

## Research Article

# Economic and Environmental Impacts Analyses of Regional Widespread Use of Electric Vehicles

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**Abstract:** We focused on the economic and environmental impacts of regional widespread use of Electric Vehicles (EV). Massive introduction of battery and plug-in hybrid EV will affect the regional energy consumption significantly and therefore, influence environment situations. In this study, we adopted performance price ratio to evaluate cost effectiveness of conventional vehicles and electric vehicles and introduced Grey Relational Analysis method to evaluate environmental changes. Sensitivity analyses indicate that electricity and gasoline price fluctuation will not significantly change cost effectiveness of conventional vehicles and that large scale introduction of EV requires improvement of EV's driving range and adequate charging stations. Electricity generation system also needs to be adjusted to reduce incremental SO<sub>2</sub> pollution.

**Keywords:** Electric vehicle, grey relational analysis, sensitivity analyses, vehicle-born pollutants

## INTRODUCTION

After the financial crisis, many governments have enacted a variety of electric vehicle (EV) development plans not only to spur economy but also to deliver better environment conditions. New York City (NYC) unveiled her first charging station in 2010. The logic behind this prevalent trend is that EV is much more energy efficient than conventional vehicle (CV) and EV produces little air pollutants, which is often generated by internal combustion engines. However, electric vehicle development is limited by high cost and low power density of batteries and lack of charging infrastructures (Gaines and Roy, 2000; Michael *et al.*, 2010). Another key issue is that massive introduction of EV in a region will influence regional energy consumption and pollutant emissions greatly (Mikhail *et al.*, 2010). Widespread use of electric vehicles will significantly increase the region's electricity consumption and therefore raise power plants related pollution, especially Green House Gas (GHG) and SO<sub>2</sub>.

Thiel *et al.* (2010) studied CO<sub>2</sub> emissions, costs and CO<sub>2</sub> reduction costs of generic European cars from a well-to-wheel perspective and thought EV offers a promising future to reduce CO<sub>2</sub> emissions when electricity generation are decarbonizes. Ivan *et al.* (2010) studied province-wide emissions in Ontario, Canada and also urban air pollution in Toronto. They presented modeling of penetration rates of Plug-in Hybrid Electric Vehicle (PHEV), Fuel Cell Vehicle (FCV) and Fuel Cell Plug-In Hybrid Electric Vehicle (FCPHEV) that based on maximum capacity of

Ontario's electricity grid. They concluded that all vehicles exert similar influences on the precursors for photochemical smog but the province wide effects differ significantly.

We specifically focus on the economic and environmental impacts of widespread use of Battery Electric Vehicle (BEV) and PHEV on a metropolitan region. New York City (NYC) is selected as our research region mainly because her large amount of non-fossil fuel power plants and accessible data. The introduction of EV to NYC will improve energy efficiency of their transportation industry and conventional vehicle related air pollution can be alleviated. But it will also increase electricity consumption. Incremental electricity consumption will result in more consumption of coal and gas in power stations, emitting more greenhouse gas and SO<sub>2</sub>.

Instead of evaluating economic and environmental changes of all vehicles, we analyze impacts per unit of CV, BEV and PHEV. For economic metrics, we consider vehicle's performance: acceleration, top speed, driving range, energy consumption and vehicle's total costs of ownership in the form of performance price ratio. As for environmental changes, we adopt Grey Relational Analysis method to assess environment changes with respect to emissions of six common air pollutants: Nitrogen Oxides (NO<sub>x</sub>), Carbon monoxide (CO), Volatile Organic Compounds (VOC), Particulate Matter (PM<sub>2.5</sub>), GHG and Sulphur Oxides (SO<sub>2</sub>). Finally, we present sensitivity analyses for:

- Vehicle proportion
- Government subsidies or tax cuts
- Pollutants comparison
- Electricity and gasoline price
- Technology progress
- Electricity source

Our research can help clarify how economically and environmentally the introduction of EV affects the region now. Exhaustive sensitivity analyses provide more understanding of this complex issue and keep policy makers more informed and prepared for EV development.

### PERFORMANCE PRICE RATIO

The utilities such as transportation function and driving pleasure that a vehicle brings to the owner is related to its performance. High performance is more desirable. However, the owner will also consider the costs for these utilities to decide whether it's worthwhile and lower costs are more preferred. To describe these facts, we introduce performance price ratio in our model. It's the quotient of performance and price:

$$P_j = \frac{perf_j}{c_j} \quad (1)$$

where,  $P$  is performance price ratio,  $perf$  is the performance of a vehicle in the form of utilities,  $C$  is the price of a vehicle,  $j$  is the type of vehicle,  $j = 1, 2, 3$  means CV, PHEV and BEV respectively.

**Performance metrics:** When it comes to evaluation of a vehicle's performance, people are concerned with four major aspects: acceleration time (0-100 km), top speed, Driving Range (DR) and Energy Consumption (EC). We obtain these physical attributes and costs of midsize CV, BEV and PHEV from the research of Thiel *et al.* (2010), of which attributes of CV is adjusted to the average level.

Acceleration time of CV, BEV and PHEV varies very little (less than 0.4 sec) and top speeds are out of common US highway speed limit (around 121 km). In urban transportation, the performance of these three vehicles in terms of acceleration and top speed is enough for ordinary people. Their utilities are all the same to owners. However, DR and EC vary in a wide range and are essential economic elements in evaluation of a vehicle's performance. Therefore, acceleration and top speed aren't included in calculation. So the utility of performance is described as:

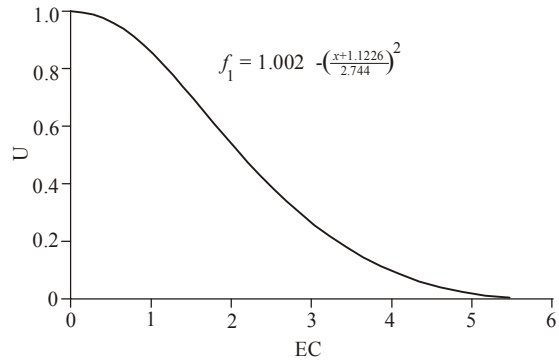


Fig. 1: The fitting Gaussian membership function of EC

$$perf = w_1 f_1(EC) + w_2 f_2(DR) \quad (2)$$

where,  $w_1, w_2$  are weights of EC and DR while  $f_1(EC), f_2(DR)$  are membership functions of EC and DR. we assume vehicle owners have the same preference for EC and DR and thus  $w_1 = w_2 = 0.5$ .

When evaluating utilities, we can't deny the fact that marginal utility changes according to utility itself. Utility changes more slowly when the performance is pretty high or low. For example, if present performance is high and the owner is satisfied with that, incremental performance only provides a little increase of utility, vice versa. Thus we adopt Gaussian membership functions to describe utility changes (Hang, 2005).

Gaussian membership function of energy consumption should be an increasing function to reflect the fact that individuals prefer lower energy consumption. To describe utilities of energy consumption of vehicles in the market, we introduce three more vehicles: Mercedes-Benz S-Class, Volvo V50 and Honda Insight:

$$f = a \cdot e^{-\left(\frac{x-b}{c}\right)^2} \quad (3)$$

It's assumed that individuals are very unsatisfied with Benz's energy consumption while they are happy with that of Honda. In addition, they are most satisfied when energy consumption is as low as 0.00001. Then  $f_1(0.00001) = 1, f_1(1.186275) = 0.8, f_1(3.3611) = 0.20$ . So the fitting Gaussian membership function is  $f_1 = 1.002e^{-\left(\frac{x+1.1226}{2.744}\right)^2}$ , as Fig. 1 shows.

The fitting membership function of DR is obtained in the same way and the equation is:

$$f_2 = 1.025e^{-\left(\frac{x-600}{276}\right)^2} \quad (4)$$

**Price metrics:** The electric vehicle development plan is in nature one kind of government intervention to the transportation sector, aiming to improve better energy efficiency and environment situation. Therefore, the costs of government in the forms of subsidies etc. should be analyzed.

**Cost for consumers:** The costs of one vehicle mainly include purchase cost, insurance, taxes, registration cost, load repayments, fuel costs, maintenance and service charges. However, only purchase cost, fuel costs, maintenance and service charges are critical to comparison of CV, BEV and PHEV.

**Government cost:** One prevalent opinion is that EV reduces air pollution and thus benefits us all. Hence EV should be funded by federal and local governments in the forms of tax cut or subsidies for its environmental externality (Mark, 2001). Apart from tax cuts and subsidies, EV also needs to be supported and protected by the governments since EV's potential benefits are limited by immature technologies and lack of charging stations.

Adequate charging stations for EV are essential to the widespread use of EV for two reasons. First, driving range is limited by lack of high power density batteries, which greatly decreases EV's feasibility. Second, driving range limitation requires many more charging stations so that EV can be practical in daily life.

### GREY RELATIONAL ANALYSIS OF POLLUTANTS

One major environmental problem of CV is that incomplete combustion of gasoline produces large amounts of vehicle-born air pollutants. However, EV also produces hidden air pollution, because energy source of EV power plants generate ashes, GHG and SO<sub>2</sub> emissions, which will cause acid rains. It's assumed that only coal-based power plants produce SO<sub>2</sub>. Hence we need to determine whether the incremental SO<sub>2</sub> emissions will change environment situation more significantly than waste gas of CV does. The emission data are from Argonne National Laboratory and SO<sub>2</sub> emission rate are estimation data from U.S. Energy Information Administration. Essential data are presented in Table 1.

Complexity of this problem lies in comparison of different pollutants. To study environmental impacts of these pollutants in detail is not cost-effective. So we applied Grey Relational Analysis (GRA) method to the comparison of air pollution changes (Joseph and Thomas, 2007). GRA can solve multi-criteria problems.

Table 1: Essential data of vehicles and evaluation

|   | CV     | BEV    | PHEV   |
|---|--------|--------|--------|
| Acceleration 0-100 km/h (in s)          | 11.375 | 11     | 11     |
| Top Speed (mile/h)                      | 185.75 | 140    | 161    |
| Total Range (mile)                      | 568.7  | 77.7   | 348    |
| EC <sup>1</sup> (MJ/mile)               | 2.583  | 0.7886 | 1.384  |
| Utility of total range                  | 1.0176 | 0.1379 | 0.6426 |
| Utility of EC <sup>1</sup>              | 0.379  | 0.8974 | 0.7412 |
| Performance                             | 1.3967 | 1.0353 | 1.3838 |
| Purchase cost <sup>2</sup> (\$/mile)    | 0.2109 | 0.3273 | 0.2871 |
| Fuel cost (\$/mile)                     | 0.1319 | 0.0324 | 0.0822 |
| Maintenance Charges (\$/mile)           | 0.0459 | 0.0367 | 0.0459 |
| Total Price (\$/mile)                   | 0.3887 | 0.3964 | 0.4152 |
| Performance price ratio                 | 3.5931 | 2.6118 | 3.3328 |
| Emission rate <sup>3</sup> (pound/mile) |        |        |        |
| CO×10 <sup>-3</sup>                     | 3.43   | 2.156  | 1.715  |
| VOC×10 <sup>-4</sup>                    | 2.1    | 1.22   | 1.05   |
| NO <sub>x</sub> ×10 <sup>-4</sup>       | 4.19   | 2.19   | 2.1    |
| PM <sub>2.5</sub> ×10 <sup>-6</sup>     | 1      | 1.5    | 0.3    |
| GHG×10 <sup>-2</sup>                    | 9.2588 | 4.3774 | 4.6294 |
| SO <sub>2</sub> ×10 <sup>-4</sup>       | 0.53   | 1.3842 | 0.9571 |
| WGRC                                    | 0.691  | 0.8834 | 0.7273 |

There are six vehicle-born air pollutants: CO, VOC, NO<sub>x</sub>, PM<sub>2.5</sub>, GHG and SO<sub>2</sub>. They have different scales though they are adjusted to be the emission amount one car per mile. Their ranges are normalized as:

$$h_{ij} = \frac{x_{ij} - \min_j(x_{ij})}{\max_i(x_{ij}) - \min_i(x_{ij})} \quad (5)$$

where, the  $x_{ij}$  is the  $i$  pollutants of the  $j$  vehicle. Then we get a 3×6 matrix of non-scale emissions data of six pollutants from CV, BEV and PHEV.

Our reference sequence of the pollutants' magnitude is supposed to be the US emission standard. However, we found that the companies can use "bins" with higher emissions (Plotkin *et al.*, 2002). Then we assume the reference sequence to be zero emission of all pollutants, that is  $h_0 = (0, 0, 0, 0, 0, 0)$ .

We need to compare each sequence with the reference sequence by calculating the grey relational coefficient:

$$r_j(i) = \frac{\min_j \min_i(\Delta_j(i)) + \zeta \cdot \max_j \max_i(\Delta_j(i))}{\Delta_j(i) + \zeta \cdot \max_j \max_i(\Delta_j(i))} \quad (6)$$

where,  $j = 1, 2, 3$  and  $i = 1, 2, \dots, 6$ ;  $r_j(i)$  is the grey relational coefficient of the  $j$  vehicle  $i$  pollutant;  $\zeta = 0.5$  and:  $\Delta_j(i) = |h_{ij} - h_{i0}|$  (Joseph and Thomas, 2007). So the environmental changes can be evaluated by Weighted Grey Relational Coefficient (WGRC):

$$R_j = \frac{1}{6} \sum_{i=1}^6 r_{ij} \quad (7)$$

**Sensitivity analyses:** Sensitivity analyses are intended not only to determine whether the selected CV, BEV and PHEV are suitable for widespread use in NYC according to current electricity generation system but also to find out important factors involved in massive introduction of EV.

**Vehicle proportion sensitivity:** To analyze the average performance price ratio and environmental changes of all vehicles in NYC, we present vehicle proportion sensitivity analysis in a two dimensional coordinate system. If the planned ratios of BEV, CV and PHEV present at NYC are  $\alpha$ ,  $\beta$  and  $\gamma$  respectively, then the average performance price ratio  $P$  and the average WGRC  $R$  is expressed as:

$$P = \alpha P_C + \beta P_B + \gamma P_H \tag{8}$$

$$R = \alpha R_C + \beta R_B + \gamma R_H \tag{9}$$

where,  $\alpha, \beta, \gamma$  subject to the equation  $\alpha + \beta + \gamma = 1$ . Then the equations of  $P$  and  $R$  above can be expressed as:

$$\beta = \frac{P_H - P}{P_H - P_B} - \frac{P_H - P_C}{P_H - P_B} \alpha \tag{10}$$

$$\beta = \frac{R_H - R}{R_H - R_B} - \frac{R_H - R_C}{R_H - R_B} \alpha \tag{11}$$

Equation (10) and (11) are monotonic functions with intercepts related to average performance price ratio  $P$  and average WGRC  $R$ . Then model sensitivity can be analyzed in the form of translation of these monotonic functions in a two dimensional coordinate system as Fig. 2.

In the coordinate system of  $\alpha$  and  $\beta$ , line AB is  $\alpha + \beta = 1$  and points on it means there are no PHEVs while the points inside the triangle AOB indicate that a combination of three types of vehicles. And the intersection points are some possible proportions of different types of vehicles.

In Fig. 2, both  $l_1$  and  $l_2$  are the Eq. (10) with different intercepts;  $l_3$  is the Eq. (11). The difference of intercepts of lines  $l_1$  and  $l_2$  indicates that different performance price ratios that result from different vehicles proportions. But the two intersection points stand for the same environment situation when there are different proportions of vehicles.

The key to the relationship between environment situation and vehicle performance lays in the slope coefficient of Eq. (10) and (11):

$$\frac{P_H - P_C}{P_H - P_B} \quad \frac{R_H - R_C}{R_H - R_B} \tag{12}$$

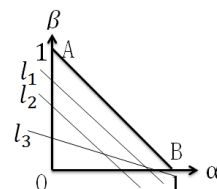


Fig. 2: Vehicle proportion sensitivity analysis illustration

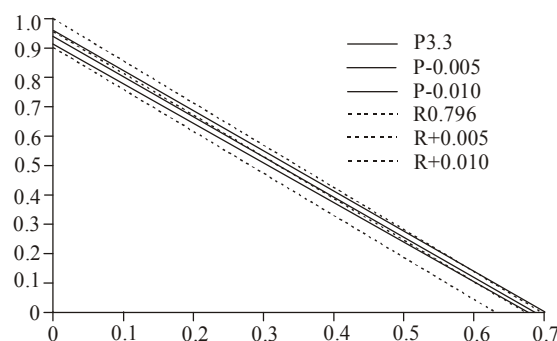


Fig. 3: Vehicle proportion sensitivity analysis result

In Fig. 2, larger magnitude of the slope coefficient of any of these two functions indicates that any improvement of its counterparts' intercept requires greater change of vehicle proportion changes. As it's assumed that emission of PHEV is the average of CV and BEV in the model, thus the slope coefficients are in fact the economic and environmental comparisons of internal combustion technology and electric vehicle technology. If internal combustion technology performs better, the slope coefficient of Eq. (10) will be large. And therefore improvement of environment situation while keep the average performance price ratio stable, only requires a small change in vehicle proportion. It's worthwhile because a small change in vehicle proportion suggests lower costs to improve environment situation.

Figure 2 also suggests that the best economic plan is 100% CV and the best environment-oriented plan is 100% BEV. This is easy to figure out by the max translation of one of the lines.

We change the PPR and the WGRC by 0.5% and 1% and then we get Fig. 3. The slope coefficient of Eq. (11) is larger than that of Eq. (10). Improvement of environment situation will require greater change of vehicle proportion than that of performance price ratio does and thus not cost effective. It suggests that BEV and PHEV aren't power enough to reduce pollution. In

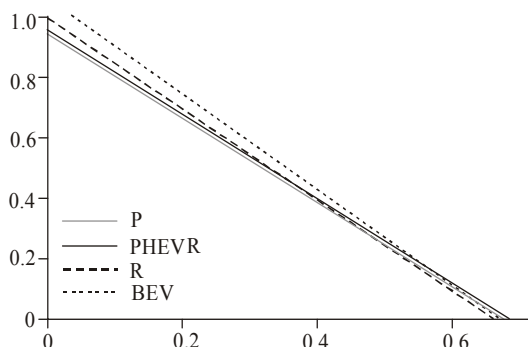


Fig. 4: Sensitivity analysis of government subsidy

other words, current EV technology isn't enough and electricity system isn't suitable for widespread use of BEV or PHEV.

**Sensitivity analysis of government subsidy:** We analyzed the changes of average PPR of vehicles when BEV or PHEV is supported by government subsidies or tax cuts. Figure 4 shows the changes of average PPR.

It's assumed that each BEV or PHEV are given \$ 1, 160 subsidies (8 cents per mile). Average PPR changes more significantly when the BEV is supported. And thus given the same subsidies, the proportion of BEV contributes more to average performance price ratio. This is because the purchase cost of BEV is very high.

**Impact of so<sub>2</sub> on GRA results:** SO<sub>2</sub> is an essential pollutant in pollution metrics. Whether it is included or not can result in different electric vehicle development plan. Table 2 is grey relational analysis results under different circumstances.

Table 2 suggests that BEV and PHEV are much better than CV regarding to environment changes when SO<sub>2</sub> is out of consideration. CV does better than BEV and PHEV is still best choice for environment protection when SO<sub>2</sub> is included. Hence the impacts of SO<sub>2</sub> can't be ignored in the consideration of electric vehicle development plan. Provided current EV technologies and energy source proportion, the best choice for NYC is to develop PHEV as for environment protection.

**Pollutants emission comparison:** Table 3 indicates that BEV does better than CV with respect to most gas emissions. The emission of BEV in fact comes from power plants. Therefore electricity source and generation technologies need to be optimized to meet EV's demand, especially regarding to the emission of SO<sub>2</sub> and PM<sub>2.5</sub>.

Table 2: SO<sub>2</sub> impact

|                          | CV     | BEV    | PHEV   |
|--------------------------|--------|--------|--------|
| No SO <sub>2</sub>       | 0.6224 | 0.7    | 0.7755 |
| SO <sub>2</sub> included | 0.7949 | 0.7865 | 0.8867 |

Table 3: Pollutants emission comparison

|                         | CO     | VOC    | NO <sub>x</sub> | PM <sub>2.5</sub> | GHG     | SO <sub>2</sub> |
|-------------------------|--------|--------|-----------------|-------------------|---------|-----------------|
| CV (10 <sup>-4</sup> )  | 34.30  | 2.10   | 4.19            | 0.01              | 925.88  | 0.53            |
| BEV (10 <sup>-4</sup> ) | 21.56  | 1.22   | 2.19            | 0.02              | 437.74  | 1.38            |
| Variation (%)           | -59.09 | -71.82 | -91.30          | 58.76             | -111.51 | 61.47           |

Table 4: Market and technology influence

| Performance price ratio (%) | CV     | BEV    | PHEV   |
|-----------------------------|--------|--------|--------|
| Electricity price +20       | 3.5931 | 2.5698 | 3.3074 |
| Change rate                 | 0.00   | -1.61  | -0.76  |
| Electricity price -20       | 3.5931 | 2.6552 | 3.3595 |
| Change rate                 | 0.00   | 1.66   | 0.8    |
| Gasoline price +20          | 3.3648 | 2.6118 | 3.2306 |
| Change rate                 | -6.36  | 0.00   | -3.07  |
| Gasoline price -20          | 3.8547 | 2.6118 | 3.4426 |
| Change rate                 | 7.28   | 0.00   | 3.29   |
| Same driving range          | 2.9161 | 3.8659 | 3.427  |
| Change rate                 | -18.84 | 48.02  | 2.82   |
| Purchase cost -20           | 4.0305 | 3.1284 | 3.8683 |
| Change rate                 | 12.17  | 19.78  | 16.07  |
| EC -20                      | 3.9823 | 2.6921 | 3.5218 |
| Change rate                 | 10.83  | 3.08   | 5.67   |
| Grey relational coefficient |        |        |        |
| Coal electricity 3.75       | 0.6426 | 0.7273 | 0.8669 |
| Coal electricity 0.06       | 0.4604 | 0.666  | 0.6659 |

**Market and technology influence:** To study market price's influence on these three vehicles, we present some sensitivity analyses for market price fluctuations, technological progress and electricity generation changes in Table 4.

Over the long term, as the oil resources depletes and investment in wind and solar power increases, gasoline price will go up while electricity price goes down. Cost effectiveness of conventional vehicles depends on the gas price while that of battery electric vehicle relies on electricity price. However, as the sensitivity results show, even electricity price or gasoline price fluctuates around 20%, CV still has the best performance price ratio. We further assume that purchase cost or energy consumption of these three vehicles decrease by 20% because of technological progress. CV is still the best regarding to cost effectiveness. Finally, we find that if the driving ranges of the three vehicles are adjusted to the average level, BEV and PHEV will perform better and BEV is the best in terms of cost effectiveness. BEV's current driving range has only 77 km, much less than that of the other two. It suggests that the key issue of EV's feasibility is battery technology. It's estimated that American people drive an average 33 miles per day (Kevin *et al.*, 2011). BEV only satisfies urban transportation need now. One possibility to raise the cost effectiveness is to provide adequate charging stations and high power density batteries.

We also change the electricity source of NYC for sensitivity analysis. It's found that when electricity from coal is 0.06%, BEV wills performance just a little better than PHEV with respect to the environment impact. And they will be more environmentally-friendly than CV.

## CONCLUSION

This study aims to offer models to analyze whether it's economically and environmentally sound for a region to adopt massive electric vehicles. Based on NYC's current electricity generation system, market status quo and current electric vehicle technology, our model compares cost effectiveness, gas emissions of CV, BEV and PHEV per unit.

It's found that the cost effectiveness of CV is best but CV produces a lot of vehicle-born air pollutants such as CO, PM<sub>2.5</sub> etc. and therefore exerts strong influence on urban environment situation. BEV can reduce vehicle-born air pollutants greatly but has the lowest cost effectiveness as its total cost is very high. For PHEV, it has medium cost effectiveness and is the best choice in terms of reducing vehicle-born air pollutants and power plants related pollutant SO<sub>2</sub>. However, given the same subsidies, BEV has more potential for improvement of environment situation. It's also found that electricity and gasoline price fluctuation around 20% will not change the cost-effectiveness advantage of CV. And this advantage of CV remains even energy consumption or purchase cost fluctuates about 20%. Only when the driving range of BEV reaches average level, will it have distinguished competitiveness. As for environment protection, the impact of SO<sub>2</sub> on BEV's contribution to environment is so significant that BEV will be better than PHEV when the coal electricity is as low as 0.06%.

In conclusion, massive introduction of BEV or PHEV for environment improvement requires not only technology improvement in driving range of BEV and huge investment in charging stations and battery technologies, but also shift of electricity generation system to a more environmentally-friendly one.

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## End note:

- 1: Energy consumption
- 2: One vehicle drives 145000 miles totally, US transportation department.
- 3: Emission data is drew from reference (Plotkin *et al.*, 2002).