

Comprehensive comparison of hybrid and electric vehicles using a multi-dimensional techno-economic assessment diagram

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Summary

In this paper, I present a visualization methodology - a multi-dimensional techno-economic assessment diagram - to comprehensively illustrate the relationship between assumptions (sets of input parameters) and results (corresponding output variables). This methodology is applied to analyse lifecycle cost and CO₂ emissions of hybrid vehicles (HV) and electric vehicles (EV). I then develop an eight-dimensional interactive diagram showing the relative advantages of HV or EV in the input space consisting of the following eight parameters: HV fuel efficiency, EV energy efficiency, annual vehicle mileage, gasoline price, electricity price, battery price, gasoline CO₂ intensity, and electricity CO₂ intensity. This diagram can be further extended to include other vehicle types and performance variables, allowing analysis of multiple scenarios. This methodology provides, as it were, a map visualizing the comprehensive relationship between inputs and outputs of the model used; specific scenarios (specific sets of inputs and its output) are represented by points plotted on the map. This methodology can support systematic comparison of electrified vehicles and related uncertainty analysis.

Keywords: LCA (Life Cycle Assessment), LCC (Life Cycle Cost), HEV (hybrid electric vehicle), EV (electric vehicle)

1 Introduction

The proportion of CO₂ emissions from road transport to overall energy-related CO₂ emissions is 15.9%, 27.8%, and 16.9% in Japan, the US, and the world, respectively [1]. The introduction of effective technologies and policies to reduce CO₂ emissions from road transport is thus critical for automotive manufacturers and policy makers to contribute to sustainable development.

Life cycle assessment (LCA) is a useful methodology to evaluate technologies that contribute to lower environmental loads. Together with colleagues [2], I conducted techno-economic analysis of advanced vehicles using LCA. In general, the LCA procedure (strictly speaking, Life cycle Inventory analysis (LCI), which forms part of LCA) can be summarized as follows. First, assumptions are set. Second, assumptions are input into the model. Third, results are obtained via model outputs. Finally, results are interpreted and conclusions are drawn. The results obtained are, however, based purely on the assumptions selected. If

assumptions are altered, different results will thus be obtained. A significant challenge for LCA is therefore finding means to obtain more general insights.

One of the approaches used to address this challenge is sensitivity analysis. Sensitivity analysis is used in a wide variety of studies using models and is not limited to LCA; it is usually used to observe the change in one output variable in response to the change in one input variable, i.e. to find the value of coefficient of partial differentiation of function that a model is based on. Comprehensive sensitivity analysis, to grasp the corresponding relationship between inputs and outputs, has not yet been sufficiently explored.

Fukushima et al. [3] proposed a method to separate LCI into life cycle and scenario models, with the former describing the relationships between variables and the latter determining the values of variables. This method can contribute to transparency of the LCI process and better reusability of model and data. It also contributes to rendering LCA a more systematic analysis tool. This study is thus premised on the view that LCI is a model representing relationships between variables.

Researchers in the LCA community have also tried to develop a visualization methodology to comprehensively show relationships between assumptions and results, in order to aid understanding. Barter et al. [4] developed a model to evaluate future scenarios for the road transport sector; this showed relationships between inputs (required pay-back time for consumers, carbon price, energy price) and outputs (e.g. share of electric vehicles, decreasing ratio of average fuel economy) using contour diagrams. Chen et al. [5] developed a visualization methodology for LCA results and applied it to show the CO₂ reduction potential of introducing renewable energies into the road transport sector. Braff et al. [6] evaluated the value of energy storage technologies for wind and solar power under different conditions, showing results using two dimensional by two dimensional diagrams (nine contour diagrams with different combinations of other two variables with three different values, respectively). None of these studies, however, was able to provide comprehensive visualization because only a limited number of variables was selected.

In this study, I develop a visualization methodology, i.e. a multi-dimensional techno-economic assessment diagram, to comprehensively illustrate the relationship between assumptions (sets of input parameters) and results (corresponding sets of output variables). Applying this methodology to comparative comparison of life cycle cost (LCC) and CO₂ emissions (LCCO₂) of hybrid vehicles (HV) and electric vehicles (EV), I develop an eight-dimensional interactive diagram showing advantageous areas for HV or EV in the input space consisting of eight parameters: HV fuel efficiency, EV energy efficiency, annual vehicle mileage travelled, gasoline price, electricity price, battery price, gasoline CO₂ intensity, and electricity CO₂ intensity.

2 Methods

2.1 General description

2.1.1 Current LCI procedure

The current general LCI procedure consists of the following three steps:

- 1) Formularize a model to evaluate specific indices (e.g. life cycle CO₂ emission, life cycle cost).
- 2) Set input values of the variables that the model is made up of.
- 3) Compute the model with input values and obtain output values, and interpret the results to evaluate the technologies (see Fig. 1).

In this procedure, researchers determine the values of input variables by surveying the literature or through measurement, then deriving results. As noted above, results are thus wholly dependent on inputs (assumptions). When there is wide variety of uncertainty relating to inputs, some may argue that input values can be chosen arbitrarily to obtain desired results.

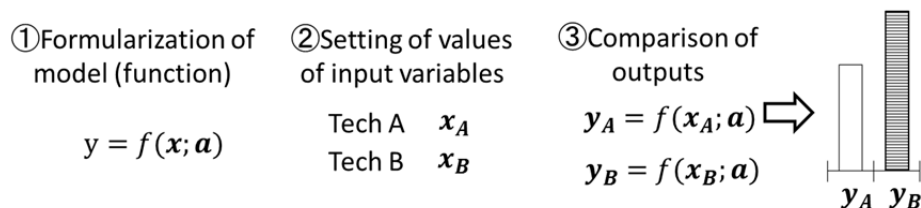


Figure 1: The current general LCI procedure

2.1.2 Concept adopted in this study

This study aims at comprehensively visualizing the corresponding relationships between inputs and outputs. The basic concept is general, based on an approach similar to that used for constructing a water phase diagram (see Fig. 2). This shows the state of water (gas, liquid, or solid) corresponding to two variables: temperature and pressure. It enables comprehensive understanding of state with any combination of values.

Such diagrams would also contribute to better understanding of results in the case of LCI. The difficulty is, however, that an LCI model consists of many variables and visualization through multi-dimensional maps is thus required.

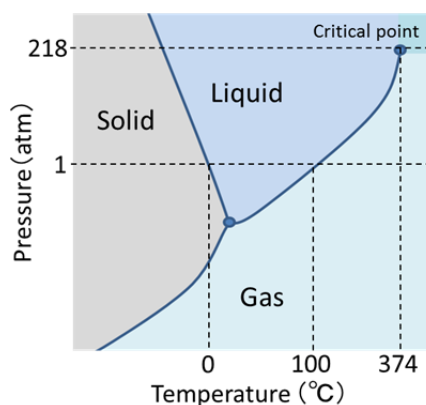


Figure 2: Phase diagram of water

2.2 Problem setting

In this paper, I undertake a comparative comparison of life cycle cost (LCC) and CO₂ emissions (LCCO₂) of HV and EV to apply the developed methodology.

2.2.1 Model

LCC of HV and EV is given by:

$$y_{HV} = C_{HV} + \frac{P_{gas}}{E_{HV}} L \quad \text{and} \quad (1)$$

$$y_{EV} = C_{EV} + \frac{P_{elec}}{E_{EV}} L, \quad (2)$$

where

y_i = LCC of vehicle i ($i = HV$ or EV),

C_i = vehicle cost,

E_i = energy efficiency,

P_j = price of energy j ($j = gas$ or $elec$), and

L = lifecycle mileage.

Eq. (1) and (2) are drawn as Fig. 3. By combining eq. (1) and (2), eq. (3) is obtained:

$$\Delta y = \Delta C + \left(\frac{P_{elec}}{E_{EV}} - \frac{P_{gas}}{E_{HV}} \right) L, \quad (3)$$

where $\Delta y = y_{HV} - y_{EV}$ and $\Delta C = C_{HV} - C_{EV}$.

Eq. (3) consists of seven variables (six inputs and one output, where variables are not distinguishable from parameters).

LCCO₂ for HV and EV can also be given by

$$z_{HV} = D_{HV} + \frac{Q_{gas}}{E_{HV}} L \quad \text{and} \quad (4)$$

$$z_{EV} = D_{EV} + \frac{Q_{elec}}{E_{EV}} L, \quad (5)$$

where

z_i = LCCO₂ of vehicle i ($i = HV$ or EV),

D_i = vehicle CO₂, and

Q_j = CO₂ intensity of energy j ($j = gas$ or $elec$).

By combining eq. (4) and (5), eq. (6) is obtained:

$$\Delta z = \Delta D + \left(\frac{Q_{elec}}{E_{EV}} - \frac{Q_{gas}}{E_{HV}} \right) L, \quad (6)$$

where $\Delta z = z_{HV} - z_{EV}$ and $\Delta D = D_{HV} - D_{EV}$.

Eq. (6) consists of seven variables (six inputs and one output, where variables are not distinguishable from parameters).

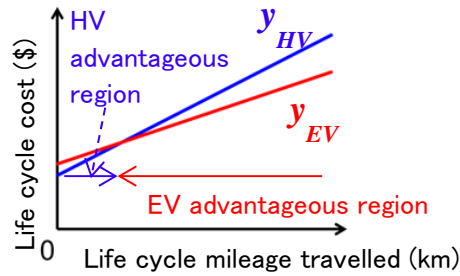


Figure 3: An example LCC comparison between HV and EV

2.2.2 Ranges of values of variables

The ranges of values of variables are set as shown in Table 1. These settings can be changed depending on purpose.

Table 1: Input variables and their ranges

Variable	Unit	Min.	Max.
Fuel efficiency of HV	km/L	20	40
Energy efficiency of EV	km/kWh	5	15
Lifetime mileage travelled	km	30,000	100,000
Difference in vehicle price	\$	1,000	10,000
Gasoline price	\$/L	0.1	0.25
Electricity price	\$/kWh	200	400
Difference in vehicle CO ₂	kgCO ₂	500	4,000
CO ₂ intensity of gasoline	kgCO ₂ /L	2.5	3.2
CO ₂ intensity of electricity	kgCO ₂ /kWh	0.2	0.8

3 Results

3.1 LCC

Fig. 4 shows the result of the comprehensive comparison of LCC between HV and EV, or a visualization of eq. (3). Different combinations of values of the six input variables, i.e. HV fuel efficiency, EV energy efficiency, total mileage, gasoline price, electricity price, and difference in vehicle price, are considered. The settings of the first three variables are shown in the centre as a cube with eight points within it. Each point corresponds to the settings of the three variables of each of eight 3D diagrams around the centre.

These eight 3D diagrams around the centre show the corresponding relationships between difference of LCC, Δy , and the last three variables with fixed values of the first three variables. Different values of Δy are represented by different colours; a negative value, indicating that the LCC of HV is lower (i.e. HV is advantageous) is represented in blue, while a positive value, indicating that the LCC of EV is lower, is represented in red. Near zero values are shown in magenta. Black planes represent thresholds at which the LCC of HV and EV is equal.

It is apparent that the blue coloured region is larger than the red one, indicating that the advantageous region of HV is larger than that of EV in terms of LCC. Based on a comparison of 3D diagrams nos. 1 and 4, the better the EV energy efficiency, the larger the advantageous EV region. Similarly, the worse the HV fuel efficiency or the longer the total mileage, the better the EV energy efficiency. However, even taking these conditions into account, HV is advantageous if EV price is \$ 8000 or more than that of HV.

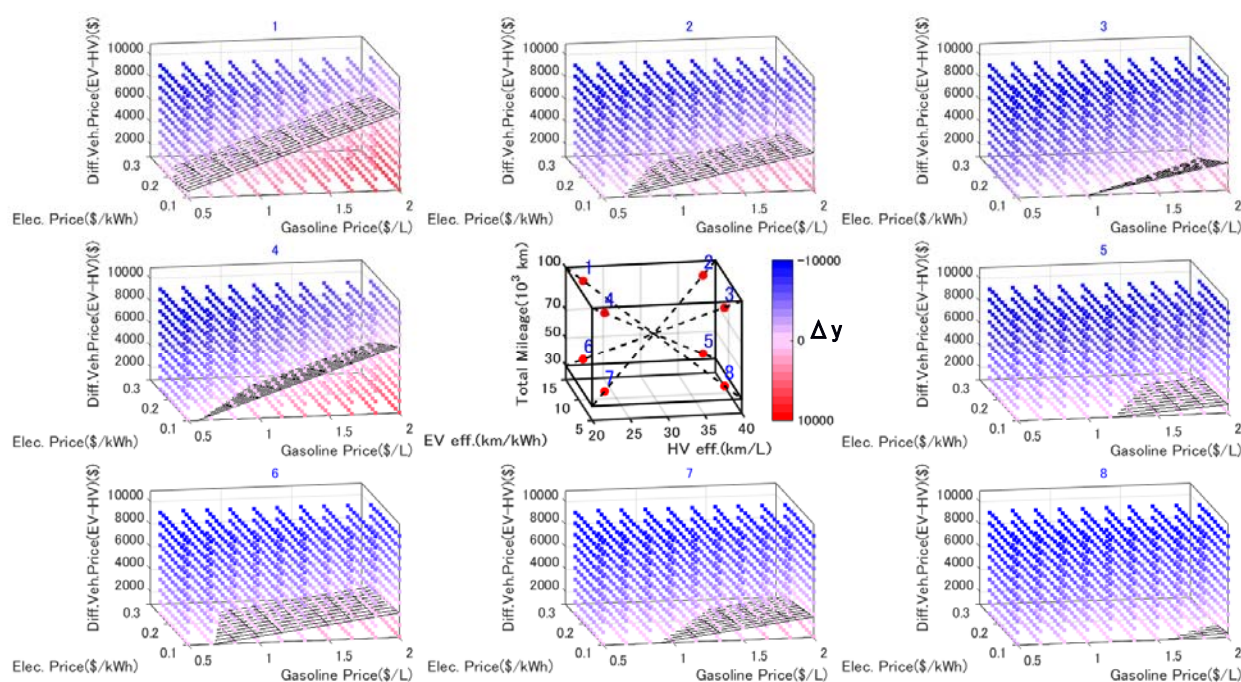


Figure 4: Six-dimensional diagram showing the results of a comprehensive comparison of LCC between HV and EV (regions coloured in blue represent advantageous HV, while regions coloured in red represent advantageous EV)

3.2 LCCO₂

Figs. 5 and 6 show the result of the comprehensive comparison of LCCO₂ between HV and EV, or a visualization of eq. (5). Different from the case of Fig. 4, the difference in vehicle CO₂, ΔD , is treated as constant, and two cases (lower and higher case) are shown in Figs. 5 and 6, respectively. The figure thus consists of a combination of a 3D diagram representing three common variables (HV fuel efficiency, EV energy efficiency, and total mileage) in the centre, and 2D contour diagrams showing the relationships between difference in LCCO₂, Δz , and the other two input variables (gasoline and electricity CO₂ intensity). For ease of understanding, the dimension of diagrams around the centre is reduced to 2D by treating ΔD as constant. The colours used to indicate the relative advantages of HV and EV are the same as in Fig. 4; blue represents the HV advantageous region, while red indicates advantageous EV. The ranges of gasoline and electricity CO₂ intensities are the same in the eight 2D diagrams.

The colouring of 2D diagrams evidently differs depending on the combination of values of three common variables and the difference in vehicle CO₂. The key conclusions that can be drawn from Figs. 5 and 6 are summarized as follows.

1) EV is advantageous in almost all areas (combinations of the ranges of gasoline and electricity CO₂ intensity) of 2D diagrams Nos. 1, 2, 5, and 6 in Fig. 5, and No. 1 in Fig. 6. That means:

1-1) when EV energy efficiency is better (about 15 km/kWh or more) and total mileage is adequate, EV is advantageous regardless of HV fuel efficiency, and

1-2) the extent of EV's advantage is increased when gasoline CO₂ intensity is greater, or when electricity CO₂ intensity is lower.

2) Comparing Figs. 5 and 6, or the diagrams with different settings of ΔD , the colouring of each diagram differs but the width of contours remains the same. This is because the difference between the two figures is an intercept of the comparison of LCCO₂ of HV and EV.

3) When assuming HV and EV efficiency at current levels (No. 4 in Figs. 3 and 4), then HV is advantageous in the region of larger electricity CO₂ intensity (about 0.8 kgCO₂/kWh or more).

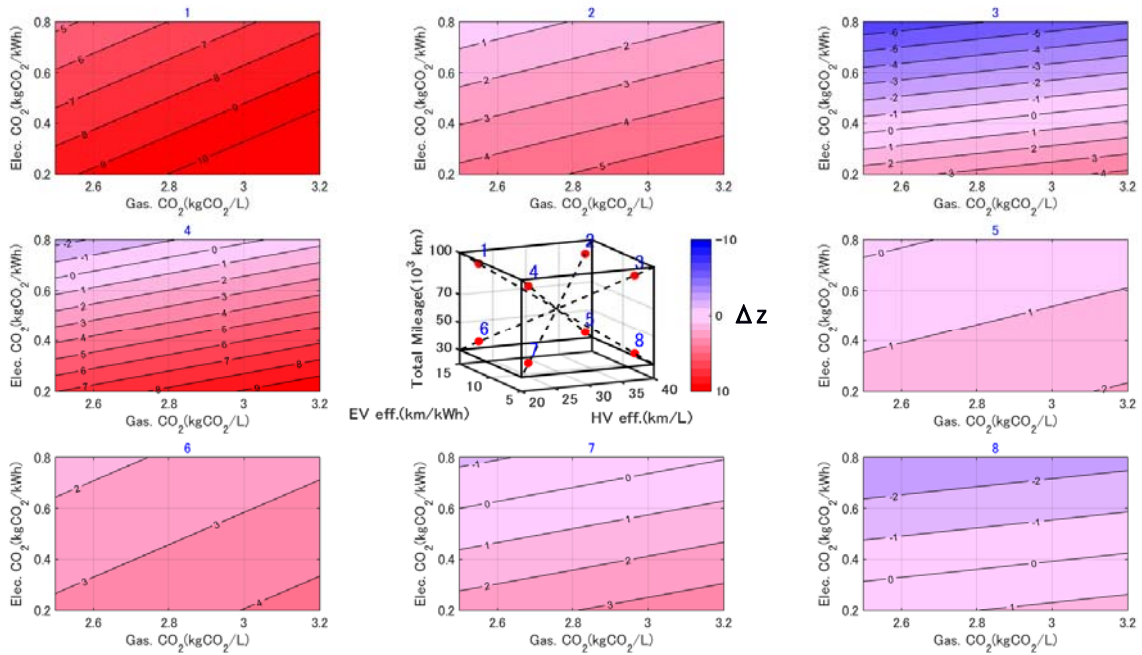


Figure 5: Five-dimensional diagram showing the results of a comprehensive comparison of LCCO₂ between HV and EV (the difference of vehicle CO₂, ΔD , is set to be 500 kg)

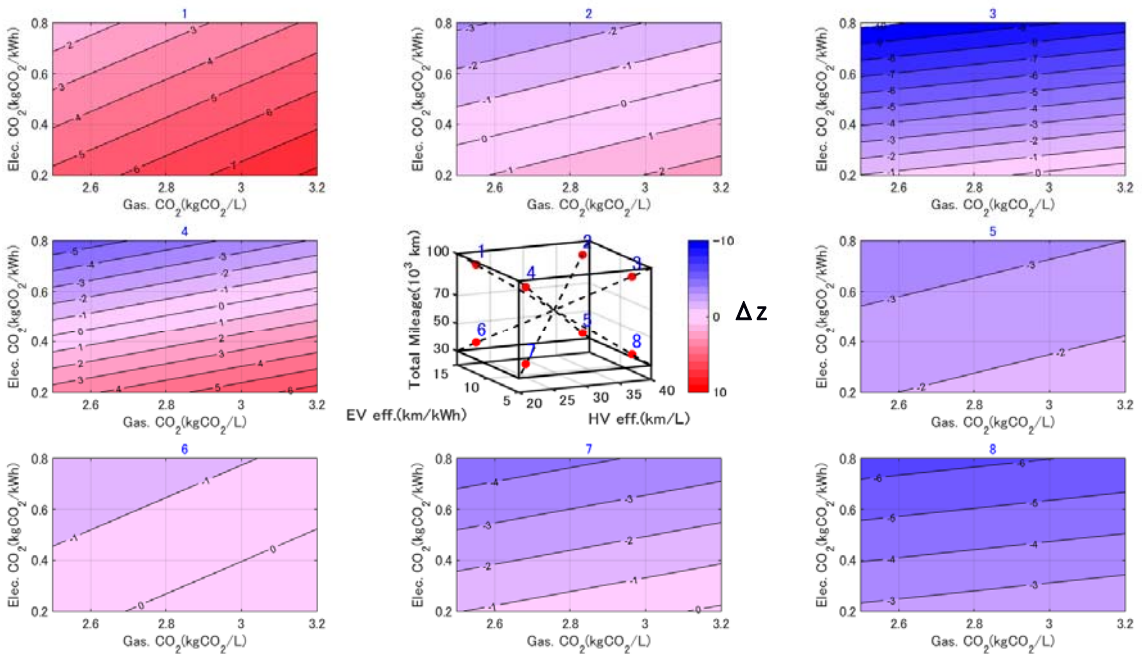


Figure 6: Five-dimensional diagram showing the results of a comprehensive comparison of LCCO₂ between HV and EV (the difference of vehicle CO₂, ΔD , is set to be 4,000 kg)

3.3 LCCO₂ (different axes)

Figs. 7 and 8 consist of different combination of axes, i.e. the three variables in the centre diagram represent gasoline CO₂ intensity, electricity CO₂ intensity, and the difference of vehicle CO₂, and the axes of the 2D contour diagrams show HV and EV efficiency. Total mileage is treated as a constant (two cases, 30,000 km and 100,000 km, are considered, with two figures shown).

The contour lines are not linear, with this being a difference from Figs. 5 and 6. In the region where electricity CO₂ intensity is greater, the colouring of diagrams varies, indicating that the relative advantage of different vehicles is highly dependent on combinations of HV and EV efficiency.

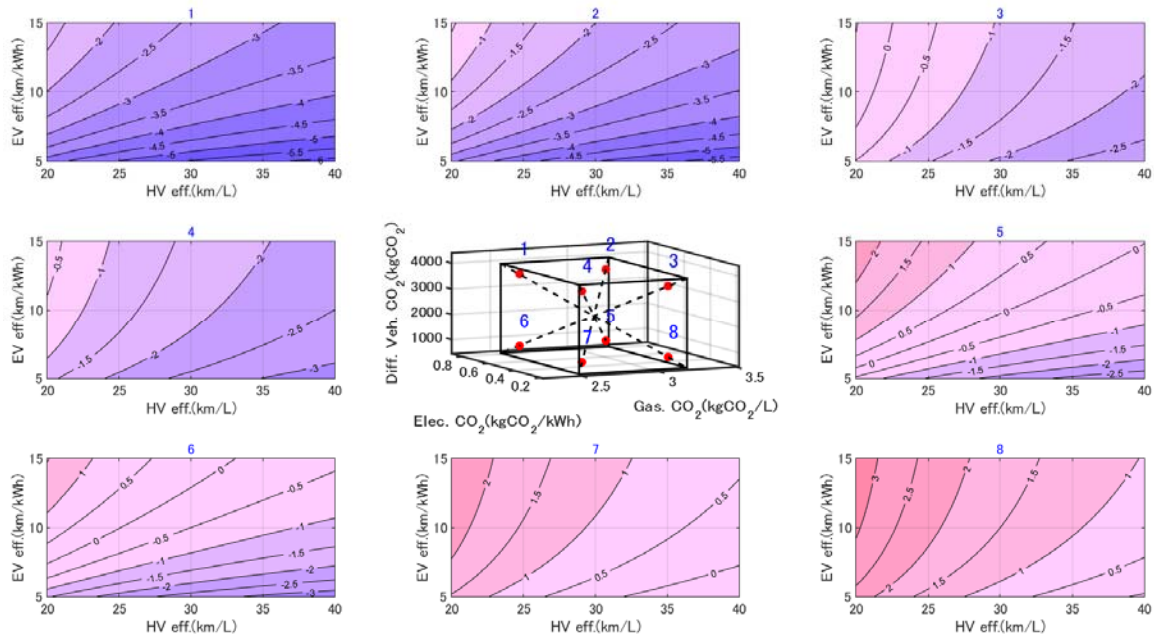


Figure 7: Five-dimensional diagram for LCCO₂ comparison with different combinations of axes (the difference of vehicle CO₂, ΔD , is set to be 500 kg)

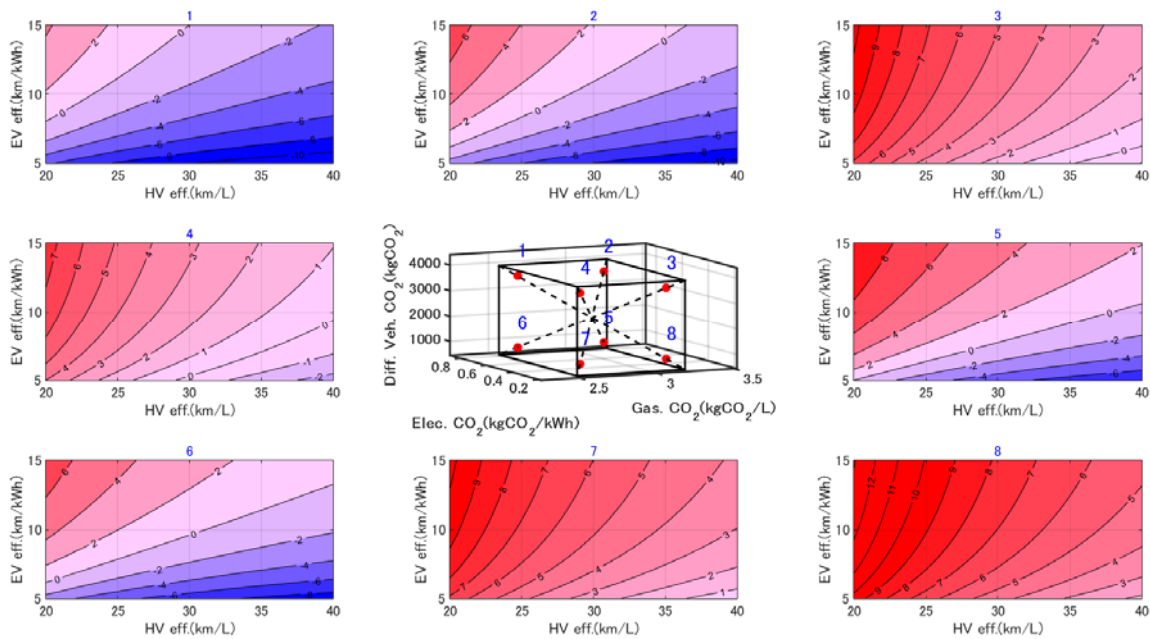


Figure 8: Five-dimensional diagram for LCCO₂ comparison with different combinations of axes (the difference of vehicle CO₂, ΔD , is set to be 4,000 kg)

3.4 LCC and LCCO₂ with interactive graphical user interface

Combining the equations for LCC and LCCO₂, I developed an eight-dimensional interactive diagram that shows the advantageous area for HV or EV in terms of LCC and LCCO₂. Common variables are HV fuel efficiency, EV efficiency, and total mileage. For LCC comparison, three variables (gasoline price, electricity price, and vehicle price) were selected. For LCCO₂ comparison, two variables (gasoline and electricity CO₂ intensity) form the axes of the diagram. Some variable settings were kept constant for the sake of simplicity. Fig. 9 shows the graphical user interface of the diagram, which enables interactive visualization of the analysis. The ranges of variables can be reset by inputting new numbers into the text boxes, and the values of common variables can be changed by moving the slider bars, with the system then providing the results of a techno-economic comparison of HV and EV. The graphical user interface was developed using MATLAB GUIDE.

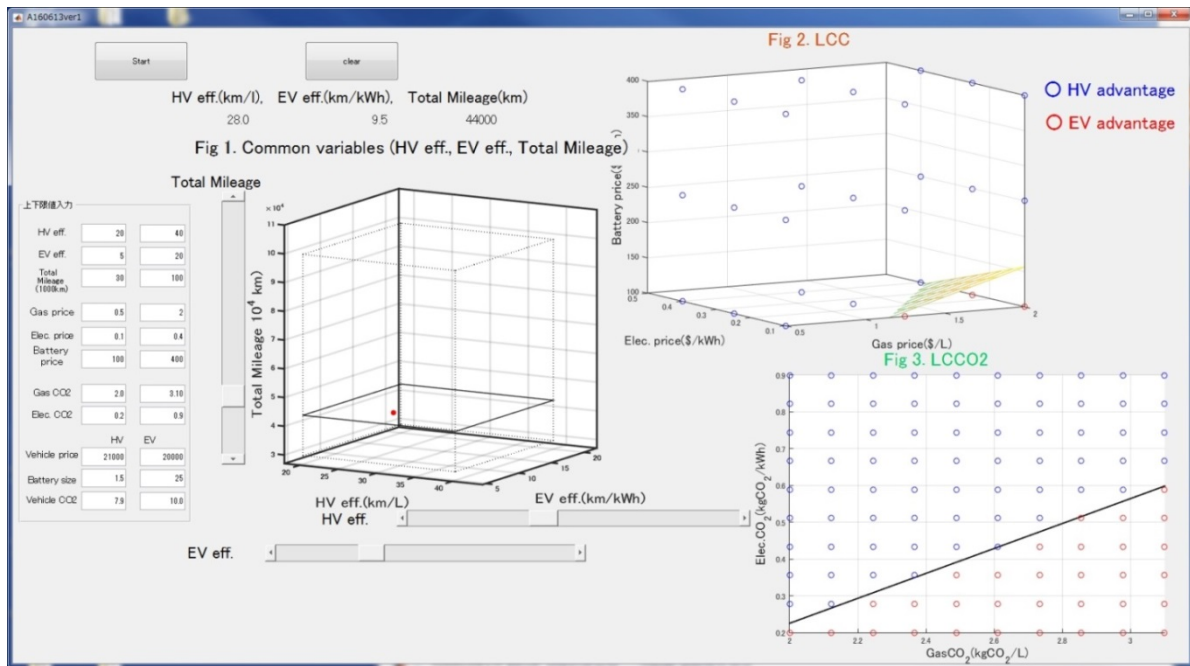


Figure 9: Graphical user interface of an eight-dimensional interactive diagram showing advantageous areas for HV or EV in terms of LCC and LCCO₂

4 Conclusion

In this paper, I presented a concept of a multi-dimensional techno-economic assessment diagram, to comprehensively show the relationship between assumptions and results. I also demonstrated the application of the methodology for comparison of LCC and LCCO₂ of HV and EV. The results indicate that even simple functions exhibit complicated relationships between assumptions and results, making it difficult to wholly understand these relationships by intuition. This means that application of this methodology to relatively simple problems may facilitate comprehensive understanding. This diagram can be further extended to include other vehicle types (e.g. plug-in hybrid vehicles or fuel cell vehicles) and performance variables, allowing for analysis of multiple scenarios.

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