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Development of Zero-Emission Vehicle Evacuation Readiness Score Formulation Methodology

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***Abstract*—The rapid increase in the adoption of Electric Vehicles (EVs) and Zero-Emission Vehicles (ZEVs) in California has led to significant changes in transportation infrastructure, power systems, and power distribution networks. In the first quarter of 2024 alone, 102,507 EVs were sold in California, with total sales for the year projected to exceed 410,000 vehicles if current trends continue. This shift necessitates policy changes, particularly in evacuation procedures. Traditionally, evacuation plans have assumed that evacuees use gasoline vehicles, ignoring the unique challenges posed by EVs and ZEVs, such as the need for charging and potential impacts of power outages. This study introduces the *ZEV Evacuation Readiness Score* (ZEV Score), a metric designed to evaluate how well a community can respond to an evacuation scenario involving ZEVs. The effectiveness of the ZEV Score is demonstrated through a case study of Santa Cruz County California, highlighting its potential application for stakeholders and policymakers.**

***Index Terms*—EV evacuation, zero emission vehicle, evacuation readiness Score, renewable resource**

I. Introduction

A. Motivation and background

California leads in zero-emission vehicle (ZEV) adoption to combat carbon emissions [1]. However, the state faces challenges due to its susceptibility to severe weather events [2]. Over the past five years, all 58 counties in California have experienced multiple disasters, predominantly wildfires [3]. Evacuation mandates are common, especially during wildfires, yet historically relied on fossil-fuel vehicles [4]. However, the shift to electric vehicles (EVs) raises concerns about evacuation preparedness, particularly regarding charging infrastructure limitations [5]. Battery EVs (BEVs) require substantial time to recharge, hindering rapid evacuation [6]. The lack of fast-charging infrastructure, especially in certain counties, may further delay evacuations [7]. Power outages, stemming from natural disasters or safety measures like public safety power shutoffs, exacerbate the problem [8]. Addressing these challenges requires a reassessment of evacuation strategies to accommodate the growing presence of ZEVs [9].

B. Literature review

This research pioneers the development of a standardized score to assess EV evacuation preparedness, an area with limited exploration. The literature review aimed to identify criteria and metrics for formulating a zero emission vehicle score (ZEV Score) and to perform multi-criteria decision analysis (MCDA) for sustainable energy decision-making, seeking relevant indicators for the ZEV score's development [10,11]. The review revealed the complexity of sustainability objectives and the prominence of MCDA methods like the analytical hierarchy process (AHP) in sustainable energy decision-making [10]. Foundational proposals for the ZEV score emphasized the importance of analyzing transportation networks, EV charging infrastructure, power grid capabilities, hazard maps, and local jurisdiction hazard analyses as potential indicators [11].

This paper employs AHP techniques to develop the ZEV score using identified indicators, with indicator weighting determined through stakeholder and expert surveys, focusing on relevance, availability, and source reliability. The paper's structure includes a discussion of indicators and the basic ZEV score model, a methodology for weight determination through surveys, implementation on Santa Cruz county data, and implications for future research [10,11]. Section II discusses available indicators and the basic model for the ZEV score. Section III details the survey methodology for determining indicator weights. Section IV describes the implementation of the methodology for Santa Cruz county. Section V concludes with implications, applications, and future research directions.

II. Development of Scoring Methodology

This section outlines the process of selecting indicators for the formulation of the ZEV score, emphasizing their significance

in assessing readiness for ZEV-based evacuations. It also explains the mathematical formulation of the ZEV score to ensure a nuanced representation of selected indicators.
To evaluate a county or region's preparedness for a ZEV-based evacuation during natural disasters, the ZEV score considers:

1) **Exposure Analysis**: Assessing the area's vulnerability to various natural hazards, such as wildfires, floods, or earthquakes, through hazard analysis maps and estimation methods. This generates an Exposure Index (EI).
2) **Infrastructure Vulnerability Assessment**: Evaluating the resilience of existing infrastructure, including electric chargers, roads, and electricity transmission networks, to withstand natural disasters, quantified as the Infrastructure Vulnerability Score (IVS).
3) **Adaptive Capacity of Infrastructure**: Examining the adaptability of infrastructure components like electric chargers and power generation units to manage increased load during evacuations, represented by the Adaptive Capacity of Infrastructure Score (ACIS).

The selection of indicators ensures comprehensive coverage of each criterion's impact by considering the likelihood of natural hazards (exposure analysis), current infrastructure resilience (infrastructure vulnerability assessment), and infrastructure adaptability (adaptive capacity of infrastructure). These definitions provide a structured framework for developing the ZEV score. Figure 1 illustrates the ZEV score calculation process, showing how each criterion contributes based on its predetermined weight, reflecting factors such as emissions reduction and environmental sustainability. This framework will be employed to define and aggregate the scores for each criterion.

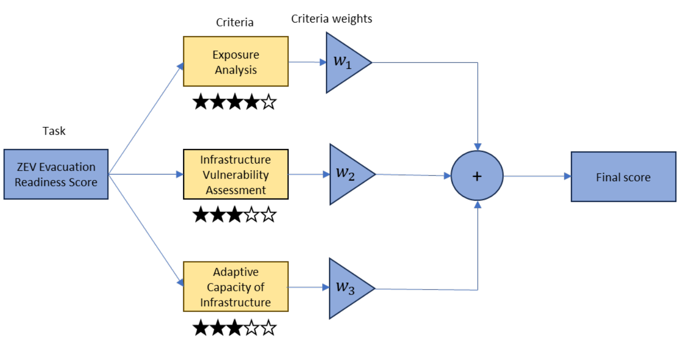

Fig. 1. ZEV Score Calculation Methodology

A. Exposure Index (EI) Calculation

This sub-section will discuss how to implement the RGB analysis methodology to find a EI score given that there is hazard map available. An example of hazard map is given in figure 2.
Basic algorithm for the analysis is as follows:

Algorithm 1 EI Analysis

```
Set img_path to 'CountyHazardMap.png'
Define colour_shades with RGB ranges for different colors
Initialize pixel_counts with keys from colour_shades and values set to 0
Define function is_in_range(pixel, color_range):
    return True if all pixel values are within the color_range, else False
for each row in img_array do
  for each pixel in row do
    for each shade, color_range in colour_shades do
      if is_in_range(pixel, color_range) then
        Increment pixel_counts[shade]
      end if
    end for
  end for
end for
Calculate the total of pixel_counts for all color ranges
Calculate relative pixel counts E1, E2, E3, E4, E5 for each color range
Print relative pixel counts for each color range
Calculate Exposure Index EI using the formula:
   EI = E1*5 + E2*4 + E3*3 + E4*2 + E5*1
Print "Exposure Index for the county is: " EI
```

B. Infrastructure Vulnerability Score (IVS) Calculation

In this criterion, we utilize three major metrics: probability of blackout (I_{11}), total charging stations per EV (I_{12}), and evacuation center distance and location (I_{13}). These metrics are foundational in calculating the integrated vulnerability score (IVS) for the following reasons:

- **Probability of Blackout** (I_{11}): This metric addresses the balance of power generation, removing the need to separately calculate total energy and power generation for the region.
- **Total Charging Stations per EV** (I_{12}): This metric is critical as it considers the impact of different charger types.
- **Evacuation Center Distance and Location** (I_{13}): This metric assesses the worst-case scenario for the distance any EV must cover to reach safety.

After scoring each metric, we calculate the IVS using a simple mean:

$$\text{IVS} = \frac{I_{11}(\text{range 1-5}) + I_{12}(\text{range 1-5}) + I_{13}(\text{range 1-5})}{3}$$

C. Adaptive Capacity Infrastructure Score (ACIS) Calculation

As the adaptive capacity of infrastructure deals with the ability of existing systems to manage the influx of electric vehicles (EVs) and their charging demands on the power grid, the score should reflect the capabilities of transportation infrastructure (Road/Highway capacity) ($I_{2,1}$), the charger-to-EV ratio ($I_{2,2}$), and the availability of backup/excess power in a county/region ($I_{2,3}$). The reasons for selecting these indicators are:

- **Road/Highway Capacity** ($I_{2,1}$): Ensures that there are no traffic jams on major roads during evacuations, allowing EVs and residents to reach safety efficiently.
- **Charger-to-EV Ratio** ($I_{2,2}$): Ensures there are sufficient chargers in the region, which is crucial for maintaining a high score.
- **Backup/Excess Power** ($I_{2,3}$): Ensures there is enough electric power available to handle the charging needs during evacuations.

After scoring each metric, we calculate the adaptive capacity infrastructure score (ACIS) using a simple mean:

$$\text{ACIS} = \frac{I_{2,1}(\text{range 1-5}) + I_{2,2}(\text{range 1-5}) + I_{2,3}(\text{range 1-5})}{3}$$

D. Final ZEV Scoring Formulation

As all the criteria have been determined. ZEV (R) score can be formally defined as follows:

$$R(EI, IVS, ACIS) = EI \cdot w_1 + IVS \cdot w_2 + ACIS \cdot w_3$$

where w_1 represents the weight associated with the EI analysis, w_2 represents the weight associated with the IVS analysis, w_3 represents the weight associated with the ACIS analysis.

III. Weight Determination Process

In this section, a comprehensive calculation for weight determination utilizing the *AHP* is carried out.

This research paper adheres to a systematic procedure, a simple code in python is developed, that inputs the comparative importance of each criterion and then outputs the weights for each criteria. Simple psuedo code for the algorithm is shown in the block in the next column.

The relative importance have been defined using survey results from stake-holders and experts. This weight distribution will remain the same for ZEV score calculation for any county/region. The output of the implementation of the psuedo code is as follow:

$$w_1 = 0.157 \quad (1)$$

$$w_2 = 0.183 \quad (2)$$

$$w_3 = 0.657 \quad (3)$$

IV. Implementation of Scoring Methodology

This section presents the implementation of the defined methodology to formulate a ZEV score for a county. For this study, Santa Cruz County is considered, and data for the county is obtained from credible sources. First, the algorithm defined in Section II, Subsection II.1 is implemented to determine the EI for Santa Cruz County. Next, Subsection II.2

Algorithm 2 Weight Calculation

Step 1: Define importance values
$a \leftarrow 1$ {Importance of IVS to EI}
$b \leftarrow 4.85$ {Importance of ACIS to EI}
$c \leftarrow 3.125$ {Importance of ACIS to IVS}
Step 2: Create the pairwise comparison matrix
$M \leftarrow \begin{bmatrix} 1 & 1/a & 1/b \\ a & 1 & 1/c \\ b & c & 1 \end{bmatrix}$
Step 3: Calculate the sum of each column
Step 4: Normalize the matrix
Step 5: Calculate the weights
$w1 \leftarrow \sum M_{\text{new}}[0, :]/3$
$w2 \leftarrow \sum M_{\text{new}}[1, :]/3$
$w3 \leftarrow \sum M_{\text{new}}[2, :]/3$

is followed to formulate the IVS for Santa Cruz County. Similarly, Subsection II.3 is used to formulate the ACIS for the county, which will be used in the final calculation of the ZEV score as defined in Subsection II.4 Moreover, weights are determined using the survey results and computations explained in Section III.

A. EI for Santa Cruz

A hazard map for Santa Cruz county [12] will be used in this computation. Same as the one defined in Section II, Subsection II.1 The hazard map used for this purpose is give in figure 2. After the RGB analysis of this map, EI for Santa Cruz comes

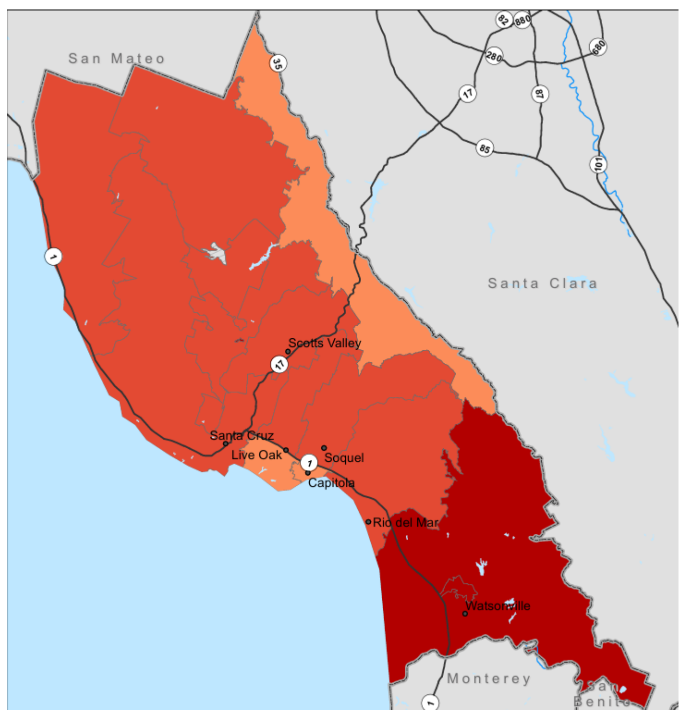

Fig. 2. Multi-Hazard Map for Santa Cruz

out to be 0.887. It will be labeled as follows:

$$\mathrm{EI}_{\text{Santa Cruz}} = 0.887 \tag{4}$$

B. IVS for Santa Cruz

The *IVS* is a key component of the ZEV score, calculated using three main indicators: probability of blackout (I_{11}), total charging stations per EV (I_{12}), and evacuation center distance and location (I_{13}).

- **Probability of Blackout** (I_{11}): Based on [13], the estimated power outage duration in 2024 is 285 hours per year, with 20% due to weather conditions, resulting in:

  $$\text{Estimated power outages} = 20\% \times 285 = 57 \text{ hrs/yr}$$

  Now, in order to standardize it from 1 to 5. A simple piece-wise function can be used as follows: Let the outage be x. The scoring criteria based on the outage duration is as follows:

  $$\begin{cases} \text{If } x \geq 2400 \text{ hours} & \rightarrow \text{ score } = \text{0-1} \\ \text{If } 2400 > x \geq 1920 \text{ hours} & \rightarrow \text{ score } = \text{1-2} \\ \text{If } 1920 > x \geq 1440 \text{ hours} & \rightarrow \text{ score } = \text{2-3} \\ \text{If } 1440 > x \geq 960 \text{ hours} & \rightarrow \text{ score } = \text{3-4} \\ \text{If } x < 960 \text{ hours} & \rightarrow \text{ score } = \text{4-5} \end{cases}$$

  Using a the above mentioned piece-wise function, Santa Cruz scores 5 as its outage duration is less than 960 hours.

  $$\text{probability of blackout}(I_{11}) = 5$$

- **Total Charging Stations per EV** (I_{12}): The county has 369 chargers and 10,875 EVs [14], resulting in a ratio of approximately 30 EVs per charger:

  $$\text{Ratio of EVs to chargers} = \frac{10{,}875}{369} \approx 30$$

  Developing a metric for giving a score:
  Let x be the ratio of EVs to Chargers.

  $$\begin{cases} x = 1:1 \text{ to } 10:1 & \rightarrow \text{ index } = 5 \\ x = 10:1 \text{ to } 20:1 & \rightarrow \text{ index } = 4 \\ x = 20:1 \text{ to } 30:1 & \rightarrow \text{ index } = 3 \\ x = 30:1 \text{ to } 40:1 & \rightarrow \text{ index } = 2 \\ x > 40:1 & \rightarrow \text{ index } = 1 \text{ or lower} \end{cases}$$

  Using the developed metric, the score is 2.

  $$\text{Total Charging Stations per EV}(I_{12}) = 2$$

- **Evacuation Center Distance and Location** (I_{13}): With 6 shelter sites within 5-6 miles of downtown areas [15], but lacking EV chargers, the score is adjusted to 2.

  $$\text{Evacuation Center Distance and Location } I_{13} = 2$$

  Detailed scoring criteria is as follows:
  - **Condition 1:** If distance ≤ 3 miles && EV chargers = Capacity of shelter centers
    $\rightarrow I_{13} = 5$
  - **Condition 2:** If 3 < distance ≤ 6 miles && $\frac{3}{4}$(Capacity of Shelter center) < EV chargers < Capacity of shelter center
    $\rightarrow I_{13} = 4$
  - **Condition 3:** If 6 < distance ≤ 10 miles && $\frac{1}{2}$(Capacity of Shelter center) < EV chargers < $\frac{3}{4}$(Capacity of shelter center)
    $\rightarrow I_{13} = 3$
  - **Condition 4:** If 10 < distance ≤ 15 miles && EV chargers < $\frac{1}{2}$Capacity of shelter center
    $\rightarrow I_{13} = 2$
  - **Condition 5:** If 15 < distance && EV chargers = few
    $\rightarrow I_{13} = 1$ or 0

The overall IVS is calculated as:

$$\mathrm{IVS} = \frac{I_{11} + I_{12} + I_{13}}{3} = \frac{5 + 2 + 2}{3} = 3$$

$$\mathrm{IVS}_{\text{Santa Cruz}} = 3 \tag{5}$$

Therefore, the IVS score for Santa Cruz is 3.

C. ACIS for Santa Cruz

For this subsection, detailed analysis of the indicators discussed in Section II, Subsection II.3 will be carried out. The indicators are: capabilities of transportation infrastructure (Road/Highway capacity) ($I_{2,1}$), the charger-to-EV ratio ($I_{2,2}$), and the availability of backup/excess power in a county/region ($I_{2,3}$).

- **Capabilities of Transportation Infrastructure (Road/Highway capacity)** (I_{21}): For Highway 17 in Santa Cruz [16]:
  - It has 4 lanes: 2 for incoming and 2 for outgoing traffic, $N_L = 2$.
  - Road capacity of Highway 17 is 60,000 cars/day or 2500 cars/hr.

  Road capacity per lane λ_L:

  $$\lambda_L = \frac{2500}{4} = 625 \ \frac{\text{cars}}{\text{hr/ln}}$$

  Total one-way highway capacity λ_{HC}:

  $$\lambda_{HC} = 625 \times 2 = 1250 \text{ cars/hr}$$

  Time required for evacuation:

  $$N_v = 10{,}875 \text{ cars} \quad \text{and} \quad \text{Time} = \frac{10875}{1250} = 8.7 \text{ hrs}$$

  let total given evacuation time x = 12 hrs. So, using the scoring criteria:

  $$\begin{cases} y < x \text{ by } 50\% \text{ of } x \rightarrow 5 \\ y < x \text{ by } 25\% \text{ of } x \text{ or } y = x \rightarrow 4 \\ y > x \text{ by } 25\% \text{ of } x \rightarrow 3 \\ y > x \text{ by } 50\% \text{ of } x \rightarrow 2 \\ y > x \text{ by } 75\% \text{ of } x \rightarrow 1 \end{cases}$$

Given $y = 8.7$ hrs, which is less than x by 38%, $I_{21} = 4.5$.

- **Charger to EV ratio (I_{22})**: As previously discussed, $I_{22} = I_{12} = 2$.
- **Backup/Excess Power (I_{23})**: Total generation [17] and consumption [18] for Santa Cruz:

$$E_G = 1314 \text{ GWh} \quad \text{and} \quad E_C = 1177 \text{ GWh}$$

Backup power:

$$E_{\text{back-up}} = 1314 - 1177 = 137 \text{ GWh}$$

Scoring system:

$$\begin{cases} \text{Generation} < \text{Consumption} \rightarrow I_{23} = 0\text{-}1 \\ \text{Generation} > \text{Consumption by } 10\% \rightarrow I_{23} = 2 \\ \text{Generation} > \text{Consumption by } 20\% \rightarrow I_{23} = 3 \\ \text{Generation} > \text{Consumption by } 30\% \rightarrow I_{23} = 4 \\ \text{Generation} > \text{Consumption by } 50\% \text{ or more} \rightarrow I_{23} = 5 \end{cases}$$

Given E_G exceeds E_C by 11%, $I_{23} = 2$.

The overall ACIS is:

$$\text{ACIS} = \frac{I_{21} + I_{22} + I_{23}}{3} = \frac{4.5 + 2 + 2}{3} = 2.83$$

$$\text{ACIS}_{\text{Santa Cruz}} = 2.83 \tag{6}$$

So, the ACIS score for Santa Cruz is 2.83.

D. Final ZEV Score

Using the weights calculated in Section III, and the criteria values calculated in previous subsections, ZEV score can be calculated using the formula defined in II.4. Substituting in values using (1), (2), (3), (4), (5) and (6):

$$R(EI, IVS, ACIS) = 0.887 \cdot 0.157 + 3 \cdot 0.183 + 2.83 \cdot 0.659$$

$$R(EI, IVS, ACIS) = 2.552$$

Thus final ZEV score for Santa Cruz comes out to be 2.552.

V. Conclusion

This research paper outlines the initial steps in emergency planning for the growing presence of electric vehicles (EVs) in transportation networks, formulating a problem statement to address planning evacuations reliant on EVs. It introduces a preliminary plan centered on creating a ZEV score to rank regions based on their readiness for EV evacuations, incorporating indicators such as exposure analysis, infrastructure development, and capacity. The ZEV score, with weight parameters derived from surveys, is demonstrated through a case study in Santa Cruz County. This score serves as a decision-making tool for stakeholders to enhance EV evacuation capabilities, with further research needed to refine the scoring mechanism and improve emergency preparedness strategies.

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