



Never stop thinking

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**Reducing CO<sub>2</sub> Emissions and Achieving 2020  
Fuel-Efficiency Requirements:  
A US Perspective on Demand-driven Electric Power Control**

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# Abstract

Increasing fuel efficiency and thus reducing CO<sub>2</sub> emissions in motor vehicles is becoming an increasingly important goal in all regions. While necessary engineering and component costs will increase the cost of a new car, improved fuel efficiency will lead to economic benefits for automobile buyers and manufactures. The consumer saves on fuel cost, and the manufacturer avoids penalties imposed on missing the Corporate Average Fuel Economy (CAFE) targets. In a previous paper [1], a number of application examples in the electrical and electronic domain that improve fuel efficiency were analyzed with respect to their cost-benefit balance in the European Community. This paper expands this idea to the specific situation in the US, in particular with respect to the different cost-benefit situation. As a result, an improvement in fuel efficiency by 1mpg corresponds to an added value of approx. \$50 per year; and we can identify a number of demand-driven applications in the electric/electronic domain that collectively offer a commercially viable increase in fuel efficiency of over 4 mpg compared to today's American automobile fleet average of less than 27 mpg.

## 1 Introduction

A walk through recent auto shows clearly illustrates that one theme common to all major car manufactures is fuel efficiency. The motivation is a combination of higher fuel cost for the end customer, the need to meet regulatory targets, such as the CAFE fuel-efficiency targets in the United States (US), or CO<sub>2</sub> emission-based targets in the European Union (EU), and growing desire by manufacturer's and consumers to be "green" in actions as well as words.

The EU, which is traditionally aggressive in pushing CO<sub>2</sub> reductions, has been quite clear that it has no intention to change the fleet average targets of 140 g of CO<sub>2</sub>/km for 2008 and of 120 g CO<sub>2</sub>/km for 2012. Recent discussions within the EU are trying to refine this target, e.g. by introducing vehicle-weight balanced targets or expanding the timeline to 2015. A recently published article goes into the details of the EU situation in this respect [1].

In the US, the CAFE target of 35 mpg in 2020 looks less ambitious both in figure and in timeline. Considering the differences in fleet mix (US consumers drive bigger cars and more trucks), and the current fleet average of just under 27 mpg, it will be equally challenging for OEMs that sell cars in the US to meet the 2020 CAFE target. In contrast to the EU, where financial penalties are still subject to discussions between political and industry lobbying groups, manufacturers already pay significant penalties for missing CAFE fleet targets in the US. For example, Porsche paid US \$6.3 million in 2004.

Table 1 summarizes fleet fuel efficiency figures in various units. The underlying drive-cycles in the US and EU are different, so the figures are not exactly equivalent.

	mpg	ltr/100 km	g CO <sub>2</sub> /km (gasoline)
<b>2007 US fleet actual</b>	26.6	8.83	208
<b>2020 US fleet target</b>	35.0	6.71	158
<b>2006 EU fleet actual</b>	34.4	6.82	161
<b>2012 EU fleet target</b>	46.2	5.08	120

**Table 1: US and EU fleet averages and legislation targets overview**

In both the US and Europe, missing fleet targets set by regulatory authorities will have a significant financial impact on the OEMs. In addition, increasing fuel prices also increases the benefit of a more fuel-efficient car for the end customer. This is the motivation to conduct a cost-benefit analysis to determine how much money can or must be spent on achieving improved gas mileage and reduced CO<sub>2</sub> emissions.

While there is significant work required to improve the efficiency of core power train technologies, the purpose of this article is to suggest ways of improving fuel efficiency in other systems that draw power from the engine without contributing to vehicle acceleration. Many common on-board systems consume power at a steady state, instead of at varied levels corresponding to

actual requirements. For example, a recent study of the German automotive club (ADAC) on the additional fuel consumption resulting from air conditioning systems compared systems with variable controlled compressors to systems with traditional technology [2]. The result was that an improvement of up to 0.8 l/100 km, or 5 mpg (at a 35 mpg baseline, see Section 2) can be achieved. This provides an excellent example of the effectiveness of demand controlled power consumption relative to always-on or non-controlled power consumption.

This paper will identify potential system improvements based on the following criteria:

- Relatively easy to implement with current technologies
- High potential savings by switching from always-on units to demand-driven operation
- Shorter payback period due to relatively low implementation costs
- Implementable with today's 12 V vehicle power

## 2 Saving g CO<sub>2</sub> per km and improving miles per gallon – lost in conversion?

Due to the fixed amount of carbon per liter of fuel, the combustion of a given amount of gas translates directly into a given amount of CO<sub>2</sub> emissions. In other words, CO<sub>2</sub> is not an unwanted side-product such as NO<sub>x</sub> or particulates that can be reduced by optimized combustion or filtering. CO<sub>2</sub> is the unavoidable result of the chemical reaction that releases the energy stored in gasoline fuel, and the more fuel you consume, the more CO<sub>2</sub> you emit. This means that mpg, ltr/100 km and CO<sub>2</sub>/km are basically equivalent figures of merit for the fuel efficiency of a car, following the conversion numbers given in Figure 1.

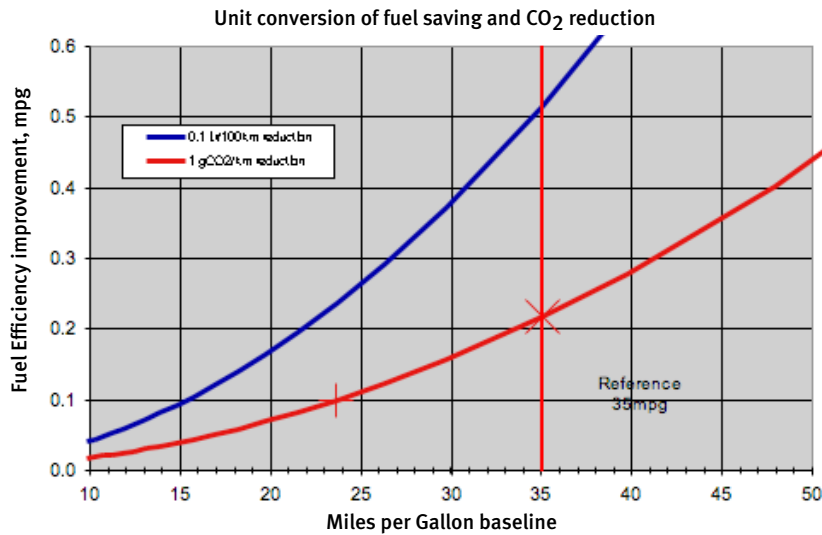
$1[\text{g CO}_2/\text{km}] = 23.6 [\text{l}/100 \text{ km}] \text{ (gasoline)}$ $1[\text{g CO}_2/\text{km}] = 26.5 [\text{l}/100 \text{ km}] \text{ (Diesel)}$
$1[\text{mpg}] = \frac{235}{[\text{l}/100\text{km}]} \quad 1[\text{l}/100\text{km}] = \frac{235}{[\text{mpg}]}$
$1[\text{g CO}_2/\text{km}] = \frac{5546}{[\text{mpg}]} \text{ (gasoline)}$

Figure 1: Fuel efficiency conversion figures

The conversion from l/100 km to g CO<sub>2</sub>/km is a simple linear factor, which makes it easy to convert incremental fuel savings. For instance, an emission reduction of 1g CO<sub>2</sub>/km is equivalent to a fuel saving of  $1/23.6 = 0.042$  l/100 km gasoline, no matter if from 10.042 to 10 or from 5.042 to 5.

The conversion into mpg, however, is more complicated when discussing incremental fuel savings. It is not possible to simply convert saving 1 g CO<sub>2</sub>/km to an improvement in mpg because the result depends heavily on the fuel economy you begin with. This is illustrated in Figure 2, which shows how an emission reduction of 1 g CO<sub>2</sub>/km translates into an improvement in mpg as a function of the mpg baseline. For instance, saving 1g CO<sub>2</sub>/km is equivalent to a gas mileage improvement of approx 0.22 mpg from 34.8 to 35 mpg (marker “x” in Figure 2). It is also equivalent to an improvement of 0.1 mpg from 23.9 to 24 mpg (marker “+” in Figure 2). Saving 0.1 l/100 km is also shown in Figure 2 for reference.

Figure 2: Conversion of a 0.1 l/100 km fuel saving and a 1g CO<sub>2</sub>/km emission reduction into an increase in miles per gallon



For the purpose of this paper, we will use the 2020 CAFE target of 35 mpg as the reference point for further discussion, so in the following, all mpg improvement figures assume the 35 mpg reference point. This makes it possible to access incremental energy efficiency measures relative to their impact on reaching the 35 mpg target.

As another simplification, we only consider the CO<sub>2</sub> emission factor for gasoline fuel, because Diesel is much less significant in the US. Establishing these assumptions leads to a set of conversion factors summarized in Table 2:

Fuel economy improvement		Reduction in CO <sub>2</sub> Emissions (gCO <sub>2</sub> /km, gasoline)
mpg at a 35 mpg baseline	l/100 km	
0.219	0.0424	1
0.51	0.1	2.36
1	0.197	4.6

Table 2: Conversion of incremental fuel efficiency changes

### 3 Fuel economy cost-benefit analysis

Designing automobiles with the capability to control equipment on a demand-driven basis in order to improve fuel efficiency generally entails higher costs. In the past, only the reduced fuel consumption counted, but today the situation looks somewhat different:

- The customer benefits from saving fuel, which is getting more and more expensive.
- The manufacturer benefits from complying with fleet fuel economy standards and avoids penalty payments (US CAFE, EU CO<sub>2</sub>-based legislation in preparation).
- The customer benefits from reduced CO<sub>2</sub> emission, (avoiding taxation in the EU) and achieving personal “green” goals in the US.
- The manufacturer benefits from having to grant fewer discounts required to sell unattractive cars.

Taking all these factors into account, the question is: What value or benefit does an increase of 1 mile per gallon represent for the consumer as well as for the automobile manufacturer?

Figure 3 lists some of the benefits of improving gas mileage. First of all, a vehicle with low gas mileage will be harder to sell in the future than competing models. To be able to sell a \$20,000 vehicle with a 10 mpg lower gas mileage, the dealer may have to grant a discount of 5% or \$1,000. Scaled to the mpg improvement, this would cost the manufacturer \$100 per vehicle per mpg. To put it another way, the manufacturer could invest \$100 into his vehicle to achieve an improvement of 1 mpg without reducing his profit. However, this figure is somewhat arbitrary and is thus not included in the following cost-benefit analysis.

A cost-benefit can be readily calculated for the CAFE penalties. The penalty level for 2020 is not decided yet, so we assume the current penalty of \$5.5 per car for every tenth gallon/mile by which the target is exceeded. This means that a fuel economy improvement of 1 mpg has a value of \$55 to the OEM. Using the conversion factors established in the previous section, this corresponds to \$12 per g CO<sub>2</sub>/km.

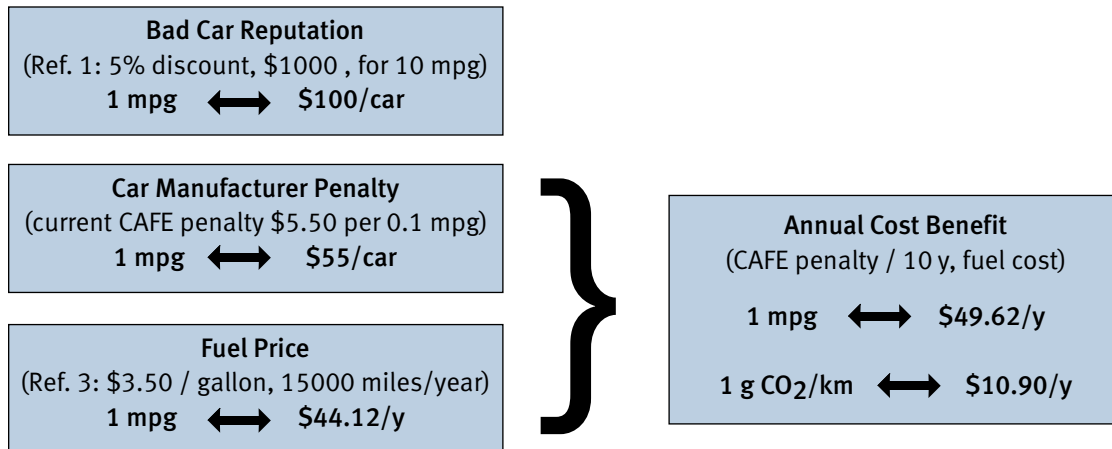


Figure 3: Financial benefits of fuel efficiency improvements.

The most obvious saving is, of course, the actual fuel cost. Assuming a gasoline price of \$3.50/gallon and 15,000 miles travelled per year, the annual saving from improving the fuel efficiency by 1 mpg from 34 to 35 mpg is \$44.10 per year. Or in other units, an emission reduction of 1 g CO<sub>2</sub>/km leads to a fuel cost saving of \$9.70 per year. For the cost-benefit analysis, we need to calculate a total annual cost benefit. If we assume a 10-year car lifetime, we can simply divide the CAFE penalty saving by 10 and combine with the fuel savings. The result is \$10.90 per year, as shown in Figure 3. Converted back into miles-per-gallon, an improvement from 34 to 35 mpg adds about \$50 of additional value per year to the car over a 10 year period. This is in the same range as the result of 10.23 EUR per 1g CO<sub>2</sub>/km mentioned in [1], including fuel and tax savings in Europe. This means that the cost-benefit analysis is also in the same range, mainly depending on the USD-EUR exchange rate that is used for the cost conversion. As a summary, the added value of improved fuel efficiency for both OEMs and consumers is in a similar range in the US and in the EU. So the authors believe that the trend to “fight for every tenth of a liter” as recently mentioned by Uwe Michael, head of development of electrical and electronic systems at Porsche AG [3], will also drive the US car industry in the coming years.

## 4 Saving CO<sub>2</sub> with variable power control systems

To get a feeling for CO<sub>2</sub> emission reduction that can be achieved with electrical system improvements, let’s review the often-quoted relationship between the consumption of fuel and the consumption of electrical power. Figure 4 shows that the consumption of 100 watts of electrical power equals an additional consumption of 0.1 l/100 km. Using the conversion factors established earlier, this means that reducing the consumption of electrical power in the car’s power network by 100 W is equal to a fuel efficiency improvement of 0.5 mpg. Converted to CO<sub>2</sub> emissions, a reduction of 1g CO<sub>2</sub>/km is equivalent to saving 40 W of electrical power, which is about 3 A of current at 13.5 V.

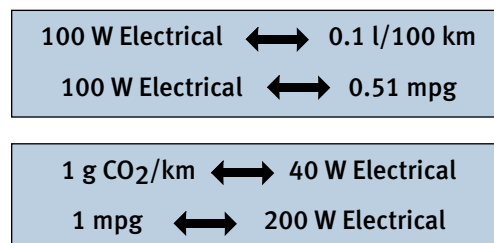


Figure 4: Relationship between gas mileage (at a 35 mpg baseline), CO<sub>2</sub> emissions (for gasoline combustion) and the consumption of electrical power.

Reducing the usage of electrical power will undoubtedly lead to higher development and manufacturing costs, but these can ideally be compensated for by yet-to-be-determined fuel efficiency improvements. Below we will take a closer look at the potential benefits of fuel savings introduced by different technologies.

## **4.1 Variable controls of general body applications**

Based on the above analysis of savings and benefits for manufacturers and buyers, we can now try to determine whether the additional costs of implementing CO<sub>2</sub> reductions are worthwhile and how long (time or mileage) they will take to pay for themselves.

### **4.1.1 Variable PWM control of light bulbs**

The light bulbs now used in the majority of automobiles are usually run directly off the battery voltage. They are designed for 12 V, but are mostly operated at the higher charging voltage of 14.4 V, i.e. at a voltage that's 20% higher. This leads to a higher current flow and reduces the life of the bulb, both of which are not desirable. PWM (Pulse Width Modulation) controllers for light bulbs are frequently standard equipment today and are used mainly to make bulbs last longer and prevent brightness fluctuations. The current CO<sub>2</sub> debate adds a new aspect, namely the prevention of unnecessary electrical loads through excessive voltage. If a bulb is operated at 14.4 V, the performance of all connected bulbs increases from, say, 200 W to 270 W. Variable PWM for light bulbs can prevent this and save 70 W when the lights are on. Assuming a day-night ratio of one-to-one, the average savings in electrical power would be 35 watts, which corresponds to a CO<sub>2</sub> reduction of 0.8 g/km or fuel savings of 0.18 mpg (according to the formulas in Section 2). Implementing such a system is not difficult. Experience in many existing car models establishes an estimated additional cost of \$10 per vehicle. Based on these numbers, adoption of PWM light bulb control pays for itself after about 17,000 miles or 1.1 operating years while delivering the additional benefits listed above such as longer lifespan for light bulbs and constant light output.

### **4.1.2 Saving electricity by replacing light bulbs with LEDs**

LEDs have been used in tail lights for several years. Using them for headlights is under discussion. Their benefits include better design possibilities as well as manufacturing and lifetime advantages. But the major benefit in connection with the CO<sub>2</sub> debate is their improved light output. Future LEDs will produce significantly more than 50 lumens/W compared to the less than 25 lumens/W output by today's halogen and regular light bulbs. Today's vehicle lighting requirements with incandescent light bulbs requires about 200 W, while tomorrow's LED lighting would consume 100 W at the most. Again assuming a day-to-night ratio of one-to-one, the average savings would be 50 W. Any additional consumption by the control electronics will be more than made up for by the very conservative estimate of the light output of future LEDs. Saving 50 W will save approximately 1.2 g CO<sub>2</sub> per km or 0.26 mpg.

Although the control technology for vehicle LEDs is readily available, converting vehicle front and rear lighting to LED technology is relatively expensive today. Conservatively estimated, LED lighting incurs about \$63 in additional costs per vehicle. Even at this implementation cost, LED lighting would pay for itself after 72,000 miles or 4.8 years.

### **4.1.3 Reducing the operating current of ECUs**

Reducing the standby current of Electronic Control Units (ECU) has been a goal of developers for a long time, but the normal operating current of these devices is frequently ignored. So it should not come as a surprise that current control equipment such as an infotainment system requires about 8 A of continuous current, although there are ways to run such a system with only 4 A. Since the possibilities are very diverse, let's look at only a few in this context. In many cases, terminal resistors that are too small are selected for no apparent reason, or in particular, simple trick circuits are implemented with so-called dummy loads at the expense of increased power consumption. Some loads or switching components could also be deactivated or set to a lower level if they are not immediately needed. The frequently included sleep mode of the ECU can possibly be activated not only when the vehicle is parked, but also while the engine is running when one application or another is not needed with full performance.

In other ECUs, relay currents can be lowered, for example, from 250 mA to 50 mA, by holding current after powering up. On the other hand, the many voltage regulator applications that have to supply a higher current at low voltage could be operated with a low-loss DC/DC voltage regulator instead of an inefficient linear voltage regulator. Finally, more attention could be paid to low operating currents when it comes to selecting microcontrollers. For example, 16-bit microcontrollers that require only 60 mA instead of the common 100 mA are already available on the market.

The benefit of these measures is that they can be applied not only in a single instance but in many control units, which increases their impact on CO<sub>2</sub> reduction.

Let's return to our example: Reducing the operating current for the infotainment system to 4 A is equivalent to saving 50 W of electrical power or 1.2 g CO<sub>2</sub> per km, or gaining 0.26 mpg. Such system improvements can be implemented with existing technologies and are estimated to cost only \$7 per control unit, which means they would pay for themselves after only 8,000 miles or 0.5 operating years.

## **4.2 Variable control of motors and power train systems**

### **4.2.1 PWM control of a fuel pump**

Particularly in the area of electrically driven systems, there are many examples of how small design changes can make a significant contribution to reducing CO<sub>2</sub> emissions.

First and foremost there is the fuel pump. Many vehicles have an electric fuel pump that is turned on statically via a relay or a MOSFET. The pump's delivery rate is designed for the maximum requirement of the combustion engine. Any excess pump performance or energy is converted to heat that often heats up the fuel.

Using PWM to variably control the fuel pump would save up to 40% of its power consumption. The technology is well-known and does not present an engineering challenge. As far as costs are concerned, we assume that an additional controller will be installed directly on the fuel pump. Since it would cost about \$28 and reduce the CO<sub>2</sub> output by 1.9 g/km (equivalent to 0.42 mpg), it would pay for itself after only 1.4 years or 20,000 miles.

### **4.2.2 Air conditioning fan with PWM controller**

A PWM controller for the air conditioning fan is already standard in many vehicles. Nevertheless, there are still many fans on the market where a linearly controlled MOSFET functions as a series resistor for the fan motor. This component converts between 80 and 130 W of power into waste heat.

For our example, we assume an average waste reduction of 80 W or 1.9 g of CO<sub>2</sub> per km (equivalent to 0.42 mpg). The additional cost of a PWM fan over an analog system is certainly less than \$14, which means that it would pay for itself after only 0.7 years or 10,000 mi.

### **4.2.3 Alternator with active and low-loss rectification**

Unlike the previous example, this change would not reduce the consumer's use of electrical power, but improve the efficiency of the power generation.

Normal alternators use diodes to rectify the voltages. If you replace these diodes with switching MOSFETs and thus eliminate the diodes' forward loss, you can improve the effectiveness of the alternator by about 10 percent. A typical alternator output is about 1 kW. Since the trend goes towards removing additional components from the fan belt and powering them electrically, tomorrow's alternators will most likely put out 1.5 kW. Assuming an average output power of 1kW and an improvement of 10 %, we save 100 W of electrical power, which leads to a reduction in CO<sub>2</sub> emissions of 2.4 g/km, equivalent to 0.53 mpg. The significant additional cost of about \$85 would be recouped after about 48,000 miles or 3.2 years. While this is longer than other examples in this paper, the bottom line is clearly positive.

### **4.2.4 Electric Power Steering (EPS)**

An example with a very attractive relationship between investment and benefit is electric power steering. With conventional hydraulic power steering systems, the hydraulic pump is driven directly by the combustion engine via the fan belt. The system is designed to provide the greatest support when parking, which means that it must supply lots of power when the engine runs with very low rpms. But when the vehicle runs on the freeway with high rpms, the power produced by the hydraulic pump is at its maximum while the need for steering support is minimal. The excess pump energy is once again converted into heat. The power consumption of the hydraulic steering system is equivalent to 300 W. On the other hand, if the steering power were to be supplied by an electric motor only when it is actually needed, the average power consumption would drop to far less than 50 W, saving

250 W. Assuming that electric power steering costs an additional \$85, the investment would pay for itself after only 1.3 years or 20,000 miles. The CO<sub>2</sub> reduction by approximately 5.9 g/km, equivalent to a 1.3 mpg increase, is only exceeded by that of the electric water pump, discussed next.

#### 4.2.5 Variable controlled electric water pump

When you compare a conventional, engine-driven water pump with an electrically driven solution, two benefits become immediately apparent:

On the one hand, the pump can be run as needed. For example, it can be completely turned off during the engine start phase when it is still cold. On the other hand, it makes the combustion engine more efficient by contributing to improved thermal engine management.

Some reports claim that fuel savings of up to 0.6 l per 100 km are possible. For the purposes of this paper we assume 0.3 l per 100 km, resulting in a CO<sub>2</sub> reduction of 7.1 g/km or a fuel efficiency increase of 1.5 mpg – the highest of all the examples presented so far. Due to the relatively small investment of about \$77, this measure pays for itself after only one year or 15,000 miles.

### 4.3 Accumulated CO<sub>2</sub> savings potential of variable controllers

Table 3 shows an overview of all the potential savings presented in this paper.

Application	CO <sub>2</sub> Reduction [g CO <sub>2</sub> / km]	Fuel Efficiency Increase [mpg]	Cost Increase [\$]	Payback Time [years]
PWM for bulbs	0.8	0.18	10	1.1
Use of LED	1.2	0.26	63	4.8
Infotainment	1.2	0.26	7	0.5
Fuel pump	1.9	0.42	28	1.4
HVAC Fan	1.9	0.42	14	0.7
Alternator	2.4	0.53	85	3.2
EPS	5.9	1.30	85	1.3
Water pump	7.1	1.56	77	1.0

**Table 3: Overview of examples in this paper.**

Based on our estimates, implementing all these examples in a vehicle would produce the following net benefits:

<b>Total improvement of CO<sub>2</sub> emission</b>	<b>22.4 g/km</b>
<b>Total fuel efficiency improvement</b>	<b>4.3 mpg</b>
<b>Total estimated additional costs</b>	<b>\$369</b>
<b>Total estimated fuel and CAFE savings after 4 years and 60,000 miles</b>	<b>\$977</b>
<b>Total CO<sub>2</sub> savings per car lifetime</b>	<b>5.3 tons</b>

**Figure 5: Net benefits of the proposed CO<sub>2</sub> reduction measures.**

An investment of \$369 would reduce CO<sub>2</sub> emissions by about 22.4 g/km and save the end customer \$977 over four years. Over ten years, the vehicle would emit 5.3 metric tons less of CO<sub>2</sub>.

At the same time, these technologies would increase fuel efficiency, e.g. from today's fleet average of 26.6 mpg to 29.8 mpg or make the final step towards the 2020 CAFE target of 35 mpg from a baseline of 30.7 mpg.

## 5 Summary

1. Improvements in a few key applications make it possible to improve fuel efficiency significantly, helping to achieve the 2020 CAFE target of 35 mpg.
2. Wasted electrical power can be directly converted into CO<sub>2</sub> saving or mpg improvement. Wasting 40 W of electricity is the equivalent of 1 extra g of CO<sub>2</sub> per km, so saving 200 W is equivalent to improving gas-mileage by 1 mpg.
3. At a baseline of 35 mpg, 1g CO<sub>2</sub>/km reduction equals 0.22 mpg improvement
4. Improving fuel efficiency by 1mpg increases the vehicle value by \$50 per year
5. The cost of the improvements is paid off within one to five years of an auto's lifetime, depending on the application, through fuel savings and avoiding CAFE penalties.
6. The application improvements made to reduce CO<sub>2</sub> emissions produce additional benefits that represent significant advantages for the customer.

Some examples of Item 6) include: Longer bulb life through PWM controllers, more security through electric power steering with electric steering corrections in emergencies, or lower hydrocarbon emissions since the controlled fuel pump keeps the fuel tank cooler.

We can state that new factors such as higher fuel costs and the announced lower CAFE limit make the cost-benefit balance clearly positive for many applications. Taking measures to reduce CO<sub>2</sub> clearly pays off, both for the vehicle manufacturer and for the consumer.

## 6 References

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