.fhwa.dot.gov/policyinformation/statistics/2020/vm1.cfm (accessed Sep. 09, 2022).

[2] US EIA, “Annual Energy Outlook 2022 Table 36. Transportation Sector Energy Use by Fuel Type Within a Mode.” https://www.eia.gov/outlooks/aeo/data/browser/#/?id=46-AEO2022&cases=ref2022&sourcekey=0 (accessed Sep. 09, 2022).

[3] US EPA, “Greenhouse Gases Equivalencies Calculator - Calculations and References,” Aug. 10, 2015. https://www.epa.gov/energy/greenhouse-gases-equivalencies-calculator-calculations-and-references (accessed Sep. 09, 2022).

[4] US EPA, “Greenhouse Gas Inventory Data Explorer | US EPA.” https://cfpub.epa.gov/ghgdata/inventoryexplorer/ (accessed Jun. 16, 2022).

[5] NREL, “Drive Cycle Analysis Tool — DriveCAT.” https://www.nrel.gov/transportation/drive-cycle-tool/index.html (accessed Sep. 12, 2022).

[6] NREL, “DRIVE: Drive-Cycle Rapid Investigation, Visualization, and Evaluation Analysis Tool.” https://www.nrel.gov/transportation/drive.html (accessed Sep. 12, 2022).

[7] NREL, “Fleet DNA: Commercial Fleet Vehicle Operating Data.” https://www.nrel.gov/transportation/fleettest-fleet-dna.html (accessed Sep. 12, 2022).

[8] O. US EPA, “Drayage Truck Best Practices to Improve Air Quality,” Aug. 14, 2017. https://www.epa.gov/ports-initiative/drayage-truck-best-practices-improve-air-quality (accessed Sep. 12, 2022).

[9] NREL, “South Coast Air Quality Management District Truck Testing.” https://www.nrel.gov/transportation/fleettest-electric-scaqmd.html (accessed Sep. 12, 2022).

[10] NREL, “FASTSim: Future Automotive Systems Technology Simulator.” https://www.nrel.gov/transportation/fastsim.html (accessed Sep. 12, 2022).

[11] L.-H. Björnsson and S. Karlsson, “The potential for brake energy regeneration under Swedish conditions,” *Applied Energy*, vol. 168, pp. 75–84, Apr. 2016, doi: 10.1016/j.apenergy.2016.01.051.

[12] “The Magic of Tesla Roadster Regenerative Braking,” Jun. 29, 2007. https://www.tesla.com/blog/magic-tesla-roadster-regenerative-braking (accessed Sep. 13, 2022).

[13] A. Elgowainy, Ed., *Electric, Hybrid, and Fuel Cell Vehicles*. New York, NY: Springer New York, 2021. doi: 10.1007/978-1-0716-1492-1.

[14] US DOE, “Alternative Fuels Data Center: Fuel Properties Comparison.” https://afdc.energy.gov/fuels/properties (accessed Sep. 09, 2022).

[15] US EIA, “Gasoline and Diesel Fuel Update.” https://www.eia.gov/petroleum/gasdiesel/index.php (accessed Sep. 13, 2022).

[16] J. Stinson, “Why hybrid diesel trucks never quite caught on,” *Transport Dive*, Mar. 23, 2021. https://www.transportdive.com/news/hybrid-diesel-class-8-truck-long-haul/596782/ (accessed Sep. 13, 2022).

[17] US EIA, “Annual Energy Outlook 2022 Table 40. Light-Duty Vehicle Miles per Gallon by Technology Type.” https://www.eia.gov/outlooks/aeo/data/browser/#/?id=50-AEO2022&cases=ref2022&sourcekey=0 (accessed Sep. 21, 2022).

[18] US EIA, “Frequently Asked Questions (FAQs) - U.S. Energy Information Administration (EIA). How much carbon dioxide is produced per kilowatthour of U.S. electricity generation?,” Nov. 04, 2021. https://www.eia.gov/tools/faqs/faq.php?id=74&t=11 (accessed Sep. 13, 2022).

[19] US EPA, “The 2021 EPA Automotive Trends Report,” EPA-420-R-21-023, Nov. 2021. [Online]. Available: https://www.epa.gov/automotive-trends/download-automotive-trends-report

[20] US EIA, “New-vehicle fuel economy continues to increase.” https://www.eia.gov/todayinenergy/detail.php?id=13351 (accessed Sep. 13, 2022).

[21] US EIA, “Motor Vehicle Mileage, Fuel Consumption, and Fuel Economy.” https://www.eia.gov/totalenergy/data/browser/?tbl=T01.08 (accessed Sep. 13, 2022).

1. Use 50%, but a better value ~ 40%, Björnsson et al. it looks like it is less than 50% due to engine braking. Vanek et al. reports 40% [↑](#footnote-ref-1)