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OPTIMAL IMPLEMENTATION OF LIGHTWEIGHTING AND POWERTRAIN EFFICIENCY TECHNOLOGY IN PASSENGERS' VEHICLES

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Abstract. Improving powertrain efficiency and reducing vehicle weight are two options for reducing vehicle energy use, emissions, and operating cost that often increase the purchase cost of passenger vehicles. Increasing drivetrain efficiency shrinks the potential for reducing energy use by lightweighting and conversely lighter vehicles benefit less from efficiency improvement. This paper describes a methodology for finding the optimum combination of lightweighting and efficiency measures to achieve minimum lifetime vehicle cost. Using representative technology cost assumptions for a mid-sized passenger car, marginal efficiency improvement in the range of 20 to 30% and lightweighting between 200 and 600 kg are optimal, depending strongly on marginal cost curve characteristics. A reduction in the total cost of vehicle ownership of between 18 and 42% is possible for the representative technology implementation scenarios. In the absence of reliable cost data, a general strategy of designing lightweight vehicles with lower powertrain efficiency or else higher-efficiency powertrains which are integrated in heavier vehicles is recommended.

Keywords: capital investments, fuel consumption, weight, models and algorithms, performance evaluation, strategy development.

1. Introduction

The primary contemporary automotive design challenge is to decrease society's dependence on increasingly expensive and unreliable fossil oil resources while decreasing fleet emissions of greenhouse gasses. These global, strategic goals must be translated into specific combinations of vehicle technologies that give the best possible trade-offs between multiple, competing criteria cheaply enough that individual, cost-sensitive customers are willing to pay for them. Manufacturers are faced with a wide range of choices, including advanced conventional drivetrains, hybrid and electric drivetrains, vehicle lightweighting options, and other options like reducing aerodynamic drag, rolling resistance and drivetrain losses (Otterbach 2010).

Hybrid and electric drivetrains reduce on-board vehicle energy use at all vehicle weights (Wohlecker *et al.* 2007). Fig. 1 illustrates the real-world trend that inspired the research discussed in this paper. In the Fig. 1, the slope of the regression lines decreases with increasing electrification, indicating that the more efficient a vehicle's drivetrain is, the less sensitive it is to change in weight.

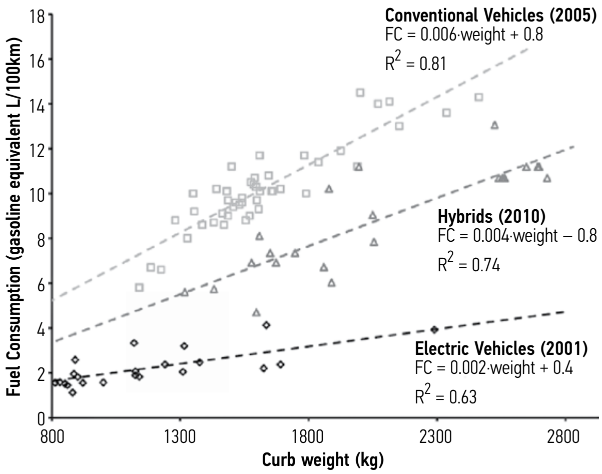


Fig. 1. Fuel use versus vehicle weight for conventional, hybrid and electric drivetrains illustrating that the more efficient a powertrain is, the less its energy use depends on weight (ADAC 2008; National Highway Traffic Safety Administration 2006; Meier-Engel 1999)

The impact of weight reduction on advanced powertrains has been investigated by quantifying the mechanisms of the diminishing energy use reduction with increased technology application (Pagerit *et al.* 2006). The trade-off incurred while adding hybrid technology which simultaneously increases weight and efficiency is commonly treated when performing powertrain sizing studies (Shiau *et al.* 2009). A comprehensive treatment of the relationship between vehicle weight, powertrain efficiency, and total cost of vehicle ownership has also been undertaken in a notable study (Lipman, Delucchi 2006). An effort was made to frame the general optimization problem within the context of a review (Dyakov, Prentkovskis 2008). What is missed in the literature is a comprehensive methodology based on the first-principles for solving the techno-economic problem of deciding how to best implement advanced powertrain and lightweighting technology.

This paper focuses on the relationship between two primary means of meeting the objectives of reduced energy use and CO_2 emissions, i.e., increasing drivetrain efficiency and reducing vehicle weight. The costs to implement these technologies are combined with their fuel cost savings over the expected vehicle life. Therefore, the main research questions are what the optimum, constrained mix of investment in these two measures is and what conclusions can be drawn for the best strategies for combining them in practice. The results presented here are expected to hold for all driving cycles, as the trend shown in Fig. 1 results from a composite of several cycles as well as the real world data. Other methods of lowering fuel consumption such as reducing rolling resistance through advanced tire technology or redesigning of reduced aerodynamic drag also result in increased purchase price, and could also be considered using a similar approach to the one introduced in this work.

First of all, this paper introduces the methodology developed to calculate lifecycle vehicle costs based on a parameterized equation for vehicle energy demand, similar to the one used by (Makaras *et al.* 2011). Then, these equations are combined and differentiated to see how minimum cost is related to vehicle mass and efficiency. Marginal cost functions for lightweighting and increased drivetrain efficiency are introduced based on technology cost estimates. It must be acknowledged that the cost data for this type of analysis is often uncertain and/or controversial based on the variability in data sources and assumptions about technological maturity and economies of scale at different production levels. Therefore, the applications of the methodology provided in this paper were selected based on relatively conservative (high) estimates of future costs in order to draw general conclusions about the patterns of results. It is hoped that the presented methodology may also be adopted by other analysts whose cost data may differ.

2. Methods

The main goal of this method is to find the optimal degree of lightweighting and powertrain improvement given diminishing marginal returns on technology investment. First, the interrelationship between the total energy savings from reducing weight and from increasing drivetrain efficiency is determined, and then the net effect of increasing the manufacturing cost (and therefore purchase price) is calculated, including the decrease in fuel costs over the vehicles' life.

The energy consumption for the simple vehicle model assumed here is based on the force balance shown in Fig. 2. The net acceleration or deceleration of the vehicle is based on the tractive force at the wheels $F_{traction}$, net of gravitational forces $F_{gravity}$ and aerodynamic drag F_{aero}, rolling resistance $F_{rolling}$ and disturbance forces like wind $F_{disturbance}$ etc. Normally, this force balance is used to determine the drivetrain energy requirements, and may be combined with an engine efficiency map based on engine speed and torque to form the basis for simulation of the tank-to-wheel energy demand. Such simulations are often performed based on a regulatory driving cycle such as the New European Driving Cycle (NEDC) with a net altitude change of zero, and which may also include regenerative energy recovery from braking when a hybrid or electric drivetrain is used.

For the purposes of the current work, we are interested in the fundamental relationship between weight and efficiency for an arbitrary, fixed driving cycle. It was therefore judged to use appropriate a simplified method for calculating average vehicle energy demand which assumes no recuperation of braking energy expressed in Equation (1). A full derivation of this formula is beyond the scope of this work, but can be found in (Guzzella, Sciarretta 2010). The variable $m'_{vehicle}$ represents the mass of the vehicle after lightweighting technology is applied and variable $\eta'_{powertrain}$ represents average drivetrain efficiency improvements after additional powertrain technology improvements have been implemented. A single efficiency variable was selected based on the fact that all efficiency improvements influence the vehicle's sensitivity to a change in mass (Pagerit *et al.* 2006).

$$FuelConsumption = \frac{A + (B + C) \cdot m'_{vehicle}}{\eta'_{powertrain}}, \tag{1}$$

where:

$$A = A_f \cdot c_d \cdot \frac{CC_1}{LHV_{fuel} \cdot \rho_{fuel}};$$

$$B = c_r \cdot \frac{CC_2}{LHV_{fuel} \cdot \rho_{fuel}};$$

$$C = \frac{CC_3}{LHV_{fuel} \cdot \rho_{fuel}}.$$

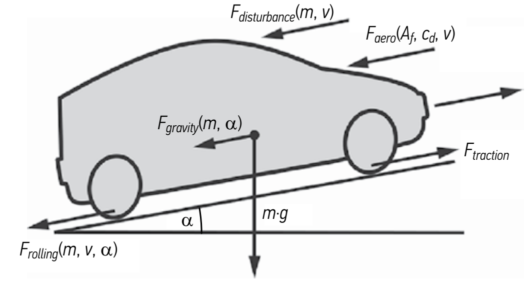


Fig. 2. Vehicle mass influences many of the forces acting on a linear dynamics vehicle model

It is clear that lightweighting will proportionally reduce the latter two loss terms, while increasing drivetrain efficiency will inversely reduce overall fuel use. Aerodynamic losses depend on the vehicle's frontal area A_f and drag coefficient c_d, as well as the weighted average of the velocity squared over the driving cycle. The rolling friction c_r and kinetic losses are also proportional to the vehicle mass. The three cycle-dependent parameters CC_1, CC_2, CC_3 are converted from energy to volumetric units using the fuel's lower heating value LHV_{fuel} and density ρ_{fuel} for later economic calculations. The numerical values in the parameterization used throughout this work were based on the NEDC driving cycle.

The total lifetime cost of a vehicle paid by its owner consists of the original purchase cost plus the present value of the future fuel costs. A fixed cost mark-up (*markup*) of 40% is applied to technology cost to convert from production cost to purchase price in order to account for the manufacturer's overhead, profit and distribution costs. For the purposes of this analysis, Equation (2) neglects other lifetime costs including maintenance, insurance, etc. that were regarded as fixed:

$$Cost_{total} = Cost_{fuel} + Cost_{technology} \cdot markup. \quad (2)$$

The fuel cost is directly proportional to a vehicle's fuel consumption per kilometer *FuelConsumption*, the annual kilometres driven T_{km}, its service life, and the price of fuel per litre *FP*. The technology cost is a one-time cost incurred at the time of purchase. To be rigorous, the time value of money should be considered in the annual fuel cost calculation in order to calculate the lifetime cost of transportation fuel in Equation (3). In order to simplify the analytical procedure, however, the 5% discount rate consumers would be assumed to place on future fuel cost that can be safely neglected. Throughout this analysis the fuel price is assumed to be *FP* = \$2/litre, unless otherwise noted.

$$Cost_{fuel} = \frac{FuelConsumption \cdot T_{km} \cdot FP}{100}. \quad (3)$$

The technology cost in Equation (4) consists of a fixed base cost, plus the costs for added technology improvements. The cost of the lightweighting technology is determined by the difference between mass of the vehicle $m_{vehicle}$ before and after lightweighting, and the cost of improved powertrain efficiency is determined by the difference in efficiency of the powertrain $\eta_{powertrain}$ before and after improvement based on the NEDC driving cycle each multiplied by a respective cost function. Equation (4) is only valid for fixed marginal costs for lightweighting MC_{lw} and efficiency MC_{pteff} technologies. If marginal costs vary with implementation, an expression must be substituted which considers differential marginal cost increases and which will be discussed later in this work.

$$Cost_{technology} = BaseCost + \left(m_{vehicle} - m'_{vehicle}\right) \cdot MC_{lw} + \left(\eta'_{powertrain} - \eta_{powertrain}\right) \cdot MC_{pteff}. \quad (4)$$

To simplify analysis, we will use the differences $dm_{vehicle}$ and $d\eta_{powertrain}$ represent the terms as follows:

$$dm_{vehicle} = m_{vehicle} - m'_{vehicle};$$

$$d\eta_{powertrain} = \eta'_{powertrain} - \eta_{powertrain}.$$

Combining Equations (1) to (4) and simplifying by substituting the differences, yields Equation (5) which is valid for fixed marginal costs:

$$Cost_{total} = Base\ Cost + \frac{D + E \cdot \left(m_{vehicle} - dm_{vehicle}\right)}{\eta_{powertrain} + d\eta_{powertrain}} + dm_{vehicle} \cdot MC_{lw} + d\eta_{powertrain} \cdot MC_{pteff}, \quad (5)$$

where:

$$D = \frac{A}{100} \cdot FP \cdot T_{km} \cdot Service\ Life;$$

$$E = \frac{\left(B + C\right)}{100} \cdot FP \cdot T_{km} \cdot Service\ Life.$$

The input assumptions for the constants (*A*, *D*, *C*) which describe the baseline mid-sized passenger vehicle assumed for this work are listed in Table 1, together with the bounds assumed on technology implementation for the optimization. For simplicity, it was also assumed that powertrain efficiency measures do not significantly add to the vehicle weight, or equivalently that the lightweighting required to maintain the baseline vehicle weight after powertrain improvement comes at no additional cost (Kromer, Heywood 2007). It is relatively simple to modify the characteristic equations to consider the additional weight of powertrain efficiency.

Table 1. Assumed baseline vehicle characteristics, driving cycle dependent parameters, and bounding values for new mid-sized passenger vehicle weight and powertrain efficiency based on technology implementation levels

Variable	Unit	Baseline	After improvement
$m_{vehicle}$	kg	1600	1000
$\eta_{powertrain}$	%	15	45
A_f	m^2	1.9	–
c_d	–	0.37	–
c_r	–	0.012	–
LHV_{fuel}	kJ/g	42.5	–
ρ_{fuel}	g/litre	750	–
T_{km}	km	12000	–
CC_1	$kJ/m^2/100$ km	19000	–
CC_2	kJ/kg/100 km	840	–
CC_3	kJ/kg/100 km	10	–

Equation (5) above can now be examined for the sensitivity of lifetime cost to change in both mass and efficiency. Differentiating Equation (5) with respect to vehicle mass change $dm_{vehicle}$ yields Equation (6):

$$\frac{\partial Cost_{total}}{\partial dm_{vehicle}} = MC_{lw} - \frac{E}{\eta_{powertrain} + d\eta_{powertrain}}. \quad (6)$$

Note that this equation does not contain a term in $m'_{vehicle}$. The independence of weight reduction from the other variables is seen graphically in Fig. 3 through the linear quality of the total cost for changing lightweighting costs while reducing weight. This figure clearly shows that reducing vehicle weight using technology with a marginal cost of \$12.1/kg or higher results in an increase in the total cost of vehicle ownership.

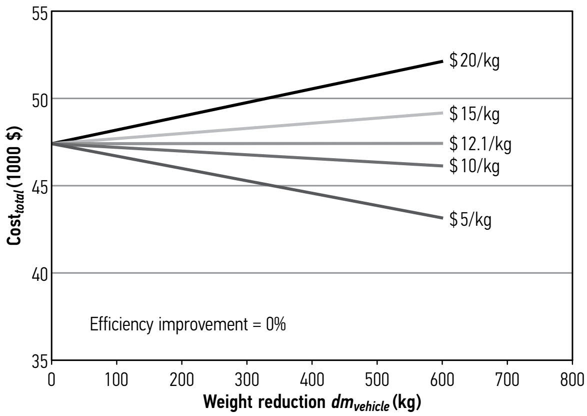


Fig. 3. Total lifetime cost variation for various lightweighting technology costs without efficiency improvement and a fuel price of \$2/litre

The observation of this 'critical cost' of lightweighting technology becomes important when analyzing the optimal level of technology implementation in following sections.

3. Results

This section presents how these methods can be applied to real problems as well as some general characteristics of the solutions which have policy and strategy implications. The section begins with an analytical solution to fixed marginal costs in order to introduce some important characteristics of the optimal implementation of lightweighting and efficiency technology. What is more, closed-form solutions to the optimization problem are discussed to highlight how well-behaved the functions are and to solidify the understanding of their characteristics. The section ends with several real-world application examples and an analysis of the results' sensitivity to cost function shape, fuel price, and engine downsizing.

3.1. Static Marginal Cost Optimization

In order to minimize the lifetime cost of light-duty vehicles by implementing lightweighting and powertrain efficiency technology, Equation (5) must be minimized. In this section, static marginal costs that do not depend upon the level of technology implementation are assumed. To find the optimal degree of lightweighting and efficiency improvement, the partial derivatives of Equation (5) with respect to $dm_{vehicle}$ and $d\eta_{powertrain}$ are set to zero. Unfortunately, Equation (6) does not depend on and therefore cannot be solved for $dm_{vehicle}$ directly.

If Equation (6), which depends on to marginal cost of lightweighting and applied efficiency improvement, is greater than zero, then total costs increase with applied lightweighting. If Equation (6) is smaller than zero, total costs decrease with applied lightweighting. This defines the lightweighting 'critical point' which leads to a discontinuous optimal implementation of lightweighting and efficiency improvement. Accordingly, the optimal implementation of lightweighting – within the limits $0 \le dm_{vehicle} \le dm_{vehicle}^{max}$ – as a function of applied efficiency improvement and marginal cost of weight reduction can be expressed as a Heaviside step function in Equation (7):

$$dm_{vehicle}^{opt}\left(MC_{lw}, d\eta_{powertrain}\right) = dm_{vehicle}^{max}\Theta\left(MC_{lw} - \frac{E}{\eta_{powertrain} + d\eta_{powertrain}}\right). \quad (7)$$

In order to find the minimum of Equation (5) and the optimal implementation of efficiency improvement $d\eta_{powertrain}^{opt}$, the result in Equation (7) is substituted in $\frac{\partial Cost_{total}}{\partial d\eta_{powertrain}}$ and the expression is set to zero and solved. For the general case of $MC_{lw} \ge 0$, and $MC_{pteff} \ge 0$, two local minima exist. To identify the global minimum, the intersection of Equation (5) for both local solutions is calculated, which gives a unique solution for $d\eta_{powertrain}^{opt}$ as a function of marginal costs as shown in Equation (8):

$$d\eta_{powertrain}^{opt} = \begin{cases} -\eta_{powertrain} + \sqrt{\dfrac{\left(A + \left(B + C\right) \cdot m_{vehicle}\right) \cdot FP \cdot T_{km} \cdot Service\ Life}{MC_{pteff}}}, & \text{when } MC_{pteff} < \alpha \cdot MC_{lw}^2; \\ -\eta_{powertrain} + \sqrt{\dfrac{\left(A + \left(B + C\right) \cdot \left(m_{vehicle} - dm_{vehicle}^{max}\right)\right) \cdot FP \cdot T_{km} \cdot Service\ Life}{MC_{pteff}}}, & \text{when } MC_{pteff} \ge \alpha \cdot MC_{lw}^2, \end{cases} \quad (8)$$

where:

$$\alpha = \frac{A + \left(B+C\right) \cdot \left(m_{vehicle} - \dfrac{dm_{vehicle}^{max}}{2}\right) + \sqrt{\left(A + \left(B+C\right) \cdot \left(m_{vehicle} - \dfrac{dm_{vehicle}^{max}}{2}\right)\right) \cdot \left(A + \left(B+C\right) \cdot m_{vehicle}\right)}}{2 \cdot FP \cdot T_{km} \cdot Service\ Life \cdot \left(B+C\right)^2}.$$

The parameter α separates two cases in which optimally no/all available lightweighting is applied, and the optimal efficiency improvement is at a relatively high and low level, respectively. The factor α, which depends on the fuel price among other things, determines the relative marginal costs at which this discontinuity occurs. In general, Equation (8) needs to be defined separately in different regions of static marginal technology costs depending on the maximum implementation limits of the efficiency technology $d\eta_{powertrain}^{max}$ that is assumed. The optimal implementation of lightweighting as a function of marginal costs $dm_{vehicle}^{opt}\left(MC_{lw}, MC_{pteff}\right)$ is then found by replacing $d\eta_{powertrain}$ in the Equation (7) by Equation (8), where $dm_{vehicle}^{max}$ and $d\eta_{powertrain}^{max}$ need to be taken into account to achieve the correct solution within each static marginal cost region.

The optimal degree of lightweighting and efficiency technologies implemented as a function of static marginal costs is shown in Fig. 4 for the baseline vehicle. In this figure, the costs of implementing efficiency improvement or lightweighting technology are fixed as shown on the x and y axes, i.e. there is no marginal diminishing return assumed for either technology lever. The second pane in Fig. 4 shows that it is only optimal to implement lightweighting technology if its marginal cost is less than approximately \$9/kg with very expensive efficiency measures and \$4/kg with cheap efficiency measures. The shape of the surface reflects the fact that lightweighting should be applied in an 'all or nothing' fashion, and, as intuition would suggest, vehicles should be increasingly made lighter as efficiency measures become more expensive. The optimal degree of efficiency improvement changes much more continuously with technology cost, and has a similar slope for all levels of lightweight technology cost, although efficiency improvement can be applied to a greater degree if lightweighting technology is not applied. At a marginal cost of about \$200/% or less, it is optimal to improve efficiency to the maximum limit of 30% above baseline.

An effective technology policy can be based on the 'critical point' for applying lightweighting technology (at constant marginal cost) relative to applying powertrain efficiency improvement (also at constant marginal cost). In summary, these results show that the optimal lightweighting technology depends in an 'all or nothing' way on the relative lightweighting and efficiency technology costs, and hence it can be advantageous for manufacturers to design all lightweight models with lower powertrain efficiency or higher efficiency powertrains without lightweighting technology assuming that marginal costs are fixed, which is not always the case as will be discussed in the following sections.

3.2. Applying the Methodology to Specific Examples

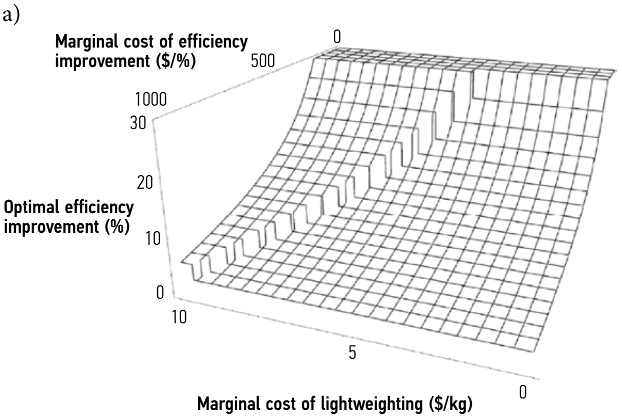
A review of cost estimates for different lightweighting and energy efficiency measures is now presented, an attempt to fit representative marginal cost functions for them is made, and the methodology derived in this paper to find the optimal combinations of lightweighting and efficiency improvement is demonstrated and tested.

The marginal cost functions describing future technology costs for both lightweighting and efficiency improvement are the subject to significant uncertainty and depend on various factors discussed in this section. These costs and results are therefore presented as illustrations of how the methodology described in this paper can be applied, and not as definitive. The options described here were chosen to adequately represent the current technological landscape and estimate the costs associated with each lightweighting and efficiency technology measure. As such, these cost figures and implementation scenarios should be taken as illustrations of the method outlined in this paper only, and are useful for describing some general characteristics of the results of applying this method to guide strategy and policy.

3.2.1. Lightweighting Scenarios

Modern vehicle components are chosen to meet specific performance and cost criteria and are made from a wide variety of materials. A full approach to lightweighting therefore needs to consider what materials can be substituted for others, component downsizing and decompounding, fabrication methods, and whether components can be combined to reduce their number (Verbrugge *et al.* 2009; Merklein, Geiger 2002; Cousins *et al.* 2007).

a)



b)

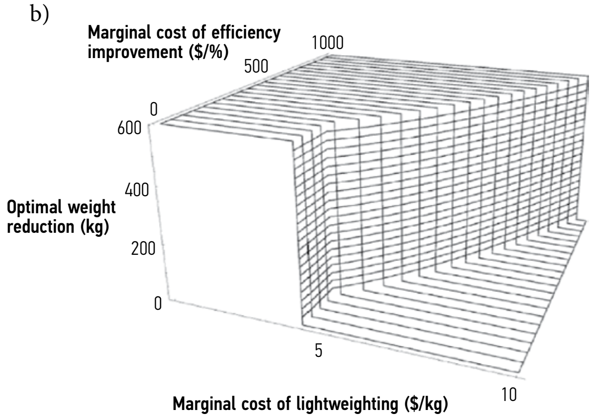


Fig. 4. Optimal levels of efficiency improvement above baseline (a) and weight reduction (b) for various fixed (i.e. constant) lightweighting and efficiency marginal technology costs

Fortunately, the main methods for lightweighting the largest vehicle systems can be based on the materials substituted for currently used materials, normally common ductile steels. In increasing order of cost and weight savings, these materials include high strength steel (HSS), aluminum, magnesium, fibreglass and carbon fibre composites. A range of lightweighting options, ranked in order of their cost/savings ratio, is shown in Fig. 5, which requires several remarks. First, some substitutions using HSS actually save money, because their additional strength is expected to reduce part count and therefore cost (Shaw, Roth 2002). Second, some of the largest weight savings are available at such low or negative costs. Third, many of these different substitutions are for the same large parts (e.g. the body), so the options are actually mutually exclusive, and cannot be combined exhaustively to produce a weight reduction supply curve. The data comes from (Cheah 2010; Committee on the Assessment… 2011).

The reason that many of the marginal costs for saving weight are uncertain is that they depend upon 1) a learning curve as they move from R&D into production, 2) assumptions about the final scale of production, 3) design time required for integrated weight decompounding, and 4) compatibility with other OEM design and fabrication choices (Li *et al.* 2003). As one example, magnesium offers additional weight savings over aluminium, but the hot pressing, assembly procedures, and corrosion issues combine to restrict its current application. In practical terms therefore, an OEM may concentrate on one material over others and develop more expertise in it. For these reasons, as well as to respect sub-system specific material implementations, the various lightweighting options shown in Fig. 5 were placed into four groups based on materials (HSS, aluminium, glass and carbon fibre), as shown in Fig. 6. The graphs show separate 'blocks' for materials substitution with an exponential curve fitted to the mid-points of each box. It was assumed that HSS substitutions can be applied to the front-end of a vehicle (hood and trim) so this technology was assumed to be applicable for all four groups, with further substitutions then based on each technology group's base material.

3.2.2. Efficiency Options

The efficiency improvement potentials offered by advanced powertrain technologies and their associated marginal costs are plotted in Fig. 7 in order of increasing cost (Cheah 2010; Committee on the Assessment… 2011). Own estimates were used for the 'downsizing and turbo-charging' and 'micro hybrid' efficiency technologies. Note that the least expensive options (also with the smallest improvement potentials) relate to reducing the energy loss terms shown in Equation (1), i.e. rolling resistance, aerodynamic drag and drivetrain losses.

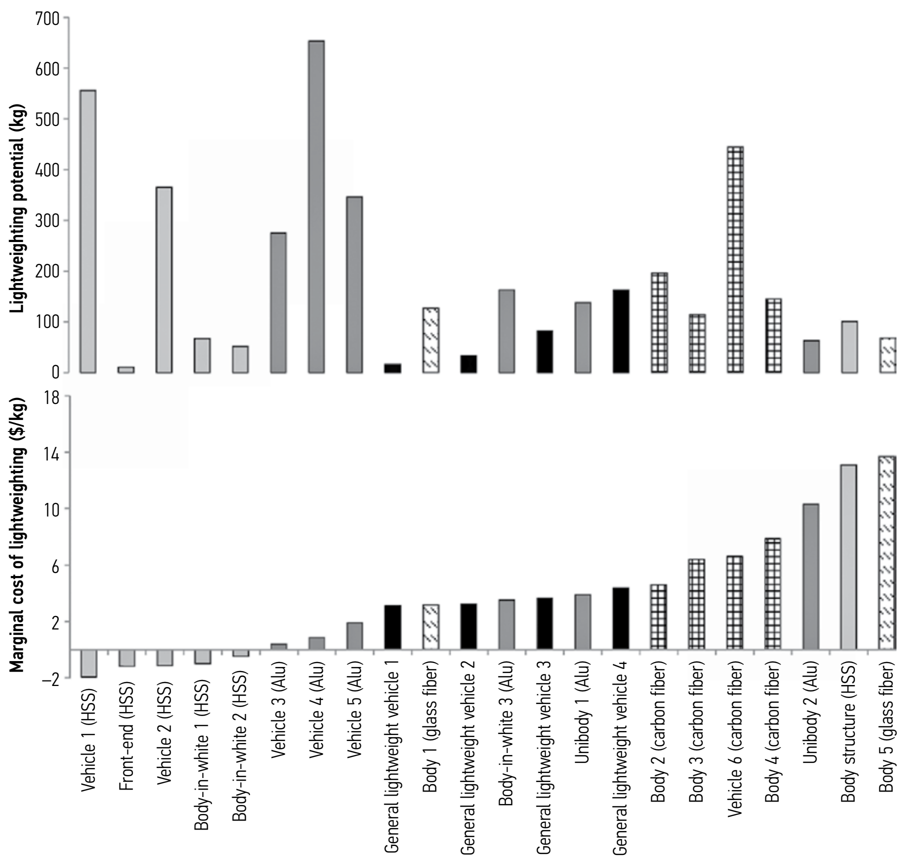


Fig. 5. Estimates for the marginal cost of lightweighting technology sorted from lowest to highest and shaded by material type shows that some of the largest gains are expected to be possible at the lowest costs

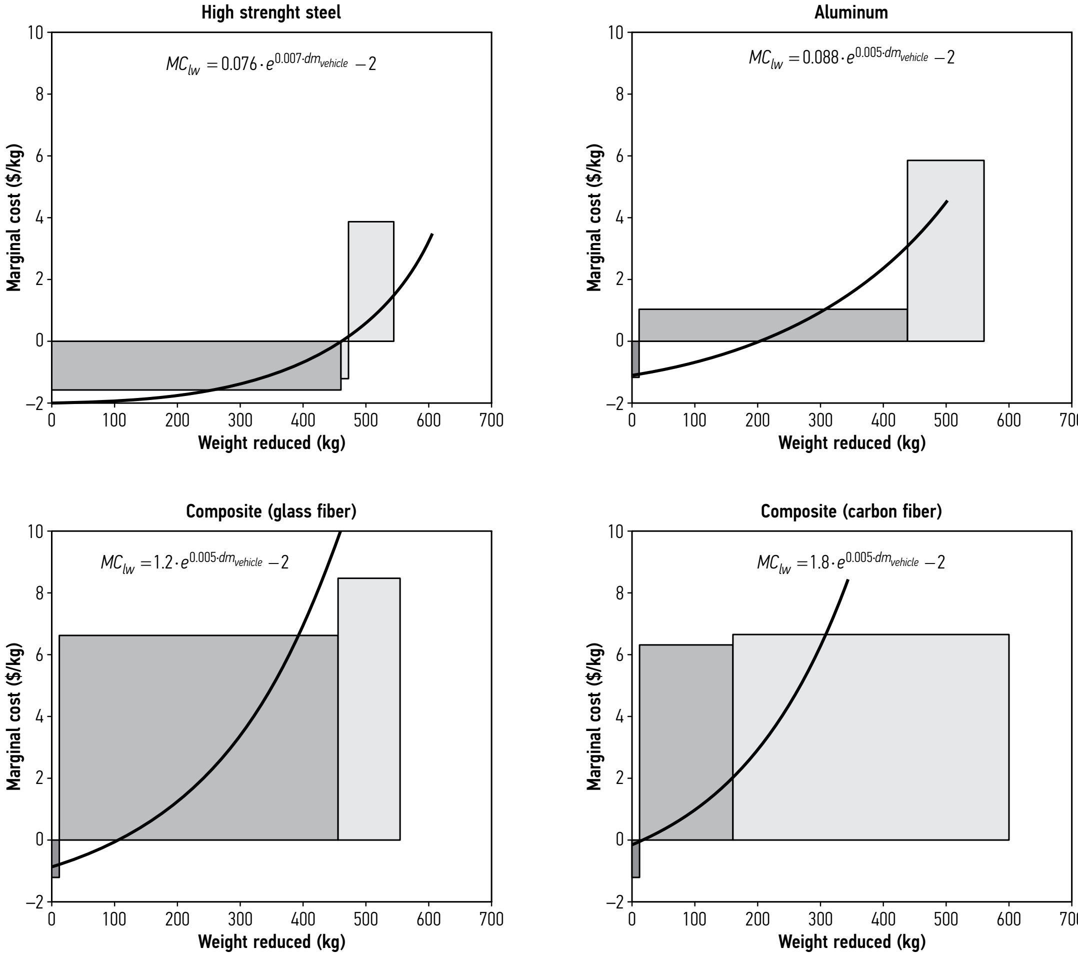


Fig. 6. Marginal cost of reducing vehicle weight for four scenarios based on different materials applied to three vehicle subsystems

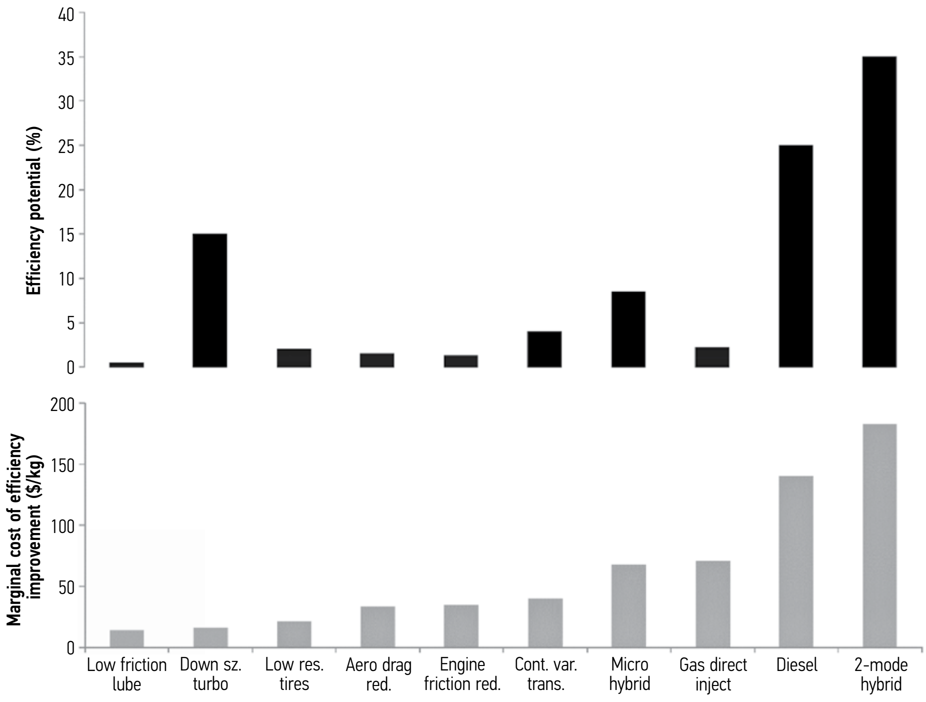


Fig. 7. Estimates for the marginal cost of powertrain efficiency technology sorted from smallest to largest shows that in the most cases, the larger the gain, the larger the marginal cost

The larger and more expensive options are related to increasing engine efficiency by downsizing, or using diesel or hybrid engines. It is worth commenting that downsizing (i.e. reducing engine size relative to vehicle weight) is a reversal of the trend from the last several decades, where increases in the engine's power/weight ratio were predominantly used to increase vehicle size and performance. More analysis of downsizing is performed later in this section. As a matter of definition, the direct gas injection sprays the fuel directly into the cylinder rather than the intake manifold, the micro hybrid adds automatic engine stop and start to eliminate idling losses, and the 2-mode hybrid is an advanced powertrain with multiple electric machines and complex transmission architecture (Eberle, Von Helmolt 2010).

Four scenarios, assembled according to how technology improvements in Fig. 7 can be applied in the same vehicle, form the basis for the marginal cost of efficiency improvement functions and are plotted in Fig. 8. An exponential curve was assumed for all of the technology implementation scenarios, although for the diesel and 2-mode hybridization scenarios a linear trend would result in a better fit. Nevertheless, it was deemed important for consistency to consider one form of the marginal cost characteristic equation throughout.

While an analytical solution for this techno-economic optimization problem was introduced in Section 3.1, a numerical approach was implemented in MATLAB to select the optimal degree of lightweighting and powertrain efficiency technology implementation based on Equation (5). The well-behaved nature of the techno-economic system, as well as the need to analyze complex cost functions, led to the selection of the sequential quadratic programming algorithm '*fmincon*' from MATLAB's library to find the optimal solutions for various cost. For more detail about optimization methodologies and caveats when using this methodology see – Gobbi *et al.* (2006); MathWorks (2011). To use Equation (5) for non-static marginal costs, a differential expression for the implementation of the advanced technologies must be applied, as seen in Equations (9) and (10) for marginal cost functions with exponential character where coefficients *a*, *b*, *c*, *g*, and *s* are used to condition the functions' character:

$$Cost_{lw} = \int_0^{dm_{vehicle}} MC_{lw} d\left(dm_{vehicle}\right) = \int_0^{dm_{vehicle}} \left(b \cdot e^{a \cdot dm_{vehicle}} - s\right) d\left(dm_{vehicle}\right) = \frac{b}{a}\left(e^{a \cdot dm_{vehicle}} - 1\right) - s \cdot dm_{vehicle}; \quad (9)$$

$$Cost_{pteff} = \int_0^{d\eta_{powertrain}} MC_{pteff} d\left(d\eta_{powertrain}\right) = \int_0^{d\eta_{powertrain}} c \cdot e^{g \cdot d\eta_{powertrain}} d\left(d\eta_{powertrain}\right) = \frac{c}{g}\left(e^{g \cdot d\eta_{powertrain}} - 1\right). \quad (10)$$

Substituting, Equation (5) becomes Equation (11):

$$Cost_{total} = BaseCost + \frac{A + D \cdot \left(m_{vehicle} - dm_{vehicle}\right)}{\eta_{powertrain} + d\eta_{powertrain}} + \frac{b}{a}\left(e^{a \cdot dm_{vehicle}} - 1\right) - s \cdot dm_{vehicle} + \frac{c}{g}\left(e^{g \cdot d\eta_{powertrain}} - 1\right). \quad (11)$$

The optimization results using the MATLAB '*fmincon*' function on the marginal cost functions derived from literature marginal cost for the four lightweighting and four efficiency measures scenarios results in the sixteen optimal levels of weight reduction and efficiency improvement that are shown in Fig. 9. Several insights about the optimal levels of technology implementation are possible from the figure. Firstly, the optimal level of efficiency improvement is relatively high, and is implemented to the greatest degree for the cheapest technologies. The two cheapest efficiency measures (micro-hybridization and downsizing) are implemented completely to their limits (20% and 26.5% respectively as defined in the scenarios shown in Fig. 8). Secondly, HSS and aluminium scenarios are implemented to the limit of 600 kg, whereas the more expensive fibre-based lightweighting technologies are still implemented but much less drastically. The lowest total cost of any of the technologies is achieved by downsizing/turbocharging and using HSS ($27,327), due in large part to the negative marginal cost assumed for high-strength steel. The most expensive scenario is the micro-hybrid with carbon composite one ($38,926), which is counter-intuitive until one considers that the micro-hybrid is not able to improve efficiency to the same degree as the other options. Thirdly, it is also interesting to note that the optimal efficiency implementation displays very little dependence on the cost of lightweighting technology, which agrees with the trend observed when examining static marginal costs in Fig. 4. Finally, when considering that the total cost of ownership for the baseline vehicle without any technology implementation is $47,400, the lowest reduction in total cost is 18% and the greatest reduction in total cost is 42% both of which are significant reductions in vehicle cost of ownership through the application of advanced technology.

3.3. Technology Cost Sensitivity

In this section, as in Section 3.2, marginal cost is assumed to vary according to the degree of lightweighting or powertrain efficiency technology applied. This accurately represents the reality of technology implementation, because once the 'low hanging fruit' measures are implemented, both reducing weight and increasing powertrain efficiency become more expensive. Results for exponential increasing marginal cost curves are presented. The sensitivity of the results to technology costs, the form of various continuous marginal cost functions, future fuel prices, and finally discrete marginal costs is presented.

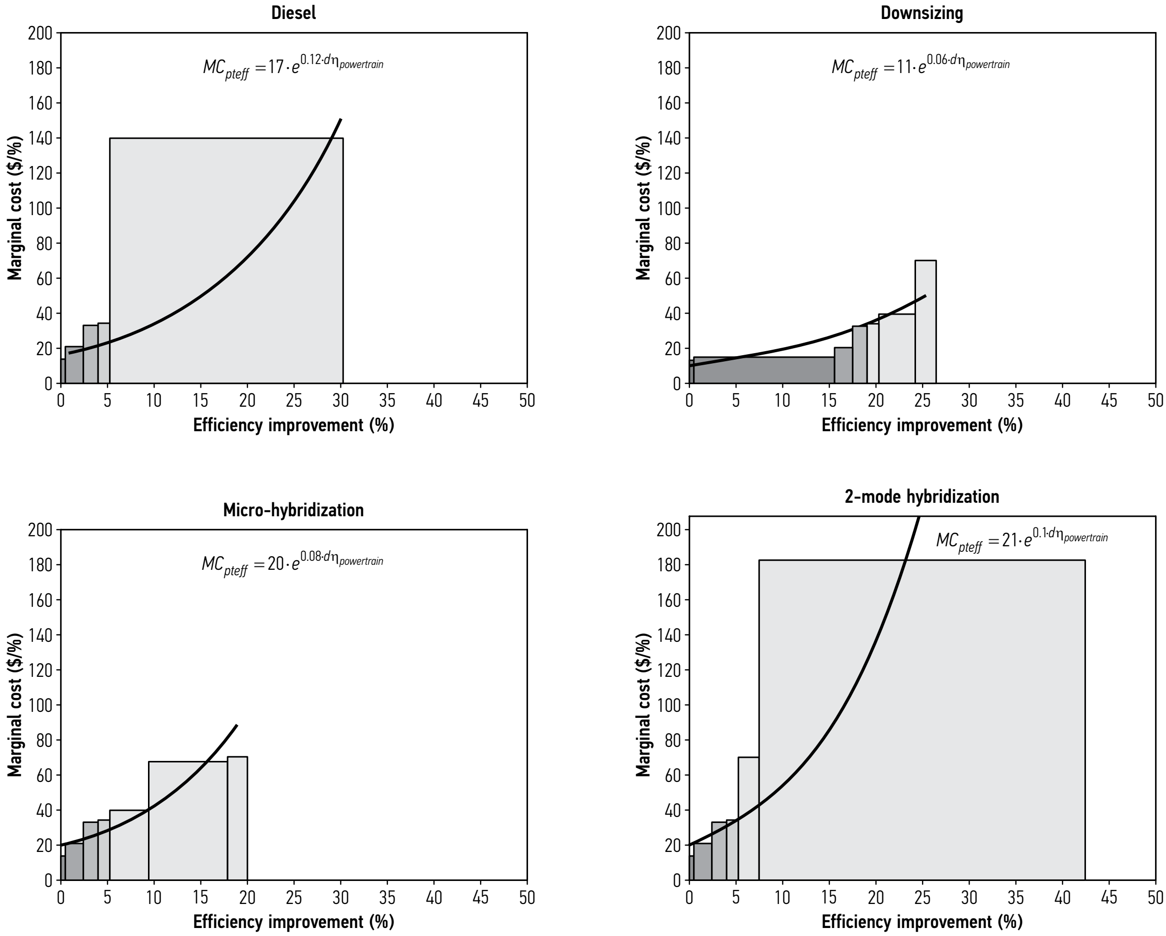


Fig. 8. Four efficiency technology implementation scenarios are used to develop marginal cost of implementation functions assuming that the lowest marginal cost will be implemented first

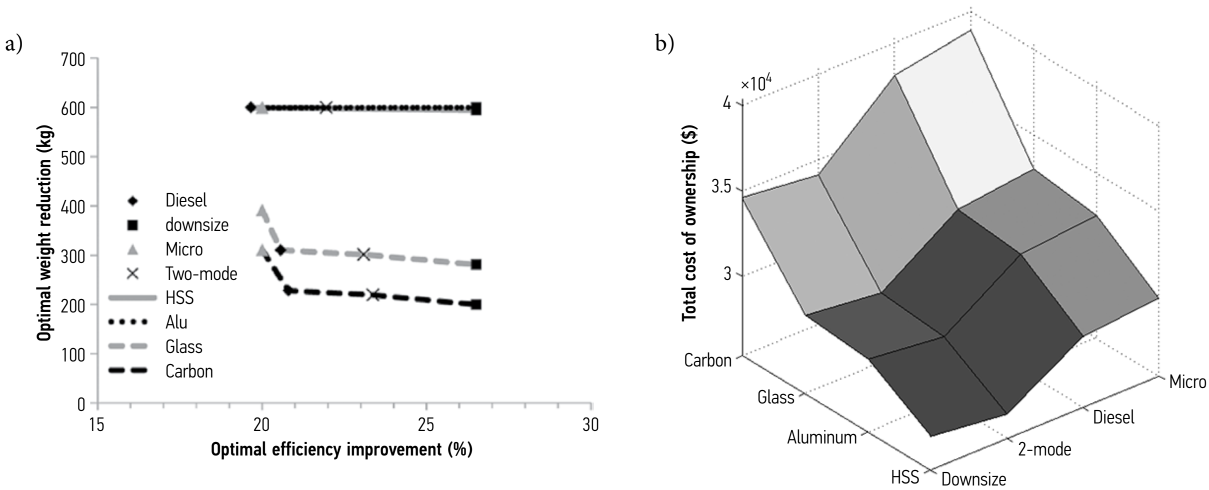


Fig. 9. Optimal levels of efficiency and lightweighting technology implementation for the sixteen marginal cost scenarios (a) and total cost of ownership (b)

As found in Sections 3.2.1 and 3.2.2, a realistic way of characterizing the marginal increase in technology cost is described by using an exponential cost function. The exponential characteristic accounts for the reality that as cheaper alternatives are implemented, the cost of further reducing vehicle weight and increasing vehicle powertrain efficiency increases. In this section, the sensitivity of the results obtained in the Section 4.2 is explored with respect to the marginal cost function characteristics. The carbon fibre cost function (with baseline $a = 0.005$) is represented by Equations (12) and the 2-mode hybrid (with baseline $g = 0.1$) is represented by Equation (13) which is plotted in Fig. 10 for three marginal cost coefficients. These equations were calculated by integrating Equations (9) and (10) using the parameters from the respective cost scenarios.

$$Cost_{lw} = \frac{1.8}{a} \cdot \left(e^{a \cdot dm_{vehicle}} - 1\right) - 2 \cdot dm_{vehicle}; \quad (12)$$

$$Cost_{pteff} = \frac{21}{g} \cdot \left(e^{g \cdot d\eta_{powertrain}} - 1\right). \quad (13)$$

The optimal degree of efficiency improvement and lightweighting technology implementation is shown in Fig. 11. The application of both optimal efficiency and weight reduction technology behaves relatively smoothly for diminishing marginal costs, although the 'critical cost' characteristic can also be observed in the figure, just as it occurred in the optimization presented in the previous section with a static marginal cost function.

3.4. Fuel Price Sensitivity

According to this research, increasing the fuel cost raises the value of future fuel savings due to increased vehicle efficiency. It therefore increases the amount that can be spent on lightweighting and/or drivetrain efficiency in order to minimize overall lifetime cost. Increasing fuel price is a key factor in reducing transportation energy use, both by reducing vehicle kilometres traveled in the short-term and by persuading consumers to choose lower consumption vehicles in the long-term.

Throughout this analysis, fuel price has been held constant at $2/L. The effect of changing fuel price is shown in Fig. 12 for the static marginal cost functions introduced in Section 3.1. It is immediately obvious that higher fuel price shifts the 'all-or-nothing' weight reduction boundary which results in a higher price tolerance for both lightweighting and efficiency improvement technologies at static marginal costs. The shape of the boundary line can be recognized from Fig. 4 as the 'cliff' that separates high and low implementation of both technologies.

3.5. Discrete Cost Function Optimization

The methodology described in the previous section assumed that cost functions are continuously differentiable and convex within the bounds listed in Table 1. Real engineering problems involve selection between various discrete technologies for reducing weight and increasing powertrain efficiency. In order to examine whether the same optimization results are observed for a more real-

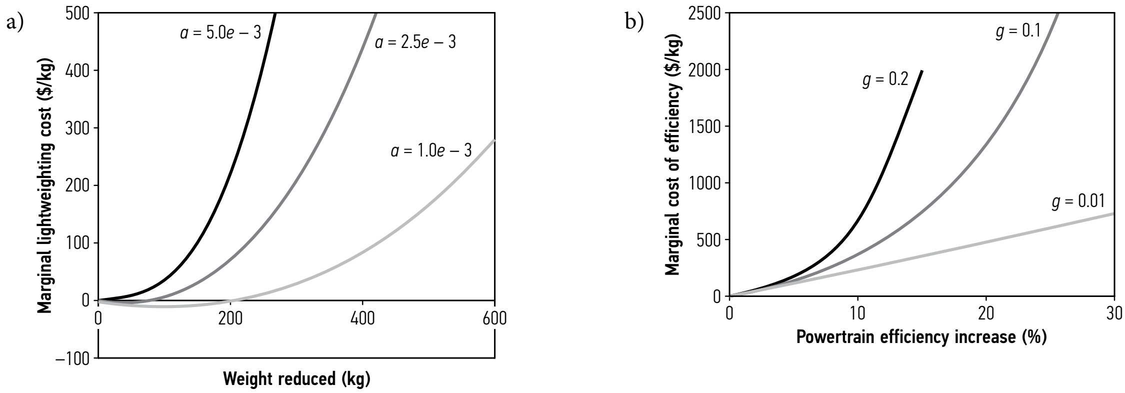


Fig. 10. Sensitivity of exponential lightweighting and powertrain technology cost functions to marginal cost coefficients *a* and *g*

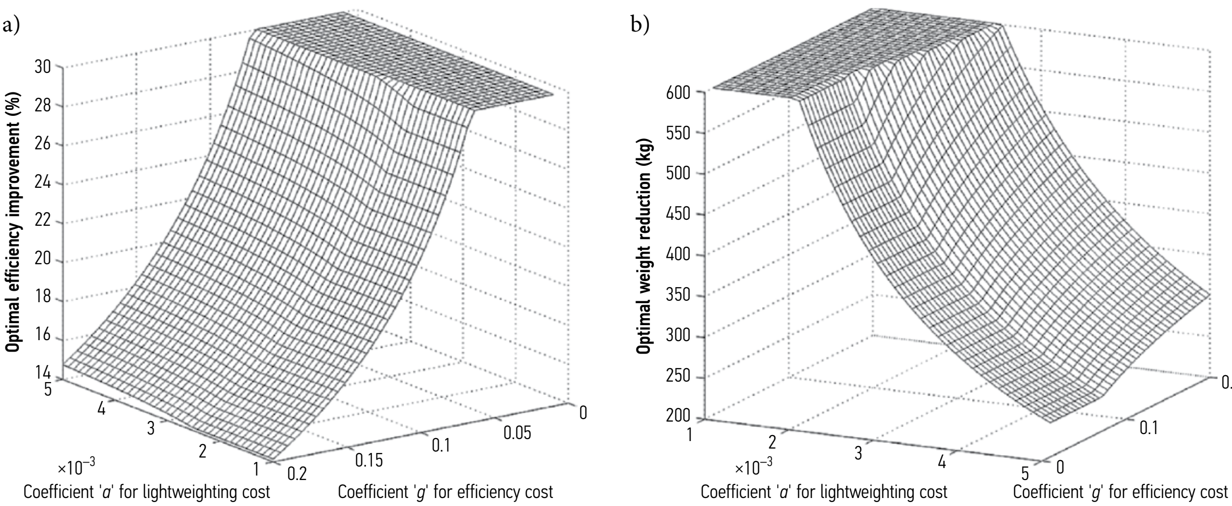


Fig. 11. Optimal efficiency and lightweighting technology implementation at various exponential cost levels

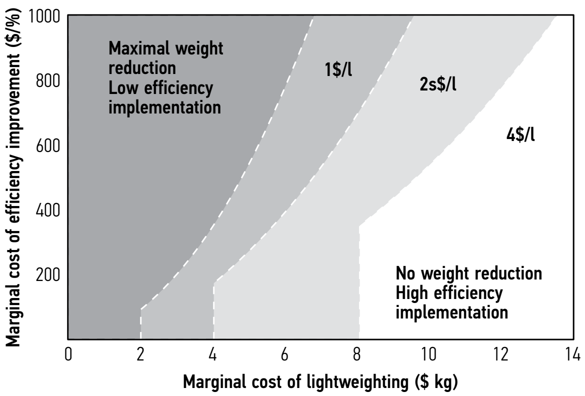


Fig. 12. Tolerance for high-cost technology implementation increases with increasing fuel cost for static marginal costs of technology implementation

istic problem structure, a modified '*fmincon*' function which was developed to solved mixed integer non-linear optimization problems was applied (Solberg 2000). The discrete technology levels shown in Fig. 13 illustrate the 33 lightweighting and 19 efficiency options available to be chosen by the optimization algorithm. These technology levels were obtained by including each individual technology, as well as the cumulative scenario improvements in the allowed technology groups. This does not represent an exhaustive set of potential technology applications, but rather serves to illustrate the discrete optimization problem.

The discrete optimization algorithm uses the continuous optimization routine '*fmincon*' recursively to ensure that only valid optimization points are selected within a specific tolerance. While there are other approaches to discrete minimization, this approach is similar to most others and involves limited computational intensity. The results of solving the optimization problem described in Section 3.2 using a discrete optimization algorithm are shown in Table 2. The figure shows how an 'all-or-nothing' approach to lightweighting has been found to be optimal, with the cheapest lightweighting technology, high-strength steel, being implemented completely while all other more expensive technologies are not implemented at all. This does not match the solution found with the continuous method where Aluminum was also implemented at a maximum level,

Table 2. Optimal levels of technology implementation using discrete optimization algorithms

Technology	Optimal efficiency improvement (%)	Technology	Optimal lightweighting (kg)
Downsize	30	HSS	600
Two-mode	25	Aluminum	0
Diesel	25	Glass	0
Micro	25	Carbon	0

and suggests that there is value in examining the results of both continuous and discrete optimization methods before choosing a set of technology options.

The costs for each of the technology implementations found by the discrete optimization routine are shown in Fig. 14. They differ slightly from the continuous results, which can be expected due to restrictions imposed for the discrete problem formulation. The cost curve also reflects the reality that when a non-continuous choice between technologies must be made, the most expensive technologies result in an overall higher cost. This aspect of the optimization methodology will be further explored in future work.

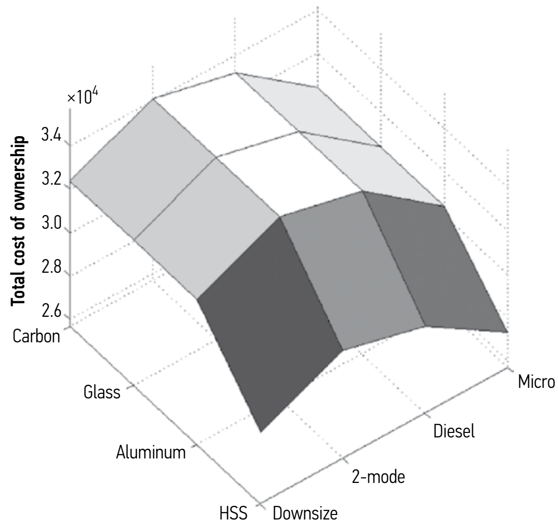


Fig. 14. Optimal lightweighting and efficiency implementation using discrete optimization for the 16 cost scenarios

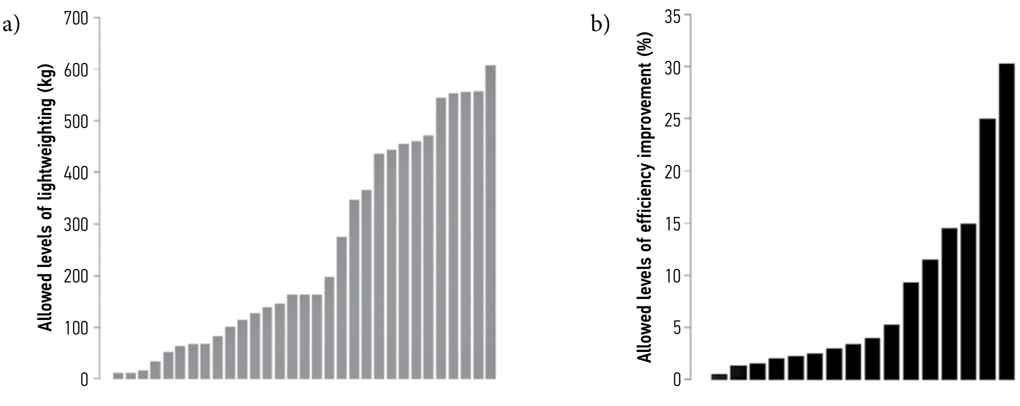


Fig. 13. Allowed levels of technology implementation: lightweighting (a) efficiency (b)

3.6. Engine Downsizing

By reducing vehicle weight at a fixed acceleration level, the peak power delivered by the powertrain may also be reduced, thereby potentially saving cost. Vehicle acceleration as a function of mass and peak power can be approximately modelled using Equation (14) (Guzzella, Sciarretta 2010), which then can be used to calculate the new marginal cost of lightweighting according to Equation (15). Maximum power P_{max} and vehicle mass determine a vehicle's acceleration time t_{0to100} to a given final vehicle speed v_f. The cost of lightweighting with downsizing $Cost_{lw-downsize}$ is then a function of the change in power after downsizing multiplied by engine technology cost.

$$P_{max} = \frac{v_f^2 \cdot m_{vehicle}}{t_{0to100}}. \tag{14}$$

$$Cost_{lw-downsize} = Cost_{lw} - \left(P_{max-old} - P_{max-new}\right) \cdot Cost_{engine}. \tag{15}$$

Engine technology costs $Cost_{engine}$ of \$729/L (Simpson 2006) and a lightweighting cost defined by the 'Aluminium scenario' characteristic curve shown in Fig. 8 were assumed, and the cost savings incurred through engine downsizing were subtracted from the cost of implementing lightweighting. The resulting marginal costs for various levels of weight reduction with and without engine downsizing are shown in Fig. 15.

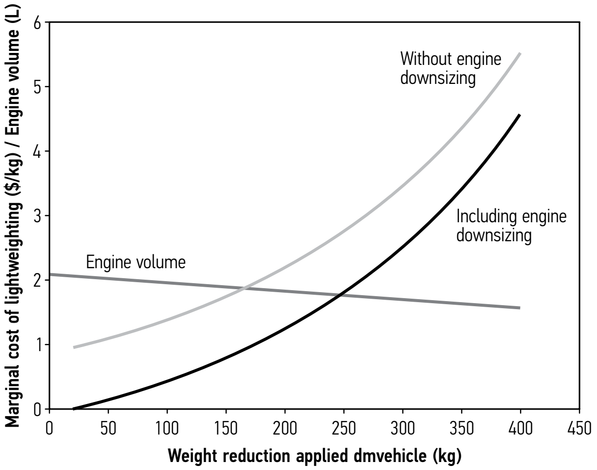


Fig. 15. Marginal cost of lightweighting with and without an offset induced by considering the reduction of engine size possible to maintain the same acceleration level for a lighter vehicle

For the sake of simplicity and clarity, the case studies performed in this work assumed that the acceleration performance would improve slightly with lightweighting. This brief analysis shows that the effect of engine downsizing may influence the absolute marginal cost in significant ways, and can also impact the characteristic of the marginal cost function. In this case, the engine downsizing curve is the best fit using a power-law approximation, whereas the aluminium marginal cost function has an exponential character. The reader is encouraged to consider these and potentially other mass decompounding effects (such as suspension, and hybrid powertrain changes) when developing marginal cost functions.

4. Conclusions

The conclusions which can be drawn based on the results presented in this paper are:

- diminishing marginal returns for investing in lightweighting and powertrain efficiency technologies should be considered in order to make strategic technology development decisions;
- if marginal costs are fixed, lightweighting technology should only be applied until the optimal cost level is reached, and should be applied either to this specific level or not at all;
- identifying a diminishing marginal returns characteristic curve is non-trivial due to the variety of technologies which can be applied to reduce vehicle weight and improve on-road efficiency. In cases where marginal cost functions cannot be computed, an optimal strategy can be based on the 'all-or-nothing' approach described in the previous conclusion;
- using representative continuous marginal cost functions it was shown that lightweighting technology is much more sensitive to the cost of powertrain efficiency measures than vice versa, and that marginal efficiency improvement in the range of 20 to 30% and lightweighting between 200 and 600 kg is optimal, depending strongly on marginal cost curve characteristics;
- application of advanced powertrain efficiency and lightweighting technologies reduces the total cost of vehicle ownership between 18 and 42% assuming continuous marginal cost functions apply;
- not surprisingly, the results are very sensitive to the price of fuel with a higher optimal degree of advanced technology implementation which is optimal to high fuel costs;
- discrete optimization yields efficiency implementation results similar to what is achieved with continuous optimization methods, but optimal levels of weight reduction deviate justifying the use of both types of analysis before making decisions.

The costs in this work were presented in US dollars for convenience due to the data sources used, but the methods presented are currency-neutral and can be easily applied to other markets.

When analyzing vehicle technologies, factors other than cost are also important to consumers. In particular, there is strong evidence that total cost of ownership is much less important to consumers than initial purchase price (Wilhelm 2011). Safety, handling, comfort etc. must also be considered. Further analysis is possible at *http://multicriteria-analysis.com*.

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