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2019

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

Team Control Number: 10407

Problem Chosen: B

A barrage of small towns and cities have banned the sale of single-serving Polyethylene terephthalate plastic water bottles. Supporters argue that the ban will encourage better environmental practices, while opponents predict a rise in the consumption of unhealthy drinks. Our model makes it clear that, while both sides are correct, the ban will have a net positive impact on many locations.

Part I of our model evaluates the pre-ban beverage consumption habits in a location of any type, regardless of the availability of previous consumer data. Since bottled water currently makes up 22% of fluid consumed in the US, a ban forces consumers to find other sources to stay hydrated.[1]

Part II of our model predicts the shift in consumer habits toward eight beverage types. First, we calculated the redistribution in their consumption by employing a research-based convenience value for each beverage type. Then we adjusted the fluid redistribution rates based on the cost difference between bottled water and the alternative beverage, taking into account consumer tendency to conform to Prospect Theory where losses are valued greater than gains.[2] For the San Francisco Airport, the city of San Francisco, and the town of Concord, the pre- and post-ban data suggests a significant increase in tap water, soda, tea, and coffee consumption when bottled water is no longer an option. In fact, at the airport, the daily consumption of tap water increased by 10,600 L, while the consumption of Coffee, Tea, and Soda increased by 3,500, 1,290, and 3,700 L, respectively. The other beverages, dairy, juice, and alcohol, showed minimal change due to their costliness and inconvenience.

Part III employed these changes in beverage consumption to predict downstream impacts on the community. We expressed the impact of each beverage as a vector with three components (environmental, economic, and health) scaled by the change in the beverage's consumption following the ban. To obtain the overall impact of the ban in a given location, we calculated the distance from a "zero impact plane" to the terminal point of a vector of each beverage's impacts. For each of the three locations, the overall impact was positive, affirming the legislature's intentions. We calculated per 1000 citizen impact values of 47, 46, and 34, for the San Francisco Airport, the town of Concord, and the city of San Francisco, respectively. Although each location yielded a negative health impact, the positive environmental and economic impacts dwarfed the minimal health losses.

Finally, *Part IV* describes how increasing the convenience of tap water by installing water fountains, among other things, can increase the benefits while mitigating the consequences.

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[1] United States, Congress, Food Surveys Research Group. *Beverage Choices of U.S. Adults*
[2] Haim Levy, Moshe Levy, "Experimental test of the prospect theory value function

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THE WATER BOTTLE BATTLE

You're out in public and suddenly you're thirsty. What is your immediate instinct? Buy a bottle of water, right? Not so fast!

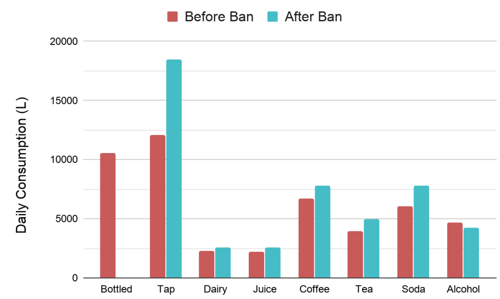
In recent years, a barrage of small towns and cities have implemented a ban on the sale of single-serving plastic water bottles. Until now, the effects of this ban have not been properly understood, with proponents arguing that the ban will spur better environmental practices, and opponents predicting a rise in the consumption of unhealthy drinks. While it is now clear that both sides are correct, our research confirms an overall positive impact of the proposed ban.

Although the ban specifically targets Polyethylene terephthalate (PET) bottles less than or equal to one liter in volume, containing only plain water, its effects are far-reaching. Our team, working for the COMAP High School Mathematical Contest in Modeling, analyzed both the changing consumer drinking habits resulting from the ban and how these changes impact the environment, economy, and public health.

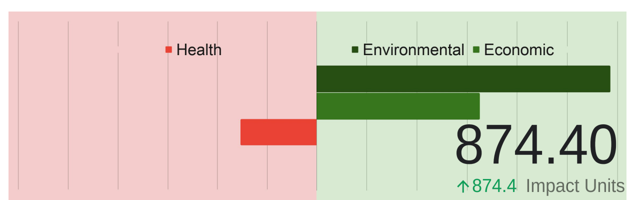
Our team developed a model, applicable to any type of location, whether previous consumer data is available or not. This makes it perfect for any city or street corner, large or small. Bottled water currently makes up 22% of fluid consumed in the US, therefore, when bottled water is banned, consumers must find other sources to stay hydrated. Therefore, we began our model by predicting the shift in consumer habits for eight drink categories.

Of course, both the convenience and cost of alternative drinks are important in our analysis; hence, we combined these two factors into a single model to examine the changing purchasing habits at any location.

For Concord, Massachusetts, the pre- and post-ban data is conclusive, suggesting a significant increase in tap water, soda, tea, and coffee consumption when bottled water is no longer an option.



Next, we examined the impacts of each drink given its predicted change in volume consumed. Our results were conclusive: a single-serve PET water bottle ban is beneficial for the environment and the economy, while only slightly negatively affecting public health.



Our research suggests that banning the sale of plastic water bottles could help many communities: from big cities like San Francisco to small towns like Concord. Yet these bans are not the end of the story.

Our town should consider the benefits of banning the sale of PET water bottles, as well as other actions we can take as a community to mitigate negative health impacts while making room for positive change. From the global community to our little town, humanity is facing adversity and every decision has an impact on our future. Next time you're thirsty, think about that.

\- Team # 10407

INTRODUCTION

The idea of banning the sale of single-use plastic water bottles has been met with controversy. The ban has been tested in communities such as Concord, Massachusetts; San Francisco; and the San Francisco Airport. People in each of these communities have cited various impacts of the ban, both pros, and cons. Thus far, all impacts mentioned by the citizens have come from a subjective perspective. Because of this, it would be useful to have a mathematical model to calculate these impacts in an objective manner and to examine whether the ban would be beneficial to a certain community. This idea of a 'community' could span almost anything, from a whole nation, down to an airport, so it is important that such a model could adjust to different locations.

Based on our research and assumptions about the problem, the most direct impact of banning the sale of single-use plastic water bottles is the change of citizens' drinking patterns. Thus, this is how we began our examination. These effects must be examined and quantified. Once the direct impacts are understood, the secondary impacts can be examined to evaluate the comprehensive effect of the ban, as a change in drinking patterns is not inherently good or bad without finding the effects of this change. For example, a ban on plastic water bottles may directly increase sugary drink consumption, therefore indirectly hurting public health while also stimulating the economy. With the goal to model the positive and negative impacts of a ban, it is unnecessary to consider the severity of impacts of beverages before and after the ban, only the change in impact. Therefore, only the change in beverage consumption is necessary to determine the impacts.

Once these effects are quantified, community-specific regulations can be suggested and implemented to minimize negative impacts and maximize positive impacts. For example, in communities where carrying a reusable water bottle or simply holding a cup is convenient, a recommended increase in the availability of water fountains could prevent the sale of extraneous sugary drinks and beverages in plastic bottles. Further, in communities where sodas are popular, metal or reusable straws could be offered to decrease the environmental impact of these drinks. Using our model, we can find which adjustments to a community will exhibit the most positive impact. In short, we have created a model that can be used to find the benefits and harms of a PET water bottle ban and optimize it as needed.

ASSUMPTIONS AND JUSTIFICATIONS

1. **Assumption:** The impacts of a product have a negligible effect on an individual's purchasing decisions.

   Justification: While most consumers would like to support sustainable products, according to the Harvard Business Review, very few people actually allow this to impact their purchasing habits.[3] This applies similarly to other impacts such as the economy.

2. **Assumption:** The consumption rate of daily fluids is highly regular and independent of specific personal characteristics.

   Justification: It is impossible to predict an average person's exact consumption rate of fluids each day because it depends on various factors. Nevertheless, regression toward the mean and the sheer number of people present at a location allow us to assume that the volume of fluids consumed is nearly constant and equal to the population multiplied by the average consumption per person.

3. **Assumption:** There are no significant non-PET single-serving water bottle choices, and therefore the effects of these drinks are negligible and can be ignored.

   Justification: According to the British Plastics Federation, the vast majority of disposable water bottles are manufactured out of PET.[4]

4. **Assumption:** The volume of fluid required by the consumers within a location is directly proportional to the population of those consumers (ie. citizens, travelers in an airport) and is not impacted by the types of beverages preferred.

   Justification: Humans need to consume a relatively similar volume of fluid each day.[5]

5. **Assumption:** The variation of the price of beverages in different locations affects all beverages proportionally.

   Justification: We assume this to maintain consistency in our model for the sake of the HiMCM competition.

6. **Assumption:** Drink options are as chosen: Bottled Water, Tap Water, Soda, Coffee, Dairy, Tea, Juice, alcohol.

   Justification: These options are derived from a USDA study entitled *Beverage Choices of U.S adults*.[6] We are considering water fountains and water from reusable bottles as tap water.

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[3] White, Katherine, et al. "The Elusive Green Consumer."
[4] BPF. "PET Plastic Bottles - Facts Not Myths."
[5] Carter, R., et al. "Human Water Needs."
[6] United States, Congress, Food Surveys Research Group. *Beverage Choices of U.S. Adults*.

7. **Assumption:** A fluid drinking day is 16 hours.

   Justification: We define a fluid drinking day as the portion of the day where someone is awake and can drink fluid. We assume the average person sleeps 8 hours.

8. **Assumption:** Fluid is consumed by an individual at a constant rate throughout the fluid drinking day.

   Justification: This can be assumed as non average cases balance out because of regression toward the mean. We are examining the phenomenon on amply large populations.

9. **Assumption:** The population of a location is not impacted by beverage consumption habits.

   Justification: Changes in population only occur from deaths, births, or the movement of people. We assume a change in drinking habits would not result in any of these cases.

10. **Assumption:** The penalties for selling PET water bottles under the ban are ample to prevent illegal sales in their entirety.

    Justification: This is the intention of the legislature and any assumption as to otherwise would undermine the validity of the ban and add a layer of uncertainty to our solution.

MODELS

Part I — Modeling the Consumption of Fluids Prior to a PET Ban

The goal of *Part I* is to determine the percentage by volume of the total consumed fluid of each drink before the ban on the sale of single serving PET water bottles is introduced. This percentage will be known as the Base Rate for a given beverage in a given place.

The clear starting point for obtaining this data was the USDA's National Health and Nutrition Examination Survey on beverage sales. This provided insight into the volume of each type of beverage consumed by the average American each day. This could then be converted into a Base Rate by dividing the volume of the specific fluid by the total fluid consumed by the individual.

$$Personal\ Base\ Rate\ =\ \frac{Personal\ Daily\ Beverage\ Intake}{Personal\ Daily\ Fluid\ Requirement}$$

Generalizing to the population, this Base Rate acts as a proportion of the amount of a specific beverage consumed to the total fluid consumed. Although each individual may have different habits, regression toward the mean allows our model to overlook these irregularities. Therefore:

$$Base\ Rate\ =\ Personal\ Base\ Rate$$

For example and later reference, the national Personal Daily Beverage Intakes and Base Rates for specific drinks are as follows, where the Personal Daily Beverage Requirement is 2.55 liters.

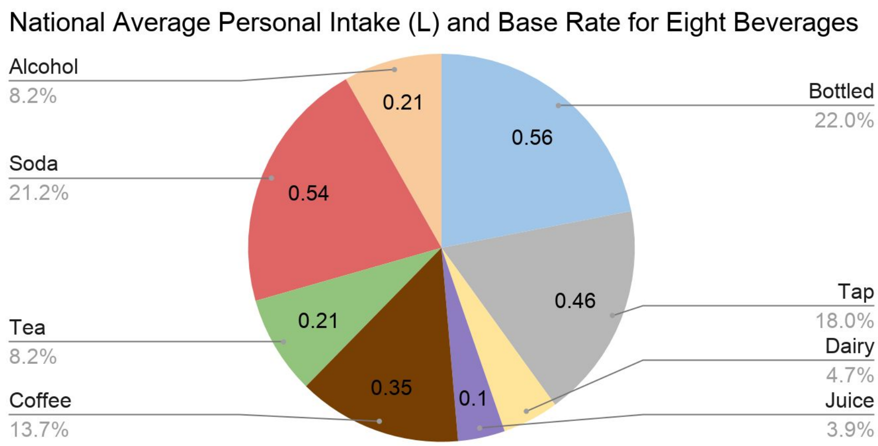


Figure 1: National Intake and Base Rate for Beverages[7]

The USDA provides data on the daily intake of water only as a whole, so this value must be broken down into bottled and tap variants. *BioMedCentral Public Health* provides a volumetric breakdown of the quantity of each variant of water consumed daily by the average individual. These figures are then applied to the Personal Daily Beverage Intakes of water to calculate the Base Rates of bottled and tap water separately.

Next, these Base Rates must be adjusted to fit a specific location, such as a state, city, airport, or shopping mall. Hence, *Models 1 and 2*.

Model 1 — A Simple Solution Given Reliable Consumption Data at Location

Of course, the statistics of consumption at a given location will vary from the national averages based on a plethora of factors. For the ease of modeling, these factors will all be combined into a scalar, known as Convenience. Luckily, *Model 1* can overlook the specific Convenience values for each beverage type for reasons to follow.

When consumer data on the specific location is available, a simple model can be used to examine the Base Rates at a given location. This data will assume a table similar to *Figure 1: National Intake and Base Rate for Beverages*. Currently, this model can be used only infrequently, but as more consumer data is recorded in the coming years as per our recommendations below, *Model 1* will assume a greater role.

For small locations such as airports or shopping malls, this data can be collected by recording reported sales of beverages by vendors. Knowing price per volume of various beverage types, sales revenue can be converted to volume consumed which can be converted to a Base Rate. For larger locations such as cities and states, grocery and restaurant sales can be used to estimate consumption for some beverages, while others can be extrapolated.

[7] United States, Congress, Food Surveys Research Group. *Beverage Choices of U.S. Adults*

Importantly, consumption of non-bottled water is difficult to measure as water fountains and taps do not usually record the volume consumed from them. Here, we must either use the national base rate for tap water or apply the more rigorous principles discussed in *Model 2*.

As the volume of each beverage is already known in this *Model*, the base rate does not need to be converted back into volume. Rather, it will become useful when approximating the changes following the PET ban in *Part II*.

Model 2 — Adapting to a Novel Location

To adapt to novel locations, a more general model must be developed that is independent of previous data. The myriad of factors mentioned in *Model 1* that can determine purchasing habits can be reduced to two main factors: Cost and Convenience. As the cost variation from the national average of each beverage at a location is consistent across all types of beverages, as stipulated in *Assumption 6*, Cost can be overlooked when determining the new Base Rates. Therefore the remaining factors can be simplified into a variable known as Convenience.

Each beverage has a Convenience value, ranging from 1 to 10, at a given location that reflects the increase or decrease in its consumption at this location. This takes into account desire, availability, and other factors related to the convenience of purchasing said beverage. For example: in colder cities people may be more likely to consume warm drinks and in younger communities people may be more likely to consume caffeinated drinks. The base rate can be adjusted by multiplying it by a Convenience scalar as shown:

$$Unmapped\ Locational\ Base\ Rate\ =\ Convenience\ *\ National\ Base\ Rate$$

It is important to note the new base rates have to add up to 100. The convenience rates can be adjusted freely but after these adjustments, the Base Rates that they modify must be remapped in order to sum to 100. The values are remapped to a sum of 100 by dividing each one by the group's sum and multiplying by 100.

$$\begin{aligned} Sum\ =\ & Unmapped\ Locational\ Base\ Rate_{bottled}\ +\ Unmapped\ Locational\ Base\ Rate_{tap} \\ & +\ Unmapped\ Locational\ Base\ Rate_{dairy}\ +\ Unmapped\ Locational\ Base\ Rate_{juice} \\ & +\ Unmapped\ Locational\ Base\ Rate_{coffee}\ +\ Unmapped\ Locational\ Base\ Rate_{tea} \\ & +\ Unmapped\ Locational\ Base\ Rate_{soda}\ +\ Unmapped\ Locational\ Base\ Rate_{alcohol} \end{aligned}$$

It follows that, for an individual beverage:

$$Mapped\ Locational\ Base\ Rate\ =\ \frac{Unmapped\ Locational\ Base\ Rate}{Sum}\ *\ 100$$

While initially, the Convenience values may be mere educated estimations, over time the values can be refined. Simple surveys within a location could produce more accurate estimations of Convenience and therefor a more accurate Locational Base Rate. For example, passengers could be surveyed with questions, such as:

"How many sodas have you purchased at the airport today?"

Or:

"Have you used the water fountain at the airport today?"

Now, the Locational Base Rate is known, but the volume of each type of fluid consumed daily is unknown. As the Mapped Locational Base Rate is a percentage of the total fluid required that is consumed in the form of the specific beverage, simply multiplying it by the Daily Requirement provides the Daily Intake:

$$Mapped\ Locational\ Base\ Rate\ *\ Daily\ Requirement\ =\ Daily\ Intake$$

By substitution:

$$100\ *\ \frac{Convenience\ *\ National\ Base\ Rate}{Sum}\ *\ Daily\ Requirement\ =\ Daily\ Intake$$

In *Part III*, this volumetric figure of Daily Intake prior to the PET ban will be used in conjunction with the post-ban Daily Intake, modeled in *Part II*, to model the effects of the PET ban.

Solution — Beverage Volumes Consumed at the San Francisco Airport

Applying *Model II* to the San Francisco Airport, Convenience values can be approximated for the initial iteration and updated after survey data is collected. Here, initial Convenience values were assumed with a brief explanation provided. Over time, surveys, as discussed in *Model 2*, can be used to optimise the Convenience values.

Item	Convenience (0 - 10)	Explanation of Convenience	National Base Rate (%)	Unmapped Locational Base Rate (%)
Water	-	-	-	-
Bottled	4	Accessibility of water fountains competes with bottled water	22 [8]	88
Tap	6	Water fountains are quick and accessible for travelers in a hurry	18 [9]	108
Dairy	1	Increases need to use airplane bathrooms which are undesirable	4.7	4.7
Juice	3	Air conditioning decreases	3.9	11.7

[8] Drewnowski, A., Rehm, C.D. & Constant, F. Water and beverage consumption among adults in the United States:
[9] Drewnowski, A., Rehm, C.D. & Constant, F. Water and beverage consumption among adults in the United States:

		desire for cold drinks		
Coffee	8	Extended Travel Requires Caffeine	14	112
Tea	3	Tea Requires Time to Brew	8.2	24.6
Soda	3	Air conditioning decreases desire for cold drinks	21	63
Alcohol	3	Alcohol inhibits efficiency while traveling	8.2	24.6

Next the sum of the Unmapped Locational Base Rates must be calculated:

$$88 + 108 + 4.7 + 11.7 + 112 + 24.6 + 63 + 24.6 = 436.6$$

Then, applying this equation for each individual beverage,

$$Mapped\ Locational\ Base\ Rate = \frac{Unmapped\ Locational\ Base\ Rate}{436.6} * 100$$

the Mapped Locational Base Rates are as follows:

Item:	Bottled	Tap	Dairy	Juice	Coffee	Tea	Soda	Alcohol
(%)	20.0	24.7	1.08	2.68	25.7	5.63	14.4	5.63

Next, this must be converted to the total volume of each drink consumed in the airport. This presents a challenge: calculating the Daily Requirement of the airport. According to the *Financial Times*, the average traveler at San Francisco Airport spends 2.22 hours on site.[10] According to a San Francisco Airport press release[11], the airport saw 55.8 Million Passengers in 2017 which averages to 153,000 passengers per day. The airport also contains 30,000 workers working a standard 8 hours per day.[12] This calculates to a weighted average time a person spends at the airport per day as follows:

$$\frac{2.22\ hours/passenger\ (153{,}000\ passengers) + 8\ hours/worker\ (30{,}000\ workers)}{183{,}000\ people} = 3.2\ hours/person$$

Since San Francisco Airport visitors only spend a fraction of their Drinking Day at the airport, they will only consume a fraction of their required fluid. These fractions are equal, giving the following proportion:

$$\frac{3.2\ hours}{16\ hours} = \frac{?\ l}{2.55\ l}$$

[10] Weinland, Don. “Airport Retailers Look to Make Every Minute Count.”
[11] “Community.” *SFO Connect*, https://www.sfoconnect.com/community.
[12] Community.” SFO Connect, https://www.sfoconnect.com/community.

This yields an average 0.51 Liters per person consumed. Given that on average, 183,000 people consume fluids at San Francisco Airport every day[13,14], 93,330 Liters are consumed at the airport each day. Multiplying this by the Mapped Locational Base Rates and dividing by 100 provides the following estimations of the volume of each type of beverage consumed at San Francisco Airport each day:

Item:	Bottled	Tap	Dairy	Juice	Coffee	Tea	Soda	Alcohol
(L)	18,700	23,100	1,010	2500	24,000	5,250	13,400	5,250

While these figures seem incredibly large, their distribution makes intuitive sense, suggesting that our model is accurate within reason. Of course, these values will become more accurate over time as convenience values are tuned.

Part II - Modeling the Consumption of Fluids After a PET Ban

The objective of *Part II* is to predict the theoretical consumption of beverage types after the ban of PET water bottles. As stated in *Assumption 4*, the fluid requirements of a population are constant regardless of the means of their consumption. Further, as stated in *Assumption 10*, the number of people at a given location will not vary after the ban of PET water bottles is enforced. In combination, it is extrapolated that the fluid requirements of people at a location will not change following the introduction of the ban. Therefore, the volumes consumed from PET water bottles must be redistributed to other beverages in order to maintain a constant Daily Requirement. This presents the challenge of redistribution. Additionally, it is possible that the volume of certain permitted beverages will decrease after the ban takes effect, as the difference in cost from what they are used to will now be on the consumers mind when making a decision.

Model — Adapting the Results of Part I After the Ban of PET Water Bottles

Redistribution of the water formerly consumed in PET bottles to each other beverage is predicted by two variables: a value derived from the previous Mapped Locational Base Rate while PET bottles were permitted, and a Cost Variance value based on the principles of Prospect Theory.

First, these variations will be calculated simply by using only their former Mapped Locational Base Rates. By removing the PET water bottles from the list of beverages, the formerly Mapped Locational Base Rate for each beverage becomes a new Unmapped Locational Base Rate. Then these rates can be remapped into percentages as follows:

$$\begin{aligned} Sum = {} & Unmapped\ Locational\ Base\ Rate_{tap} + Unmapped\ Locational\ Base\ Rate_{dairy} \\ & + Unmapped\ Locational\ Base\ Rate_{juice} + Unmapped\ Locational\ Base\ Rate_{coffee} \\ & + Unmapped\ Locational\ Base\ Rate_{tea} + Unmapped\ Locational\ Base\ Rate_{tea} \\ & + Unmapped\ Locational\ Base\ Rate_{alcohol} \end{aligned}$$

[13] Weinland, Don. "Airport Retailers Look to Make Every Minute Count."
[14] "Community." *SFO Connect*, https://www.sfoconnect.com/community.

It follows that, for an individual beverage:

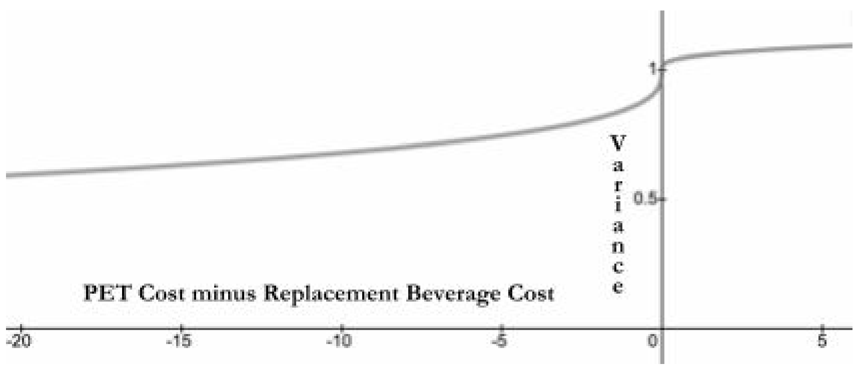
$$Mapped\ Locational\ Base\ Rate\ =\ \frac{Unmapped\ Locational\ Base\ Rate}{Sum} * 100$$

Yet this still does not factor in the cost difference between the PET water bottles (that people were accustomed to purchasing) and the alternative beverages they are now forced to buy. As it is unlikely that people will purchase a replacement beverage that is significantly more expensive than the PET bottles they are accustomed to, this must be taken into account. This could assume two different forms, a simple difference equation, or a more psychologically sound model grounded in prospect theory. This model employs the later.

Humans place greater weight on losses than on gains. Therefore, as a PET replacement beverage becomes more expensive, its base rate grows smaller at a rate greater than a cheaper beverage would become popular.[15] This leads to a variance in the above calculated Mapped Locational Base Rate based on the following equation where the costs are in dollars per Liter:

$$Variance\ =\ 1\ +\ \frac{1}{20}\left(2\sqrt[3]{PET\ Cost\ -\ Beverage\ Cost}\ -\ \sqrt[3]{|PET\ Cost\ -\ Beverage\ Cost|}\right)$$

This function is shown visually as:



As the base rates of beverages cheaper than PET water bottles must be increased while those more expensive must be reduced, the conversion from the previously calculated base rate to the Updated Base Rate is as follows:

$$Updated\ Locational\ Base\ Rate\ =\ Mapped\ Locational\ Base\ Rate\ *\ Variance$$

Next, the Updated Base Rates must be remapped in the same manner discussed above as they must ultimately sum to 100. Refer to the Sum and Mapped Locational Base Rate equations above.

Solution — Non-PET Beverage Volumes Consumed at the San Francisco Airport

Applying the *Model* to the San Francisco Airport yields the following figures:

[15] Haim Levy, Moshe Levy, "Experimental test of the prospect theory value function:

Item	Mean Cost ($ per Liter)[16]	PET minus Beverage Cost ($)	Variance	Mapped Locational Base Rate (%)	Updated Locational Base Rate (%)
Bottled	1.66	-	-	-	-
Tap	0.00	1.66	1.06	30.0	31.8
Dairy	4.56	-2.90	0.786	1.35	1.06
Juice	4.46	-2.80	0.789	3.36	2.65
Coffee	3.84	-2.16	0.806	32.2	26.0
Tea	2.23	-0.57	0.876	7.05	6.18
Soda	2.03	-0.37	0.892	18.0	16.1
Alcohol	17.0	-15.3	0.627	7.05	4.42

Finally, the Remapped Locational Base Rates, the volume of each type of beverage, and the change in their respective liters consumed at San Francisco Airport each day are as follows:

Item:	Bottled	Tap	Dairy	Juice	Coffee	Tea	Soda	Alcohol
(%)	0	36.1	1.20	3.00	29.5	7.01	18.3	5.01
Post-Ban (L)	0	33,700	1,120	2,800	27,500	6,540	17,100	4,680
Δ (L)	-18,700	10,600	110	300	3,500	1,290	3,700	-570

This data suggests a negligible change in Dairy, Juice, and Alcohol consumption while demonstrating large increases in Soda, Tap Water, Tea, and Coffee consumption. This reflects the expected desires of citizens and makes intuitive sense. Further analysis of convenience values could be used to optimise the accuracy of the model.

Solution — Beverage Volumes Following PET Ban in Concord and San Francisco

To demonstrate its utility, our model was applied to Concord, MA (population 19,000)[17], and San Francisco, CA (population 885,000)[18]. This will allow *Part III* to analyze the impact of the ban at these locations.

As San Francisco is a large city, it can be assumed to perform very close to the national average. The major difference is that the city has a sugar-sweetened beverage tax. Fortunately, there is reliable data

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[16] Watters, Corilee A et al. "Prices of healthy and unhealthy beverages in high and low per capita income areas."
[17] NBC News, US News. (2012, September 7). Concord, Mass., the first US city to ban sale of plastic water bottles.
[18] NBC News, US News. (2012, September 7). Concord, Mass., the first US city to ban sale of plastic water bottles.

on the effects of this. A UC Berkeley study on drinking habits before and after the tax showed that sugar-sweetened beverage consumption went down 52.3% and water consumption went up 29.3%.[19] This was applied to the national base rates to obtain accurate Locational Base Rates specific to San Francisco. Finally, after remapping, for San Francisco, CA, the *Model* yielded the following:

Item:	Bottled	Tap	Dairy	Juice	Coffee	Tea	Soda	Alcohol
Pre-Ban (L)	624,000	512,000	104,000	123,000	309,000	180,000	221,000	180,000
Post-Ban (L)	0	850,000	129,000	153,000	390,000	248,000	307,000	178,000
Δ (L)	-624,000	338,000	25,000	30,000	81,000	68,000	86,000	-2,000

For Concord, the conveniences differed from the national average based on the facts that the average age of the town is higher than the national average and that the town is known for producing wines and grape juices. Finally, for Concord, MA, the *Model* yielded the following:

Item:	Bottled	Tap	Dairy	Juice	Coffee	Tea	Soda	Alcohol
Pre-Ban (L)	10,500	12,100	2,250	2,240	6,700	3,930	6,030	4,710
Post-Ban (L)	0	18,500	2,560	2,560	7,810	4,970	7,790	4,280
Δ (L)	-10,500	6,430	310	310	1,110	1,050	1,760	-430

An interesting trend exhibited here is a slight decrease in expensive alcoholic beverages, after the PET water bottle ban takes effect. This is an artifact of our Prospect Theory driven model where financial losses are valued more than financial gains. In essence, this can be described by the fact that, once PET water bottles, which consumers are accustomed to purchasing, are removed from sale, they must "shop" around for an alternative. This makes cost a greater focus than it previously was, decreasing expensive purchases.

Part III — Modeling the Impacts of PET Water Bottle Ban

Part I and *II* predict the volumetric change in consumption of beverages as a result of a ban on PET water bottles. *Part III* describes the impacts of these volumetric changes. With the goal to model the positive and negative impacts of a ban, only the change in beverage consumption is necessary to determine the impacts. Therefore, it is unnecessary to consider the severity of impacts of beverages before and after the ban. Because we are looking at the change in consumption, the input to *Part III* is the **Δ** (L) for each beverage as calculated by *Part II*.

[19] "The American Journal of Public Health (AJPH) from the American Public Health Association (APHA) Publications."

Model — The Benefits and Damages of a PET Water Bottle Ban

The per liter impact of each beverage can be represented using a row style Impact Vector of the magnitudes of the impacts on three distinct fields: environmental, economic, and health. This vector (**V**base) solely represents the impact of the beverage by volume consumed, regardless of the PET water bottle ban. Therefore, scaling a beverage's Impact Vector, **V**base, by the change in its consumption following the ban, **Δ** (L), outputs a scaled Impact Vector, **V**change, whose components represent the impact of the beverage following the ban.

Bellow are tables for each field containing the Impact Components for each beverage and an explanation of the reasoning behind the chosen value.

Item	Environmental	Explanation of Impact
Bottled	-0.3	The tap water bottling process releases 2.5 million tons of carbon dioxide annually and 38 billion bottles are sent to landfills per year[20]
Tap	0	Only 1% of tap water is used for drinking, therefore drinking from the tap has an insignificant effect on the production of tap water overall[21]
Dairy	-1	144 gallons of water are used to produce 1 gallon of milk, and manure from cows releases greenhouse gasses[22]
Juice	-0.6	Fruits can only be grown in certain areas meaning transportation makes up a significant portion of emissions from juice production[23]
Coffee	-0.5	Coffee farming contributes to deforestation and water pollution.[24] Plus, natural resources are needed to farm and transport the coffee.
Tea	-0.5	In 2018, Americans consumed over 84 billion servings of tea, or more than 3.8 billion gallons of water plus the water needed to farm the tea.[25] This has a significant effect on the environment.
Soda	-0.4	A 2-liter soda bottle costs 132 gallons of water to make and the packaging and transportation process generates a significant amount of carbon emissions[26]
Alcohol	-0.7	The process of creating alcohol can be very long and resource intensive[27]

[20] "The Negative Environmental Impact of Bottled Water."
[21] "Types of Water - Municipal Water."
[22] "Milk's Impact on the Environment."
[23] Knudsen, M.T., Fonseca de Almeida, G., Langer, V. et al.
[24] Moore, Victoria. "The Environmental Impact of Coffee Production:
[25] "Tea Fact Sheet." *Tea USA News*, Tea Association of the USA Inc
[26] Vick, Danielle. "Is Soda as Bad for the Environment as It Is for Your Health?"
[27] Phillips, Avery. "The Environmental Impact of Alcohol."

Item	Economic	Explanation
Bottled	0.1	The bottled water industry made $16 billion in revenue in 2016[28]
Tap	0.0	Tap water infrastructure exists whether or not we drink tap water and its cost is negligible
Dairy	0.2	The dairy industry made $37.8 billion in revenue in 2019[29]
Juice	0.1	The Juice industry made $12 billion in revenue in 2019[30]
Coffee	0.4	The Coffee industry made $74.8 billion is revenue from coffee sales in 2015[31]
Tea	0.01	The tea industry made $1.6 billion in revenue in 2019[32]
Soda	0.9	The soda industry made $245 billion in revenue in 2019[33]
Alcohol	1	The alcohol industry made $253.8 billion in revenue in 2018[34]

Item	Health	Explanation
Bottled	-0.1	Bottled water may contain BPA and is tested for pollutants less than tap water[35]
Tap	0.0	Water has no nutritional value
Dairy	0.1	Milk is filled with nutrients including vitamin D and protein[36]
Juice	-0.5	Juice can often have as much sugar as sodas and often has small amounts of vitamins[37]
Coffee	-0.2	Coffee is often consumed with sugar and cream leading to harmful health impacts.
Tea	-0.2	Tea is often consumed with high amounts of sugar leading to harmful health impacts. However, since it also has positive health impacts, tea is healthier than soda and juice[38]

[28] "The Negative Environmental Impact of Bottled Water."
[29] "Milk's Impact on the Environment."
[30] "Industry Market Research, Reports, and Statistics."
[31] "National Coffee Association."
[32] "Tea Production in the US Market Size 2005–2025."
[33] "Soft Drinks - United States: Statista Market Forecast."
[34] Morris, Seren. "US Alcohol Sales Increased by 5.1% in 2018."
[35] "The Negative Environmental Impact of Bottled Water."
[36] Fernstrom, Madelyn. "Is Milk Really Good for You?"
[37] Healthline. Fruit Juice Is Just as Unhealthy as a Sugary Drink.
[38] E-ajbc.org

Soda	-0.7	Consumption of soda increases body weight in forms of fat, conclusively causing health problems[39]
Alcohol	-1	Consumption of alcohol is associated with many negative health effects, such as liver damage

Given these scalars, the **V**base vectors are represented as:

$$V\,base\ =\ [environmental,\ economic,\ health]$$

It follows that the **V**change vector can be calculated using the $\Delta\,(L)$ from *Part II* by:

$$V\,change\ =\ \Delta\,(L)\ *\ V\,base$$

This final **V**change vector represents the overall impact of the beverage. Each component relates to the specific field of the impact.

Next, to calculate the overall impact of the specific beverage, each element must be considered together. A simple magnitude of the vector cannot achieve this as it is unsigned and undervalues smaller impact components. In other words, a magnitude cannot determine how good or bad the impact of a beverage is, simply how large of an impact it has. Instead, a zero impact plane was selected to represent all of the points where the impacts of environment, economy and health cancel out to an impact that is neither positive nor negative, defined as:

$$V\,environmental\ +\ V\,economic\ +\ V\,health\ =\ 0$$

To obtain a final beverage impact, we calculate the distance from this zero impact plane to the terminal point of **V**change. This yields how far **V**change is from possessing no impact. We calculate the signed distance to this zero impact plane using a variation of a linear algebra style projection to derive a final equation for the beverage impact:

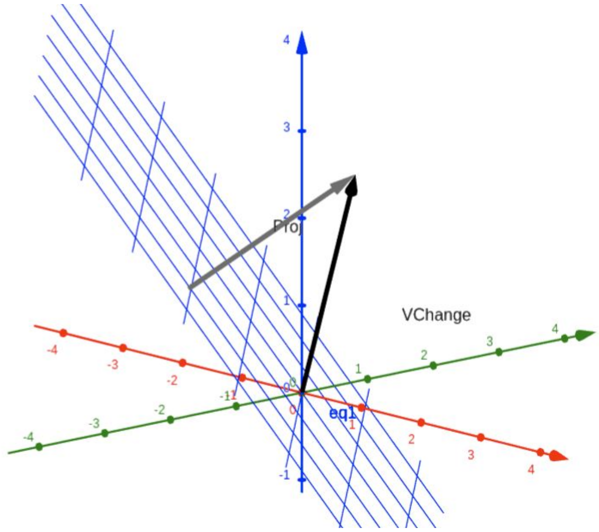
$$Signed\ ||Proj_{[1,\,1,\,1]}V\,change\,||\ =\ \frac{V\,change \circ [1,1,1]}{[1,1,1]\circ[1,1,1]}||[1,\ 1,\ 1]||\ =\ \frac{V\,change \circ [1,1,1]}{||[1,1,1||^2}||[1,\ 1,\ 1]||$$

This simplifies to:

$$Beverage\ Overall\ Impact\ =\ \frac{V\,environmental + V\,economic + V\,health}{\sqrt{3}}$$

This process is shown visually, where the grey vector represents the Beverage Overall Impact, or the signed distance from the black **V**change vector to the blue zero impact plane, as:

[39] Cdc.gov



Finally, given each Beverage Overall Impact, the overall impact of the ban can be calculated. This Ban Overall Impact can be quickly derived from summing each Beverage Overall Impact together. This is defined as follows:

$$Ban\ Overall\ Impact = Beverage\ Overall\ Impact_{bottled} + Beverage\ Overall\ Impact_{tap} + Beverage\ Overall\ Impact_{dairy} + Beverage\ Overall\ Impact_{juice} + Beverage\ Overall\ Impact_{coffee} + Beverage\ Overall\ Impact_{tea} + Beverage\ Overall\ Impact_{tea} + Beverage\ Overall\ Impact_{alcohol}$$

In essence, this quantifies the overall impact of the PET water bottle ban on the community and can be used to inform policy decisions about implementing a ban in a given location.

Solution — The Impacts of the Ban at the San Francisco Airport

Finally, the impacts of the PET water bottle ban at the San Francisco Airport must be calculated. This provides a real world example of the utility of our model and can be used to advise public policy decisions moving forward.

Using the **Δ** (L) for San Francisco Airport calculated in *Part II*, the *Model* proceeds as follows, where the impact vectors are structured as [environmental, economic, health]:

Item	**V**base	**Δ** (L)	**V**change	Beverage Overall Impact
Bottled	[-0.3, 0.1, -0.1]	-18,700	[5610, -1870, 1870]	3239
Tap	[0.0, 0.0, 0.0]	10,600	[0, 0, 0]	0.00
Dairy	[-1, 0.2, 0.1]	110	[-110, 22, 11]	-44.46
Juice	[-0.6, 0.1, -0.5]	300	[-180, 30, -150]	-173.2
Coffee	[-0.5, 0.4, -0.2]	3,500	[-1750, 1400, -700]	-606.2

Tea	[-0.5, 0.01, -0.2]	1,290	[-645, 12.9, -258]	-513.9
Soda	[-0.4, 0.9, -0.7]	3,700	[-1480, 3330, -2590]	-427.2
Alcohol	[-0.7, 1, -1]	-570	[399, -570, 570]	230.4

Finally, summing the Beverage Overall Impact values and **V**change vectors together provides the following results for the San Francisco Airport:

Vchange Overall	Ban Overall Impact
[1844, 2354.9, -1247]	1704

Overall, this confirms the expectations and intentions of the PET water bottle ban, at least for the San Francisco Airport. The Beverage Overall Impact of 1704 describes a net positive impact and an overall success of the ban. Additionally, the environmental and economic benefits of the ban are significant, 1844 and 2354.9, respectively. Interestingly, the *Model* concludes that there is a small negative health impact to banning PET water bottles. This is represented by the -1247 figure in the **V**change Overall vector and can be explained by the large increase in coffee and tea consumption following the enforcement of the ban.

Solution — The Impacts of the Ban in Concord and San Francisco

To calculate the impact of the ban for Concord, MA, and San Francisco, CA, our model follows the same procedure as outlined in the previous sections. The **Δ** (L) from *Part II* for each location is used and the **V**base vectors do not change. The *Model* yields the following results for Concord, MA:

Vchange Overall	Ban Overall Impact
[1171, 651.5, -308]	874.5

And the following results for San Francisco, CA:

Vchange Overall	Ban Overall Impact
[36700, 54080, -38100]	30,410

Both locations confirm the positive environmental and economic impacts of a PET water bottle ban while suggesting a negative impact on public health. Yet, the Ban Overall Impact is positive. This is consistent with the intention of the legislature and confirms that the ban will be overall beneficial to both large and small cities.

Part IV — Recommendations for Improving the PET Water Bottle Ban

Our results show that all drinks except tap water have an overall negative impact (alcohol has a negative **V**base but also a negative **Δ** (L), giving it the illusion of a positive impact. This is only due to the decrease in its consumption, though). Tap water has virtually no impact in any of the categories so, by increasing tap water consumption, we decrease the consumption of other drinks creating a net positive change. Our results clearly show that increasing consumption in tap water is in the best interest of the environment, economy, and the health of US citizens.

After implementing a ban on PET water bottles, this can most effectively be continued by increasing the convenience of tap water and decreasing the convenience of other drinks. It is important to note that we consider water fountains as tap water, even when consumed from a reusable water bottle because it is not PET bottled water. Some of the easiest ways to increase the convenience of tap water and decrease the convenience of other drinks are as follows:

Install cold, filtered, and easy to locate water fountains at many public locations.

Other drinks are often refrigerated and this constitutes much of their appeal, so making water fountains cold and better filtered will make them more attractive when competing against other beverages.

Implement laws to decrease the convenience of beverages with negative impacts.

By decreasing the conveniences of negative impact beverages, the **Δ** (L) of bottled water will be redistributed to cheaper and more convenient sources, thereby shifting consumption to lower impact beverages. This has been attempted using a soda tax in San Francisco. However, a better way to do this would be to tax all drinks relative to their sugar concentrations, decreasing their convenience, and possibly, encouraging companies to lower sugar concentrations. Additionally, the government should tax all drinks sold in containers with negative environmental impacts. Once again, this will encourage the consumption of tap water and motivate companies to shift to sustainable packaging.

These suggestions paired with a PET water bottle ban would be highly beneficial to the US economy, environment, and the health of its citizens.

DISCUSSION

Our models provide an insightful and practical view into the dynamics and impacts of a single-serving PET water bottle ban, yet the real-world scenario is much more nuanced than anticipated. In this discussion, we will outline a selection of these nuances and variances from our predictions and provide guidance for improving our procedures moving forward.

Final Impact Results for Each Location

Often it is useful to accessibly compare results side by side. Our model indicates the following results for the impacts of a single serving PET water bottle ban in San Francisco Airport, Concord, MA, and San Francisco, CA:

Location:	San Francisco Airport	Concord, MA	San Francisco, CA
Ban Overall Impact	1704	874.5	30,410
Ban Overall Impact Per 1,000 People	47	46	34

The impact of the ban is decidedly positive in all three locations. The magnitude of this positive impact is roughly proportional to the population of the location. This is evident by the Ban Overall Impact Per 1,000 People being of the same magnitude for each location.

Strengths and Weaknesses of the Model

While our model presents a coherent view of the impacts and effects of a single serving PET water bottle ban, it possesses many flaws to compliment its successes. Here, we have outlined those strengths and weaknesses.

Strengths:

- Our model can be applied to a location regardless of the availability of previous consumer data. *Part I* contains two variations to more accurately estimate impact in locations of high and low prior knowledge.
- Our model is modular and returns useful data at every step. This provides an easy route to understanding how to tune the model to improve accuracy.
- Our model could be easily modified to find the impacts of other proposed regulations such as a sugary drink tax.
- Our model returns a final numerical value on how beneficial a change would be so that different changes can be easily compared and legislators can easily consider whether its implementation will be beneficial.
- Our model establishes a framework for a much more intricate model which could seamlessly incorporate dozens of new concepts.

Weaknesses:

- Convenience values are derived by interpreting research subjectively. It would be better to create an objective formula to determine these critical values.

- Non-PET single-serving water bottle choices are not considered. At the present, this should not present an issue, but in the future, when new bottle technology becomes widespread, it may.
- The volume of fluid required by consumers is assumed constant, yet some drinks seem more thirst quenching than others.
- Beverage waste is not considered and instead the total volume purchases is assumed to be the same as the total volume biologically required by the population.
- The irregularities of beverage price scaling across locations is not considered.
- Retailers are assumed to be 100% in compliance with the ban, so the illegal sale of PET bottles is not considered. This may be unrealistic as the penalty for each infraction is low.
- Our Overall Impact score is unitless, so it has no practical value outside of comparison against itself.

Future Plans

While these shortcomings are appropriate for an initial model, moving forward they could be corrected by following the procedure discussed below.

- Integrate a model which could more objectively generate Convenience values.
- Incorporate the following irregularities into the current model:
    - Non-PET single-serving water bottles
    - Variation in volume of fluid required by consumers
    - Beverage waste
    - Disproportionate beverage price scaling across locations
    - Other drink categories (ie. energy drinks, non-single serving containers)
    - Illegal sale of PET bottles
- Address how a beverage's impact affects the decisions a consumer will make regarding its purchase and consumption.

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