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QUANTIFYING THE ENVIRONMENTAL AND ECONOMIC IMPACT OF MOTOR VEHICLE BRAKING: A METHOD FOR COMPUTING ENERGY, FUEL, MONETARY, AND CARBON DIOXIDE EMISSIONS COSTS

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Abstract

This paper presents a simple method to compute cost values or "price tags" for each step on the motor vehicle's brake pedal, quantified in terms of energy consumption, fuel consumption, monetary cost, and carbon dioxide emissions. The price tags are computed based on the kinetic energy loss due to braking, using the vehicle weight and speed only. They are presented for a reference vehicle, specifically a gasoline car weighing 1000 kg. Scaling factors for gasoline and diesel vehicles with different weights are also provided. The price tags encourage rational drivers to adopt a driving style that results in less braking and improved road safety. They could also be used for energy analysis and savings computations. It is shown that braking accounts for approximately 45% of the total fuel consumption during urban driving. Furthermore, by adopting strategies to avoid unnecessary braking, it is possible to achieve a saving of 50% or more in braking loss. These findings are highly consistent with other published studies, demonstrating the potential applicability and usefulness of the proposed price tags.

Keywords: Braking avoidance strategies, Carbon dioxide emissions, Energy savings, Fuel consumption, Sustainable driving.

1. Introduction

Climate and weather related disasters have surged five-fold over the past 50 years [1, 2]. Many have attributed the extreme weather to anthropogenic global warming [3]. Excessive greenhouse gases emissions, carbon dioxide in particular, has been identified to be the main cause of anthropogenic global warming [3, 4]. More efficient use of energy is key to reduce carbon dioxide emissions and achieve the climate change goal of limiting the increase in the global average temperature to well below 2°C above pre-industrial levels as stipulated in the Paris Agreement [3-6].

Based on the latest energy statistics published by Malaysia Energy Commission [7] and United Nations Statistics Division [8], the transportation sector (mostly motor vehicles) constitutes about 30% of the total energy consumption. Hence, more efficient use of energy by motor vehicles should bring about impactful and promising results. Driving patterns have been shown to have a significant impact on motor vehicles' emissions and fuel consumption [9-11]. Borek et al. [12] have reported that the avoidance of braking is among the most important factor in improving fuel economy, especially in the presence of lead vehicles. Similar findings have been reported by the US Department of Energy and Environmental Protection Agency [13] based on data sources listed therein. Improving fuel economy not only reduces carbon dioxide emissions, contributing to environmental sustainability, but also leads to financial savings due to reduced fuel costs.

The brakes are required for fast and precise control of the vehicle speed and are therefore indispensable. Braking avoidance strategies are techniques that drivers can use to reduce the need for braking, thereby saving energy, reducing fuel consumption and cost, and decreasing carbon dioxide emissions. They include eco-driving practices, such as maintaining a larger gap from the lead vehicle and employing predictive driving. It is utmost important to highlight here that the aim of the braking avoidance strategies is never to avoid the use of brakes when needed. Instead, they are to avoid situations whereby the brakes are needed. The key idea is to exploit uncontrollable, non-brake counterforces, such as vehicle frictions (other than the brakes) and gravity, to meet or partially meet speed reduction requirements, and hence, avoid or reduce the need of brakes. Speed reduction by non-brake actions takes a longer time but is achievable with proper planning for predictable speed reduction requirements. Savings are achieved because the inevitable energy loss due to the non-brake counterforces is put to good use, saving the energy that would otherwise be expended on the brakes.

SenterNovem [14] has reported that a driver trained on eco-driving could achieve over 20% fuel savings and other savings such as reduced wear and tear and damage repair (due to improved safety). Similar findings have been reported by the US Department of Energy [15] and others [16, 17]. Eco-driving training could potentially be more effective if drivers are provided with specific facts and figures. For instance, in the context of avoiding unnecessary braking, this could involve assigning a cost or "price tag" to each application of the brake pedal. As far as I am aware, no such cost assignments have been documented.

The hypothesis of this paper is that it is possible to assign cost values or price tags to each application of the brake pedal. While it is feasible to compute such a cost using powertrain dynamics [12, 18-22], the calculation process is rather complex and requires an estimation of the brake force. In this paper, I will present a simple, albeit approximate, method to compute a price tag for each press on the brake pedal without using brake force. The proposed method relies solely on the vehicle's weight and speed, which are more readily available than brake force. The price tags in terms of excess fuel consumption and carbon dioxide emissions are presented for a reference case. The price tag in monetary cost or for deviation from the reference case can be computed using simple conversion and scaling factors. The formulation of the price tags is presented in Section 2. Results and discussion in Section 3. Conclusions in Section 4.

2. Formulation

When the brakes are applied, the vehicle losses speed. The loss of the kinetic energy is transformed to unusable heat, and is given by

$$E = \frac{1}{2}m(v_2^2 - v_1^2) \tag{1}$$

where m is the vehicle mass and v_1, v_2 are the vehicle speed before and after the braking event. Equation (1) represents the energy cost, or the 'energy price tag', of the braking event. If the braking event could be avoided, this cost would instead represent energy savings. The price tag in other terms, e.g., fuel consumption, monetary cost, and carbon dioxide emissions, can be computed using suitable conversion factors.

The fuel consumption of the braking event is determined by the amount of fuel required to produce the associated energy cost. The higher heating values (HHV) or gross calorific values (GCV) of gasoline and diesel fuel are about 35 MJ/litre and 39 MJ/litre, respectively [23]. It has been reported that the tank-to-wheel (TTW) efficiency of gasoline internal combustion engines (ICE) ranges from about 15% in urban driving to about 30% in highway driving [24, 25]. A good estimate of the TTW efficiency for mixed urban and highway driving would be 20% [26]. Diesel ICE have been reported to be more efficient, with a TTW efficiency of about 35% [27]. With the above, it can be determined that the gasoline fuel price tag of the braking event is given by

$$F = \frac{E\ (\mathrm{MJ})}{35 \times 20\%} = \frac{E\ (\mathrm{MJ})}{7}\ \text{litre}. \tag{2}$$

The diesel fuel price tag would be one-half that of gasoline. The conversion to monetary cost is straightforward, i.e., multiplying *F* in litre (gallon) by the per-litre (per-gallon) fuel price. Gasoline (diesel) engines produce an average of 2.3 kg (2.7 kg) of carbon dioxide per litre of gasoline (diesel) consumed [28]. Hence, the carbon dioxide price tag of the braking event is given by *F* in litre multiplied by 2.3 kg (2.7 kg) for gasoline (diesel) vehicles.

The price tags are linearly proportional to the vehicle mass. This is evident from the linear relationship between the price tags and the kinetic energy loss, as well as between the kinetic energy loss and the vehicle mass. The price tags for constant speed reduction are, approximately, linearly proportional to the vehicle speed. This is because the kinetic energy loss is the finite difference of kinetic energy, i.e.,

$$E \approx \Delta v \cdot \frac{d}{dv}\left(\frac{1}{2}mv^2\right) = (m\Delta v) \cdot v \tag{3}$$

where v is the vehicle speed and Δv is the speed reduction. Different driving conditions affect the price tags through their impact on TTW efficiency. The price tags are inversely proportional to the TTW efficiency. This is evident from Eq. (2).

3. Results and Discussion

Figure 1 shows the computed fuel and carbon dioxide emissions price tags of each step on the brake pedal for a reference motor vehicle, i.e., a small 1000 kg gasoline car. A 20% TTW efficiency for mixed driving conditions is assumed. If desired, these price tags can be scaled for different TTW efficiencies. For instance, the scaling factor for a 30% TTW efficiency under highway driving conditions would be 2/3.

Figure 1 consists of multiple straight lines. The straight lines verify the linear relationship between the price tags and the instantaneous speed when the brakes are applied. Each line corresponds to a constant reduction in speed, from 10 km/h speed reduction at the bottom to 80 km/h at the top, at a step of 10 km/h. The lines represent how hard the brakes are applied, from soft (10 km/h) to hard (80 km/h). For instance, consider a braking event that reduces the vehicle speed from 60 km/h to 40 km/h, such as when making a turn. The fuel consumption for this event would be about 0.011 litre, as indicated by the cross marker in Fig. 1.

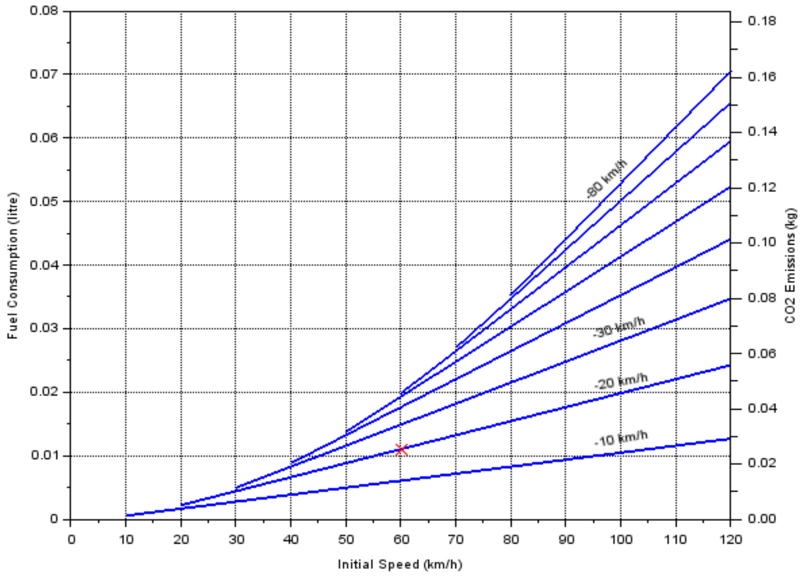

Fig. 1. Price tags for each step on the brake pedal.

The price tags can be scaled for different types of vehicles. For example, consider a 40,000 kg diesel trailer. The mass and the diesel engine would introduce factors of 40 and 0.5, respectively, amounting to an overall factor of 20. The accuracy of the results depends on the accuracy of the input parameters and data, such as the vehicle mass, TTW efficiency, and HHV of the fuel. Take note that the actual duration of the speed reduction does not impact the results, provided that the duration is brief (in seconds), and braking is the primary cause of speed reduction, which is usually the case.

It is not necessary to avoid a braking event entirely. Savings are achieved as long as the required speed reduction is partly accomplished by non-brake actions. The savings can be determined from Fig. 1 too. For instance, if the speed reduction from 60 km/h to 40 km/h is accomplished by non-brake actions and further speed reduction by brake actions, the fuel savings would be 0.011 litre (for the reference vehicle). Figure 2 shows the savings percentage if the braking event is preceded by a mere 10 km/h speed reduction by non-brake actions. The savings are 100% when the brake action is avoided entirely. If the vehicle speed is under 80 km/h most of the time, e.g., during urban driving, the savings percentage would be more than 23%, for a 10 km/h speed reduction by non-brake actions. Figure 3 shows the lower bounds of the savings percentages for different degrees of speed reduction by non-brake actions, for 80 km/h (urban driving) and 120 km/h (highway driving) upper speed limits. For example, a speed reduction by non-brake actions of 20 km/h (30 km/h) preceding a braking event during urban (highway) driving, which is readily attainable, would result in a saving of more than 45%.

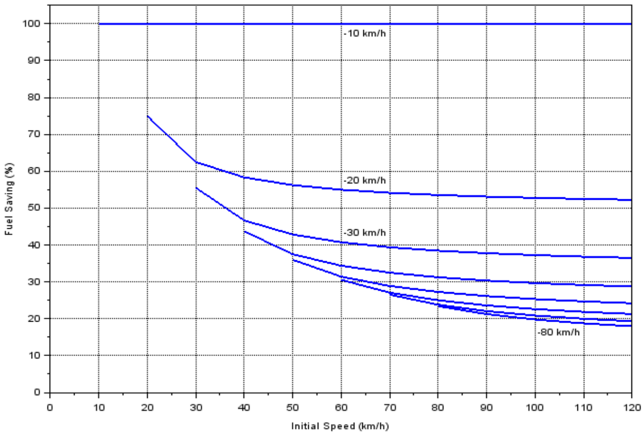

Fig. 2. The percentage of fuel saved in one braking event when it is preceded by a speed reduction of 10 km/h through non-brake actions.

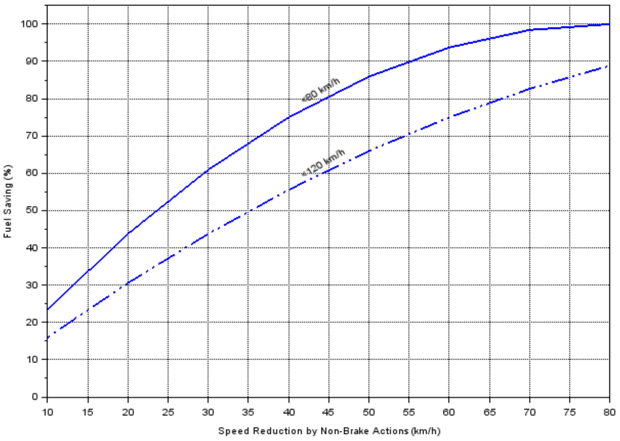

Fig. 3. The minimum percentage of fuel savings in one braking event.

A simple experiment was carried out to investigate the frequency of braking events. During a 26 km urban driving, an average of 80 braking events were recorded, i.e., about 3 braking events per km. Approximately half of these could be avoided by maintaining a larger distance from the lead vehicle and anticipating speed reduction requirements. This has been verified experimentally. With full energy savings in half of the braking events and partial savings in the other half, the average energy savings on the brakes would likely be significantly more than 50%.

The vehicle used in the experiment is a gasoline car weighing 1300 kg. The average fuel consumption, measured over a distance of 2462 km, is approximately 0.088 litres per kilometre. This equates to approximately 2.3 litres for 26 km. From Fig. 1, it can be reasonably assumed that for initial speeds below 80 km/h, the average fuel consumption per braking event is approximately 0.01 litre for the reference vehicle (0.013 litre for the 1300 kg car). This equates to approximately 1.04 litres for the 80 braking events. In other words, the braking events constitute about 45% of the total fuel consumption over the 26 km trip. This is an excellent match to the data published by the US Department of Energy and Environmental Protection Agency [13], which documented a 50% braking loss from energy transferred to the wheels during urban driving. Assuming 50% energy savings in the braking events with braking avoidance strategies, the savings in the total fuel consumption would be about 23%. This is consistent with [14-17]. Although these computations are based on rough approximations, they clearly demonstrate the significance of braking in fuel consumption and hence the importance of braking avoidance strategies in fuel savings.

4. Conclusions

I have presented a simple, albeit approximate, method to compute price tags for each step on the brake pedal, quantified in terms of energy consumption, fuel consumption, monetary cost, and carbon dioxide emissions. Interestingly, the proposed method does not rely on powertrain dynamics or brake force. Instead, it uses only the vehicle mass and speed. This method assumes that braking is the primary cause of speed reduction. This is a valid assumption especially if the braking duration is brief, which is usually the case.

I have also presented the fuel consumption and carbon dioxide emissions price tags for a reference vehicle, from which similar price tags for other vehicles can be determined using appropriate scaling factors. These price tags primarily serve as direct evidence that each brake application incurs charges, thereby encouraging rational drivers to adopt a driving style that results in less braking. This contributes to the United Nation’s Sustainable Development Goals 11 to 13, specifically, sustainable transportation, sustainable consumption, and climate action. Moreover, braking avoidance strategies, such as maintaining a larger gap from the lead vehicle and employing predictive driving, are well-known practices that enhance road safety. Maintaining a larger gap provides more room for the vehicle to slow down naturally without braking.

Predictive driving involves anticipating the need for speed reduction and planning ahead, allowing the vehicle to slow down naturally without braking. For instance, if it is anticipated that the vehicle will need to stop or reduce speed at some choke point in the distance, and the vehicle has enough momentum to cover that distance, it should be allowed to slow down naturally. This helps avoid or reduce the intensity of braking. Furthermore, if the choke point is not momentary, such as a traffic light or slow-moving traffic, accelerating does not offer a time advantage. The vehicle simply reaches the choke point faster.

The presented price tags can also be used for analyses and savings computations, such as those presented above, which show great consistency with other published results. Savings can be computed for each braking event, thereby identifying potential improvements. This underscores the potential usefulness of the proposed price tags. Furthermore, it has been shown that braking accounts for about 45% of the total fuel consumption during urban driving. Additionally, it has been found that the implementation of braking avoidance strategies can potentially reduce braking loss by more than 50%.

Other examples of analyses that can be explored using the presented price tags include the trade-off between braking, travel time, and other factors, such as idling engine. For example, consider a vehicle approaching a traffic light regulated junction where it needs to make a left or right turn. The driver has two options: they could safely accelerate to catch the green light and apply the brakes when making the turn, or they could slow down naturally without braking and stop at the junction to wait for the next green light. The first option offers a travel time advantage but incurs a higher braking cost. The second option has a lower braking cost but includes idling engine cost. The first option might seem like the better choice unless its braking cost is excessively high or there is a good chance that the vehicle would not make it for the green light.

Last but not least, it is important to reiterate that avoiding braking does not mean avoiding the use of brakes when they are needed, as this would jeopardize road safety. Instead, it is about avoiding situations where the brakes would be needed. In any case, the bottom line is always safety first. Furthermore, it is not necessary to avoid braking entirely. Significant savings can be achieved by reducing the intensity of braking, which is more practical in most cases.

Nomenclatures

E	Energy cost, J
F	Fuel consumption, litre
m	Vehicle mass, kg
v	Vehicle speed, m/s

Abbreviations

GCV	Gross Calorific Value
HHV	Higher Heating Value
TTW	Tank-to-Wheel

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