



Supporting Online Material for

The MPG Illusion

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Supporting Online Material

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I. Applications and Extensions of the MPG Illusion

In this section we briefly discuss other applications and extensions of the MPG illusion.

The MPG Illusion and Misunderstanding Average MPG

The MPG illusion leads to other mistaken judgments, including an “averaging” illusion. Consider a family that has an SUV that gets 10 MPG and a sedan that gets 25 MPG. Both are driven equal distances in a year. Is the family better off replacing the SUV with a minivan that gets 20 MPG (a 10 MPG improvement) or replacing the sedan with a hybrid that gets 50 MPG (a 25 MPG improvement)? The former combination has a lower linear mean than the latter (22.5 versus 30 MPG). However, a household with two cars that use 20 and 25 MPG is more efficient than a household with two cars that use 10 and 50 MPG for the distances driven. The first combination uses 500 and 400 gallons per 10,000 miles, for a total of 900 gallons; the second combination uses 1,000 and 200 gallons per 10,000 miles, for a total of 1,200 gallons. In fact, replacing the SUV with the minivan is the superior option even if the SUV is driven *half* the distance (5,000 miles) of the sedan per year.

The correct estimate for household MPG relies on taking into account the curvilinearity in Figure 1 by calculating the harmonic mean, as the Department of Transportation does in calculating CAFE targets for automakers. Relying on linear reasoning may lead consumers astray in both their household decisions and in understanding larger policy decisions.

Examples of GPM as an Expression of Fuel Efficiency

In this section we illustrate how unfamiliar measures of GPM would translate to the more familiar MPG scale. We consider two measures of GPM—gallons used per 100 miles driven and gallons used per 10,000 miles driven. Gallons per 100 miles is similar to the measure used in many other countries (e.g., liters per 100 kilometers) and is useful for daily decisions. Many weekly commutes or vacation trips could easily be assessed at this level. Gallons per 10,000 miles is useful for calculating the amount of gas consumed during a given year. Because the base distance of 10,000 miles is a round number, gallons per 10,000 miles can easily be converted to fractions and multiples.

Table S1 shows a sequence of round MPG levels and the corresponding GPM levels. This is a translation of Figure 1 to table format. Table S2 shows a sequence of round GPM levels and the corresponding levels of MPG.

Table S1. MPG Levels Selected at Round Increments and Corresponding GPM Levels

Miles Per Gallon	Gallons Per 10,000 Miles	Gallons Per 100 Miles
10	1000	10.0
15	666	6.7
20	500	5.0
25	400	4.0
30	333	3.3
35	285	2.8
40	250	2.5
45	222	2.2
50	200	2.0

Table S2. GPM Levels Selected at Round Increments and Corresponding Levels of MPG

Gallons Per 10,000 Miles	Gallons Per 100 Miles	Miles Per Gallon
1000	10	10.0
900	9	11.0
800	8	12.5
700	7	14.0
600	6	16.5
500	5	20.0
400	4	25.0
300	3	33.0
200	2	50.0

Table S2 is useful for seeing the curvilinearity plotted in Figure 1 in a different way. For example, it is clear that a number of very small MPG increments (e.g., 11 MPG to 12.5 MPG, 12.5 MPG to 14 MPG, 14 MPG to 16.5 MPG) yield the same 100 gallon improvement in efficiency as does the jump from 33 to 50 MPG. If consumer magazines and car dealerships used gallons per 10,000 miles as the standard measure of efficiency, it would make salient the value of moving from 800 to 700 to 600 GPM on the most inefficient cars—the equivalent of a 4 MPG increase (12.5 MPG to 16.5 MPG) that could otherwise lead to the reaction of “why bother?”

GPM is also useful for comparing fuel usage across transportation options. Many people are interested in reducing their greenhouse gas emissions from air travel (1). Current per passenger fuel consumption for commercial air travel is approximately 70 MPG, which translates to roughly 140 gallons per 10,000 miles (2). If one flies 10,000 miles and drives 10,000 miles in a year, eliminating 10,000 miles of flying can save more fuel than replacing a 33 MPG car with a 50 MPG car.

The Generality of the MPG Illusion Across MPG Levels

The math underlying the MPG illusion makes clear that the illusion is not tied to the inefficiency of today's vehicles, but occurs for all levels of MPG. For example, if two future cars are driven the same distance but vary in their fuel efficiency—one gets 40 MPG and the other 100 MPG—a 10 MPG improvement on the first car reduces fuel consumption more than does a 50 MPG improvement on the second car, even though the second appears superior according to both linear and proportional reasoning. The problem of relying on MPG as a measure of fuel efficiency occurs across all levels of MPG.

Correcting the MPG Illusion through Learning

The MPG illusion can be corrected if consumers who are shopping for new cars calculate their gas consumption under different MPG scenarios. No doubt some consumers do this. However, we expect that there may be an asymmetry in the likelihood that people will calculate their gas savings (3). Specifically, people may never entertain small improvements from 15 MPG to 20 MPG because they look too small to be worthwhile. A “why bother” reaction prevents people from calculating and learning the benefits of this small improvement. On the other hand, people who are attracted to the 50 MPG level of some current hybrids may take the time to consider how long it will take for the gas savings to pay for itself. If their currently-owned vehicle is already efficient (e.g., 33 MPG), many consumers may be disappointed that such a large gain in MPG yields less savings than they expected. Finally, if people test the savings derived from large MPG changes on efficient cars (e.g., 33 to 50 MPG) and are disappointed, they may incorrectly conclude that a small MPG improvement on an inefficient car (e.g., 15 to 20 MPG) will be even less beneficial.

Implications for Behavioral Decision Research and Environmental Decision Making

This research has implications for the broader study of decision making. People's tendency to rely on MPG as a linear indicator of fuel efficiency illustrates the difficulty people have in reasoning about curvilinear relationships (4). This is a new example of how people are misled when they focus on a proxy in a decision rather than the attribute that is actually relevant to the decision (5). This research is also an example of how successful debiasing may be accomplished more effectively by a “technological” rather than a “cognitive” solution (6). Instead of trying to teach people to reason more accurately about a decision problem (in this case, to take a reciprocal), it may be possible to lead them to a better decision by restructuring the information in the environment (7, 8). Reliance on GPM “nudges” people to better decisions because it does the math for them (9). Finally, this research extends a growing line of research on the psychological study of environmental decision making (10-13).

II. Linear, Proportional, and Correct Rules for Reasoning about MPG Improvements

In this section we analyze in detail three rules for judging MPG improvements: the linear rule, the proportional rule, and the correct rule. In these analyses, assume that the MPG of a vehicle is increased from m_1 to m_2 . In Study 1 this increase is achieved by switching from an old car to a new car, in Study 2 by paying an additional cost to improve fuel efficiency, and in Study 3 by replacing cars in a fleet.

The *correct* rule assesses change in gas consumed per mile (ΔGPM) according to the formula

$$\Delta GPM = \frac{m_2 - m_1}{m_1 m_2} \quad S1$$

Looking at the formula, the gas saved per mile is simply the difference over the product of the old and new levels of MPG. The *linear* rule errs by omitting the denominator altogether, evaluating an improvement simply by the difference in MPG as shown in the numerator of S1. The *proportional* rule errs by omitting part of the denominator in Equation S1. There are different versions of the proportional rule, depending on what term is omitted. The most natural is proportional change over the starting value: $\text{Prop}\Delta\text{MPG} = (m_2 - m_1)/m_1$. For example, Study 1 asked people to rank order the improvements of five pairs of vehicles. One pair involved switching from 16 to 20 MPG, a proportional improvement of .25. A general version of the proportional rule would treat the denominator as a weighted average of the starting and ending points: $w m_1 + (1-w)m_2$, where the weight w is between zero and one. It can be shown that the proportional rule will rank order improvements in the same way regardless of the value of w . For simplicity we will use $w = 1$, corresponding to proportional change over the starting value. It should be noted that the intuitively appealing proportional rule errs even though it does calculate the percentage change correctly; however, it is then insensitive to different levels of starting fuel consumption. For example, improving from 16 to 20 MPG leads to a 20% reduction in gas consumption (from 625 gallons to 500 gallons per 10,000 miles) as does improving from 40 to 50 MPG leads to an identical percentage reduction (from 250 to 200 gallons). Clearly, the former improvement leads to greater savings, even though the percentage improvement is the same. The percentage rule errs because it does not take into account the fact that the benefit associated with a percentage gain depends on the base—20% of 625 is a larger amount than 20% of 250. What matters is the total amount of gas that is saved, not the percentage.

It is interesting to note three features about these rules. First, the linear and proportional rules can err only when they select improving the high MPG vehicle; they can never err when they select improving the low MPG vehicle. Second, the two incorrect rules are nested within the correct rule: The proportional rule omits one term in the denominator and the linear rule omits both terms. Third, the mistakes of the three rules are also nested. The proportional rule commits some mistakes in rank ordering improvement; the linear rule commits these mistakes and some additional ones. We now provide a brief mathematical discussion to give insight into these results.

Consider two vehicle pairs. In the low MPG pair an improvement can be made from m_{1L} to m_{2L} , and in the high MPG pair an improvement can be made from m_{1H} to m_{2H} . By definition the high MPG pair starts at a higher point, so $m_{1H} > m_{1L}$. Also, when the low MPG pair has both a lower starting point and a higher ending point than the high MPG pair then it is straightforward to show that all three rules favor the low MPG pair. We focus here on the more interesting case where $m_{2H} > m_{2L}$.

We begin with three conditions – derived from Equation S1 – under which each rule favors improving the low MPG vehicle.

Linear:	$m_{2L} - m_{1L} > m_{2H} - m_{1H}$	S2
Proportional:	$(m_{2L} - m_{1L})m_{1H} > (m_{2H} - m_{1H})m_{1L}$	S3
Correct:	$(m_{2L} - m_{1L})m_{1H}m_{2H} > (m_{2H} - m_{1H})m_{1L}m_{2L}$	S4

Consider two sets of relationships. First, when the linear rule favors the low MPG pair, the proportional and correct rules each involve multiplying the left-hand side of Equation S2 by a greater factor than the right-hand side, because we have assumed $m_{1H} > m_{1L}$ and $m_{2H} > m_{2L}$. Since these operations cannot reverse the inequalities, it follows that if the linear rule favors the low MPG pair then the proportional and correct rules must follow suit.

For the second relationship, consider what happens when the correct rule favors the high MPG pair, so $(m_{2L} - m_{1L})m_{1H}m_{2H} < (m_{2H} - m_{1H})m_{1L}m_{2L}$. It necessarily follows that the proportional rule favors the high MPG pair, because it is obtained by dividing the left-hand side by a larger factor than the right-hand side, since $m_{2H} > m_{2L}$. By the same logic, the linear rule will also favor the high MPG pair since $m_{1H} > m_{1L}$. Thus, when the correct rule favors the high MPG pair then both the linear and proportional rules do as well. Taken together, these relationships imply that errors can only occur when the linear rule favors the high MPG pair and the correct rule favors the low MPG pair. In such cases the proportional rule may or may not agree with the correct rule. It must be the case, therefore, that the mistakes of the rules are nested, such that the proportional rule will commit some mistakes when the correct rule favors the low MPG car, and the linear rule will commit those mistakes plus some additional ones.

III. Supplementary Data Analysis for Study 1

Participants in Study 1 saw five pairs of old and new vehicles and were asked to rank them in order of their benefit to the environment from 1 to 5. Table S3 shows the correct values for gallons of gas saved per 10,000 miles (Δ GPM) and also how each of the three rules rank the improvement of the vehicle pairs.

Table S3. Rankings of improvement (1 through 5 within a row) by linear, correct, and proportional rules

Strategy	Vehicle Pair (Old MPG to New MPG)				
	A 34 to 50	B 18 to 28	C 42 to 48	D 16 to 20	E 22 to 24
Linear Rule (Rank by Δ MPG)	1	2	3	4	5
Proportional Rule (Rank by Prop Δ MPG)	2	1	4	3	5
Correct Rule (Rank by Δ GPM)	3	1	5	2	4
Change in Gallons Per 10,000 Miles (Δ GPM)	94.1	198.4	29.8	125	37.9

Table S4 summarizes all of the responses. Altogether, 46 of the 77 (60%) participants in Study 1 *exactly matched* the linear ranks. An additional 8 (10%) participants exactly matched the proportional ranks. Finally, only one participant exactly matched the correct ranks. There are 120 possible ways to rank order the five pairs. If participants ranked the pairs at random, there is only a .0005 probability of a given ordering attracting at least 5 responses out of 77. The number of participants who exactly matched either the linear or proportional rules far exceeds what can be expected by chance. In contrast, the support for the correct rule is not beyond what could be expected by chance.

Reliance on linear or proportional reasoning leads to several reversals between perceived and actual benefit. Four reversals arise from linear reasoning: $A > B$, $C > D$, $A > D$, $C > E$. For example, linear reasoning leads people to believe that the gain of 34 to 50 MPG (Pair A) was more beneficial than the gain of 18 to 28 MPG (Pair B); the latter, however, is twice as beneficial as the former. Two reversals arise from proportional reasoning: $A > D$, $C > E$. Table S4 also shows the number of reversals that occurs for each pattern of rankings. One can see that, across all strategies, 84% (65 of 77) of participants ranked A higher than B. Table S4 allows one to calculate the proportion of participants committing each possible reversal.

After accounting for those participants who exactly matched one of the three focal rules, there remained 22 participants. Of these 22, 17 participants gave rankings that correlated more highly with the linear strategy than the correct strategy. Moreover, 7 participants (see the row marked “Prop/Linear” in Table S4) gave rankings that conformed to the linear rule with the exception that they ranked D ahead of C, committing 3 reversals overall. Notice that in pair D it

is very easy to see that the proportional improvement is .25. This contrasts with the other pairs, in which proportions are harder to compute. Thus, it appears that these 7 participants applied both the linear and proportional rules, depending on which calculation was easiest or most salient. Finally, 3 participants ranked the 5 vehicle pairs according to the highest MPG of the new vehicle (see the row marked “Highest” in Table S4).

We do not identify a specific strategy for the remaining 12 participants. We note, however, that on average they committed four reversals, with a range from one to six. Thus this group of 12, representing 16% of the participant population, provided responses that deviate substantially from the correct rule.

Table S4. All combinations of rankings (1 through 5 within a row) observed in Study 2, including the number of participants who gave each combination and the number of reversals implied by that combination.

Strategy	Vehicle Pair (Old MPG to New MPG)					Count	Reversals
	A 34 to 50	B 18 to 28	C 42 to 48	D 16 to 20	E 22 to 24		
Correct Rule	3	1	5	2	4	1	0
Linear Rule	1	2	3	4	5	46	4
Proportional Rule	2	1	4	3	5	8	2
Prop/Linear	1	2	4	3	5	7	3
Highest	1	3	2	5	4	3	4
Other:	1	2	3	5	4	3	6
	1	2	5	3	4	2	3
	1	3	2	4	5	1	6
	1	3	4	2	5	1	5
	1	3	5	2	4	1	4
	1	4	2	3	5	1	7
	2	1	3	4	5	1	3
	2	1	5	3	4	1	1
	3	1	4	2	5	1	1

IV. Supplementary Data Analysis for Study 2

The MPG levels (19, 25, 33, 43, and 55) were chosen such that MPG improvement grew in increasing increments across engines but actual fuel efficiency grew in decreasing increments. The linear, proportional, and correct strategies were computed by correlating for each participant the five increments in willingness to pay (WTP) with increments derived from each of the three focal rules – ΔGPM for the correct rule, $\text{prop}\Delta\text{MPG}$ for the proportional rule, and ΔMPG for the linear rule. We counted a participant as conforming to a given focal rule if his or her increments in WTP correlated more highly with that rule than with the other two rules. Applying this method led us to classify 46 of the 74 (62%) participants as linear, 13 (18%) as proportional, and 11 (15%) as correct. The remaining four participants could not be classified with this method because their incremental willingness to pay was constant across the five cars (implying that the correlation is mathematically undefined). Whereas Study 2 used a pricing method and Study 1 a ranking method, both studies reached similar conclusions about the frequency of the three focal rules in the participant population.

The analysis in Figure 2 in the main text assumes that future gas savings over 10 years have been discounted at a real discount rate of 3% using the price of gas when the study was conducted (\$2.80 in Spring 2007). The real discount rate reflects the nominal return on an alternative use of a consumer's money (e.g., an investment in stocks and bonds) minus expected inflation. As shown in Figure 2, participants significantly undervalued improvements to 19 and 25 MPG and overvalued improvements to 55 MPG compared to a price based on discounted gas savings.

Because the price of gas might increase or decrease faster than the rate of inflation, Figure S1 presents additional curves based on discount rates of 0% and 6%. All of the significant results based on a 3% discount rate remain significant when the discount rate assumption is relaxed. When car prices are based on gas savings discounted at 6%, participants still significantly undervalued the improvements to 19 and 25 MPG. And when car prices are based on gas savings discounted at 0%, participants still significantly overvalued the improvement to 55 MPG.

For the logic of using real discount rates, please see the following website:

http://www.ceh.nasa.gov/webhelpfiles/Present_Value,_Inflation,_and_Discounting.htm

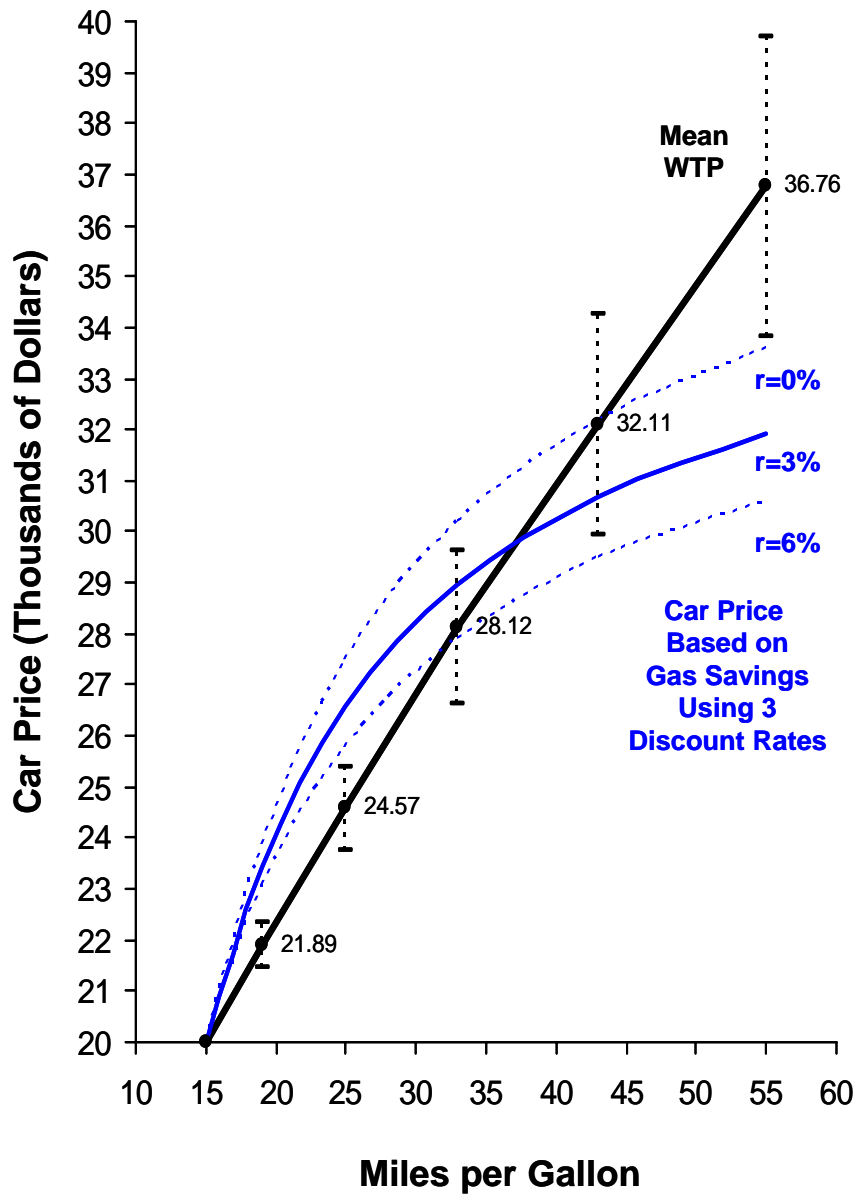


Figure S1. The black line is the mean willingness to pay (WTP) for more fuel efficient engines. 95% confidence intervals are shown for each mean. The blue lines are the car prices based on actual gas savings for the more fuel efficient engines for three discount rates (0%, 3%, and 6%). Future fuel savings are calculated over 10 years at \$2.80 per gallon of gas (Spring 2007 price).

V. Supplementary Data Analysis for Study 3

The town saves more gas (and money) by replacing the 100 vehicles that get 15 MPG than by replacing the 100 vehicles that get 34 MPG. The following is the amount of gas consumed by 100 vehicles driving 10,000 miles for each level of MPG:

100 vehicles driving 10,000 miles at 15 MPG: 66,666.7 gallons

100 vehicles driving 10,000 miles at 19 MPG: 52,631.6 gallons

100 vehicles driving 10,000 miles at 34 MPG: 29,411.8 gallons

100 vehicles driving 10,000 miles at 44 MPG: 22,727.3 gallons

The original configuration (15 MPG and 34 MPG) uses 96,078.5 gallons of gas (66666.7 + 52,631.6). The combination of 19 MPG and 34 MPG uses 82,043.4 (52,631.6 + 29,411.8) gallons, saving 14,035 gallons from the original configuration. The combination of 15 MPG and 44 MPG uses 89,394.5 (66,666.7 + 22,727.3) gallons, saving only 6,684 gallons from the original configuration.

Whereas Studies 1 and 2 in the paper asked participants to evaluate incremental changes from one level of MPG to another, Study 3 asks for a comparison of two fleets of cars. The stimuli do not allow us to compare the linear and proportional rules, as both advocate for Option 2 (a switch from 34 to 44 is preferred to a switch from 15 to 19). As discussed in the paper, Study 3 allowed us to extend our findings to policy decisions. The MPG illusion led most participants to choose Option 2, whereas Option 1 is a more fuel efficient fleet. Framing the decision in terms of GPM led the majority of participants to select the more efficient Option 1.

We note that the fleet that uses the least amount of gas is the one with the lowest mean GPM. Mathematically, minimizing the mean GPM is equivalent to maximizing the harmonic mean of MPG. This is why the harmonic mean is used in setting the CAFE standards.

VI. References and Notes

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VII. Materials for Studies 1, 2, and 3

Study 1 Materials

Many people are concerned with improving gas mileage of cars to reduce the impact of greenhouse gases on the environment. Assume that a person drives 10,000 miles per year and is contemplating changing from a current vehicle to a new one.

Rank order the following changes in vehicles in terms of their benefit to the environment (i.e., which *new* car would reduce gas consumption the most compared to the amount used by the *original* car). Use the ranks 1, 2, 3, 4, and 5. Use 1 for the change that would reduce gas consumption the most compared to the original car, and 5 for the change that would reduce gas consumption the least compared to the original car.

Vehicle Change		
	Original car	New car
_____	16 mpg	20 mpg
_____	22 mpg	24 mpg
_____	18 mpg	28 mpg
_____	34 mpg	50 mpg
_____	42 mpg	48 mpg

Study 2 Materials

Assume it is a few years from now and you are earning a comfortable income. You are thinking about buying a new car. The model you have selected is available with several different engine options. In all other respects the different versions of the model are identical (e.g., performance, handling, etc.).

Assume you drive 10,000 miles per year for work, and this total amount cannot be changed. The baseline model gets 15 miles per gallon and costs \$20,000. In the blank spaces please list the highest price you'd be willing to pay for a car with that engine.

<u>Engine</u>	<u>Miles per Gallon</u>	<u>Highest Price You'd Pay</u>
Engine A	15 mpg	\$20,000
Engine B	19 mpg	\$ _____
Engine C	25 mpg	\$ _____
Engine D	33 mpg	\$ _____
Engine E	43 mpg	\$ _____
Engine F	55 mpg	\$ _____

Study 3 Materials

Vehicle Decision [MPG Frame]

A town maintains a fleet of vehicles for town employee use. It has two types of vehicles. Type A gets 15 miles per gallon. Type B gets 34 miles per gallon. The town has 100 Type A vehicles and 100 Type B vehicles. Each car in the fleet is driven 10,000 miles per year.

The town is in the process of replacing some of its current vehicles with new vehicles. Their overriding goal is to reduce total gas consumption of the fleet and thereby reduce harmful environmental consequences.

They can afford to replace half their vehicles this year with hybrid vehicles (which are designated with an “H” in their name). Here are the options they are considering:

- 1) Replace the Type A vehicles (15 mpg) with Type AH that gets 19 miles per gallon.
- 2) Replace the Type B vehicles (34 mpg) with Type BH that gets 44 miles per gallon.

The boxes below show the mix of cars that the Town would have in its fleet.

<u>Current</u>	<u>Option 1</u>	<u>Option 2</u>
100 Type A (15 miles per gallon)	100 Type AH (19 miles per gallon)	100 Type A (15 miles per gallon)
100 Type B (34 miles per gallon)	100 Type B (34 miles per gallon)	100 Type BH (44 miles per gallon)

Which option would use less gas? (please circle one) Option 1 Option 2

Vehicle Decision [GPM Frame]

A town maintains a fleet of vehicles for town employee use. It has two types of vehicles. Type A gets 15 miles per gallon. Type B gets 34 miles per gallon. The town has 100 Type A vehicles and 100 Type B vehicles. Each car in the fleet is driven 10,000 miles per year.

The town translates miles per gallon into how many gallons are used per 100 miles. Type A vehicles use 6.67 gallons per 100 miles. Type B vehicles use 2.94 gallons per 100 miles.

The town is in the process of replacing some of its current vehicles with new vehicles. Their overriding goal is to reduce total gas consumption of the fleet and thereby reduce harmful environmental consequences.

They can afford to replace half their vehicles this year with hybrid vehicles (which are designated with an “H” in their name). Here are the options they are considering:

- 1) Replace the Type A vehicles (15 mpg) with Type AH that gets 19 miles per gallon. In this case, Type A vehicles (which use 6.67 gallons per 100 miles) would be replaced by Type AH vehicles that use 5.26 gallons per 100 miles.
- 2) Replace the Type B vehicles (34 mpg) with Type BH that gets 44 miles per gallon. In this case, Type B vehicles (which use 2.94 gallons per 100 miles) would be replaced by Type BH vehicles that use 2.27 gallons per 100 miles.

The boxes below show the mix of cars that the Town would have in its fleet.

<u>Current</u>	<u>Option 1</u>	<u>Option 2</u>
100 Type A (6.67 gallons per 100 miles)	100 Type AH (5.26 gallons per 100 miles)	100 Type A (6.67 gallons per 100 miles)
100 Type B (2.94 gallons per 100 miles)	100 Type B (2.94 gallons per 100 miles)	100 Type BH (2.27 gallons per 100 miles)

Which option would use less gas? (please circle one) Option 1 Option 2