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An assessment of PHEV energy management strategies using driving range data collected in Beijing

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Abstract

This paper assesses three typical plug-in hybrid electric vehicle (PHEV) energy management strategies by comparing the average fuel consumptions (AFC) based on the daily driving range data of Beijing. The three different strategies are developed first: with the all-electric charge-sustaining (AECS) strategy, the vehicle is propelled only by the motor until the SOC is depleted; with the fixed blended strategy, the vehicle utilizes both motor and engine according to some fixed ratio in the charge depleting stage; and with the adaptive blended strategy, the vehicle utilizes both motor and engine at an variable ratio adapted to the driving range. Then, the AFC assessment methods for the corresponding strategies are illustrated. For the strategies with the fixed charge depleting range, the utility factor method prescribed by SAE is available; for the strategy with the variable charge depleting range, a mathematic expectation method is proposed. The conclusion comes at last: with the same components, the lowest AFC is 1.2542 L/100km, with the adaptive blended strategy; and the highest AFC is 2.4130 L/100km, with one of the fixed blended strategy; for the vehicle used in the study, the AECS is the best strategy unless the blended strategy is adapted to the driving range; and it is suggested the AFC be considered instead of the specific trip fuel consumption in the strategy optimization.

Keywords: PHEV, energy management strategy, driving range, energy consumption, assessment

1 Introduction

Towards the challenge of energy saving and pressure of low-carbon, the governments and car companies all over the world have turned to electric vehicles. The Plug-in Hybrid Electric Vehicle (PHEV) is one of the most popular solutions. It has the advantage of long driving range as the conventional Hybrid Electric Vehicle (HEV). Meanwhile, it is able to operate exactly like the Battery Electric Vehicles (BEV) for short trips. Therefore, the PHEV is investigated globally with great interest [1].

A lot of work has been done to fulfil the fuel saving potential of PHEVs [1][2][3]. The optimization of the energy management is one of the most efficient ways to reduce the fuel consumption. Besides, it requires no additional cost. N. Kim's work achieved a 6% fuel saving rate on a 35 miles urban cycle by applying a PMP-based control strategy with a jump condition [4]. S. J. Moura's research proved that the fuel economy can be improved by nearly 10% by applying a blended strategy [5]. Y. He's declared in his research that the fuel economy improvement could reach 14-31% by A-ECMS strategy with an appropriate optimization window size [6]. M. Zhang improved the fuel consumption by 7-10% via minimizing the power loses [7]. In S. G. Wirasingha's study, a new classification of the strategies was proposed, which included 1) all-electric + conventional/hybrid; 2) rule-based blended; and 3) optimization-based blended strategies [1]. And according to the results, it is found that the blended strategy consumes less fuel than the All-Electric – Charge Sustaining (AECS) strategy for most cases.

However, most of the optimizations were done with the objective function to minimize the fuel consumption for a specific driving cycle. N. Kim's simulation was done with a 5 times NEDC cycle. Though S.J. Moura's research contains several cycles, such as FTP-75, US06, the fuel consumptions used in the comparison were still from a specific driving cycle. M. Zhang's work was done with UDDS and HWY cycle. Thus, the conclusion that the blended strategy reduces the fuel consumption for the specific trips indeed holds according to the studies. But will the conclusion still hold when considering variable driving cycle lengths?

In the real life, the PHEVs will definitely operate along different cycles. Even if the speed profiles is ignored, by replacing with a typical speed profile, the length of the cycle still impacts on the average fuel consumption. The average fuel consumption (AFC) is defined as the total fuel consumed in a long period divided by the total distance travelled. The AFC is important to the PHEV owner, because the AFC is linear correlated with his gasoline fee. The AFC, despite of the fuel consumption for a specific trip range, decides his expenses. For a nation or a state, the AFC is also important. The AFC could also be interpreted as the total fuel consumed by all the PHEV owners in the nation divided by all the distances travelled by these people. The total gasoline saved by PHEV, compared with the conventional vehicles, is also decided by AFC, rather than the fuel consumption of a specific trip range.

As a result, the AFC, considering the trip range distribution, is recommended as an index assess the energy management strategy. This is a novel perspective to evaluate the control strategies. This research will assess three strategies, including AECS strategy, fixed blended strategy and adaptive blended strategy by comparing the AFC based on the daily driving range data of Beijing passenger vehicles.

The rest of the paper consists of the following parts: Section 2 gives a brief introduction to the vehicle powertrain architecture employed in the study; Section 3 shows the result of a survey on the daily driving range data of Beijing passenger vehicles; Section 4 describes the details of the strategies to be assessed; Section 5 explains the methods to calculate the AFCs for each strategy; The discussion on the result is presented in Section 6; and the conclusion comes at last in Section 7.

2 Powertrain Architecture

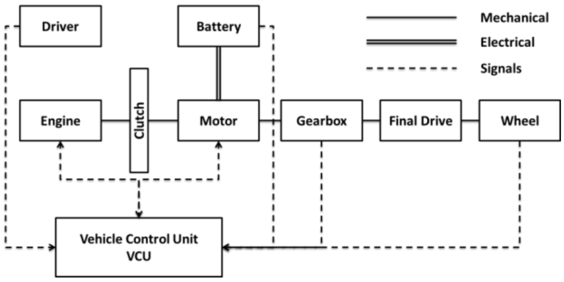

Figure 1. The parallel hybrid architecture

The powertrain architecture discussed in this paper is generally a parallel hybrid architecture shown in Figure. 1. A 1.5 L engine MAP from a Chinese manufacturer is installed in the powertrain model. The clutch between engine and motor enables the all-electric mode. The max power of the motor reaches 60 kW. The automatic gearbox with 4 gears is controlled by a local controller. The gear is simply determined by the accelerate pedal and the current vehicle speed. The details are listed in Table 1.

Table 1. PHEV Specification

Engine	Displacement (L)	1.5
	Max Torque (N m)	124
	Max Power(kW)	63
Motor	Max Torque (N m)	458
	Max Power (kW)	60
Battery	Cell Capacity (Ah)	12.35
	Cell Nominal Voltage (V)	3.28
	Cell Mass (kg)	0.395
	Cell Terminal Voltage (V)	2.8-3.7
	Cells in series	100
	Modules in parallel	4
Vehicle	Curb Mass (kg)	1500
	Wheel Radius (m)	0.334
	Frontal Area (m^2)	2.25
	Gear 1 Ratio	3.45
	Gear 2 Ratio	1.98
	Gear 3 Ratio	1
	Gear 4 Ratio	0.75
	Final Drive Ratio	3.63

The battery used in the architecture is a Li-Fe PO_4 battery from a Chinese battery manufacturer. The whole battery pack contains 400 cells, uniformly distributed into 4 modules in parallel. 100 cells are connected in series within each module. The max power delivered by the battery is limited by the cell terminal voltage constraint. The total energy of the battery package is estimated as 16 kWh, while the max power is 88 kW. As the battery parameters are very close to those of the Chevy Volt, the PHEV investigated in the study is supposed to be a PHEV 40, just like the Volt, even though the architectures are completely different. The detailed battery specifications are in Table 1 together with the vehicle specifications.

3 Beijing Daily Driving Range

Both driving cycles and driving range distribution impact a lot on the fuel consumption of the PHEV. However, unlike driving cycle, the driving range diversity only impacts the fuel consumption of PHEV. For other vehicles, such as conventional ICE vehicles and HEV vehicles, the total fuel consumed by a vehicle is simply linear with the driving range. But for PHEV, the total fuel consumed during a trip has a piecewise linear relationship with the driving range. The instantaneous fuel consumption equals to the fuel consumption of the charge depleting (CD) stage when the range is shorter than the CD range. When the distance covered in the trip exceeds the CD range, the PHEV works in charge sustaining (CS) stage with the instantaneous fuel consumption equalling to that of the CS stage. The NEDC cycle, as the Chinese official certificated driving cycle, is supposed to be representative for the local driving habit in the study. Thus, the driving range distribution, excluding the driving cycle, is within the scope of the study.

Another basic assumption in the study is that, the PHEV is charged at night every day. The situation of multi-charge on a day is supposed to be offset by the situation of miss-charge on a day. This assumption is referred to SAE J1711 standard [8]. Therefore, the distribution of the daily driving range can be seen as the distribution of the trip length between two charges in daily use.

A survey on the daily driving range of passenger vehicles in Beijing was carried out in 2009 and 2010[9]. A questionnaire was designed carefully to investigate the daily driving range and its correlated factors. Each respondent is required to fill the questionnaire based on his/her personal experience. Finally, 480 pieces of valid data are collected over more than 500 car owners.

According to the survey, the average daily driving range is 45.35 km, with the standard deviation of 38.66 km. The shortest daily range is 3 km, while the longest range is 300 km. 25% of car owners travel less than 20 km in a day, 30% travel less than 30 km, and about 75% travel no more than 50 km. The cumulative proportion of the original data is plotted in Figure 2 denoted by the dotted line. Because the survey was based on the personal experience, large steps are found near the ‘tens’, such as 30, 40 and 50 kilometres. Thus, a lognormal distribution is used to smooth the curve. The fitted cumulative distribution function (CDF) of the daily driving range is then conducted as Equation 1, shown as the solid line in Figure 2.

$$F(x)=\Phi[\frac{\ln(x)\text{-}3.5343}{0.8943}] \quad 0<x<\infty \qquad (1)$$

However, when calculating the average fuel consumption for PHEVs, the range percentage rather than the trip percentage is required for the calculation. The calculation method proposed by SAE J1711 and SAE J2841 defined the range percentage as the utility factor (UF) [8][10]. The difference between the CDF and UF curve is that: for a given range *x*, its corresponding CDF indicates the ratio of the number of trips whose length is no longer than *x* to the total trip number; and its UF equals to the ratio of the total kilometres shorter than *x* in all trips to the total kilometres. Based on Equation (1) and a conversion method from CDF to UF [11], the UF curve of Beijing passenger cars is generated and depicted as the dash-dot line in Figure 2.

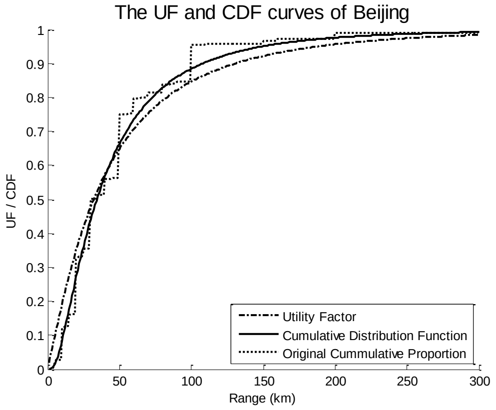

Figure 2. The UF and CDF curves of Beijing

4 Strategies

4.1 AECS

The AECS strategy is the simplest strategy for PHEV. With the AECS strategy, the vehicle operates in all-electric mode during its CD stage, and it performs as a conventional HEV in its CS stage.

In order to have a fair comparison among the strategies, the vehicle equipped with any of the strategy is required to follow the NEDC cycle. Thus, 'passive blended' may occur during the all-electric mode in the CD stage, either due to the motor limit, or due to the battery limit. But for the situation, the engine only makes up the gap between the maximum electric power and the required power.

For the CS stage operation, the equivalent consumption minimization strategy (ECMS) control strategy is used to maintain the SOC while providing a near optimal fuel consumption [3]. Because the driving cycle does not change during all the study, the equivalent factor between gasoline and electricity in ECMS can be tuned in advance.

The SOC trace with AECS strategy is denoted as the black curve in Figure 3.

4.2 Fixed Blended

Unlike the AECS strategy, with blended strategy the engine starts, when necessary before the charge is depleted, to minimize the fuel consumed during a specific trip.

A previous blended strategy developed by the authors called A-PMP is introduced in the study [12]. The basic idea of A-PMP is to minimize the fuel consumption during a specific trip by optimally choosing the torque split ratio between motor and engine. The global optimization is transformed to a local optimization problem through the Pontryagin's Minimum Principle (PMP). The A-PMP method provides a quick way to minimize the local Hamiltonian in PMP.

The optimization process is illustrated by Equation (2), (3) and (4), where t indicates the current time, $x(t)$, $u(t)$ and $p(t)$ respectively stand for the SOC, the torque split ratio and the co-state, V_{oc}, P_{batt}, R_i, Q_{batt} are the battery open circuit voltage, battery power delivered, internal resistance and capacity, and the $\dot{m}$ is the fuel rate of the engine. For each time step in the CD stage, the A-PMP controller calculates the Hamiltonians, denoted by H in Equation (2), of all candidates, and chooses the one with the minimum Hamiltonian as the optimal torque split ratio, shown in Equation (3). Meanwhile, the controller updates the co-state $p(t)$ as Equation (4).

The key issue for the blended strategy is the decision of the blended range. Or, in other words, how far do we want to blend the vehicle? With a specific cycle, the CD range is simply decided by the initial value of the co-state value $p(t)$ in A-PMP. Based on the previous work [12], the vehicle is supposed to get the minimum fuel consumption for the specific trip when the CD range just equals to the trip range.

However, it is not easy to adaptively choose the initial value of the co-state before every single trip, and the choice of the initial co-state has to be made before the vehicle delivered to the market. Respecting to the facts, a number of strategies with different fixed CD range are developed, which are called fixed blended strategies.

The fixed blended strategies are named based on the length of their respective CD range. For example, the vehicle with 7-NEDC fixed blended strategy has the CD range equivalent to the length of 7 NEDC cycles. Integral times of NEDC are used to develop the fixed blended strategy with the respect to the fair comparison among strategies under the same driving cycle.

The vehicle with the fixed blended strategy will operate in the CS stage after the range exceeds the default CD range. The ECMS control method, exactly the same as the one applied in AECS, is used for the CS stage control.

The SOC trajectory is one of the most typical curves to identify different strategies including AECS strategy and fixed blended strategies. Figure 3 depicts the SOC trajectories of the strategies developed for this study. It is seen from the plot, the shorter the CD range is, the more aggressively the electric energy is depleted.

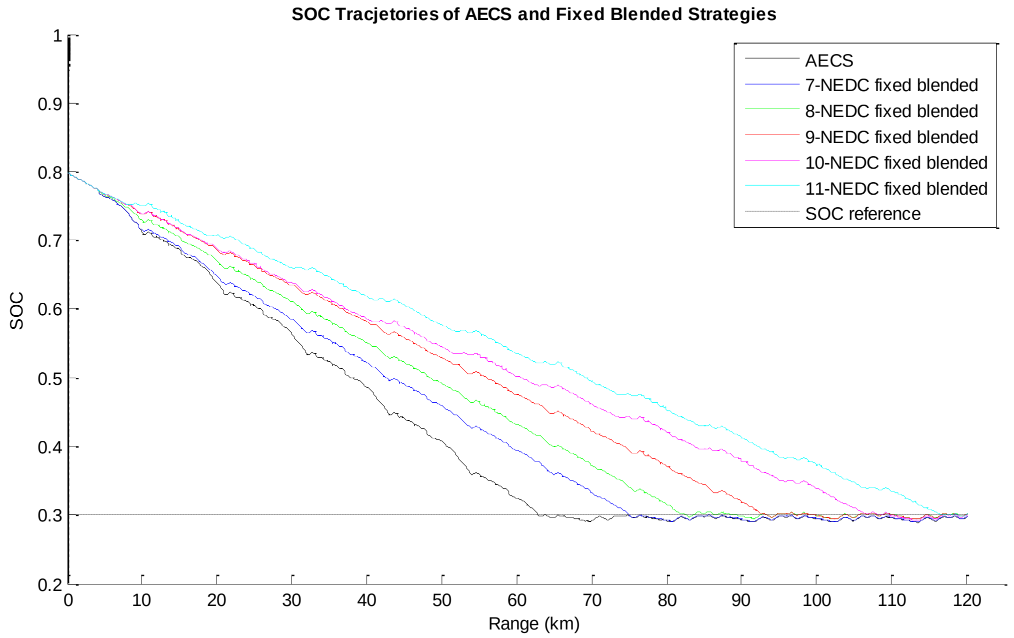

Figure 3. The SOC curves of AECS and fixed blended strategies

$$H(x(t),u(t),p(t),t)=\dot{m}(u(t),t)+p(t)\cdot\frac{V_{oc}(x)\text{-}\sqrt{V_{oc}^{2}(x)\text{-}4P_{batt}(u(t))R_i(x)}}{2R_i(x)Q_{batt}} \tag{2}$$

$$u^{*}(t)=\arg\min\{\dot{m}(u(t),t)\text{-}p(t)\cdot\frac{V_{oc}(x)\text{-}\sqrt{V_{oc}^{2}(x)\text{-}4P_{batt}(u(t))R_i(x)}}{2R_i(x)Q_{batt}}\} \tag{3}$$

$$\dot{p}^{*}(t)=-p(t)\frac{\partial(V_{oc}(x)\text{-}\sqrt{V_{oc}^{2}(x)\text{-}4P_{batt}(u^{*}(t))R_i(x)}\,/\,2R_i(x)Q_{batt})}{\partial x} \tag{4}$$

4.3 Adaptive Blended

The adaptive blended is an ideal strategy with a variable CD range. The basic assumption for the strategy is that, the exact trip length is known before each trip. Thus, the vehicle controller could look up for an appropriate initial value for the co-state, which makes the CD range just equal to the trip length. With another perspective, the adaptive blended can be seen as a collection of the fixed blended strategies. But only the best one providing the lowest fuel consumption is applied with the trip length known in advance.

According to the previous research on the optimization of the energy management strategy and the A-PMP method, when the CD range equals to the trip length, the vehicle is able to get its minimum fuel consumption for the trip. Besides, the CD range is capable of being adjusted by assigning different co-state initial values, so the vehicle with the adaptive blended strategy can get its minimum fuel consumption for all the trips.

Based on the definition of the adaptive blended strategy, the vehicle will never travel in CS mode, theoretically.

Though it is hard to implement the adaptive blended strategy in the real world, it is still with interest to investigate this strategy, as it represents the largest potential in the fuel consumption reduction for the given powertrain architecture.

5 AFC Assessment Method

The Average Fuel Consumption (AFC), based on the driving range distribution in Beijing, is used to evaluate the strategies. The strategy with a higher AFC is expected to consume more fuel than the one with a lower AFC, or to say, it is worse. As mentioned in Section 3, only the driving range is within the scope of the study, despite of the driving cycle. The NEDC cycle is used for simplicity. Thus, the ‘average’ referred in AFC is only with the perspective of driving ranges.

To have some relative comparisons with the conventional HEV, the relative fuel saving rate (FSR) to a corresponding HEV is going to appear in the coming analysis. The performance of the PHEV in its CS stage is referred as the performance of the corresponding HEV. As ‘they’ share the same architecture, the same components and the same CS strategy, the comparison is considered as fair to explore the fuel reduction by employing PHEV technology on a conventional HEV.

In order to have a fair comparison among the strategies, the average driving cycles for simulation have to be exactly the same, which means only integral times NEDC cycles are allowed. Besides, the delta SOC during the simulation also has to be within the acceptable tolerance, 0.01 in the study. All the data used in the research is gained by simulating a PHEV model developed by the author’s research group in MATLAB SIMULINK.

There are two methods to calculate the AFC for the strategies: the SAE method prescribed by SAE J1711 and J2841 are suitable for the AECS and fixed blended strategies with a fixed CD range [8]; the expectation method is used to obtain the AFC with adaptive blended strategy.

5.1 SAE method

The AFCs with AECS strategy and fixed blended strategies are calculated via the SAE method. SAE J1711 stipulates the test details of the fuel consumption and corresponding range. Both SAE J1711 and J2841 prescribe the calculation of AFC weighted by UF.

There are two main test procedures in SAE J1711. The full charge test is the test for the CD stage while the charge sustaining test is for the CS stage. The ‘end of test’ criterion in SAE J1711 separates the two stages by checking the delta SOC before and after the cycle. All the test results are cycle based, which means a cycle cannot be split into pieces in any of the test. The SOC correction is used in the study to compensate the fuel consumption caused by the slight SOC change in CS stage.

With the test results, the AFC can be evaluated by adding the corresponding UFs to the fuel consumptions in different stages. There are two methods with different precisions suggested in SAE J2841 to calculate the AFC. The fractional UF calculation for each cycle method, rather than the lumped UF calculation method, is chosen for this study.

In Equation 5, *UF* means the corresponding utility factor value, D_{cycle} means the cycle length, *i* means the sequence of the CD cycles, FC_{CDi} means the fuel consumption during the *i*th CD cycle, R_{CDC} means the length of all the CD cycles, and FC_{CS} means the fuel consumption during the CS stage. The cycle UF is calculated through the curve in Section 3. The cycle UF indicates the weighting of the corresponding cycle fuel consumption in AFC. The fuel consumptions in the CD stage are listed in Table 2. It is obvious that the cycle fuel consumption changes from cycle to cycle. Thus, it is reasonable to prefer the fractional UF calculation method to the lumped UF calculation method. The cycle fuel consumption in the CS stage is omitted and replaced by the SOC corrected fuel consumption in the CS stage. With the cycle UFs and cycle fuel consumptions, Equation (5) leads to the results of AFCs and FSRs. Detailed analysis on the result will be shown in Section 6.

5.2 Expectation Method

The expectation method is developed to calculate the AFC with the adaptive blended strategy. The SAE method is not available for such strategy, because the vehicle with adaptive blended does not have a fixed CD range.

The expectation is often interpreted as the average value of a random variable. In the PHEV case, the daily driving range (equals to trip length between two charges in this study) is a random variable, yielding some distribution. Thus, the fuel consumption of each day involved with the daily driving range is also a variable. With the increasing of the investigated days, the AFC of all the days equals to the total fuel consumed during the days divided by the total range travelled, shown as Equation (6).

$$AFC = \sum_{i=1}^{lastCDcycle} [(UF(i*D_{cycle}) - UF((i-1)*D_{cycle}))*FC_{CDi}] + [1 - UF(R_{CDC})]*FC_{CS} \tag{5}$$

Table 2. Cycle UF and Fuel Consumption with different strategies

Cycle No.	Cycle UF	Fuel Consumption (L/100km)					
		AECS	7-NEDC fixed blended	8-NEDC fixed blended	9-NEDC fixed blended	10-NEDC fixed blended	11-NEDC fixed blended
1-NEDC	0.2054	0.0703	0.2600	0.9008	1.4770	1.5144	2.0995
2-NEDC	0.1668	0.1025	0.5126	1.0167	1.4819	1.5543	2.1031
3-NEDC	0.1282	0.1235	0.8994	1.1142	1.4955	1.5704	2.1059
4-NEDC	0.0975	0.1357	0.9415	1.1622	1.5065	2.0983	2.1126
5-NEDC	0.0747	0.1608	0.9609	1.1737	1.5090	2.0995	2.1129
6-NEDC	0.0579	1.3522	1.0252	1.1782	1.5103	2.0983	2.1128
7-NEDC	0.0455	——	1.3268	1.1983	1.5117	2.0971	2.1127
8-NEDC	0.0361	——	——	2.8187	1.5368	2.0985	2.1125
9-NEDC	0.0290	——	——	——	2.8647	2.1043	2.1147
10-NEDC	0.0236	——	——	——	——	2.1053	2.2505
11-NEDC	0.0194	——	——	——	——	——	2.5110
FC_{CS}(L/100km)		4.6625					
AFC(L/100km)		1.4049	1.5799	1.7973	2.036	2.1659	2.4130
FSR(%)		69.80	66.04	61.37	56.24	53.45	48.14

$$AFC = \frac{TF}{TR} = \frac{E[DF(x)] \cdot N}{E[x] \cdot N} \tag{6}$$

Where the *TF* is the total fuel consumed in the N days, *TR* is the total range travelled in the N days, *x* is the range travelled on a day, *DF(x)* denotes the daily fuel consumed on that day, and the operator *E[]* means the expectation of the subscribed random variable.

With Equation (6), the AFC could be expressed as the ratio of the expectation of the daily fuel consumed to the expectation of the daily range. As the distribution of the daily range is known in advance, Equation (6) could be transformed to Equation (7) based on the definition of the expectation.

$$AFC = \frac{\int_0^{+\infty} x \cdot dfc(x) \cdot f(x) dx}{\int_0^{+\infty} x \cdot f(x) dx} \tag{7}$$

Where *x* is the daily driving range, *f(x)* is the probability density function of the daily driving range *x*, and *dfc(x)* indicates the daily fuel consumption (L/100km) of the day.

According to the description of the adaptive blended strategy in Section 4.3, it is intuitive to approximate the *dfc(x)* curve by connecting the star markers assigned by the CD ranges and CD fuel consumptions of existing fixed blended strategies, shown in Figure 4. The star markers denote the CD cycle fuel consumptions of the fixed blended strategies. It also sets the bottom line for the fuel consumption of that range, as the A-PMP control strategy is based on the global optimization. With the adaptive blended strategy, the CD range is always set to equal to the daily driving range. Therefore, the best fuel consumption of any given range is able to be reached, as depicted by the solid curve in Figure 4.

The probability density function *f(x)* could be derived from the CDF stated in Section 3, shown as the dashed curve in Figure 4. With the *f(x)* and *dfc(x)* known, the AFC with the adaptive blended strategy is calculated via Equation 7, equalling to 1.2542 L/100km for the studied vehicle.

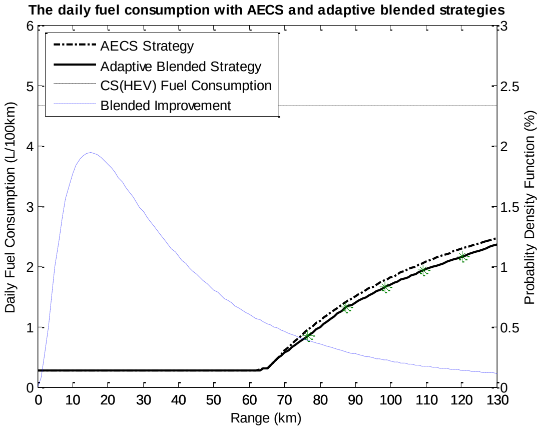

Figure 4. The daily fuel consumption curves of AECS and adaptive blended strategies

6 Result and Discussion

The AFCs and the FSRs (compared with the HEV), plotted in Figure 5, are used as the main indexes to evaluate the strategies.

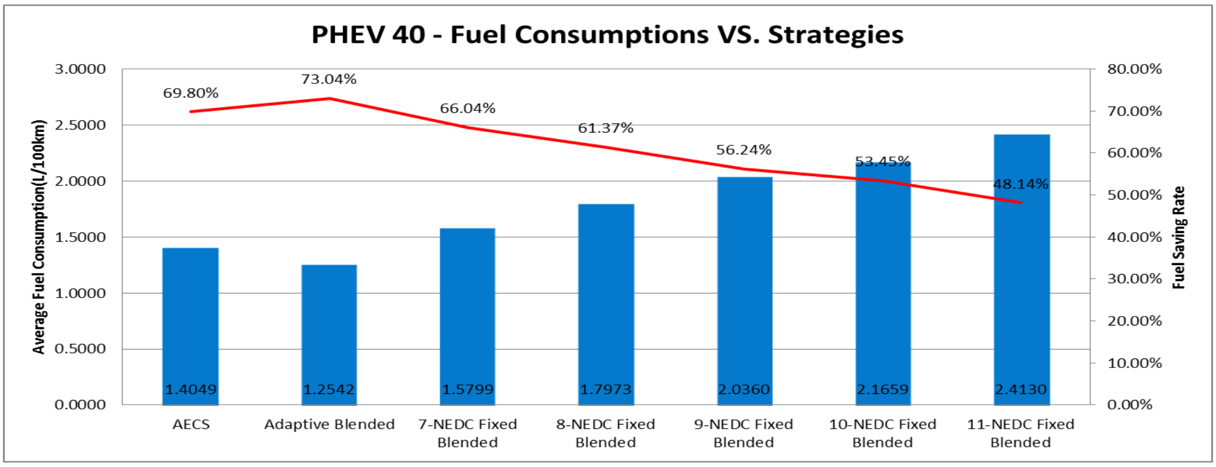

Figure 5. The average fuel consumption and fuel saving rate

With exactly the same components, the AFCs and FSRs with different strategies have large deviations. The lowest AFC is 1.2542 L/100km, with the adaptive blended strategy; and the highest AFC is 2.4130 L/100km, with the 11-NEDC fixed blended strategy. Assuming the AFC with the AECS strategy as the base case, the fuel consumption could be reduced by 10.73% by the adaptive blended strategy. Nevertheless, it could be increased by 71.76% by the 11-NEDC fixed blended strategy. The highest FSR introduced by PHEV compared to the HEV is 73.04%, while the lowest is 48.14%.

From the bar plot, it is obvious that the adaptive blended strategy causes the lowest fuel consumption, followed by AECS strategy. However, the fixed blended strategies cause the worst AFCs. Two major questions about the fixed blended draw the curiousness: Does the fixed blended strategies really work? And what makes the AFCs with fixed blended strategies so high?

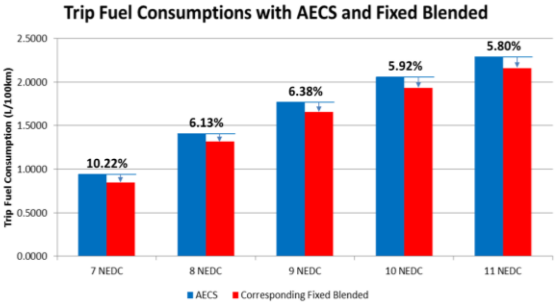

Figure 6. The trip fuel consumption comparison

For the first question, the blended strategy does reduce the fuel consumption of the specific trip, shown in Figure 6. The 8-NEDC fixed blended strategy saves 6.13% of the fuel consumption for the trip length of 8-NEDC cycles, compared with the AECS strategy. Figure 6 demonstrates that all the fixed blended strategies have reduced the fuel consumption for the specific trip. It is also confident to declare that the fuel consumption of the trip whose length is longer than the specific trip has also been reduced, as all the strategies share the same ECMS strategy for the CS stage.

For the second question, Figure 7 helps to unveil the reason why the AFC with the fixed blended strategy is higher than that with the AECS strategy, even though the fuel consumption of the specific trip is lower. The 8-NEDC fixed blended strategy (referred as ‘fixed blended’ in this paragraph) is used to compare with the AECS strategy. During a drive mission of 8 NEDC cycles, the cycle fuel consumptions differs from cycle to cycle, from strategy to strategy. With the fixed blended strategy, the vehicle distributes the fuel more averagely to each cycle, to get an optimal fuel consumption for the specific 8 NEDC cycles. With the AECS strategy, the vehicle consumed very little fuel in the early cycles, then the vehicle is obliged to enter the CS stage with relative high fuel consumption. By doing this, the fixed blended strategy succeed in reducing the total fuel consumption of total 8 NEDC cycles. But the price paid for this is to consume fuel in the early cycles. The high UF value in the early cycles makes the price high enough to increase the AFC. It is clear now the high AFC with fixed blended is due to the high cycle fuel consumption for the frequent short trips. Therefore, it is unnecessary to optimize the fuel consumption aiming at long distance trips, which are less likely to happen. The fuel consumptions for the high frequent short trips are more important.

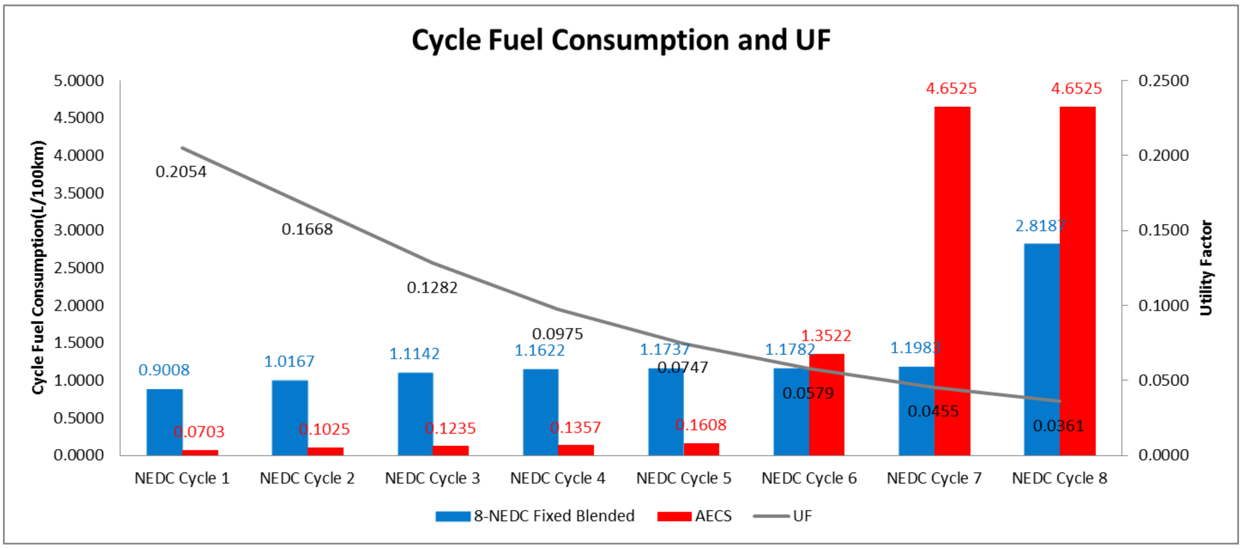

Figure 7. The cycle fuel consumptions and UFs

In conclusion, the fixed blended strategies are not optimal with the perspective of AFC, though they are optimal for the specific trip length according to the former studies. That is because the utility of the electric energy for the short trips is not considered in these studies. Thus it is recommended to take the AFC into consideration instead of the specific trip fuel consumption when optimizing the energy management strategy for PHEVs.

Even though the adaptive blended strategy causes the lowest fuel consumption, it is the most difficult strategy to be applied in the products. Besides, the adaptive blended strategy risks in overestimating the driving range. If the input range is longer than the actual one, some available electric energy will be left in battery, which causes high fuel consumption.

According to the comparisons, the AECS strategy, which is the easiest to implement, is recommended for the studied PHEV 40 in Beijing because of the high utility of the electric energy and the ease to implement.

7 Conclusion

(1) According to the assessment, with the same components, the lowest AFC is 1.2542 L/100km, with the adaptive blended strategy; and the highest AFC is 2.4130 L/100km, with one of the fixed blended strategy.

(2) For the studied powertrain architecture applied in Beijing, the AECS is the best strategy unless the blended strategy is able to be adapted to the driving range.

(3) The AFC, instead of the specific trip fuel consumption, should be taken into consideration when optimizing the energy management strategy for a PHEV.

Acknowledgments

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