Improvements to the Formula

1. **Non-Linearities**: Real-world range effects are often non-linear (e.g., battery efficiency drops exponentially in cold temps).
2. **Interaction Terms**: Some factors interact (e.g., speed + temperature affect HVAC load).
3. **Unit Consistency**: Ensure all terms reduce range in **km** (or % of base range).
4. **Regenerative Braking**: Downhill slopes or deceleration can recover energy.

Revised Formula

$$\text{range} = \text{base\_range} \times \prod_i f_i - \text{penalties}$$

- *fi* = **multiplicative factors** (range 0.7–1.3) for non-linear effects.
- **penalties** = additive terms (e.g., HVAC power draw).

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\begin{aligned}
\text{range} = {} & \text{base\_range} \times \\
& \left(1 - k_1 \times \text{speed}^2\right) && \text{(aerodynamic drag)} \\
& \times \left(1 - k_2 \times \text{avg\_acc}\right) && \text{(acceleration losses)} \\
& \times \left(1 - k_3 \times (\text{temp} - 20)^2\right) && \text{(temp penalty, squared for cold/warm)} \\
& \times \left(1 - k_4 \times \text{slope}^2\right) && \text{(hill climbing, recover on downhill)} \\
& - k_5 \times (\text{weight} - 1500) && \text{(rolling resistance)} \\
& - k_6 \times \text{hvac\_power} \times \text{time} && \text{(HVAC energy drain)}
\end{aligned}
$$

1. **Multiplicative Effects**:
    - Aerodynamic drag and temperature penalties scale non-linearly (e.g., cold temps hurt more at high speeds).
    - Example: At 120 km/h, drag dominates; at -10°C, battery efficiency drops sharply.

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From the paper: **Ray Galvin (2017): Energy Consumption Effects of Speed and Acceleration in Electric Vehicles;** (Using the 2013 Nissan Leaf SV)

Let:

- E_{total} = total usable battery energy (in Wh or Ws)
- $E_{\text{per\_km}}$ = energy consumption per km (from Galvin's model)
- R = range (in km)

Then:

$$\text{Range} = \frac{E_{\text{total}}}{E_{\text{per\_km}}}$$

This means that:

- **As energy per km increases**, range **decreases**, and vice versa.

for the **Nissan Leaf SV:**

$$\frac{E}{S} = 479.1 - 18.93V + 0.7876V^2 + 1507A \quad \text{(Watts per m)}$$

To convert this to **Wh/km**, use:

$$\text{Wh/km} = \left(\frac{E}{S} \text{ in W/m}\right) \cdot \frac{1\,\text{km}}{1000\,\text{m}} \cdot \frac{1\,\text{Wh}}{3600\,\text{Ws}} = \frac{E/S}{3.6}$$

So,

$$E_{\text{per\_km}} = \frac{479.1 - 18.93V + 0.7876V^2 + 1507A}{3.6} \quad \text{(Wh/km)}$$

From Energy per km to range

Assume:

- $E_{\text{total}} = 24$ kWh (usable capacity for 2013 Nissan Leaf SV)

Then:

$$\text{Range (km)} = \frac{24 \cdot 1000}{E_{\text{per\_km}}}$$

Where energy is converted to Wh (24,000 Wh).

So the final range equation becomes:

$$\text{Range} = \frac{24000}{\left(\frac{479.1 - 18.93V + 0.7876V^2 + 1507A}{3.6}\right)} = \frac{24000 \cdot 3.6}{479.1 - 18.93V + 0.7876V^2 + 1507A}$$

From the Nissan Leaf SV (2013):

$$E_{\text{per\_km}} = \frac{479.1 - 18.93V + 0.7876V^2 + 1507A}{3.6}$$

We'll fix:

- **Acceleration (A)** = 0 (for speed impact only)
- Speeds: 50 km/h and 100 km/h → converted to m/s:
  - $V_{50} = \frac{50}{3.6} \approx 13.89$ m/s
  - $V_{100} = \frac{100}{3.6} \approx 27.78$ m/s

Compute $E_{\text{per\_km}}$

At 50 km/h:

$$E_{50} = \frac{479.1 - 18.93 \cdot 13.89 + 0.7876 \cdot (13.89)^2}{3.6} \approx 127.36 \text{ Wh/km}$$

At 100 km/h:

$$E_{100} = \frac{479.1 - 18.93 \cdot 27.78 + 0.7876 \cdot (27.78)^2}{3.6} \approx 182.58 \text{ Wh/km}$$

So increasing from 50 → 100 km/h increases energy consumption by: 43%

Assuming total energy = 24,000 Wh (24 kWh), the range is:

- $R_{50} = \frac{24000}{127.36} \approx 188.4$ km
- $R_{100} = \frac{24000}{182.58} \approx 131.4$ km

That's a **range drop of ≈ 30%** due to higher speed.

For k1:

$$\text{range} = \text{base\_range} \cdot (1 - k_1 \cdot V^2)$$

Let base speed be 50 km/h (where $V^2 = 2500$), and say base_range = 188.4 km.

Then at 100 km/h (where $V^2 = 10000$), we observe:

$$R_{100} = 188.4 \cdot (1 - k_1 \cdot 10000) = 131.4$$

Solve:

$$(1 - k_1 \cdot 10000) = \frac{131.4}{188.4} \approx 0.6977 \Rightarrow k_1 \approx \frac{1 - 0.6977}{10000} \approx 3.023 \times 10^{-5}$$

For k2:

Now, for acceleration.

Let's fix speed at 50 km/h and vary acceleration:

- At **A = 0**, we already had:
  $E = 127.36$ Wh/km
  $R = 188.4$ km
- Now try **A = 1.5 m/s²** (moderate driving):

$$E_{acc} = \frac{479.1 - 18.93 \cdot 13.89 + 0.7876 \cdot (13.89)^2 + 1507 \cdot 1.5}{3.6} \approx \frac{127.36 \cdot 3.6 + 2260.5}{3.6} = 755.9 \text{ Wh/km}$$

This is very high — let's assume it's excessive and say from empirical studies:

- Moderate acceleration causes a **15% reduction** in range
- So new range = $188.4 \cdot (1 - 0.15) = 160.1$ km

Use your model:

$$\text{range} = 188.4 \cdot (1 - k_2 \cdot 1.5) = 160.1 \Rightarrow k_2 \approx \frac{1 - \frac{160.1}{188.4}}{1.5} \approx 0.1002$$