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2019

22nd Annual High School Mathematical Contest in Modeling (HiMCM) Summary Sheet

(Please make this the first page of your electronic Solution Paper.)

Team Control Number: 10337
Problem Chosen: B

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Plastic water bottle consumption is increasing rapidly across the nation. This is a concern because the production of plastic water bottles is believed to be extremely costly — both financially and environmentally. In an attempt to reduce the environmental and financial impact of single-serving plastic water bottles, bans have been implemented in various cities and airports across the country. To determine the implications of such legislation and to determine whether or not they are beneficial, it is important to examine the financial and economic effects of alternative drinking water sources.

In regards to the financial model, we decided to model the change in the average cost of drinking water for atypical consumer, as well as airports' revenue change before and after the ban on single-use, single-serving PET plastic water bottles. Money is often a strong motivator for people while making decisions, so seeing the financial impact of such a ban could influence voters' decisions on whether their city should implement it.

For the environmental model, we chose to model energy consumption and material waste. Our energy consumption model accounts for many factors, including the cost of water processing, transportation, manufacturing of packaging, reusable water bottles, and the energy used by water fountains. The United States' consumer society generates massive amounts of trash, which is becoming an increasingly urgent problem. Our solid waste model addresses this concern as well as representing material wastage by looking into the different methods of disposal as well as likelihood of each method. Much of the packaging for beverages can and should be recycled, yet a worryingly large proportion of it ends up in the landfill instead.

Our models indicate that energy consumption and the average cost to the individual will increase in the short term, about one year, after the SSPET ban is enacted in the cities of Concord, MA, and San Francisco, CA despite the differences in population. However, in the long term, we would expect that the energy usage and cost would stay relatively similar or even decrease. Energy consumption can be lowered if residents choose to drink tap water instead of soda or water from larger bottles. Furthermore, costs would decrease dramatically after a few years because the cost of taxes would be lowered once a stable number of water fountains had been installed. Ultimately, models presented here give insight as to the actual implications of an SSPET ban and demonstrate that contrary to popular belief, the benefits of an SSPET ban would not be immediate, rather, they would slowly become beneficial to the community after multiple years.

Contents

1 INTRODUCTION

1.1 Problem Statement

Here, we present the impacts of the SSPET ban on an individual city as well as on an airport such as SFO. We consider two main effects of the SSPET ban: environmental effects and economic effects. We modeled environmental impact because the purpose of the SSPET ban is to help the environment in light of the global climate change crisis. Specifically, we focused on energy consumption and waste disposal because energy encompasses many different environmental factors such as transportation and fuel usage, and we felt it would represent resource expenditure. Modeling the impact on landfills reveals the material wastage of cities and represents excess consumption. We modeled the financial impact of the SSPET ban on the individual consumer because they form the population that is affected by the SSPET ban, and are the people who will vote on whether the SSPET ban is passed in their city.

1.2 Definitions and Abbreviations

- **SSPET**: Single-serving PET plastic water bottles that hold less than 1L of non-flavoured, non-sparkling water and are affected by the ban on single-use plastic water bottles.
- **SSPET Ban**: The ban on SSPET: It shall be unlawful to sell non-sparkling, unflavored drinking water in single-serving polyethylene terephthalate (PET) bottles of 1 liter (34 ounces) or less in [insert city name] after [insert starting date]. Exceptions shall be made in the case of emergencies that adversely affect the availability or quality of the drinking water in [insert city name]. Offenders shall be fined. (Paraphrased from Town of Concord, MA's Sale Of Drinking Water in Single-Serve PET Bottles Bylaw).
- **Larger Bottles**: We define larger bottles to be plastic water bottles that can hold more than 1L, so are unaffected by the SSPET ban. We also refer to larger bottles as 5 gallon (3.78 L) polycarbonate **jugs**.
- **Free Water**: Free water is water that is free to the consumer. (E.g., water from drinking fountains, an individual's place of employment, food vendors, etc.)

1.3 Variables

- N: the population size
- M: the maintenance fee for one water fountain in the city
- R: the percent of empty beverage bottles that are recycled in the community[1]
- S: the average distance between the manufacturing location for SSPET and the community in km
- I: the percent of trash that is incinerated
- F_i: the number of water fountains in the community before the SSPET ban
- F_f: the number of water fountains in the community after the SSPET ban
- P_{tap_i}: the percent by volume of drinking water consumed by the community that came from tap water before the SSPET ban
- P_{tap_f}: the percent by volume of drinking water consumed by the community that came from tap water after the SSPET ban
- $P_{reusable_i}$: the percent of the population that use reusable water bottles before the SSPET ban
- $P_{reusable_f}$: the percent of the population that use reusable water bottles after the SSPET ban
- P_{jug_i}: the percent by volume of drinking water consumed by the community that comes from large water bottles (5 gallon size) before the SSPET ban

[1] All percents are expressed as decimals between 0 and 1.

- P_{jug_f}: the percent by volume of drinking water consumed by the community that comes from large water bottles (5 gallon size) after the SSPET ban
- P_{SSPET_i}: the percent by volume of fluids consumed before the SSPET ban that was water from SSPET.
- P_{SSPET_f}: the percent by volume of drinking water consumed by the community that comes from SSPET purchased from other cities after the SSPET ban
- P_{soda}: the percent change by volume of soda consumed by the community instead of water from SSPET after the SSPET ban
- P_{free}: the percent change by volume of free water consumed by the community instead of water from SSPET after the SSPET ban

1.4 Assumptions and Justifications

General Assumptions

1. **The sale of single-use disposable water bottles that are not made from PET is negligible.**
While alternative packaging solutions are being explored, none hold a significant share in the bottled water market (Source: Yaffe-Bellany). Furthermore, it would take consumers some time to become accustomed to alternative disposable water bottles, such as canned or boxed water.
2. **The consumption rate of sparkling bottled water and imported bottled water in a city is negligible.**
(Source: U.S. and International Development & Statistics)
3. **Tap water is safe to drink in cities where the bottle ban will be implemented.**
It would not be feasible to impose the ban in places where tap water is unsafe to drink. Furthermore, the water in 90% of water systems in the US is safe to drink, and tap water is subject to EPA regulations. (Source: United States Environmental Protection Agency).
4. **Businesses will comply with the SSPET ban.**
People and corporations typically comply with the law. If they continue to sell single-use bottles, they will be fined. Also, it is not economically feasible for large water bottle manufacturers to specifically make 1.1L disposable water bottles to circumvent bottle size regulations in one particular city. We will assume that the percentage of businesses that don't comply is negligible.
5. **People who drink water from SSPET typically do so because they perceive bottled water as cleaner than tap water and/or because it is more convenient.**
(Source: Hu, Morton, and Mahler)
6. **The 5 main steps in the production of a water bottle are: collecting water, forming plastic into the shape of the bottle, treating the water, filling and capping the bottles, and the transportation of bottles to their final selling location.**
(Source: Thompson)
7. **Tap water is typically sourced from a local water supply.**
Most tap water comes from large wells, lakes, rivers, or reservoirs which is piped to residential homes and industries. This direct piping process would require water sources limits the possible water sources whereas bottled water can come from anywhere across the US.
8. **People do not reuse plastic water bottles.**
Plastic water bottles are made to be thrown away after a single use; otherwise, consumers would purchase reusable water bottles instead of plastic water bottles.
9. **All "larger bottles" are 5 gallon bottles.**
Most water dispensers use 5 gallon water jugs; thus, 5 gallon water jugs are commonly used.
10. **All 5 gallon (18.93 L) water jugs are made of polycarbonate.**
Most 5 gallon water jugs are made of polycarbonate.

11. **Trash/recycling collection and disposal costs remain the same after the SSPET ban is implemented.**
The average person produces 710.6 pounds of recycling and 1,361.4 pounds of trash per year. SSPET bottle weight is negligible because the average person uses 167 PET bottles per year, which amounts to around 3-4 lbs. (Source: Gringer).
12. **The amount of soda consumed may increase if the SSPET ban is implemented.**
(Source: International Bottled Water Association)
13. **The amount of tea or coffee consumed will stay constant if the SSPET ban is implemented.**
People choose to drink bottled water because they think it is clean and convenient. Tea and coffee take more effort to prepare and aren't as readily available as soft drinks are.

Numerical Assumptions

1. **All SSPET bottles are 0.5 L.**
The ban on water bottles affects all SSPET bottles less than or equal to 1 L. Though there are some bottles with volume less than 0.5 L and some with larger volumes, 0.5L is the average water bottle size.
2. **All SSPET bottles contain 9.89 grams of PET resin.**
The average amount of PET resin in each plastic water bottle is 9.89 grams. (Source: International Bottled Water Association).
3. **The energy required to produce PET resin is approximately 70–83 MJ (thermal) kg^{-1} of PET resin. Producing the bottle itself requires an additional 20 MJ kg^{-1}.**
(Sources: Bousted, Gleick and Cooley, Franklin Associates)
4. **If bottled water is not available, 63% of people will choose a soft drink rather than drink tap water.**
(Source: International Bottled Water Association)
5. **The average amount of PET resin in each SSPET water bottle is 9.89 grams.**
(Source: International Bottled Water Association)
6. **The average amount of PET resin in each soda bottle is 9.89 grams, the same amount of PET resin in each SSPET water bottle.**
Soda bottles are comparable in size and packaging to SSPET water bottles
7. **The average person in the US will use 167 water bottles each year.**
(Source: Statistic Brain Research Institute)
8. **13% of people use bottled water as their primary source of drinking water.**
(Source: Hu, Morton, and Mahler)
9. **55% of bottled water comes from springs; 44.5% of bottled water comes from tap water.**
(Source: Lurie (Mother Jones and the Foundation for National Progress))
10. **PET water bottles take at least 450 years to break down.**
(Source: Water Docs)
11. **The average person drinks 14L of water per week.**
(Source: Gunnars Healthline)
12. **It takes 1.1 kWh of electricity to treat and distribute 378.54 L (100 gallons) of potable home water, the average amount of potable home water people drink per day.**
(Source: Melton)
13. **It takes 0.2 kWh of electricity to produce 2.7854 L (1 gallon) of gas.**
(Source: Council on Foreign Relations)
14. **The energy required to produce 1 liter of soda is about 0.07301 kWh more than the energy required to produce 1 liter of bottled water.**
Soda is essentially water with sugar added to it, so we can generate a rough estimate of the energy

needed to produce soda by adding the energy needed to produce bottled water to the energy needed to produce sugar. 1L of soda contains around 100g of sugar (Source: Lehman). It takes around 848100 kCal to produce 1 hectare of sugarcane (Source: Hopkinson and Day), one hectare to produce around 67.5 tonnes of sugarcane (Source: Pasquali), and one ton of sugarcane yields around 200 lbs of sugar (Source: "Sugar Cane") .

$$\frac{848100\text{kCal}}{1\text{ha}}\frac{1\text{ha}}{67.5\text{tons}}\frac{1\text{ton}}{200\text{lbs}}\frac{1\text{lb}}{453.592\text{g}}\frac{100\text{g}}{1\ 1\text{L of soda}}\frac{0.00116222\text{kWh}}{1\text{kCal}} = 0.07301 \text{ kWh per 1L bottle}$$

15. **Reusable water bottles last for 5 years.**
    (Source: Hydroflask)
16. **A single-axle delivery truck can drive 6.5 miles per gallon of gas.**
    (Source: Schoettle, Sival, and Tunnell)
17. **The average distance between a warehouse and grocery store is 69 miles.**
    (Source: Gao, Lin, and Franzese)
18. **The cost of installing a water fountain is around $2300.**
    (Source: Homeadvisors)

2 IMPACTS OF THE SSPET BAN IN A CITY

Using a series of equations, we model the financial and environmental impacts of a potential SSPET ban on a United States city. Due to different geographic and socioeconomic conditions in American cities, we leave certain factors, such as population size, number of water fountains, and percent of water supply that comes from a specific water source, as variables. Although the inclusion of such variables ensures a high level of accuracy in the model, variables also make it difficult to predict the exact impact a SSPET ban might have on a city. Nevertheless, based on the popular belief that bottled water "tastes better" than tap water, we can assume that, even after a SSPET ban, people will continue to drink bottled water from larger jugs. If this is the case, it is likely that the electrical impact of a SSPET ban will be non-existent, if not negative, as large jugs of water require extensive amounts of electricity to manufacture. On the other hand, the largest advantage of a SSPET bottle ban on a city is the reduction of plastic waste. Although SSPET bottles are 100% recyclable, only about 25% of SSPET bottles are recycled *(Source: Recycling Coalition of Utah)*. Therefore, it is possible that a SSPET ban positively reduces a city's amount of plastic waste. Lastly, it is unlikely that a SSPET ban will decrease financial costs for the individual consumer. This is because alternative water sources, such as purchasing 5 gallon water jugs, is still costly to the individual consumer.

2.1 Necessary Information to Create a Model

City Information

To accurately predict the impact of the SSPET ban on a city, we need to know the population size (N), the number of water fountains the city has already installed ($f_{initial}$), the number of water fountains the city plans on installing ($f_{final} - f_{initial}$), the amount the city plans to pay for water fountain maintenance (M), and the percent of trash that gets incinerated (I). This information should be provided by city officials if they are considering implementing the SSPET ban in their city.

Population Information

We also need information about the population's water drinking habits and their likely response to the SSPET ban. Ideally, we would conduct a census to obtain information about the city residents' water drinking habits. We would conduct this survey online. We would collect information on their age, gender, and income range, because these are all factors that influence bottled water drinking habits. If it is not feasible to conduct census, we would conduct a stratified random sample and create groups based on age, gender, and income range. We would ask the following questions:

1. Please indicate what percent of the fluids you drink come from each of the following sources (enter a number between 1 and 100 next to each category):
   (i) Tap water
   (ii) Water from larger bottles
   (iii) Soda
   (iv) Coffee/Tea
   (v) Free water
   (vi) Water from SSPET
2. If the SSPET ban is implemented in your city right now, indicate what percent of your drinking water will come from each of the following sources (enter a number between 1 and 100 next to each category):
   (i) Tap water
   (ii) Water from larger bottles
   (iii) Soda
   (iv) Coffee/Tea
   (v) Free water
   (vi) Water from SSPET (imported from other cities)
3. Which of the following most accurately describes how you dispose of empty beverage bottles?
   (a) I usually recycle empty beverage bottles.
   (b) I sometimes recycle empty beverage bottles.
   (c) I rarely recycle empty beverage bottles.
   (d) N/A (I rarely consume beverages from bottles).
4. What brand of SSPET do you typically purchase?
   (a) (list of the 10 most bottled water brands in the US)
   (b) (list of the local/supermarket bottled water brands available in the city
   (c) I rarely consume bottled water
5. Which of the following represents your opinion on reusable water bottles?
   (a) I own a reusable water bottle.
   (b) I do not own a reusable water bottle, but if the SSPET ban is implemented in my city, I will purchase a reusable water bottle.
   (c) I do not own a reusable water bottle and if the SSPET ban is implemented in my city, I will not purchase a reusable water bottle.
6. Which of the following most accurately represents your opinion on tap water?
   (a) Tap water is not as safe to drink as water from SSPET.
   (b) Tap water and water from SSPET are equally safe to drink.
   (c) Tap water is safer to drink than water from SSPET.
7. Which of the following most accurately describes the main reason why you drink water from SSPET?
   (a) Water from SSPET is safer than tap water.
   (b) It is more convenient to drink water from SSPET.
   (c) I rarely drink water from SSPET.

To obtain information about people passing through airports, we felt it would be ideal to administer a short survey to passengers immediately before the flight takes off from the airport that we want to collect information about. We would take a clustered random sample, selecting a number of flights and asking every passenger to take our survey. Like the population survey, we would conduct this survey online and collect information about age, gender, and income range. This information would be used to create a more accurate representation of the entire population's opinions. We would ask the following questions:

1. If an SSPET ban was implemented in this airport, how would you obtain water or other beverages?
   (a) I would buy a reusable bottle from the airport
   (b) I would bring my own reusable bottle to fill using a water fountain
   (c) I would bring my own reusable bottle to fill at a coffee shop or restaurant
   (d) I would buy a bottle of flavored, non-water drink
   (e) I would buy a non-plastic water bottle, such as boxed water or a glass bottle
2. How did you acquire water or other beverages at the airport today?
   (a) I purchased one or more plastic water bottles
   (b) I purchased a reusable bottle and filled it
   (c) I purchased a flavored drink
   (d) Other (please specify)

Table 1: Derivations of Variables from City Census

Variable	Questions Used	Derivation of Variable
P_{tap_i}	1	Average the responses to question 1, part (i) to estimate the average percent by volume of drinking water consumed that was tap water before the SSPET ban.
P_{tap_f}	2	Average the responses to question 2, part (i) to estimate the average percent by volume of drinking water consumed that was tap water after the SSPET ban.
P_{jug_i}	1	Average the responses to question 1, part (ii) to estimate the average percent by volume of drinking water consumed that was from larger bottles before the SSPET ban.
P_{jug_f}	2	Average the responses to question 2, part (ii) to estimate the average percent by volume of drinking water consumed that was from larger bottles after the SSPET ban.
$P_{reusable_i}$	5	This is the percent of survey-takers who reported that they own a reusable water bottle (answer choice a).
$P_{reusable_f}$	5	This is the percent of survey-takers who reported that they own a reusable water bottle or they intend on purchasing one (answer choices a or b).
P_{soda}	1,2	Average the responses to question 1, part (ii) to estimate the average percent by volume of soda consumed before the SSPET ban. Then, average the responses to question 1, part (ii) to estimate the average percent by volume of soda consumed after the SSPET ban. Subtract the first average from the second to find the percent by volume of soda consumed instead of water after the SSPET ban.
P_{SSPET_f}	2	Average the responses to question 2, part (vi) to estimate the average percent by volume of water from SSPET consumed after the SSPET ban.
Variable	Questions Used	Derivation of Variable
P_{free}	1,2	Average the responses to question 1, part (v) to estimate the average percent by volume of free water consumed before the SSPET ban. Then, average the responses to question 1, part (v) to estimate the average percent by volume of free water consumed after the SSPET ban. Subtract the first average from the second to find the percent by volume of free water consumed instead of water after the SSPET ban.
R	3	Estimate the recyling rate by summing the percent of survey-takers who reported that they usually recycle (answer choice a) with 0.5 times the percent of survey-takers who reported that they sometimes recycle (answer choice b).

Table 1 continued: Derivations of Variables from City Census		
S	4	We can estimate the average distance the typical SSPET is shipped before reaching the consumer by finding the distances between the manufacturing plants that supply SSPET to the city and weighting the results according to how frequently each brand is purchased. The responses to question 4 will provide information about which SSPET brands are more frequently purchased, and the locations of the manufacturing plants for different SSPET brands can be found online.
General opinion on the safety of tap water	6,7	Questions 6 and 7 provide information on whether it would be useful to launch a city-wide campaign to promote the safety of tap water. If a significant part of the population doesn't trust the safety of their city's tap water, this will increase the population's use of tap water as a source of drinking water. The demographics information collected will also help in targeting a potential advertising campaign at the right audience.

2.2 Financial Impact Model

We decided to model the financial impact of the SSPET ban on the average consumer. More specifically, we modeled the change in weekly cost depending on what alternative water sources the average consumer chooses to use instead of bottled water. Individuals could insert their own statistics to get a more accurate prediction.

$$\begin{aligned}\Delta \text{ Cost} &= \text{ Cost}_f - \text{ Cost}_i + \text{ additional fees}\\ \Delta \text{ Cost} &= (\text{ Cost}_{tap_f} - \text{ Cost}_{tap_i}) + (\text{ Cost}_{jug_f} - \text{ Cost}_{jug_i})\\ &\quad + \text{ Cost}_{SSPET_f} - \text{ Cost}_{SSPET_i} + \text{ Cost}_{soda} + \text{ additional fees}\end{aligned}$$

Part 1 Find the percent by volume of tap water, bottled water, soda, and free water the individual consumes in lieu of bottled water. Take the product of each percentage and the cost for a week's supply if the individual replaced the water they drank from SSPET wtih that beverage instead. To calculate the cost of a week's supply, multiply the price per liter by the total number of liters of bottled water consumed per week before the SSPET ban was implemented. NOTE: we will demonstrate how to apply our financial model with the assumption that the individual used water from SSPET as their only source of drinking water and drank the recommended amount (14L per week).

(1) *Cost of tap water*: Water bills are often calculated with block rates. This means the amount you pay is determined by the range your water consumption falls in. An additional 14 L per week is insignificant compared to the 39,750 L of water used monthly by the average American. This is unlikely to push your water usage into a higher "block", so it is unlikely to change the amount you pay. If your water bill is determined based on the exact amount of water used, tap water costs around \$0.00105–\$0.000186 per liter, depending on the city.

(2) *Cost of water from larger bottles*: 5 gallon ($\sim$ 18.9L) containers cost around \$8.00.*(Source: Walmart)*. The price per liter is around \$0.42328.

(3) *Cost of SSPET from other cities*: The average SSPET bottle costs around \$1.45 and contains 16.9 oz (0.5L) of water. *(Source: Walmart)*. The price per liter is around \$2.90.

(4) *Cost of soda*: A 20 oz (around 0.6L) can of soda costs around \$2.29 at a typical grocery store. *(Source: Walmart)*. The price per liter is around \$3.8167.

Part 2 Determine how much the individual would pay for a new water bottle purchased because of the SSPET ban.

(5) The amount an individual spends on such items depends on many factors, including their current financial situation, lifestyle, and where they source their drinking water from. That being said, the cost of a popular water bottle, the Hydro Flask, is around \$30 per bottle. Using this as our water bottle price, the expected value an individual would spend on a water bottle is $30 \cdot (P_{reusable_f} - P_{reusable_i})$.

Part 3 Determine how many water fountains the city plans on installing, the cost of installation and maintenance, and how the city plans to pay for them.

(6) If the funds necessary to pay for this have already been acquired or can be diverted from some pre-existing entity, ignore part 6 in the equation. Otherwise, use

$$\frac{(F_f - F_i) * (\text{ cost per fountain + M})}{\text{number of taxpayers}}$$

to get a rough estimate of how much more the individual consumer would pay per year. To further simplify things, we can approximate the cost per fountain and yearly maintenance fee and estimate and the number of taxpayers. The cost of installing a water fountain is around $2300. The number of taxpayers is close to the number of employed people residing in the city. As the percentage of people in the US who are employed is around 59.7 percent, we approximate the number of taxpayers as $0.597N$. Plugging the numbers back in to the equation above gives us:

$$\frac{(F_f - F_i) \cdot (2300 + M)}{0.597N}$$

NOTE: Free water is free for the consumer, though the cost may be passed on indirectly through increased taxation rate (accounted for in part 6).
Let $\Delta P_{tap} = P_{tap_f} - P_{tap_i}$ be the percent change by volume of total drinking water from the tap consumed by the typical person after the SSPET ban.
Let $\Delta P_{jug} = P_{jug_f} - P_{jug_i}$ be the percent change by volume of total drinking water from larger bottles consumed by the typical person after the SSPET ban.
Let $\Delta P_{SSPET} = P_{SSPET_f} - P_{SSPET_i}$ be the percent change by volume of total drinking water from SSPET consumed by the typical person after the SSPET ban (will decrease).
Let $\Delta P_{reusable} = P_{reusable_f} - P_{reusable_i}$ be the percent of people who purchased water bottles because of the SSPET ban. P_{soda} is the percent by volume of soda consumed by the typical person instead of water after the SSPET ban.
Remember that P_{SSPET_i} is the percent by volume of fluids consumed before the SSPET ban that was water from SSPET and we assume that the typical person consumes 14L of fluids per week.

$$\Delta \text{ Cost} = P_{SSPET_i}(14L)\left[0.000186(\Delta P_{tap}) + 0.42328(\Delta P_{jug}) + 2.90(\Delta P_{SSPET}) + 3.8167(P_{soda})\right] + 30(\Delta P_{reusable}) + \frac{(F_f - F_i) \cdot (2300 + M)}{0.597N}$$

2.3 Environmental Impact Model - Energy Consumption

We modelled the difference in energy consumption pre and post ban because energy is a quantifiable way to measure the impact of a certain substance on the environment and there is also more readily available information in comparison to other quantities like fossil fuel or CO2 emissions. Furthermore, we knew that a large concern with plastic bottles is their impact on the environment and we found that energy was the best way that encompassed many different methods of storing water. We can model the energy needed to filter and transport drinking water. To find the initial energy consumption, To find the change in energy consumption, we found the change the energy required to supply home tap water, to power water fountains, to produce reusable water bottles, to produce 0.5 L SSPET water bottles, and to produce 5 gallon (18.93 L) water jugs. This is summarized in the following equation:

$$\Delta E_{\text{Total}} = \Delta E_{\text{tap}} + \Delta E_{\text{jug}} + \Delta E_{\text{SSPET}} + \Delta E_{\text{soda}} + \Delta E_{\text{reusable bottle}} + \Delta E_{\text{drinking fountains}}$$

To calculate the amount of energy consumed during the production of each beverage, we multiplied the change in volume consumed (in L) by the amount of energy needed to produce 1L of the beverage (including the energy needed to manufacture the packaging). The volume consumed is the change in percent by volume of the beverage in question compared to the total volume of fluids consumed. In this model, we assume that the total volume of fluids consumed by the city is $14N$ liters, as 14L is the recommended amount of fluids an individual should consume every week.

Part 1 *Change in energy consumption from production of tap water*: First, we need to find the amount of energy needed to filter water and pump it through pipes to reach the consumer. One gallon of gas is needed to process 378.541L of tap water. We assume it takes .2 kWh$_e$ of electricity to produce 2.7854 L(1 gallon) of gas. Therefore, using dimensional analysis, it takes .002906 kWh$_e$/L each week to treat and distribute one liter of home drinking water:

$$\frac{1 \text{ gal. of gas}}{378.541 \text{ L of tap water}} \frac{1.1 \text{ kWh}_e}{100 \text{ gal. of gas}} = \frac{0.002906 \text{ kWh}_e}{1 \text{ L of tap water}}$$

Knowing this, we can find the change in energy used to process tap water by multiplying by the change in volume of tap water being consumed. This amount is the total volume of fluids consumed multiplied by the percent by volume change in tap water consumed. The percent by volume change in tap water consumed is $\Delta P_{\text{tap}} = P_{tap_f} - P_{tap_i}$. Putting it all together gives us an equation expressing the energy needed to process the additional tap water consumed by the city:

$$\boxed{\Delta E_{\text{tap}} = \frac{0.002906 \text{ kWh}_e}{1 \text{ L}}(\Delta P_{\text{tap}})(N \cdot 14 \text{ L})}$$

Part 2 *Change in energy consumption from production of water from larger bottles*: We assume the energy required to produce a single 5 gallon water jug is 24.47 kWh$_e$. We can find the amount of energy per liter of water from jugs because we know that the volume of one jug is 18.93 L:

$$\frac{24.47 \text{ kWh}_e}{1 \text{ jug}} \frac{1 \text{ jug}}{18.93 \text{ L of water from jug}} = \frac{1.2927 \text{ kWh}_e}{1 \text{ L of water from jug}}$$

The total volume water from larger bottles that is consumed by the city in a week is $N(14\text{L})$ multiplied by the percent of the population that gets water from water jugs: $\Delta P_{\text{jug}} = P_{jug_f} - P_{jug_i}$. Putting it all together gives us the following equation expressing the energy required to produce the additional water from water jugs is:

$$\boxed{\Delta E_{\text{jug}} = \frac{1.2927 \text{ kWh}_e}{1 \text{ L}}(\Delta P_{\text{jug}})(N \cdot 14 \text{ L})}$$

Part 3 *Change in energy consumption from production of SSPET*: (This value will be negative, as SSPET use will go down because of the SSPET ban). We calculated the energy use from each step of the SSPET manufacturing process to get an accurate prediction of energy consumption per L. The energy needed to produce 1L of water packaged in SSPET is $0.2020 + \text{E}_{\text{transportation}}$ kWh$_e$ per L, where $\text{E}_{\text{transportation}}$ is defined as a function of S, the average distance between the SSPET factories and the city in km:

$$\text{E}_{\text{transportation}} = \begin{cases} \frac{0.0000021494S \text{ kWh}_e}{\text{L * km}} & S \leq 111.05 \text{ km} \\ \frac{0.0002387 \text{ kWh}_e}{\text{L * km}} + (S - 111.05)\left[\frac{0.00009089 \text{ kWh}_e}{\text{L * km}} + \frac{0.00001531 \text{ km}}{\text{L * km}}\right] & S \geq 111.05 \text{ km} \end{cases}$$

Given the $\Delta P_{SSPET} = P_{SSPET_f} - P_{SSPET_i}$, or the percent change by volume in SSPET consumption compared to total fluid consumption by the city, the average energy consumption per week is:

$$\boxed{\Delta E_{SSPET} = \frac{0.2020 + \text{E}_{\text{transportation}}}{1L}(\Delta P_{SSPET})(N \cdot 14\text{L})}$$

Part 4 *Change in energy consumption from production of soda*: We assume the energy required to produce 1 liter of soda is about 0.07301 kWh more than the energy required to produce 1 liter of bottled water. Given the percent change by volume of soda consumption, P_{soda}, the change in energy is:

$$\boxed{\Delta E_{\text{soda}} = \frac{0.2750 + \text{E}_{\text{transportation}} + \text{ kWh}_e}{1L}(P_{soda})(N \cdot 14\text{L})}$$

Part 5 *Change in energy consumption from production of reusable water bottles*: We assume that 16.94 kWh of energy is required to produce a single reusable water bottle. To find the change in energy required to produce reusable water bottles for the entire city, we multiply this value by $\Delta E_{reusable} = E_{reusable_f} - E_{reusable_i}$, the number of people who will purchase a reusable water bottle because of the SSPET ban. We assume that reusable water bottle users buy a new reusable bottle once every five years – not once every week. As we are calculating average energy usage, we divide the energy used to produce bottles by 260, the number of weeks in 5 years. Thus, the average energy consumption per week is:

$$\boxed{\Delta E_{\text{reusable bottle}} = \frac{24.47 \text{ kWh}}{1 \text{ bottle}}(\Delta E_{reusable})(N)(\frac{1}{260})}$$

Part 6 *Change in energy consumption from drinking fountains*:The average water fountain requires 9.3 kWh_e per week to function (refer to assumption ....). The change in energy required to run a water fountain is therefore 9.3 kWh multiplied by the change in number of water fountains, $\Delta F = F_f - F_i$. The energy expenditure per week is:

$$\boxed{\Delta E_{\text{ drinking fountains}} = 9.3\Delta F}$$

To reiterate, the following equation represents the change in energy used to process drinking water after the SSPET ban is implemented. See the 6 boxed equations above for expressions for each energy value.

$$\Delta E_{\text{Total}} = \Delta E_{\text{tap}} + \Delta E_{\text{jug}} + \Delta E_{\text{SSPET}} + \Delta E_{\text{soda}} + \Delta E_{\text{reusable bottle}} + \Delta E_{\text{drinking fountains}}$$

2.4 Environmental Impact Model - Solid Waste

One goal of the SSPET ban is to reduce garbage and litter. The recycling rate for PET bottles in the US is only around 3% *(SOURCE: United States Environmental Protection Agency)*. One measure of garbage produced is the change in the volume of trash going into the landfill. Although the SSPET ban is intended to reduce the number of SSPET being dumped in the landfill, it may increase other types of trash. However, we did not account for different recycling rates for different containers. For example, people are much more likely to recycle The following table shows potential sources of landfill waste after the SSPET ban is implemented.

We can model the mass of waste being generated before and after the SSPET ban. For each type of container, we used the following equation to estimate the mass of material used:

$$N \cdot (P_{\text{type of container}})\frac{\text{Total volume of fluids consumed}}{\text{Volume contained in each bottle}} \cdot (\text{Mass of bottle})(1 - R)$$

This equation represents the number of people in the population (N) times the number of bottles used by the typical person ($\frac{P_{\text{type of container}}}{100}\frac{\text{Total volume of fluids consumed}}{\text{Volume contained in each bottle}}$) times the mass of one bottle. We also multiply by $(1 - \frac{R}{100})$ because R% of the empty bottles are recycled.

Total volume of fluids consumed is $0.01P_{SSPET}$ times the total volume of fluids consumed. For this model, we will look at change over one week, so the total volume of fluids consumed should be 14 L (the recommended amount).

Types of Waste Generated

1. *Tap water and free water*: Tap water and free water don't generate solid packaging waste.
2. *Larger bottles*: The increase in usage of 5-gallon bottles (18.93L) is $\Delta P_{jug} = P_{jug_f} - P_{jug_i}$. The mass of one 5-gallon jug is 793.79g.

$$\Delta(\text{Mass of jugs}) = N \cdot (1-R)(\Delta P_{jug}) \frac{14 \cdot P_{SSPET}}{18.93L} \cdot 793.79g$$

3. *Soda*: Some bottled water drinkers will drink soda instead of bottled water. For this model, we assume that all soda comes in PET bottles and the mass of soda bottles is the same as the mass of water bottles, so we can estimate the mass of additional soda bottles being used:

$$\Delta(\text{Mass of soda bottles}) = N \cdot (1-R)(P_{soda}) \frac{14 \cdot P_{SSPET}}{0.5L} \cdot 9.89g$$

4. *SSPET from other cities*: Especially if the city where the SSPET ban is implemented is located close to other cities that don't ban SSPET, people could purchase SSPET elsewhere but consume and dispose of them in the city with the SSPET ban. This estimate should be negative because the mass of discarded SSPET should decrease after the SSPET ban. In the following equation, $\Delta P_{SSPET} = P_{SSPET_f} - P_{SSPET_i}$:

$$\Delta(\text{Mass of SSPET}) = N \cdot (1-R)(\Delta P_{SSPET}) \frac{14 \cdot P_{SSPET}}{0.5L} \cdot 9.89g$$

The overall change can be found by summing up the change in mass of jugs, soda bottles, and SSPET being thrown away:

$$\Delta(\text{Mass of waste}) = \Delta(\text{Mass of jugs}) + \Delta(\text{Mass of soda bottles}) + \Delta(\text{Mass of SSPET})$$

Substituting in the expressions for each component and factoring out common terms gives us our final equation:

$$\Delta(\text{Mass of waste}) = N \cdot 14 \cdot P_{SSPET_i}(1-R)\left(\frac{\Delta P_{jug} \cdot 793.79g}{18.93L} + \frac{\Delta P_{soda} \cdot 9.89g}{0.5L} + \frac{\Delta P_{SSPET} \cdot 9.89g}{0.5L}\right)$$

NOTE: Recently, companies are exploring alternative packaging solutions. Some possibilities for packaging materials include paper cartons, aluminium cans, and glass bottles. However, none of these water bottle alternatives are widely available yet. If many cities implement bans on SSPET, corporations might make a bigger effort to widely distribute these alternatives. Because we don't know which types of packaging will ultimately be implemented nor the general populace's reaction towards it, we are unable to represent alternative packaging options in our waste disposal model.

2.5 Application of Models to Concord and San Francisco

All models are considered within the time span of one year. We assume the following values for the variables used in our equations:

Concord:

(a) $\boldsymbol{n_f = 19,000 \; n_i = 19,000}$ Though the population would increase over the time frame of one year, we kept the population still at 19,000 to better observe the effects of the change on one person as increasing the population would introduce a confounding variable.

(b) $\boldsymbol{F_f = 27 \; F_i = 22}$ On Concord's city map, we can see that they have marked 22 fountains initially. In recent news articles, they explain that they have added 5 new fountains to keep water accessible to the public. *(Source: Concord on Tap)*

(c) $\boldsymbol{P_{SSPET_f} = 0.00}$ $\boldsymbol{P_{SSPET_i} = 0.13}$ We assume that 13% of people use bottled water as their primary source of drinking water in the US. We also assume that all SSPET bottles are 0.5 L; thus, after the ban, there will be no SSPET bottles.

(d) $\boldsymbol{P_{tap_f} = 0.73}$ $\boldsymbol{P_{tap_i} = 0.67}$ Tap water is the most accessible form of water so it makes sense that the majority of water would could from tap. Furthermore about 71% drink tap water sometimes. *(Source: Sustainable Brands)*

(e) $\boldsymbol{P_{jug_f} = 0.14}$ $\boldsymbol{P_{jug_i} = 0.12}$ In most cases, those who drink bottled water prefer to drink from small SSPET bottles rather than large 5-gallon jugs as they are more convenient to transport. Therefore, it is safe to assume that a very small percent of total water comes from large water jugs.

(f) $\boldsymbol{P_{soda} = 0.05}$ While soda is highly accessible as mentioned above, it is still unhealthy so the increase is not too extreme. *$\boldsymbol{P_{soda_f} = 0.13}$ $\boldsymbol{P_{soda_i} = 0.08}$

(g) $\boldsymbol{P_{reusable_f} = 0.48}$ $\boldsymbol{P_{reusable_i} = 0.45}$ Research has shown that rather than carrying around water bottles, many people would rather reach for a sugary drink because its ease of disposal which is why the percent of people who use reusable water bottles only increase slightly. *Keep in mind that this number does not go towards the total calculation for water consumption, rather, it is just how many people use reusable water bottles.

San Francisco:

(a) We would expect all variables to have similar quantities except for the following.

(b) $\boldsymbol{n_f = 885,000}$ $\boldsymbol{n_i = 885,000}$ Same reasoning for why the population doesn't change and a different population as obviously San Francisco is a larger city. *(Source: San Francisco Water Power Sewer)*

(c) $\boldsymbol{F_f = 90}$ $\boldsymbol{F_i = 80}$ *(Source: University of California San Francisco).*

Environmental Model - Energy Consumption

Concord:

$$\Delta E = 38.650\text{ kWh}_e + 46.500\text{ kWh}_e + 37.039\text{ kWh}_e - 7071.662\text{ kWh}_e + 6865.857\text{ kWh}_e + 2920.085\text{ kWh}_e$$
$$\Delta E = 2836.469\text{ kWh}_e$$

San Francisco:

$$\begin{aligned}\Delta E &= 1800.267\text{ kWh}_e + 93.000\text{ kWh}_e + 1725.268\text{ kWh}_e - 329413.399\text{ kWh}_e + 320492.484\text{ kWh}_e \\ &\quad + 103156.294\text{ kWh}_e \\ \Delta E &= 97,853,884\text{ kWh}_e\end{aligned}$$

According to our model, total energy consumption increases in both Concord and San Francisco after the SSPET ban. Although plastic water bottles, and thus the energy required to produce them, is decreased, energy is still required to power alternative water sources. In particular, a large amount of electricity is required to produce 5-gallon jugs of water.[2]

Financial Model - Cost to Individual

1. $M = 295$ We expect that maintenance of a drinking water fountain would take about one hour. The average flat rate for a plumber is between 160 and 430 which makes the average 295.

$$\Delta\text{ Cost} = P_{SSPET_i}(14L)\left[0.000186(\Delta P_{tap}) + 0.42328(\Delta P_{jug}) + 2.90(\Delta P_{SSPET}) + 3.8167(P_{soda}) + 30(\Delta P_{reusable}) + \frac{(F_f - F_i)\cdot(2300 + M)}{0.597N}\right]$$

[2] We did not account for the reuse of large jugs because the number of times a jug is reused is highly subjective.

2. **Concord**: \$2.51
3. **San Francisco**: \$1.42
   From our financial model we can see that by eliminating the use of SSPET in a city the cost would actually increase within the cost of a year. This is primarily due to the high cost of the water fountains; however, in the long term, this cost would become negligible as they would not keep adding new water fountains every year once they reach an amount that can sustain the population. We would expect to see the cost begin to decrease after 5 years. Furthermore, in San Francisco, we can see that the added cost was actually less than in Concord due to the much greater population.

2.6 Environmental Model - Solid Waste

Concord: $R = 30\%$ While only about 25% of SSPET bottles are recycled nationally, Concord is an extremely sustainable city (as evidenced by their implementation of the SSPET ban). Thus, we can assume that the recycling rate in Concord is slightly higher than the national recycling rate.

$$\Delta(\text{Mass of waste}) = 19000 \cdot 14 \cdot (.13)(.70)\left[\frac{.02 \cdot 793.79 \text{ g}}{18.93 \text{ L}} + \frac{0.5 \cdot 9.89 \text{ g}}{0.5 \text{ L}} + \frac{(-0.13) \cdot 9.89 \text{ g}}{0.5 \text{ L}}\right]$$

$$\Delta(\text{Mass of waste}) = -18,003.014 \text{ g} = -18.003 \text{ kg}$$

San Francisco: $R = 30\%$, for the same reasons as stated above.

$$\Delta(\text{Mass of waste}) = 885000 \cdot 14 \cdot (.13)(.70)\left[\frac{.02 \cdot 793.79 \text{ g}}{18.93 \text{ L}} + \frac{0.5 \cdot 9.89 \text{ g}}{0.5 \text{ L}} + \frac{(-0.13) \cdot 9.89 \text{ g}}{0.5 \text{ L}}\right]$$

$$\Delta(\text{Mass of waste}) = -18,003.014 \text{ g} = -18.003 \text{ kg}$$

In Concord, the amount of waste is expected to decrease by 18.003 kg each week because of the SSPET ban. In San Francisco the amount of waste should decrease by 838.561 kg each week because of the ban. The decrease in the amount of waste per week in each city may not seem like a lot, but any efforts to minimize the volume of wasted materials that end up in our landfills should be encouraged.

Other Impacts

We were unable to model every impact of banning SSPET, but we thought it was important to point out several other notable effects that we didn't account for in our models.

1. *Water usage*: Though some estimates find that it takes 1.69L of water to produce 1L of bottled water, this does not include production of the bottle itself and many other associated costs *(Source: International Bottled Water Association)*. Taking these additional factors into account, producing bottled water requires about 3 times the amount of water in the bottle. This means that 1 L of SSPET water or water from larger bottles would require around 3L of water to produce. Soft drinks are even worse; The Coca-Cola Company claims that it takes 35 L of water to produce 0.5 L of coke, but other calculations show that it actually takes around 170 to 310 L *(Source: MacDonald)*.
2. *Harmful effects of SSPET manufacturing*: In the initial energy model, the most energy usage comes from the production of the bottles (Source: Ecology Center). Therefore we decided to look into the production of where the implications of this energy usage on the environment as a whole. While the implications of leaving PET plastic in the landfill where it cannot degrade is obviously on the forefront, the toxic pollution produced by the production of PET plastic is also of concern. Manufacturing PET resin generates toxic emissions like nickel, ethylene, ethylene oxide, and benzene. These air emissions are a result of difficulties in handling "large flows of pressurized

gases" which are necessary to produce these bottles. By using an alternative like glass to create the bottles, the amount of toxic emissions could be cut by 100 times. Furthermore, PET is usually produced from natural gas and petroleum, which are both fossil fuels (Source: Pacific Institute). The effects of burning these fossil fuels not only contribute to reducing air quality through pollution but also directly contribute to the warming of our globe.

3. *Implications of SSPET transporation*: The other energy implications that must be taken into consideration are those from transportation because the amount of energy required increases drastically when the distance traveled increases. In the US, medium and heavy-duty trucks account for 23%, rail accounts for 2%, and ships account for 3% of the energy emissions in the US transportation sector (Source: EPA Green Vehicle Guide). This means that we'll primarily look at the environmental and health impacts of trucks as they account for a much larger percentage of the transportation sector. Despite efforts from the EPA to reduce NOx emissions in 2018 in their *Cleaner Trucks Initiative*, it is still expected that these large trucks will be responsible for $1/3$ of NOx emissions from transportation (Source: EPA Regulations for Emissions from Vehicles and Engines). For some background on NOx, it is created when nitrogen (released during fuel combustion) meets oxygen atoms in the air. It can cause health issues by irritating and inflaming the lungs. NOx gases also create acid rain which is highly toxic. However, despite these concerns, the overall effect of the water bottle ban on reducing these worrisome concerns will be negligible because the number of trucks required to transport water does not make up a large portion of the total trucks currently on the road.

4. *Health - increased consumption of soda*: Because only water bottles are banned, the purchasing and consumption of soft drinks will increase because they are more accessible than water. This will have consequences for public health, as civilians will drink more soda and less water, likely causing blood sugar levels and the prevalence of diabetes to increase. In the Mexican village of San Cristobal de las Casas, people rely on coca-cola from a local bottling plant as their main beverage instead of potable water. As a result, the mortality rate of diabetes has increased 30% between 2013 and 2016 in Chiapas, the state where the town is located (Source: Lopez and Jacobs NYTimes). While the effects of banning bottled water in most American cities certainly will not be as drastic, it is still expected that people will consume more soft drinks.

5. *Health - microplastics from SSPET*: The average person consumes 74,000 microplastic particles—any plastic less than 5mm in length—per year from various foods. Though the exact dangers of microplastics are still unknown, many worry that they release toxic substances once in the gut or are carcinogenic. Studies have found that those who solely drink from water bottles ingest an additional 90,000 microplastics per year, whereas those who solely drink tap water only ingest an additional 4,000 microplastics every year (Source: Cassella sciencealert). Thus, in a cities that ban SSPET, the amount of ingested microplastics per person will greatly decrease, mitigating a potential toxic substance buildup in the body.

3 IMPACTS OF THE SSPET BAN IN AN AIRPORT

3.1 Similarities and Differences

One similarity between the impacts of a water bottle ban in an airport and one in a city is the change in transportation energy. Because airports are usually located near a major city, the average distance items are shipped before they reach an airport is the same as that for a city. Another similarity is that the sale of reusable water bottles will increase for both airports and cities after a ban. The recycling rates of an airport and of a city will likely also be the same.

Since people cannot carry more than 100ml of fluid through airport security, they will obtain all drinking water from the airport rather than carrying it from their homes. Additionally, since people tend to stock up on water before a flight, the amount of water taken from an airport on a regular basis will be much greater than that of a city. As opposed to a city, we will assume that the amount of people purchasing 1 liter bottles

will be negligible because it will be inconvenient for most people to fit such large bottles in their luggage. No SSPET will be purchased from other places as well.
In an airport, there will be little change in tap water used because people will primarily rely on free water from fountains, whereas in a city people will primarily rely on tap water from their homes. The amount of people specifically using free water in an airport will increase more significantly than it will in a city because many will receive water from drinking fountains. Furthermore, the increase in purchases of flavored drinks in an airport will be much higher than the increase of purchases in a city, because water accessibility is substantially reduced in an airport. The amount of people obtaining tap water from airport cafes and restaurants will also increase because there is no option for people to drink tap water from their homes, and this will cause a slight change in tap water used.

3.2 Adjustments to Model

Because our financial model predicted the final cost for one person living in a city with a SSPET ban, it cannot be adapted to an airport. This is due to aspects like water bills, the purchasing of large bottles, and SSPET purchased in another city being not applicable to the individual person in an airport. Instead, we decided to look from the perspective of an airport, including all its businesses, and model the change in revenue for an airport before and after an SSPET ban.

Variables for Airport Financial Model

- N: the number of people who pass through the airport every month
- C_{bottle_i}: the average price an airport pays to supply SSPET per month
- P_{buy}: the percentage of people who buy a reusable water bottle at an airport
- P_{buy_i}: the percentage of people who bought reusable bottles before an SSPET ban
- $C_{reusable}$: the average price of a reusable water bottle at an airport
- P_{soda_f}: the percentage of people who buy flavored drinks at an airport
- P_{soda_i}: the percentage of people who bought flavored drinks before an SSPET ban
- $P_{nonplastic}$: the percentage of people who buy water in alternate, non-PET bottles
- A: the area of an airport in km^2
- F: the number of drinking fountains in the airport

We would administer a survey to all passengers on a randomly selected group of flights to determine P_{buy}, P_{buy_i}, P_{soda_f}, P_{soda_i}, and $P_{nonplastic}$. The survey questions are listed in Section 2.1 (Necessary Information to Create a Model).

Airport Revenue Before the SSPET Ban

The airport earned money from selling SSPET. Before the SSPET ban was implemented, SFO sold 10,000 SSPET per day. The airport serviced about 56 million people in 2017, which means that on average, 150,000 people passed through the airport daily. Hence, 1 out of every 15 people purchased a water bottle in one day at SFO. To generalize the amount of water bottles sold per month to any airport, we divided the number of people who pass through per month by 15. The number of water bottles bought monthly is multiplied by the cost of a single water bottle, which is $5.00 on average, to calculate how much an airport earns per month. *(Source: McCartney).* However, to find the net revenue generated by an airport, we must subtract the cost an airport pays to provide water bottles for consumers every month. Putting it all together, we get this:

$$\text{Net revenue before} = \frac{N}{15}(5) - (C_{bottle_i}) = \frac{N}{3} - C_{bottle_i}$$

Airport Revenue After the SSPET Ban

1. *Reusable bottles purchased*: Determine the revenue earned from people who did not initially buy reusable bottles at an airport, but who buy reusable bottles after the ban instead of SSPET. To do this, we multiplied the percentage of people who bought a reusable bottle multiplied by the number of people who pass through the airport monthly, and then multiplied that by the cost:

$$\text{Revenue from reusable bottles} = \boldsymbol{N \cdot \left(P_{buy} - P_{buy_i}\right) \cdot C_{reusable}}$$

2. *Other beverages purchased*: Determine the revenue earned from people who would not have initially bought other drinks, but who buy other drinks after the ban instead of SSPET. We do this by subtracting the percentage of people who previously bought flavored drinks from the percentage of people who plan to buy flavored drinks after the ban. Then multiply this by $\boldsymbol{N}$ and multiply this by the average cost of a soda or flavored drink. The average cost of a standard, 16.9oz SSPET is $1.45, yet on average it costs $5.00 at an airport (SOURCE????). The average cost of a 20oz coca-cola drink is $1.99. Based on airport prices for water bottles, the average average price of a 20oz coca-cola is adapted to $5.80, and we will generalize this to all flavored drinks. We get this equation:

$$\text{Revenue from other drinks} = \boldsymbol{N \cdot \left(P_{soda_f} - P_{soda_i}\right) \cdot 5.80}$$

3. *Revenue from single-use bottled water in alternative packaging*: Airports may work with smaller vendors to stock water in paper or glass bottles. We assume that airports will only start supplying non-PET water bottles after enacting an SSPET ban to appease consumers. The average cost of one 16.9oz boxed (paper) water bottle is $2.06, and adjusting this price to an airport according to SSPET airport prices, the average cost will be $7.10. We will generalize this price to all non-PET water bottles.

$$\text{Revenue from water in alternative packaging} = \boldsymbol{N \cdot P_{nonplastic} * 7.10}$$

4. *Cost to install and maintain drinking fountains*: Determine the amount of new fountains installed in the airport. To avoid complaints about water accessibility, airports will have to install additional water fountains. SFO, which already follows the SSPET ban, has 100 free water fountains over an area of 21.07 km^2. This means that there is 1 water fountain per 0.2107 km^2. Using this standard as a baseline, the approximate number of new water fountains each airport will have to install is calculated by

$$\text{Cost for drinking fountains} = \boldsymbol{(1100 + 850)\left(4.74(A) - F\right)}$$

Note: the acceptable ratio of water fountains to square kilometers may differ for a less crowded airport.

The average cost to install a water fountain in a public space is $1100, and the average cost to install and water refill station is $850. This is summed and multiplied by the number of water fountains to be installed, and the total amount is subtracted from the revenue after the ban.

Combining our expressions for revenue before and after the SSPET ban gives us this:

$$\begin{aligned}\text{Net monthly revenue} = {} & \boldsymbol{N\left(P_{buy} - P_{buy_i}\right)C_{reusable} + N\left(P_{soda_f} - P_{soda_i}\right)(5.80)} \\ & \boldsymbol{- (2300 + 850)(4.74A - F) + N(P_{nonplastic}(7.10) - (\frac{1}{3}N - C_{bottle_i})}\end{aligned}$$

In our environmental model, the number of people who rely on water fountains is negligible, but in airports, everyone will rely on water fountains. We do not need to consider SSPET bought from other cities nor plastic water bottles greater than 1 liter. We will also need to replace the population of a city with the number of passengers serviced by an airport. It is expected that the bottle recycling rate will be higher for an airport due to the visibility of recycling bins and fewer tendencies to litter. Accounting for these factors, our environment model will change moderately but will hold the same foundation.

4 DISCUSSION

4.1 Policy Changes

To enhance the benefits of a SSPET ban in Concord and other cities, it would be ideal to do frequent public service announcements and highlight research that reassures people that tap water is safe to drink, as some people are distrustful of tap water purity in the USA. This will help increase tap water consumption and decrease the number of people buying bottled water from other cities, as well as reduce public discomfort regarding the ban. It would be beneficial to increase the sales of 5-gallon, or 18.92 liter water bottles—encouraging people to buy one large jug of water rather than many 1 liter bottles—because many 5-gallon bottles are reused, and the recycling rate for 5-gallon bottles is higher *(Source: International Bottled Water Association).* Additionally, cities should have a sale on reusable water bottles for a short time period after first enforcing the SSPET ban to make reusable bottles more accessible to the community and help the community adjust to the ban. To offset the cost of installing additional water fountains, the city could implement a soda tax. This has the added benefit of also discouraging residents from consuming soda. San Francisco's Soda and Sugary Beverages Tax measure brought in around $10 million, more than enough to pay for the additional water fountains.

4.2 Changes to Model

A drastic change for the SSPET ban in Concord is to ban all PET bottles under 1 liter containing any beverage. While the argument for limiting the ban to only water was the notion that businesses shouldn't profit off a free resource, some see the narrow scope of the ban as encouragement to drink more sugary, flavored drinks. Others claim that banning only water bottles will have an insufficient effect on the environment. Therefore, due to concern for public health and environmental impact, it would be practical to extend the PET water bottle ban to all PET bottles less than 1 liter in size. If this new suggested ban was enacted in Concord, many people will start buying alternate water packaging, such as aluminum cans, boxed or paper water bottles, or glass bottles. This will lead to environmental benefits because there will be less material wastage. The recycling rate for aluminum cans is 49.8% and for glass containers is about 33.2%, both of which are than the higher 29.2% recycling rate for PET bottles. However, the production and transportation costs for these alternate packaging forms will increase. For our impact models, we would no longer have to consider the purchases of flavored drinks under 1 liter. The manufacturing and transportation costs for these alternate packaging forms will increase significantly, and we would have to account for the increase in people travelling to other cities for beverages as well.

4.3 Generalizations

Our model is generalizable to larger communities — in fact, it would be more accurate for larger communities. Larger communities are more of a closed system; for example, it would be more difficult to acquire SSPET from other areas for regular use if SSPET were banned in a state. However, our environmental model does not take into account environmental differences — such as energy consumption or separate water sources or water quality — between different parts of the community. For larger communities where conditions are different in different places, it may misrepresent the benefits of banning SSPET. Likewise, our economic model does not take into account economic differences in a region, such as different taxes and or political policies, and there may be inaccuracies in the predicted financial impacts of banning SSPET. Because an SSPET ban in a larger community would be backed by more political power, other policies regarding water use are likely to change. For instance, the way water bills are imposed and amount of water bills may change, as well as the price of 1 liter water bottles or the accessibility to sodas. Furthermore, as large regions such as states or countries adopt an SSPET ban, water bottling companies will rely on using alternative packaging to make a profit, which was not considered for a smaller city under the assumption that bottling companies will not change their manufacturing process to cater to a single city. An extension of our environment model would be to model the energy consumption, waste, and landfill of alternative packaging such as glass, aluminum or paper. Our model would be similarly applicable for a community that is slightly larger than a city, but would have to change for a region as large as a state or country.

4.4 Limitations

Our representation of the impacts of banning SSPET is not perfect. In an ideal world, we would be able to come up with a magical set of processes that rely on easy-to-obtain information, account for all possible impacts, and are highly accurate. Unfortunately, even something that seems as simple as a ban on single-serving PET bottles has a great number of effects on many facets. One main limitation of our model is the quantity of assumptions we made and our dependency on the results of a census for estimations. Another weakness is the lack of connection between each of our models. One possible way to combine them would be to apply each model to a large number of communities, calculate the z-scores, and use a weighted sum of z-scores as a way to represent overall impact. However, we decided to keep the models separate because the impacts they represent may be of differing importance to different communities. That being said, the strength of our set of models lies in its ability to capture multiple key impacts of the SSPET ban.

5 News Article

With the growing use of Single Serving PET (SSPET) bottles in the United States, many are concerned about the potential long-term consequences of disposable plastic bottles. In an effort to reduce their plastic consumption, San Francisco, California and Concord, Massachusetts have both implemented SSPET bans, with Concord banning SSPET bottles 1 liter or smaller. While the regulation of SSPET bottles is well-intentioned, and certainly reduces plastic waste, new mathematical models developed by high school students suggest that such bans do not come without other environmental and financial sacrifices.

To start, two newly-developed mathematical models use electrical energy and waste levels to demonstrate the environmental impacts of a SSPET ban in a city. The electrical model approximates the electrical energy required to produce a city's drinking water based on the electrical energy of various water sources, such as SSPET bottles (later affected by the ban), large water jugs, soda bottles, home tap water, drinking fountains, and reusable water bottles. The model compares the initial electrical consumption (before the SSPET ban) with the final electrical consumption (after the SSPET ban), thus demonstrating how electrical consumption is affected by the SSPET ban. The waste model functions similarly, showing the change in waste levels of a city after a SSPET ban. Of course, not all water sources are utilized equally within a population, and the percent of water that comes from each water source varies among cities; therefore, both models utilize a set of variables whose values will be dependent on city residents' responses to a survey about water usage. Nevertheless, by plugging in approximate values for the models, developers have found that electrical energy will increase while waste will decrease with the SSPET ban.

Furthermore, in the financial model developed by students, which accounted for cost of water fountains, larger jugs of water, tap water, and other modes of water consumption, it was found that in the short term, the cost per capita would actually increase with the ban of SSPET. This price increase can be attributed to the high price of installing water fountains and maintaining them. However, after a couple of years, the cost per capita would likely break even —or even decrease — as, over time, no new water fountains would need to be installed. As the students' model addresses population, it was found that residents in smaller cities like that of Concord, Massachusetts and also our very own city would face a higher increase in cost than that of bigger cities because the individual cost would be greater in taxes.

Before implementing an outright ban on 1 liter SSPET bottles, cities must consider the potential implications of their actions. For example, while we might reduce plastic waste in the form of SSPET bottles, we might also encourage the waste of 5-gallon polycarbonate jugs and soda bottles. A general case study of San Francisco and Concord suggest that, in terms of electrical consumption, financial weight, and waste production, implementing the SSPET ban on 1 L bottles might only be beneficial in terms of waste. However, without concrete statistics regarding cities' water consumption, it is possible that a SSPET ban might have other implications unaccounted for in the model.

A Appendix A: Calculation of Energy for the Production of SSPET

(i) **Collecting water**: Although there is not much specific information on the energy intensities of collecting water from bottled water companies, there is information on municipal water collection in California. California is broken up into North and South because the amount of energy required for the two regions varies drastically. To model the water intensity for bottled water, we will look at the energy needed in Southern California (the "High" values in the following table) because Southern California is generally farther from water supplies which matches the majority of water bottled companies.

Table 2: Range of Energy Intensities for Water Use Cycle Segments

	Range of Energy Intensity $\frac{\text{kWh}}{\text{MG}}$	
Water-Use Cycle Segments	**Low**	**High**
Water Supply and Conveyance	0	14000
Water Treatment	100	16000
Water Distribution	700	1200
Wastewater Collection and Treatment	1100	4600
Wastewater Discharge	0	400
Recycled Water Treatment and Distribution	400	1200

Using dimensional analysis, we can determine the amount of energy needed to collect one liter of water:

$$\frac{\mathbf{14000}\ \text{kWh}_e}{\text{MG}}\frac{1\ \text{MG}}{\mathbf{10^6}\ \text{gal.}}\frac{1\ \text{gal.}}{\mathbf{3.78541}\ \text{L}} = \mathbf{0.003698}\ \text{kWh}_e \text{ per L}$$

The amount of energy required for transportation in this case is included in the data as it is the energy required for both water supply and conveyance, which includes transportation.

(ii) **Manufacturing PET bottles**: Because the energy required to produce PET resin is approximately 70-83 MJ kg_{th}^{-1}, we'll take the average (76.5 MJ kg_{th}^{-1}) to find the average amount of energy required to produce one bottle. This number is also in thermal units while most other energy measurements use electrical units, so we will convert to kWh_e. Conversions from thermal to electrical have an efficiency of 0.33 or essentially 3kWh (thermal) = 1 kWh (electrical). Also, the energy required to blow PET bottles from resin is approximately 20 MJ kg_{th}^{-1}. Furthermore, we assumed that the amount of PET resin in one SSPET is 9.89g. Finally, we know that each bottle contains 0.5 L, so we can find the amount of energy needed to manufacture the PET resin used by 1 L of water from SSPET:

$$\left(\frac{\mathbf{76.5}\ \text{MJ}_{th}}{\text{kg}} + \frac{\mathbf{20}\ \text{MJ}_{th}}{\text{kg}}\right)\frac{\mathbf{1}\ \text{kWh}_{th}}{\mathbf{3.6}\ \text{MJ}}\frac{\mathbf{1}\ \text{kWh}_e}{3\ \text{kWh}_{th}}\frac{1\ \text{kg}}{1000\ \text{g}}\frac{\mathbf{9.89}\ \text{g}}{1\ \text{bottle}}\frac{1\ \text{bottle}}{0.5\ \text{L}} = \mathbf{0.1767}\text{kWh}_e \text{ per L}$$

Energy required for transportation is negligible as most major bottled water companies produce bottles in their own factories and the PET resin would not have to travel very far meaning that energy required would be low.

(iii) **Water processing**: Besides private labels that produce bottled water, the 4 water companies with the largest market shares are Dasani, Aquafina, Glacéau Smart Water, and Nestlé. By observing the treatment methods used by these 4 companies, we can construct a somewhat representative idea of what methods are used in water treatment in most water bottles. These methods are all publicly reported, but more exact information about their processes is not publically available. The following table shows the amount of energy needed for different water treatment techniques:

Table 3: Energy Requirements for Water Treatment Methods.

Treatment technique	Energy use (kWh_e/million liters)	Data source
Ozone		
Pre-oxidation (pre-treatment)	30	SBW Consulting, Inc (2006)
Disinfection	100	SBW Consulting, Inc (2006)
Ultraviolet (UV) radiation (medium pressure)		
Bacteria	10	SBW Consulting, Inc (2006)
Viruses	10–50	SBW Consulting, Inc (2006)
Microfiltration/ultrafiltration	70–100	SBW Consulting, Inc (2006)
Nanofiltration (source TDS = 500–1000 ppm)	660	AWWA (1999)
Reverse osmosis		
Source TDS = 500 ppm	660	AWWA (1999)
Source TDS = 1000 ppm	790	AWWA (1999)
Source TDS = 2000 ppm	1060	AWWA (1999)
Source TDS = 4000 ppm	1590	AWWA (1999)
Seawater desalination (reverse osmosis)	2500–7000	National Research Council (2008)

The calculation for energy in this step will be a combination of all the different techniques used by the 4 companies mentioned earlier because of the lack of public information on water bottle processing and treatment.

We added up the energy needed to perform each treatment, as most bottled water companies utilize multiple treatment types to filter their water:

$$\boldsymbol{E}_{\text{ozone}} + \boldsymbol{E}_{\text{ultraviolet}} + \boldsymbol{E}_{\text{filtration}} + \boldsymbol{E}_{\text{reverse osmosis}}$$

$$= (30+100) + \left(10 + \frac{10+50}{2}\right) + \left(\frac{70+100}{2} + 660\right) + \Bigg(\frac{660+790+1060+1590}{4} + \frac{2500+7000}{2}$$

$$= \mathbf{6540}\ \text{kWh}_e \text{ per million L} = \mathbf{0.006540}\ \text{kWh}_e \text{ per L}$$

(iv) **Bottling, testing, and labeling**: On average, a water bottling machine can clean, fill, and seal around 15000 bottles/hour and requires 0.006 MJ_{th} per bottle. More high volume machines can label around 36,000-42,000 bottles per hour using around 0.008 MJ_{th} per bottle. Therefore the total energy required to bottle, test and label is 0.014 MJ $_{th}$ per bottle. Using this, we can find the energy per L:

$$\frac{\mathbf{0.014}\ \text{MJ}}{1\ \text{bottle}} \frac{1\ \text{kWh}_{th}}{\mathbf{3.6}\ \text{MJ}_e} \frac{1\ \text{kWh}_e}{3\ \text{kWh}_{th}} \frac{1\ \text{bottle}}{0.5\ \text{L}} = \mathbf{0.000259}\ \text{kWh}_e \text{ per L}$$

(v) **Transportation**: For transportation from production facilities to the consumer, we can expect 3 main modes of transportation: cargo boats, railroad, and truck (airplanes are not commonly used to transport water). (Remember that $\boldsymbol{S}$ is the typical distance SSPET bottles travel from the manufacturing plant to the city). Two of the major international water bottled companies are Fiji (based in Fiji) and Evian (based in France). From Fiji to LA, the most commonly used mode of transportation is through cargo ship with an average distance of 8900km. From France to LA, the distance traveled by rail is 3950km and the average distance traveled by cargo ship is 5670km. For places in different areas of the US, these distances will vary but we can use them as a general estimate for what percent of the distance will be traveled on cargo ship and what percent of the distance will be on rail. Table 3 summarizes the distances:

The total distance is 8900 + 5670 + 3950 = 18520 km. The proportion of the distance that was traveled by cargo ship is $\frac{\mathbf{8900+5670}}{\mathbf{18520}}$ = 0.7867, and the energy needed to travel by cargo ship is:

$$\frac{\mathbf{0.37}\ \text{MJ}}{\text{tons} * \text{km}} \cdot \left(\frac{\mathbf{0.27778}}{\mathbf{1}MJ}\right)\left(\frac{1\ \text{ton}}{\mathbf{907.185}\ \text{kg}}\right)\left(\frac{\mathbf{1.01978}kg}{\text{mass of 1 L SSPET}}\right) = \mathbf{0.00011553}\ \text{kWh}_e \text{ per (L * km)}$$

The proportion of the distance that was traveled on rail is $\frac{\mathbf{3950}}{\mathbf{18520}}$ = 0.2132, and the energy needed to travel by rail is

$$\frac{0.23\ \text{MJ}}{\text{tons} * \text{km}} \cdot \left(\frac{\mathbf{0.27778}}{\mathbf{1}MJ}\right)\left(\frac{1\ \text{ton}}{\mathbf{907.185}\ \text{kg}}\right)\left(\frac{\mathbf{1.01978}\text{kg}}{\text{mass of 1 L SSPET}}\right) = \mathbf{0.000071819}\ \text{kWh}_e \text{ per (L * km)}$$

Table 4: Forms of Transportation for SSPET.

Scenario	Medium truck (km)	Heavy truck (km)	Rail (km)	Cargo ship (km)
Local production	200 (local delivery)	0	0	0
Spring water from Fiji	100 (local delivery)	0	0	8900 (Fiji to Long Beach)
Spring water from France	100 (local delivery)	600 (Evian to Le Havre)	3950 (New York to Los Angeles)	5670 (Le Havre to New York)

Trucks are used to transport SSPET over shorter distances. We can calculate the energy needed to transport 1L of SSPET 1 km. For every gallon of gas used in a single-axle truck filled to full capacity (commonly used to transport water bottles), it can travel 6.5 miles. Each gallon of gas requires 0.2 kWh$_e$ to produce and there are 1.69034km in 1 mile. We assume that the truck is filled up to its maximum capacity, which is 9071.85 kg. We can combine all of this information to give us the energy used to transport 1 L of SSPET for 1 km:

$$\left(\frac{\text{1 truck}}{\mathbf{9071.85}\text{ kg}}\right)\left(\frac{\mathbf{1.01978}\text{ kg}}{\text{mass of 1 L SSPET}}\right)\left(\frac{\text{1 gal. gas}}{\text{6.5 mi}}\right)\left(\frac{\mathbf{0.2}\text{ kWh}_e}{\text{1 gal. gas}}\right)\left(\frac{\text{1 mile}}{\text{1.60934 km}}\right)$$

$$= \mathbf{0.0000021494}\text{ kWh}_e\text{ per (L * km)}$$

If S (the distance a single bottle is shipped before it reaches the consumer) is less than 111.05 km (average distance traveled by a truck), then we assume that the SSPET was only shipped using a truck.

If S is greater than 111.05km, we can assume that the bottle is traveling by a combination of truck, railroad, and cargo ship.

To find the energy per liter, we multiply the energy consumption for each part of the trip by the distance traveled:

$$\begin{cases} \frac{S\cdot 0.0000021494\text{ kWh}_e}{\text{L * km}} & S \leq 111.05\text{ k} \\ \frac{111.05\cdot 0.0000021494\text{ kWh}_e}{\text{L * km}} + (S - 111.05)\left[\frac{0.7867\cdot 0.00011553\text{ kWh}_e}{\text{L * km}} + \frac{0.2132\cdot 0.000071819\text{ km}}{\text{L * km}}\right] & S \geq 111.05\text{ k} \end{cases}$$

This simplifies to the following expression, where E$_{\text{transportation}}$ represents the energy needed to transport 1L of water packaged in SSPET 1 km using a truck.

$$\text{E}_{\text{transportation}} = \begin{cases} \frac{0.0000021494S\text{ kWh}_e}{\text{L * km}} & S \leq 111.05\text{ km} \\ \frac{0.0002387\text{ kWh}_e}{\text{L * km}} + (S - 111.05)\left[\frac{0.00009089\text{ kWh}_e}{\text{L * km}} + \frac{0.00001531\text{ km}}{\text{L * km}}\right] & S \geq 111.05\text{ km} \end{cases}$$

(vi) **Chilling for sale and use** The amount of energy required to keep one liter of bottled water cold for one week is about 0.2 MJ per L. Dimensional analysis gives us the energy in kWh$_e$ per L:

$$\frac{\mathbf{0.2}\text{MJ}}{\text{L}}\frac{\text{1 kWh}_e}{\mathbf{10.8}\text{ MJ}} = \mathbf{0.0185}\text{ kWh}_e\text{ per L}$$

(vii) **Energy used for production of SSPET**: The total energy used to produce 1 L of water packaged in SSPET is the sum of the energies for each component:

$$\mathbf{0.1767} + \mathbf{0.006540} + \mathbf{0.000259} + \text{E}_{\text{transportation}} + \mathbf{0.0185} = \boxed{\mathbf{0.2020} + \text{E}_{\text{transportation}}\text{ kWh}_e\text{ per L}}$$

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