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 CO_2 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 CO_2/gallon
gasoline	8,887
diesel	10,180

   1.1. 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).

   1.2. Calculate the average CO_2 emission rate (g CO_2/mile) for the new all heavy-duty vehicle category.

   1.3. Calculate the total CO_2 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 CO_2 on-road emissions in 2019 and 2020?

   1.4. Compare the total light-duty vehicle and heavy-duty CO_2 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?

2. 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)	12,000	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:

   2.1. 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).

2.2. 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?

2.3. 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.

2.4. 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.

2.5. How much braking energy (in kW-hrs) is available for regenerative power? What would be the tractive power needed to drive the drayage cycle be if 50%[11]–[13] 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?

2.6. 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?
Note:

$$\eta_{driveline} = \frac{Energy\ out\ of\ the\ driveline}{Energy\ into\ the\ driveline} = \frac{E_{tractive}}{E_{engine} - E_{auxiliary}}$$

2.7. 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 $\eta_{engine} = 30\%$, 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.

2.8. 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 2.3) 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 E_{engine} under the regenerative braking scenario.

2.9. 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?

3. 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.

   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 CO_2 emissions per kW-hr produced from coal and natural gas from this webpage from the EIA.[20]

   3.1. Which of the three vehicle types has the lowest CO_2/mile? Which one has the worst grams CO_2/mile? Does it depend on the source of electricity for the electric vehicles?

   3.2. Note that the EIA values are significantly higher than real-world values reported by the US EPA Trends report[17], 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[18]. In addition, another AEO table for historic fuel economy provides fuel economy consistent with EPA and FHWA for model year 2020.[19]

   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?[17]

   3.3. What sources of CO_2 emissions from providing fuel, electricity, and vehicles are not included in your calculation?

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[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).
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[17] 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
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