Team Control Number

10212

Problem Chosen

B

2019
HiMCM
Summary Sheet

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Type a summary of your results on this page. Do not include the name of your school, advisor, or team members on this page.

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With the increasing global use of plastics, plastic water bottle bans have been implemented by various communities calling for change. Single-serving water bottle bans, in particular, have both positive and negative impacts on such regions despite their beneficial intents. As such, we have developed a mathematical impact model, containing four submodels relating to economics, energy, waste, and health, that aims to thoroughly evaluate the costs and benefits associated with a single-serving water bottle ban in terms of a dollar value per year.

Our economic submodel takes into account the purely economic impacts to consumers and businesses associated with the ban. For consumers, this mini cost-benefit analysis includes no longer having to spend money on single-serving water bottles and spending more on other drinks, tap water, and reusable water bottles. For businesses, they would lose revenue from not selling any more water bottles and gain revenue from increased sales of other drinks. These factors are all combined into a single equation that produces one dollar value cost associated with the economic impacts of the ban.

Next, we created an energy submodel that evaluates the energy costs associated with the single-serving water bottle ban. The submodel examines the prior energy costs of water bottles, along with the increase in energy costs associated with both other drinks and tap water as a result of the ban. It specifically deals with the energy costs of producing the water bottles, other drinks, and tap water, as well as transporting them to consumers. In addition, the submodel takes into account the recycling of both water bottles and other drinks in the energy calculations to get an accurate evaluation of the energy costs associated with the ban.

Our waste submodel, meanwhile, looks at the impact the ban may have on plastic waste, both through the elimination of plastic water bottles and the switch to other drinks instead. The model considers the climate change cost of these bottles, the overall environmental cost from clean-up and pollution, as well as the additional disposal costs from the landfill and incineration. It utilizes a modified life-cycle cost analysis focused upon waste to consider the effect produced through the creation to discarding of the bottles and attribute it to a cost.

Finally, we developed a health submodel that analyzes the medical costs associated with increased consumption of alternative beverages containing monosaccharides and disaccharides, sodium, and saturated fatty acids as a result of the ban. The submodel specifically studies the risk of disease deriving from over-consumption of these substances, employing a variation of the Population Attributable Risk model, and applies it to induced yearly medical costs.

Using our impact model, we studied the implications of the ban in Concord, San Francisco, and an airport. We further highlighted community measures that could combat detriments of the ban, such as increased recycling awareness and the implementation of water bottle filling stations, and developed recommendations for adjustment to Concord's single-serving water bottle ban regarding a tax on other bottled beverages. We then modified our submodels accordingly to fit these different environments. Overall, our model is easily scalable to different populations and regions with the consideration of a few key variables due to its flexible, modular nature.

Contents

2 News Article

New Model Predicts the Effects of Single-Serving Water Bottle Bans

November 19, 2019

City, State - With the implementation of single-serving water bottle bans in towns and cities across the nation, including Concord, MA, and San Francisco, CA, more and more people are calling for similar bans in their local areas. But in practice, how effective are these bans, and do they really achieve the goals they set out to accomplish? A local team of high school students have resolved to answer that question through mathematics.

The students have developed a mathematical impact model in order to come up with a quantifiable value for the impact of a single-serving water bottle ban in a certain geographic area. They have broken down the specific positive and negative effects of the ban into four key subcategories—economic, energy, waste, and health—and have found a way to convert all of these factors into a single dollar value as a measure of impact.

For the model to be applied, several statistics, which are presently not readily available, are necessary. To collect the required data, the students have suggested conducting surveys and evaluating available studies from agencies such as the EPA.

Yet, even without the data, the students were able to compare the impacts of a ban in the small town of Concord and the large city of San Francisco. They even extended the model to an airport to weigh the pros and cons of a ban in such an environment.

As a result of their investigations, these students have recommended adding more water bottle filling stations around the town of Concord in order to promote the usage of reusable water bottles and decrease the increased consumption of unhealthier beverages when bottled water is not present. Other suggested community actions include pushing for more awareness in both health and recycling to help reduce unnecessary waste and health costs. To further combat the detriments of the present ban in the town, they additionally recommended that Concord implement a 5- to 10-cent tax on other bottled beverages to reduce negative health risks from the initial ban as well as costs associated with consumption.

Ultimately, the mathematical impact model developed analyzes the implications of a single-serving water bottle ban, can be applied to both smaller communities and larger regions, helping tackle one of modern society's most pressing issues.

3 Introduction

3.1 Background Information

The increasing use of plastics, which requires fossil fuels and results in detrimental waste, is a growing concern for many. With the specific inclusion of polyethylene terephthalate (PET) in the modern plastic bottle, various towns and cities around the world have begun implementing bans on single-serving water bottles.

In particular, according to the New Hampshire Department of Environmental Services, a discarded plastic bottle, thousands of which reach the oceans, takes 450 years to decompose [3]. Tap water, a viable alternative to bottled water, additionally costs less and uses significantly less energy for purification compared to associated costs and energy for single-serving plastic water bottles [4]. On the contrary, such bans can promote increased consumption of other beverages that are more damaging to health. Certain geographical regions may also not have access to drinkable water, and single-serving water bottles could be necessary in emergencies. In this model, we will thus more deeply explore the benefits and detriments associated with a single-serving water bottle ban.

3.2 Defining the Problems

We are charged with creating a model or series of models discussing the impacts of a single-serving water bottle ban, to fulfill the following tasks:

- Determine the positive and negative impacts of a water bottle ban.
- Apply this model to the town of Concord and city of San Francisco, where the ban has taken effect.
- Apply this model, with any modifications, to an airport.
- Provide recommendations for changes to the single-serving water bottle ban.
- Adjust the model according to suggested recommendations.
- Analyze the application of this model to larger communities.

3.3 Definitions

- **Polyethylene terephthalate (PET)**: A polymer that is used in water bottles for its thermal and mechanical stability. It can take centuries to biodegrade [7].

- **Single-serving water bottles**: Plastic water bottles with volumes less than 1 liter that are typically discarded immediately after use. Virtually all plastic liquid bottles contain PET.

- **Other drinks**: Alternative drinks packaged in plastic PET bottles found in a store or restaurant that are not single-serving water bottles (i.e. soft drinks, energy drinks, coffee, teas, etc.)

3.4 Global Assumptions and Justifications

- **Assumption:** Individuals who do not purchase any single-serving water bottles will not be affected by this ban and do not have to be considered.

  Justification: The ban only targets single-serving water bottles, so the individuals who do not interact with single-serving water bottles throughout their day will experience no changes, so no costs and benefits will be associated with them.

- **Assumption:** The impact analysis can be initiated only after no single-serving water bottles remain on the market.

  Justification: Remaining single-serving water bottle sales would follow the patterns established before the ban and the effects of the ban will not appear until all single-serving water bottles are eliminated from the market, so we can disregard these sales.

- **Assumption:** The environment in which the ban takes place will be stable, without any emergencies/natural disasters.

  Justification: Since natural disasters and their impacts are often unpredictable, especially in the long-term, we will not consider the effect that a natural disaster may have on the water supply of a geographical area.

- **Assumption:** The cost of launching the ban is negligible and would not require additional infrastructure.

  Justification: The ban on single-serving water bottles will be considered as an individual piece of legislation that does not entail any additional resources dedicated towards promoting the use of reusable water bottles.

- **Assumption:** All sales of single-serving water bottles will be affected by the ban.

  Justification: In Concord's ban of single-serving water bottles, there are inspectors who enforce the ban on retail stores, restaurants, and other venues, covering almost anywhere a water bottle can be sold.

- **Assumption:** Vendors will follow the law and not sell single-serving water bottles after the ban.

  Justification: Because it's almost impossible to predict how vendors will react to a ban, we will not consider illegal transactions and will assume that all vendors will comply. We will also not consider the consequences of breaking the law in our model.

- **Assumption:** The recycling rate is the same for water bottles and other drinks.

  Justification: The recycling processes that water bottles and other drink bottles go through are classified into one category, suggesting that the rate at which they are recycled would be about the same.

- **Assumption:** The individuals who switch to tap water as a result of the ban still drink the same amount of water.

  Justification: For individuals who begin drinking tap water, the ban would only change the source of the water, so the need for water for each individual should be approximately the same after the ban as before.

- **Assumption:** Production of other types of materials, such as HDPE and glass, for single-serving water bottles will not increase.

  Justification: Materials like HDPE are extremely uncommon for single-serving items and thus are not viable for this use, making it unlikely for their production to increase significantly. Glass is also very expensive and would likely not be mass-produced locally for this purpose.

4 Developing the Model

4.1 Explanation of the Model

To develop a model to analyze the impacts of a single-serving water bottle ban, we will be employing a four-pronged cost-benefit analysis (CBA). The four factors we will consider in our CBA are as follows:

- Economic (effects on the material prosperity of consumers and businesses)
- Energy (energy involved in the production of bottles)
- Waste (waste production associated with the production of bottles)
- Health (effects on health of consumers)

We will be creating four different models, each analyzing the costs and benefits associated with one of these factors. This allows us to utilize different techniques specific to each situation, making the models much more flexible and modular. Each model will be standardized by converting the impacts of each factor into a dollar value (the methods of which will be explained in the respective explanations of each model), generating a result in terms of dollars per year. In this sense, the models can be combined to produce a singular number defining the impact of a single-serving water bottle ban in any particular geographical area.

The monetary value per year given by our cost-benefit analysis can be mathematically be represented as follows, where a positive value signifies a net benefit and a negative value signifies a net cost:

$$M + G + W + H$$

4.2 Submodel 1: Economic Analysis

4.2.1 Local Assumptions and Justifications

- **Assumption:** Businesses won't change their business model after ban of water sales.

  Justification: In the long-run, there may be an increase in demand for other drinks because of the scarcity of a substitute good, single-serving water bottles. However, since we don't know how exactly the market may be affected by a ban on single-serving water bottles, we will assume that prices and revenue will stay constant after the ban.

- **Assumption:** Everyone who stops drinking bottled water and would rely on tap water would need a reusable water bottle.

  Justification: A big reason people rely on single-serving water bottles is that they're convenient to bring on the go. To do the same with tap water, people must purchase a reusable water bottle.

4.2.2 Variables

Symbol	Definition	Units
M	Total purely economical costs associated with the ban per year	$/year
n_b	Number of people that buy single-serving water bottles before the ban	People
b	Average number of single-serving water bottles bought per person who buys single-serving water bottles per year	Bottles/individual/year
C_w	Average cost of 1 bottle of water	$/bottle
C_o	Average cost of 1 bottle of other drink before the ban	$/bottle
C_r	Average cost of 1 reusable water bottle	$/bottle
C_t	Average cost of tap water	$/mL
y	Average number of years that a reusable water bottle lasts	Years
a	Average amount of water in a single-serving plastic water bottle	mL
s	Substitution rate	Constant
R_w	Revenue per water bottle sale for every business in the geographical area	$
R_o	Revenue per other drink sale for every business in the geographical area before the ban	$

4.2.3 Developing the Model

To develop a model based purely off of the economic effects of a single-serving plastic water bottle ban, we will consider several economic factors as follows:

Benefits

- Consumer savings from not purchasing water bottles
- Business revenue from selling more of other drinks

Costs

- Consumer spending from purchasing other drinks

- Consumer spending on tap water as a replacement
- Business revenue lost from stopping the sale of water bottles
- Consumer spending from purchasing reusable water bottles

This model is based on an important constant, the substitution rate, as represented by the variable s. The substitution rate is the percentage of people that, given there was a water bottle ban, would switch to primarily consuming other packaged beverages rather than tap water [6].

This value can only be determined experimentally through case studies or surveys. One of the most widely cited studies regarding the substitution rate comes from the American Water Works Association Research Foundation in 1993. The study found that if there was a single-serving water bottle ban, 35% of consumers will switch to drinking tap water with their meals instead of other beverages. In this case, $1 - s = 0.35$, so our substitution rate $s = 0.65$, meaning that 65% of all original single-serving water bottle purchases will become purchases of other drinks. However, this report is somewhat outdated, and the increases in infrastructure to support reusable water bottles have not been accounted for. Therefore, an accurate substitution rate would be necessary for our models to be as accurate as possible.

To start developing the purely economical cost-benefit analysis, we first consider the effects of the ban on consumer spending, with regards to the substitution rate. This includes the amount of money saved from not purchasing water bottles, the amount of money spent on other drinks after the ban, the amount of money spent on tap water, and the amount of money spent on reusable water bottles. The number of single-serving water bottles bought per year can be represented by the product $n_b b$, where n_b is the population that buys any non-zero amount of water bottles a year and b is the average number of water bottles bought per person per year. Multiplying $n_b b$ by s would result in the increase in other drinks sold, and multiplying $n_b b$ by $1 - s$ would result in the amount of single-serving water bottles that would be replaced with tap water.

To find the amount of money consumers save by forgoing buying single-serving water bottles, we can multiply $n_b b$ by the average cost of one single-serving water bottles, C_w. Likewise, the amount of money consumers would spend on buying other drinks is $n_b b s C_o$, where C_o is the average cost of another drink. To find the cost to consumers of buying tap water, we multiply the average amount of water in one single-serving water bottle in mL, represented by a, by $n_b b$ and C_t, the cost one mL of tap water.

Finally, we must take into account the fact that to drink tap water on the go, a consumer must have a reusable water bottle which must be replaced after certain periods of time. Thus, we can multiply n_b by $1 - s$ to find the number of people that will switch to tap water, and then multiply by C_r, the average cost of one reusable water bottle, and $1/y$, y being the average number of years a reusable water bottle lasts, to find the cost to consumers of buying water bottles.

Thus, we can write the expression (with a positive value representing a net benefit):

$$n_b b C_w - (n_b b C_o s + n_b b a C_t (1 - s)) - \frac{1}{y} n_b C_r (1 - s)$$

Next, we must consider the impact of a water bottle ban on businesses. In a global context, in theory, the money saved/lost by consumers would be the money lost/gained in revenue by businesses. However, for this model, we only take into account the businesses located within the geographic area of the ban; that is, we don't factor in the economic changes associated with revenue changes of businesses that are not directly located in the geographic area, such as manufacturing and shipping. With that in mind, the change in the amount of money in the wallets of consumers would not necessarily equal the negative value of the change in revenue of businesses.

With that considered, a company in the local area will experience increased revenue in the form of other drink sales, which can be represented by the equation $n_b b R_o s$, where R_o is the average revenue per drink sold. A company in the local area will lose revenue from single-serving water bottles not being sold, which can be represented as $-n_b b R_w$, where R_w is the average revenue per single-serving water bottle sold. This would give us the net expression:

$$n_b b R_o s - n_b b R_w$$

Combining the effects to both consumers and businesses, we find the net pure economical impact of the single-serving water bottle ban to be:

$$M = n_b b (C_w - C_o s - a C_t (1 - s) + R_o s - R_w) - \frac{1}{y} n_b C_r (1 - s)$$

4.3 Submodel 2: Energy Analysis

4.3.1 Local Assumptions and Justifications

- **Assumption:** The energy cost of recycling one water bottle is the same as the energy cost of recycling one other drink.

  Justification: All plastic is recycled together, so it takes the same amount of energy to recycle different types of plastic. In addition, PET is in both water bottles and other drinks.

4.3.2 Variables

Symbol	Definition	Units
G	Total energy costs with ban per year	\$/year
C_e	Average cost of 1 joule of energy	\$/J
E_w	Average energy to produce and transport one single-serving water bottle	J
E_o	Average energy to produce and transport one other drink	J
E_r	Average energy to recycle one bottle	J
E_t	Average energy to produce and transport tap water	J/mL
ϕ	Recycling rate	%

4.3.3 Developing the Model

We will develop an energy sub-model that considers the change in energy in the production of water bottles, other drinks, and tap water as a result of the ban. We can consider the following energy values:

- G_w = Energy for water bottles per year
- G_o = Increase in energy per year for other drinks as a result of the ban
- G_t = Increase in energy per year for tap water as a result of the ban

After the water bottle ban, there will be no energy costs for water bottles, so G_w is energy saved per year. G_o and G_t are both energy spent per year, since after the ban, people will switch to either other drinks or tap water, resulting in an increase in energy. Therefore, the energy saved can be represented as $G_w - G_o - G_t$.

To provide a monetary value, we will multiply this expression by C_e, the average cost of 1 joule of energy, which yields the energy saved in dollars per year:

$$G = C_e(G_w - G_o - G_t).$$

An important constant in the model is the recycling rate, represented by ϕ. This accounts for the percent of both water bottles and other drinks that are recycled and the fact that bottles cannot be recycled forever. The recycling rate can be determined through case studies. One of the most comprehensive reports on the recycling rate of PET containers comes from NAPCOR, which found a recycling rate of 29.2% in 2017, which means that 29.2% of PET containers are recycled. However, this study is 2 years old, so for the model to be as accurate as possible, an accurate recycling rate is necessary [15].

We will first find G_w. The number of single-serving water bottles bought per year is $n_b b$ as before. Since ϕ is the percent of the water bottles that are recycled, the energy per year needed for the recycled portion of waters bottles is $\phi n_b b E_r$, where E_r is the average energy needed to recycle a bottle. Since $1 - \phi$ is the percentage of water bottles created from scratch, the energy needed is $(1-\phi)n_b b E_w$, where E_w is the average energy to produce and transport one single-serving drink. Adding these two values together yields

$$G_w = \phi n_b b E_r + (1-\phi) n_b b E_w$$

The process for finding G_o is very similar. Since s is the percentage of people that will switch to other drinks after the ban, $n_b b s$, the increase in the number of other drinks per year, will replace $n_b b$. In addition, E_o, the average energy to produce and transport one other drink, will replace E_w, since G_o is the increase in energy costs for other drinks as a result of the ban. So,

$$G_o = \phi n_b b s E_r + (1-\phi) n_b b s E_o$$

The percentage of people that switch to tap water instead is $1 - s$. Assuming that people drink the same amount of bottle water as tap water on average, the increase in tap water consumed in mL is $(1-s)n_b b a$, where a is the average amount of water in a single-serving water bottle. To get the increase in energy for tap water, we multiply by E_t, the average energy to produce and transport tap water in J per mL, which yields

$$G_t = (1-s) n_b b a E_t$$

Plugging these expressions into $C_e(G_w - G_o - G_t)$ yields

$$G = C_e(\phi n_b b E_r + (1-\phi) n_b b E_w - \phi n_b b s E_r - (1-\phi) n_b b s E_o - (1-s) n_b b a E_t)$$

Through algebraic manipulation, we get:

$$G = C_e n_b b((1-s)(\phi E_r - a E_t) + (1-\phi)(E_w - s E_o))$$

4.4 Submodel 3: Waste Analysis

4.4.1 Local Assumptions and Justifications

- **Assumption:** Waste impact of recycling is negligible.

  Justification: Recycling converts the plastic back into usable plastic that is then utilized in new bottles or other sources, thus not being put into the waste cycle and disposed of. It is reused and should not be counted as waste.

4.4.2 Variables

Symbol	Definition	Units
W	Total waste costs with ban per year	\$/year
β	Percent of plastic bottles that are incinerated	%
α	Percent of plastic bottles that are put into the landfill	%
K_w	Climate change cost of single-serving water bottles	\$/mL
K_o	Climate change cost of other drinks	\$/mL
V_p	Environmental cost of PET per gram	\$/g
m_w	Mass of single-serving water bottle	g
m_o	Mass of other drink bottle	g
L_p	Landfill cost of PET per gram	\$/g
I	Cost of incineration per gram	\$/g

4.4.3 Developing the Model

The waste submodel was developed by considering a life-cycle cost analysis model and modifying it to fit this specific situation. The model is meant to consider the overall waste impact of the ban and what this change in plastic waste would indicate for the certain geographical region and its environment. This would quantify the impact of waste as a numerical cost for the region.

A life-cycle cost analysis models all the costs that are a part of a process, from the acquiring costs to the disposal costs [10]. Our modified life-cycle cost analysis model is focused upon waste and takes into account the waste and pollution generated through the creation of these bottles as well as in the disposal of the bottles in landfills and incineration.

One specific cost was the climate change cost that would occur as a result of the production of these plastic bottles. This is directly connected to the carbon-social cost (SC-CO_2) of the production of plastic bottles which is stated to be a comprehensive estimate of climate change cost that includes "changes in net agricultural productivity, human health, property damages from increased flood risk and changes in energy system costs, such as reduced costs for heating and increased costs for air conditioning." [16] Additionally, it is a quantifiable amount which fits into our model. The social cost of carbon has been calculated by the Environmental Protection Agency to be about 42 dollars per metric ton in 2020, and this can be applied more broadly to the production of these plastic bottles. The climate change cost is defined by the amount of carbon dioxide produced in the generation of the liquid and plastic needed for each drink multiplied by the carbon-social cost [6]. This would be different for the water versus other drinks due to the distinct processes that take place for single-use water bottles and for other drinks.

$$\text{Climate Change Cost} = (\text{SC-CO}_2)(\text{Amount of CO}_2\text{ produced})$$

Overall environmental cost was also considered, which includes debris (especially marine) cleanup costs, nitrogen emission costs, and air pollution costs. The United Nations has valued the cost of plastic waste to be about 75 billion per year for the United States, but this value would need to be more specifically defined for this particular situation. This accounts for the intermediate part of the life cycle cost analysis and considers the plastic waste that is deposited outside of landfills which is not disposed properly [14].

$$\text{Environmental Cost} = \text{Debris Cleanup Costs} + \text{Nitrogen Emission Costs} + \text{Air Pollution Costs}$$

To account for the disposal and final part of the life cycle cost analysis, landfill costs were considered. This utilizes the cost of municipal solid waste going into landfills by mass [17]. The other common form of disposal for plastic waste is incineration which is also accounted for in our model. The cost of incineration is also done by mass, and is connected to the overall social cost of carbon (SC-CO_2) with the amount of CO_2 generated with specific masses of plastic waste. According to a Dutch study, about 2.82 tons of CO_2 are generated per ton of plastic waste incinerated [2]. The incineration cost includes this carbon-social cost and the amount of money required to run the incineration for certain amounts of waste.

$$\text{Cost of Incineration} = (\text{Amount of Plastic Waste})((\text{SC-CO}_2)(\text{Amount of CO}_2\text{ produced by mass incinerated}) + (\text{Cost to run incinerator by mass}))$$

Since PET takes about 450 years to degrade, it is necessary to consider the differences between single-use water bottles and other drinks [3]. Other drink bottles have a much higher amount of PET plastic in each bottle and are a lot thicker with 23.9 grams of PET in other drink bottles versus 9.89 grams in single-use water bottles [11]. This would cause an added cost when the substitution rate is taken into account. It would also affect the environmental cost because the PET plastic would stay in the ecosystem for a long time and thus have a large impact.

By putting these elements together, with the benefit being the amount saved from getting rid of single-use plastic water bottles and the cost being the amount accumulated with the substitution rate to other drinks, we can get these equations:

$$Benefit = n_b b m_w (V_p + \alpha L_p + \beta I) + a b n_b K_w$$

$$Cost = s n_b b m_o (V_p + \alpha L_p + \beta I) + a b n_b K_o$$

$$W = Benefit - Cost$$

4.5 Submodel 4: Health Analysis

4.5.1 Local Assumptions and Justifications

- **Assumption:** Indirect costs, such as related disease-induced unpaid sick leave or retirement and premature death, are disregarded in the medical and health costs associated with the ban.

  Justification: Only medical and health costs directly associated with related diseases, such as those for treatment and medication, will be considered to limit impact analysis of the ban to a reasonable scope.

4.5.2 Variables

Symbol	Definition	Units
H	Total medical/health costs with ban per year	\$/year
H_i	Average medical/health costs for diseases associated with MDS, sodium, and SFA	\$/individual/year
n	Population of geographic area	People
ϵ	Population attributable risk: the proportion of incidence of a disease in the population that is due to exposure	Constant
ω	Relative risk	Constant
p	Prevalence of exposure to risk factor in population	Constant
p_o	Base risk: the proportion that would select a different drink if bottled water was present	Constant

4.5.3 Developing the Model

As a result of a ban on single-serving water bottles, individuals are more prone to consuming other drinks with higher monosaccharides and disaccharides (MDS), sodium, and saturated fatty acids (SFA). Numerous health risks and costs can thus be identified from over-consumption of alternative beverages.

Our health analysis submodel is inspired by a Population Attributable Risk (PAR) model created by Harvard University to study bladder cancer incidence, applied instead to medical treatment costs [1]. Specifically, the PAR model reveals the proportion of incidence of a "non-transmittable disease"—all health complications that may result from over-consuption of MDS, sodium, and SFA—in the population that is due to exposure from a certain risk factor. Such risk factors are defined by aspects of behavior or lifestyle that have predictable effects on the risk of disease, which we can identify as the selection of water versus another drink (containing MDS, sodium, and SFA) as the beverage of choice. The primary unique aspects of our model compared to the standard

PAR model involve our approaches to exposure and risk as well as the extrapolation of risk to potential induced medical costs caused by the ban.

It should be noted that the PAR model relies primarily on the following relationship between risk, the probability that an event will occur, and odds, the probability that an event will an occur divided by the probability that an event will not occur:

$$odds = \frac{risk}{1 - risk}$$

By algebraic manipulation, we obtain:

$$risk = \frac{odds}{odds + 1}$$

Aligning with these ideas, we can begin by deriving the relative risk ω, or the probability of incidence of the related disease due to exposure to the risk factor. Here, the substitution rate s is considered the odds, as it is the proportion of individuals who would select a drink other than tap water if bottle water was removed. For greater precision, we can also create a modified odds that accounts for the risk of disease in the base group, $p_o(s-1)$, where p_o is the base risk that an individual would select an alternative drink even if bottled water was present and can be determined through population sampling.

$$\omega = \frac{s}{p_o(s-1)+1}$$

The next step involves representing the PAR, ϵ, in terms of ω and p, the prevalence of exposure to the risk factor in the population. Here, the odds is defined by the prevalence multiplied by the increase of risk for disease as a result of the ban on single-serving water bottles, $\omega - 1$. As such, we can express PAR as follows:

$$\epsilon = \frac{p(\omega-1)}{p(\omega-1)+1} = 1 - \frac{1}{p(\omega-1)+1}$$

We can now apply PAR to determining the total medical and health costs per year associated with the establishment of the ban, H. If H_i is the average yearly medical and health costs for one individual due to diseases associated with MDS, sodium, and SFA as determined through population sampling, and n is the population of the geographical location of interest,

$$H = -(nH_i)(n\epsilon) = -H_i\epsilon n^2$$

5 Applying the Model

5.1 Concord, Massachusetts and San Francisco, California

Our model can be applied to Concord and San Francisco with varying results. Specific variables to be considered are demographics, notably population and age; property values; prevalence of businesses; distance from water bottle manufacturing plants; and general health consciousness.

With regards to demographics, the much larger population of San Francisco would cause the magnitude of the values obtained from our model to be larger for San Francisco than for Concord, since the amount of single-serving water bottles used within a geographic area scales with population. Further, because San Francisco is also larger in area than Concord, the area covered when conducting cleanup would also expand, raising the environmental cost. Additionally, San Francisco's proximity to the ocean would require more extensive marine care, adding to the environmental cost as well.

Property values in San Francisco are much higher than those in Concord, with San Francisco having the 6th most expensive land values out of American cities [9]. This means that the prices would be much higher (for both water bottles and other drinks) for consumers while revenue for businesses stays the same. The impact of these would be uncertain, as consumers would save more money from not purchasing reusable water bottles, but would also spend more money purchasing other drinks. Landfill price would likely increase due to this higher land value, suggesting that the costs of landfill disposal would be greater in San Francisco. With these higher property values, other processes would also be more expensive to conduct.

Comparative distances from water bottle manufacturing plants for San Francisco and Concord can also affect the price and energy associated with the transport of the water bottles from the plant to the consumer. If a city is further away from water bottle plants, more energy and money would be necessary to transport the manufactured water bottles to the target location. As a result of the ban, these costs would be eliminated; the further away a city is from existing plants, the more money the ban would save. Thus, depending on how far Concord and San Francisco are away from water bottle manufacturing plants, the ban would have different impacts.

Additionally, San Francisco is considered second in the 25 healthiest cities in America as of 2016, while Concord doesn't even make the list [13]. This suggests that the substitution rate as a result of the ban would be significantly lower for San Francisco than for Concord, with fewer individuals selecting alternative beverages. This could affect our economic submodel because the amount of money lost by consumers from purchasing alternative beverages as well as the amount of revenue businesses gain from selling alternative beverages would decrease. However, the relative magnitudes of the impact on consumer spending and business revenue would be unknown, so the overall purely economic impact is questionable. The energy submodel would also be affected because more people would rely on tap water, decreasing the energy cost of production. From the lower substitution rate, the overall waste cost could also be relatively smaller in San Francisco as more people would rely on tap water rather than other drinks, decreasing the plastic waste from that category. In addition, a lower substitution rate results in a decreased risk of disease from MDS, sodium, and SFA. As a result, health costs due to the ban on single-serving water bottles would be significantly lower for San Francisco than for Concord.

San Francisco is the city in America that recycles the most with 80% of discards not going to landfills. [5]. There is a very high environmental awareness in San Francisco, which suggests that the recycling rate in San Francisco is significantly higher than in Concord. This would affect our energy and waste submodels. The energy costs would decrease substantially because recycling bottles consumes much less energy than producing new ones. For the waste submodel, the rate of plastic waste entering landfills and being incinerated would decrease significantly as people are more proactive and careful about their recycling.

5.2 Airport

Airports differ from standard cities and towns in several ways. Specifically, a geographical region acts more as a closed system, with the majority of people travelling within its borders. Though the transfer of people and any single-serving water bottles across boundaries is still large for a town, the effects of such exchange are largely insignificant: the net effect of an individual or bottle entering or leaving the area is minimal. Yet, airports can be considered open systems—their functioning is reliant on the arrival and departure of people to and from various, distant locations. As the ban can only affect sales of single-serving water bottles within the airport itself, with sales from other airports disregarded, both the positive and negative implications of the ban are minimized. Additionally, at airports, more water-related infrastructure, such as water bottle refilling stations, are established compared to cities and towns. Though these stations act as a constant since they are utilized both before and after the implementation of the ban, the ban's negative impacts are reduced due to the presence of filtered, easily-accessible water. Regardless, resultant economic, energy, waste, and health effects would still exist.

When applying our model to an airport, we must consider several key changes that would have to be made to the model itself. For example, an airport doesn't have a "population" (n), but rather an average amount of passengers that pass through the airport per year. Thus, the variable b would be the average number of single-serving water bottles bought per person in one visit to the airport, rather than per year.

Other changes to the model involve variable value alterations, rather than the addition of new variables. At an airport, the substitution rate s would change to reflect the passengers that would choose other drinks while at the airport. Due to the free availability of drinks on an airplane, short duration of the majority of the stays at an airport, and greater accessibility of filtered water, the substitution rate may not be as drastic in an airport as in a city or town. This change would largely decrease negative costs associated with the ban. Furthermore, it should be considered that because people have to go through security checks, where bringing water is not allowed, more people buy larger bottles of water inside the airport to stay hydrated through their flights, bottles of water that are typically much higher priced than in a normal retail store. Thus, it may be easier for the ban to push those who typically buy single-serving water bottles into using refillable water bottles and taking advantage of the free filtered water, which would decrease the value of s.

Aside from population and substitution rate, the value of prevalence (p), the exposure to the risk factor of selecting water or another drink, would also change for the health analysis submodel. In particular, a typical individual in a city or town would primarily be exposed to the risk factor during meals (breakfast, lunch, and dinner) or recreation. In an airport, however, the periods at which which beverages are often bought become ambiguous. The value of p would consequently increase in an airport, where individuals are significantly more prone to purchasing drinks apart from mealtimes.

6 Recommendations and Extensions

One key recommendation involving possible community measures is the addition and promotion of water bottle filling stations around the town or city that are known to contain clean, filtered tap water. These filling stations, though requiring energy and maintenance costs, could relieve negative impacts of the ban in the long-term. In particular, the success of the University of Washington's water bottle ban in 2016 can be partially attributed to the retrofitting of 100 water filling stations and addition of new fountains around the campus, similar in concept to a small town [12].

Adding water bottle filling stations in these communities, where they largely did not exist prior, would alter the substitution rate (s) by encouraging consumers to consume tap water instead of other drinks as well as require new variables in the economic, energy, and waste submodels to account for the purchase and usage of such technology. For example, the costs of the government constructing additional water bottle filling stations and promoting these stations would have to be considered in the model. However, because the substitution rate plays such an big role in boosting the cost benefits of the water bottle ban (with respect to economic, energy, and health effects), the costs associated with governmental actions would probably be negated by the decrease in the substitution rate, resulting in a overall net benefit. For the energy submodel, there would need to be a new variable for the energy cost of installing these filling stations, as well as the energy costs of running and maintaining them. Meanwhile, in the waste submodel, there would need to be components added to consider the CO_2 emissions and possible environmental impact of waste generated when constructing or operating the technology. New variables would be incorporated for the climate change cost of water bottle filling stations per station (K_f), environmental cost of the stations per station (V_f), and number of stations added per year (f). This would make the cost aspect of the model:

$$sn_b bm_o(V_p + \alpha L_p + \beta I) + abn_b K_o + f(K_f + V_f)$$

Community action regarding increasing awareness about recycling could aid in reducing waste going into landfills or being incinerated. This would change the percent of plastic bottles entering a landfill (α) and the percent of plastic bottles that are incinerated (β) in the cost side of the waste model as a greater proportion of plastic bottles are recycled rather than disposed as waste. An increase in awareness about recycling would also increase the recycling rate, causing the energy cost of other drinks to decrease. This would decrease energy costs, since recycling takes less energy than producing new bottles. Greater health awareness further reduces health costs attributable to the ban because people may be less likely to select alternative drinks with greater MDS, sodium, and SFA.

A modification to the Concord water bottle ban specifically could involve combating the shift to alternative drinks by adding a 5 to 10 cent tax on other bottled beverages, providing incentives leading to reduced adverse health effects deriving from the initial ban. This addition is more realistic than extending the ban to include larger-sized water bottles or containers, as these resources may be necessary for emergency conditions since Concord is notably prone to flooding [8]. Additionally, instead of shifting to other sources like glass which have an extremely large carbon footprint, this tax would likely decrease consumption overall, promoting more usage of tap water and reusable bottles. This would further decrease the substitution rate (s) as people would be less likely to consume and pay for these other bottled beverages with the additional tax.

One factor that was not accounted for in the economic submodel is the idea that if there was a single-serving water bottle ban, the prices of other drinks, due to higher demand, would increase, both giving businesses higher revenue and causing consumers to spend more. Furthermore, with our recommendation of a tax on other drinks to reduce a consumer's propensity to buy them, we must make alterations to the economic submodel to account for these changes. Currently, the model uses C_o as the cost of other drinks under present market conditions, but an economic analysis must be done to predict the cost of other drinks with the removal of single-serving water bottles from the equation. This price, plus the added tax, would replace C_o. Additionally, the revenue of businesses from the sale of other drinks will change, both due to an increase in profit from increased prices as well as from an increase in consumers buying the products. Thus, instead of having a single R_o, there must be a R_{oi} and R_{of} (initial and final), representing the revenue per drink sold before and after the ban. Also, because the revenue for businesses would change per drink sold before and after the ban, it would be necessary to consider the population who only rely on other beverages both before and after (represented with a new variable n_o) and the average bottles of other drinks bought per person (represented with a new variable o), since they would be providing more revenue to businesses. The revenue portion of the model would be rewritten as:

$$R_{of}(n_b bs + n_o o) - n_o o R_{oi} - n_b b R_w$$

Finally, due to the modular and flexible nature of our impact model, with four submodels, it is easily applicable to larger communities with applicable changes in variable values, such as population (n), the number of people buying single-serving water bottles (b), the substitution rate (s), and the recycling rate (ϕ). Factors different for states and countries, which are also primarily closed systems due to larger population and minimized effect of transfer, can thus be identified categorically by economics, energy, waste, and health to produce an overall number defining the impacts of a region-wide ban. For larger geographic areas, the energy costs would differ, since transportation to and from these areas would be vastly different depending on the area, as well as the waste treatment plans available. Furthermore, the economic state of the area would have an effect as well, as the purchasing power of consumers could be different and affect the substitution rate. The cost of enforcement, as well as the number of people who violate the ban will probably increase as area increase. Thus, enforcement will become a significant enough factor to consider in the model when applied to larger communities.

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