I. INTRODUCTION

In its effort to battle the effects of climate change, the Singapore government has introduced The Singapore Green Plan 2030 which targets nationwide long-term net-zero emissions by 2050. As part of this multi-ministerial effort, the Land Transport Authority of Singapore aims to reduce emissions from land transport by 80% (Land Transport Authority, 2022). One way it has tried to achieve this aim is through the introduction of electric vehicles (EVs) and providing incentives for the private transport sector to adopt them.

However, the road to EV adoption is not without its bumps. While EVs may have significantly lower carbon emission rates compared to their combustion engine counterparts (i.e. internal combustion engine (ICE) vehicles or hybrid vehicles), they may produce considerably higher emissions during their production phases as Lithium-ion batteries are emission-intensive to produce (MIT Climate, n.d.). Furthermore, the initial cost of purchasing EVs is much more expensive, which might impede demand for these cars (Anthony, 2022).

Despite these challenges, however, EVs undoubtedly offer a glimmer of hope for a greener future. With advancements in technology, they have the potential to become even more efficient and sustainable. As such, the adoption of electric vehicles is a pressing issue that Singapore must address, and our group has decided to investigate how to predict the optimum number of each vehicle type on the roads to minimize carbon emissions within a chosen timeframe. We will take into account consumer demand and trends in the efficiency of electric vehicles with time.

II. ASSUMPTIONS, VARIABLES, & DATA

A. Assumptions

The following assumptions to counter the infinite amount of variables that would affect the result of the calculations. It allows for the elimination of irrelevant information, streamlining the solution to target our actual issue.

1. Trend of vehicle efficiency follows that of the previous year's estimation
2. Car age is evenly distributed across the different types of cars as EVs were not widely owned in Singapore before the year 2012.
3. The car model is representative of the technology of its fuel consumption and hence efficiency at the time of the release of its first generation.
4. The vehicle and fuel LCA applied is based on findings from research done in Europe and is adapted to represent that of cars and fuel in Singapore.
5. The small sample size is representative of the current market in SG.
6. Amount of cars in Singapore is a constant 650,000 every year.
7. A car's lifespan in Singapore is a fixed 10 years and no car is used for a longer period.
8. In 2022, nearly 20% of cars in Singapore are 11 years in age or older. Our model assumes that these cars are to be replaced by 2023, causing a comparatively high demand for cars for the year 2023.
9. Electric vehicles are charged using electricity generated from 2% renewables (i.e. clean energy) and 98% fossil fuels. This explains the high amount of carbon emissions produced throughout the lifespan of an EV.
10. The rate of carbon emission produced throughout a car's lifespan is linear towards time and can be predicted with sufficient accuracy using linear regression analysis. This means that the carbon emitted by a car throughout its lifespan either decreases or increases constantly over time.

B. Variables

Our model was built upon several variables:

Bounds

- **T**: The upper bound on the year (e.g. 2040),
- **n**: The number of types of cars,

Independent Variables

- **X**: The number of a certain type of car
- **LCA**: The CO_2 equivalent of the cars over their lifespan (i.e. the total CO_2 produced throughout the production, usage, and end-of-life phases of the car).[1]

Dependent Variable

- CO2: The total CO2 equivalent generated by the cars.

Our variables are represented by a 2D matrix of indices ***i*** and ***t***, where ***i*** is the type of car and ***t*** is the year in question. In our solution below, we consider three types of cars: Internal Combustion Engine (ICE, *i=1*), Electric (*i*=2) and Hybrid (*i=3*). Our model can be applied to more types of cars, provided we have the data to pass to it. For instance, $X_{2025,\,1}$ would represent the number of ICE cars in 2025.

YEAR	X_1	X_2	X_3
2025	$X_{2025,\,1}$	$X_{2025,\,2}$	$X_{2025,\,3}$

This matrix is crucial for two reasons. Firstly, it is important to differentiate cars across different years even when they are of the same type of power mechanism. This is because cars can vary in their LCA rates even when they are of the same power source (e.g. two EVs have different LCA rates because they are produced in two different years). Secondly, the demand for cars in Singapore across different years changes over time, making it necessary to differentiate one year and another. These fluctuations often occur in cyclical patterns as in some years car owners have to change their cars due to expiring Certificate of Entitlements (COEs) more so than in other years.

C. Data

In order to proceed, we need to collect and sort out some crucial data. First and foremost, we need to collect

[1] From here onwards, the term LCA shall be used to denote the total carbon emission produced throughout the lifecycle of a car. Please do not confuse this term with the process of conducting a Life Cycle Assessment.

LCA rates for the three different types of cars selected. It is important to note that the LCA data is very

LCA over time was calculated by linearly extrapolating existing trends for each type. Our goal would be to minimise CO_2 by modifying X.

III. SOLUTION

Thought Process

We purposefully selected the LCA

Carbon Emissions Equation

To begin, we attempt to derive an equation to quantify the amount of CO_2 that would be produced when a certain combination of cars are manufactured and used for a selected lifespan (10 years). One model we propose to compute the total amount of CO_2 is the following:

$$\sum CO_2 = \sum_{i=1}^{n} X_i \cdot LCA_i$$

where X_i is the number of the i-th type of car and LCA_i is the total amount of CO_2 produced during the car's lifespan. This model basically sums up all the CO_2 produced by a car produced in a certain year over its lifespan. In order to calculate the total carbon emissions produced due to cars in the next 40-50 years, we can iterate this equation over and over again such that:

$$\sum CO_2 = \sum_{t=2023}^{T} \sum_{i=0}^{n} X_i \cdot LCA_i$$

Ultimately, we will obtain an equation that represents our objective function: a function to compute the total carbon emissions produced throughout the lifecycle of every car in Singapore. We will minimize this function as we want to minimize the amount of carbon emissions produced. This equation will take the general form as the one below:

$$Z = [X_1 LCA_1 + ... + X_n LCA_n]_{2023}$$
$$+ [X_1 LCA_1 + ... + X_n LCA_n]_{2024}$$
$$+ ...$$
$$+ [X_1 LCA_1 + ... + X_n LCA_n]_T$$

This problem takes the form of a single objective linear programming problem. It is an optimisation with multiple dimensions and a single objective.

Constraints

Before minimizing the above function, it would be wise to define the region of optimisation. This is because without such a region limitation, any optimisation efforts would simply produce results that are meaningless albeit mathematically valid. Thus, in this study we have selected 3 scenarios to tackle the given problem:

- **Scenario 1**

In scenario 1, we imagine a world where most private cars are powered by internal combustion engines. There are several electric vehicles and hybrid cars, but these two types of cars make up a minority of the cars produced. One way to represent this situation is by defining the following region:

$$X_1 \geq 70\%D$$
$$X_2 \geq 10\%D$$
$$X_3 \geq 10\%D$$

- **Scenario 2**

In scenario 2, we imagine a world where most people for some reason choose to use electric vehicles. ICE and hybrid-powered cars still exist, but like in scenario 1, they only make up a small minority of all the cars used in Singapore. This scenario can be represented by the following region:

$$X_1 \geq 10\%D$$
$$X_2 \geq 10\%D$$
$$X_3 \geq 10\%D$$
$$3X_2 \geq 7X_3$$

- **Scenario 3**

In scenario 3, we imagine a similar situation as in scenario 2, but now people prioritize using hybrid cars over electric vehicles and ICE-powered cars. Again, EVs and ICE cars still exist, but they only make up a comparatively small portion of all cars in Singapore. This scenario can be represented by the following region:

$$X_1 \geq 10\%D$$
$$X_2 \geq 10\%D$$
$$X_3 \geq 10\%D$$
$$3X_3 \geq 7X_2$$

By performing the study across these three different scenarios, we will be able to compare

A. **Figuring out the LCA**
B. **Figuring out the Distribution of Cars by Age and by Type of Energy**

IV. RESULTS (Nathan's)

A. **Scenario 1**

YEAR	X_1	X_2	X_3
2023	82,781	30,422	13,797
2024	12,005	6,003	2,001
2025	28,766	14,384	4,794
2026	49,480	24,739	8,247
2027	53,953	26,977	8,992
2028	48,017	24,008	8,003
2029	43,348	21,673	7,225
2030	26,545	13,273	4,424
2031	27,004	13,502	4,501
2032	18,101	9,050	3,017
2033	82,781	41,391	13,797
2034	12,005	6,003	2,001
2035	28,766	14,384	4,794
2036	49,480	24,739	8,247
2037	53,953	26,977	8,992
2038	48,017	24,008	8,003

2039	43,348	21,673	7,225
2040	26,545	13,273	4,424
2041	27,004	13,502	4,501
2042	18,101	9,050	3,017
2043	82,781	41,391	13,797
2044	12,005	6,003	2,001
2045	28,766	14,384	4,794
2046	49,480	24,739	8,247
2047	53,953	26,977	8,992
2048	48,017	24,008	8,003
2049	43,348	21,673	7,225
2050	26,545	13,273	4,424
2051	27,004	13,502	4,501
2052	18,101	9,050	3,017
2053	82,781	41,391	13,797

B. Scenario 2

YEAR	X_1	X_2	X_3
2023	12,700	101,600	12,700
2024	3,098	24,782	3,098
2025	4,794	38,356	4,794
2026	8,247	65,972	8,247
2027	8,992	71,938	8,992
2028	8,003	64,022	8,003
2029	7,225	57,796	7,225
2030	4,424	35,394	4,424
2031	4,501	36,005	4,501
2032	3,017	24,134	3,017
2033	12,700	101,600	12,700
2034	3,098	24,782	3,098
2035	4,794	38,356	4,794
2036	8,247	65,972	8,247
2037	8,992	71,938	8,992
2038	8,003	64,022	8,003
2039	7,225	57,796	7,225
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2048	8,003	64,022	8,003
2049	7,225	57,796	7,225
2050	4,424	35,394	4,424
2051	4,501	36,005	4,501
2052	3,017	24,134	3,017
2053	12,700	101,600	12,700

C. Scenario 3

YEAR	X_1	X_2	X_3
12,700	12,700	101,600	12,700
3,098	3,098	24,782	3,098
4,794	4,794	38,356	4,794
8,247	8,247	65,972	8,247
8,992	8,992	71,938	8,992
8,003	8,003	64,022	8,003
7,225	7,225	57,796	7,225
4,424	4,424	35,394	4,424
4,501	4,501	36,005	4,501
3,017	3,017	24,134	3,017
12,700	12,700	101,600	12,700
3,098	3,098	24,782	3,098
4,794	4,794	38,356	4,794
8,247	8,247	65,972	8,247
8,992	8,992	71,938	8,992
8,003	8,003	64,022	8,003
7,225	7,225	57,796	7,225
4,424	4,424	35,394	4,424
4,501	4,501	36,005	4,501
3,017	3,017	24,134	3,017
12,700	12,700	101,600	12,700
3,098	3,098	24,782	3,098
4,794	4,794	38,356	4,794
8,247	8,247	65,972	8,247
8,992	8,992	71,938	8,992
8,003	8,003	64,022	8,003
7,225	7,225	57,796	7,225
4,424	4,424	35,394	4,424
4,501	4,501	36,005	4,501
3,017	3,017	24,134	3,017
12,700	12,700	101,600	12,700

V. STRENGTH AND WEAKNESSES

Strengths

1.) The CO_2 emission function is tested using multiple scenarios which allows for a higher certainty of estimates and validation of the naïve assumptions made in section **II**.
2.) The model allows easy inclusion of additional types of cars, provided trends in LCA are available.
3.) External constraints such as policy (e.g. 100% EV by 2040) can be added as scenarios.
4.) Changes in car efficiency over time can be taken into account.

Weaknesses

1.) The model relies on the extrapolation of a fixed dataset from the past 10 years. However due to assumed relationships when extrapolating a data set beyond its range, such as the rate of improvement in efficiency of the vehicles, the likelihood of biased conclusions increases. (Hahn, 2018) It is possible that the efficiency of electric vehicles and hybrid cars plateau in the future, instead of increasing infinitely.
2.) The large number of assumptions due to lack of data lead to inaccuracy. More resources to collect data can improve accuracy.
3.) The model assumes that LCA data is a function of time. In actuality, LCA for EVs can also be functions of EV population as existing infrastructure needs to be upgraded to support a larger EV population.

4.) For EVs specifically, this model does not account for possible changes in energy sources that provide electricity to charging stations in Singapore. The model assumes that Singapore continues using 98% fossil fuels indefinitely. Given the possibility that Singapore might replace natural gas with greener sources of energy in the future, the LCA for the EV might give a drastically lower lifetime emission and the actual total carbon emission may be lower than the model predicts.

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