OPTIMISING CAR LIFE FOR MINIMUM CO_2 EMISSION

HARRY C. WATSON
School of Engineering, University of Melbourne, Australia.

ABSTRACT

In this paper, the historical trends and future projections of whole of life CO_2 emissions is followed and includes the changing effects on embedded production energy as vehicles have been made lighter. Even so, the rapid reduction in fuel consumption of conventional vehicles leads to the ratio of embedded to in-use CO_2-e to have doubled in the last 30 years. This embedded energy sourced CO_2 recurs each time a new car is made, so the front end energy has to be amortised over the life of the vehicle. It is shown that the ratio is several times higher for battery electric vehicles, while hybrids fall between electric and conventional. The importance of vehicle useful life is emphasized. In the past, the optimum life to amortise the embedded energy was about 17 years but this depends on the prevailing rate of improvement in in-use energy of the marketed fleet. The paper concludes on the basis of the evidence presented that the optimum life for present conventional vehicles is between 10 and 12 years and for battery electric vehicles approaching 20 years with hybrids falling between. As the rate of annual fuel consumption improvement reduces from the present level of 5%/y, the desirable life-times of vehicles will increase. It is recommended that some form of government policy be implemented to achieve the changes in optimum vehicle life-time, over the next few decades, through support for 'Cash for clunkers' or equivalent mechanisms. This will enable the most rapid achievement of greenhouse gas emissions reduction. Incentives or other mechanisms need to be found to encourage hybrids rather than all electric vehicles to achieve best possible vehicle fleet CO_2 reduction.

Keywords: Lifetime CO_2, embedded energy, in-use energy, conventional engines, hybrid, all electric, market trends, policy outcomes

1 INTRODUCTION

This paper is founded on research done by the author for SAE-A's submission to a government committee looking to set Australia's long-term fuel consumption standards. The author was, in 2004, responsible for advising the government on the 2010 CO_2 standards for all light duty vehicles [1, 2]. In that work, the lowest attainable CO_2 emission at reasonable cost was determined. However, no consideration was given to any impacts of the non-fuel CO2 contributions to whole of life emissions. The non-fuel-related CO_2 emissions have grown from 16% in 1980 [3], but despite initiating policies to reduce manufacturing energy consumption [4], it had grown to 20% by1997 [5] largely as the result of reduced vehicle fuel consumption in meeting government targets caused by perceived energy shortage and the 'energy crisis' initiated by the oil shocks of 1973 and 1979. Although attempts have been made to include manufacturing energy as a vehicle design objective, only small reductions in embedded energy appear to be possible[6].

Thus, today it now represents about 30% of total CO_2 assignable to light duty vehicles and therefore cannot be ignored [7]. This proportion will increase as the fuel efficiency of vehicles continues to improve more rapidly than the remaining energy inputs (sometimes with an increase in manufacturing energy as with hybrids).

2 OBJECT

The object of this paper is to compare the fixed and variable energy content in passenger car life cycles and to determine what is the optimum service life to minimise greenhouse gas emissions. The problem is treated for the EU market, although the method will be applicable to other markets.

ISSN: 2056-3272 (paper format), ISSN: 2056-3280 (online), http://www.witpress.com/journals
DOI: 10.2495/EQ-V2-N4-381-388

3 METHOD

For this investigation, it is assumed that the only CO_2-producing components are the manufacturing energy and embedded materials energy offset by recycled materials and parts, together with the in-service fuel and consumables sourced CO2-e. It is worth noting that the in-service consumables other than fuel are of second-order importance and their variation in consumption over the vehicle life or vehicle technology is assumed to be constant irrespective of age [5]. The assumption is made that the fuel consumption (use per distance travelled) does not vary as the vehicle ages [7].

Thus, the problem reduces to finding

$$CO2_{\min} = \min[\sum_{y=1}^{n} CO2_{fuel}(y_1).y + CO2_{embeded}]_{c=1}^{a}. \tag{1}$$

where $CO2_{fuel}(y)$ is part of a series in CO_2 or fuel consumption that for new cars progressively that reduces (e.g. 3%/y) as manufacturers meet the requirements of reduced fuel consumption for compliance with EU regulations.

n is the number of years of service life before it is replaced by a new vehicle.
and a is the number of life cycles c studied

Accounted for in modelling is that in the early years of use vehicles typically travel more than in later life as found in the ABS SMVU [10] This variation shown in Fig. 1 is quite consistent with the mean travel and age of the EU population [8, 9]. Subjectively, this can be explained as many new cars are used for business purposes early in their lives, and as second or third hand cars used less for only local trips late in their lives when reliability and other defects make them less attractive for long journeys. Moreover, these data represent an average car, and thus include scrapping (retiring) cars from the fleet through crashes and then later owner decisions to send the car to recycling, which significantly increases after the median age.

The relative importance of the 'front end' manufacturing and materials energy or embedded energy (and corresponding CO_2-e emissions) can be expressed as a ratio to the average annual energy/emissions from fuel use. This variation is given in Fig. 2. It can be seen that between 1978 and 2012 embedded CO_2-e rose from 15% to 31% in the whole of life analysis. During this time, the overall life cycle CO_2-e fell by just over 40% for the class-E-sized

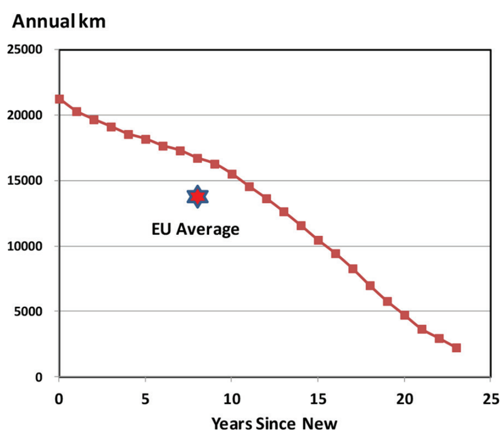

Figure 1: Annual km of travel in Australia, [7] compared with European data [8, 9].

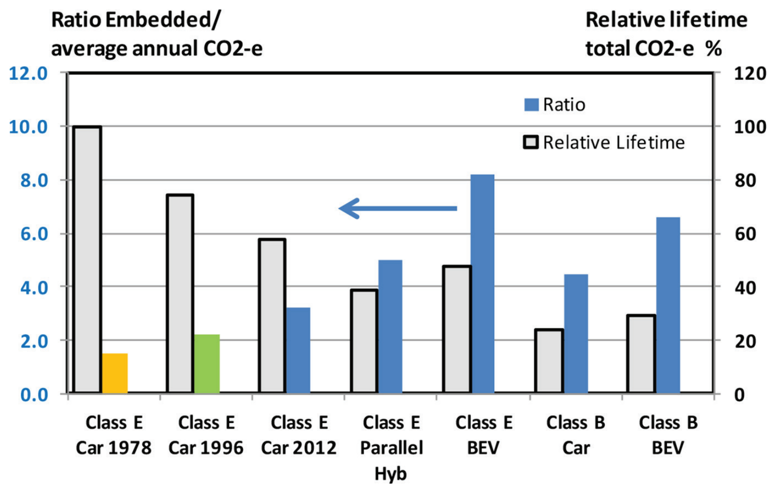

Figure 2: Embedded CO_2-e compared with annual use and relative CO_2-e for life cycle with a base of 1978 [3] orange and 1996 [6] green. Blue values 2013 [11].

car. For the Battery Electric Vehicle (BEV), there is a further 10% reduction, but the hybrid of the day had another 20% reduction or at 40% of the baseline 1978 car. Results for 2012 class B size conventional and BEV cars are given. Note worthy are the relatively high ratios of embedded versus annual use sourced CO_2-e for the BEV cars because of the significant emissions from battery production.

3.1 Example small improvement

A graphical example of the application of equation 1 is given in Fig. 3. To illustrate the concepts in the example, it is assumed that the initial CO_2 is four times the first year in-service

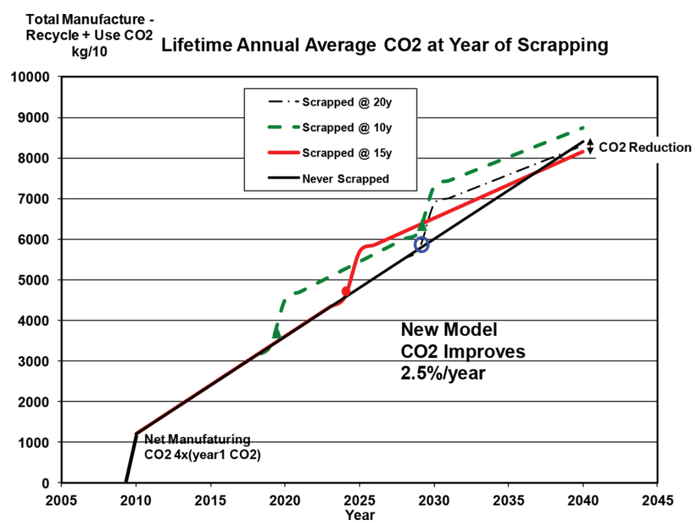

Figure 3: Example of three replacement lifetimes in a market with 2.5%/y reduction in fuel consumption and embedded energy/CO_2-e of four times first year fuel use.

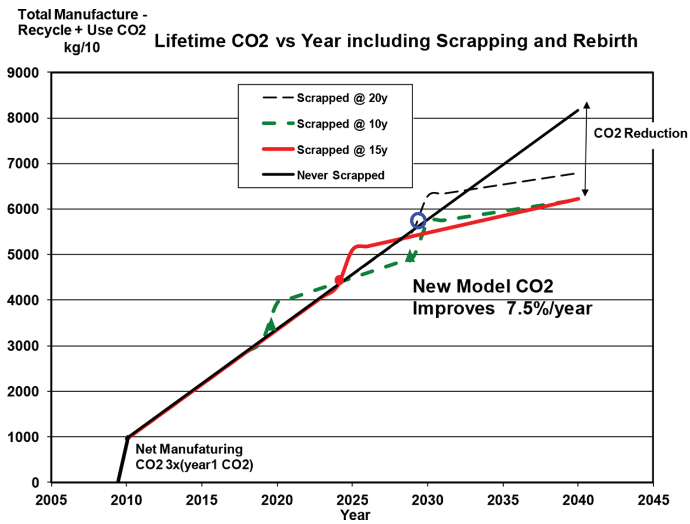

Figure 4: Example of three replacement lifetimes in a market with 7.5%/y reduction in fuel consumption and embedded energy/CO2-e of 3 times first year fuel use.

CO_2 (or equal to 4 years of fuel use). A constant average travel per year is selected (e.g. assumed to be 15,000 km/y). The vehicle chosen emits 200 g/km CO_2 at the beginning and throughout its life. This vehicle is sold into a market where replacement vehicles have a 2.5%/y improvement in fuel consumption year by year, so any replacement vehicle will have lower fuel consumption; its reduction depends on its time of delivery into the market. From the three lifetimes illustrated, the best CO_2-e reduction for somewhere between 15 and 20 y lifetimes. The CO_2 mitigated is only a few per cent.

3.2 Example of large improvement

This vehicle is now sold into a market where replacement vehicles have a 7.5%/y improvement in fuel consumption and embedded energy of three times in the first year use. Best CO_2-e emission reduction is between from a 10 and 15 y life to scrap with around 25% reduction in CO_2-e from continuous use of the original vehicle, after 30 y as seen in Fig. 4.

4 MARKET TRENDS AND NEEDS

Figure 5 shows the EU trend in fleet average fuel consumption [12] and the projection to meet the 2020 target. It is apparent that the existing trend, changing at about 4.5% reduction in fuel consumption and therefore CO_2-e emissions per year, if maintained will meet the EU target of 95 g/km. Likely, industry will achieve lower because manufacturers have to individually meet the target and will need to do so with a safety margin. This is illustrated by the fleet average of about 120 versus the 130 g/km CO_2 required for 2015. Therefore, it is highly likely that an improvement rate close to 5% will continue.

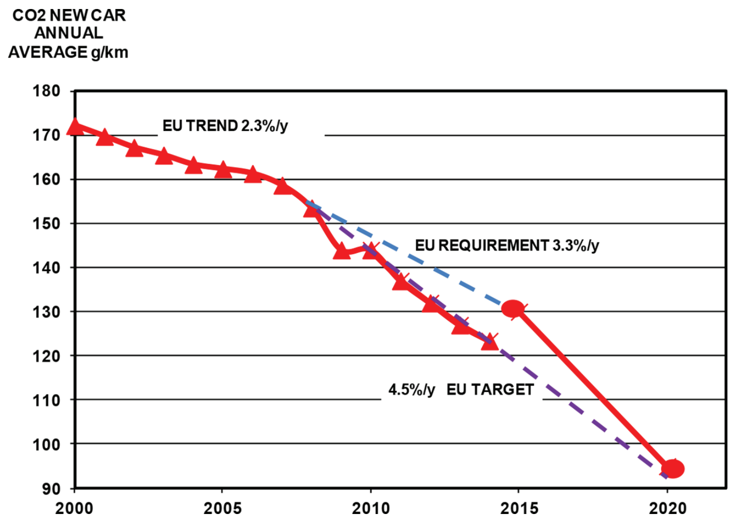

Figure 5: European new car annual average CO_2 emissions and targets.

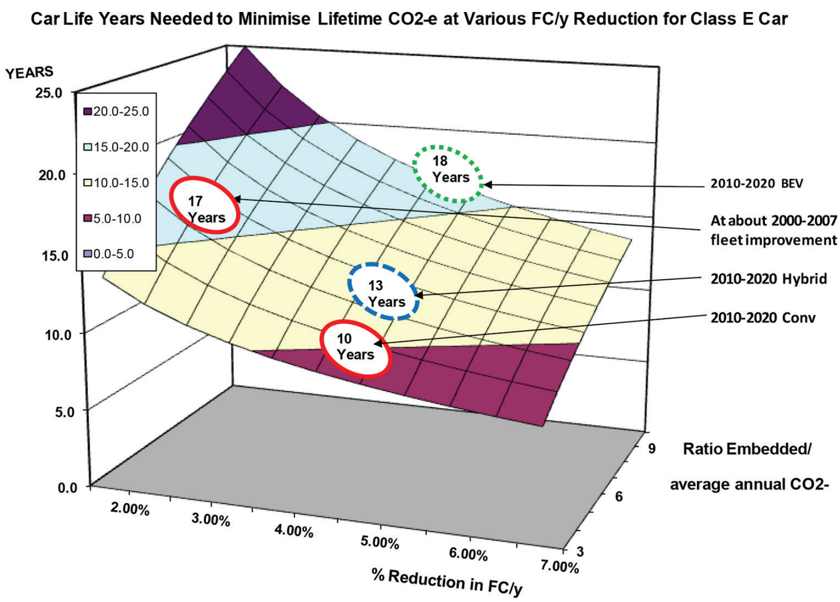

Figure 6: Optimum vehicle life for class E cars.

5 RESULTS

5.1 Results for class E cars

Modelling of a class E car has been done using eqn 1 with the variable km of travel per annum given if Fig. 1 and the ratio of embedded to year 1 emission of CO_2-e for the range seen in Fig. 2. The results, in Fig. 6, show the surface for minimum CO_2-e as it varies with this ratio and the annual rate of improvement in fuel consumption (and CO_2-e) to give the

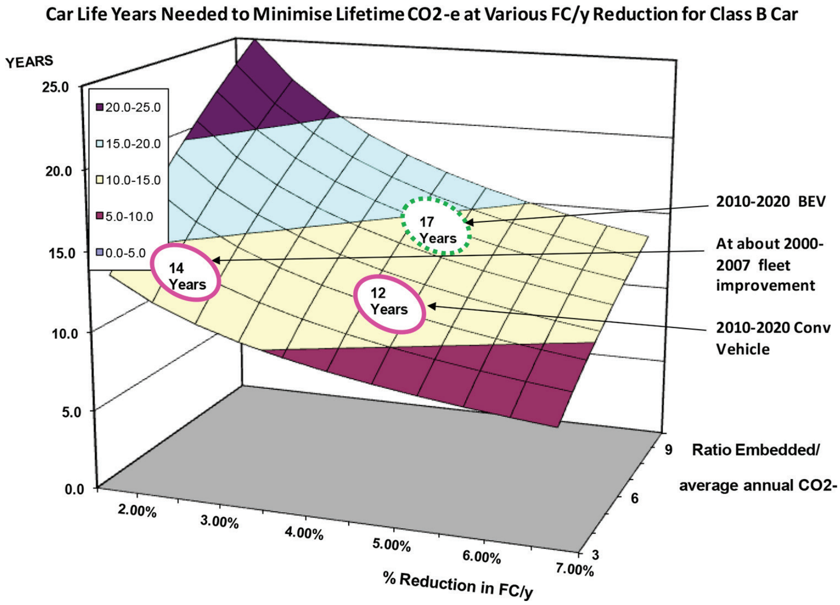

Figure 7: Optimum vehicle life for class B cars.

corresponding optimum vehicle service life. It can be seen that for the low rate of fuel consumption reduction in the period prior to 2007 the optimum vehicle life was around 17 years, whereas for current cars with a nearly 5% improvement in fuel consumption per year the optimum life reduces to 10 years.

Based on the assumption that hybrids and battery electric vehicles (BEV) improve at the same rate as the market a whole, their optimum life is longer 12 and 18 years, respectively, because of higher embedded energy (and CO_2-e) lower energy consumption in service. If their improvement rate is different, the surface allows alternative conclusions to be drawn.

5.2 Results for class B cars

The results for the smaller class B cars show a similar shaped surface with optimum lives of 14 years for older vehicles and for 12 and 17 years as the optimum for current and BEVs, respectively.

6 DISCUSSION

Inclusion of the embedded materials and production energy, with allowance for recycling, significantly delays the time of benefit from introducing a new fuel efficient car fleet. Unsurprisingly, the lower the in-use energy consumption (lowest for BEVs), the longer the cars need to operate in service to amortise their high embedded energy through their service life, which is a consequence of the low energy density of the battery and their relatively higher mass, even though more weight saving technologies are found in BEVs. The longer optimum life suggested for BEVs and hybrids leads to the question of whether these batteries have the durability to last perhaps twice the normal warranted battery life of ten years. Also for BEVs, the well-proven assumption, that in-service energy consumption does not vary with age, may not be valid as battery efficiency deteriorates with age as does battery available kWh. This is in contrast to the parallel hybrid, which in Fig. 2, already has the lowest lifetime energy consumption and is optimum when retained for a service life of 13 years as seen in Fig. 6 for class E cars.

It can be hypothesised that as the law of diminishing returns takes effect, that the per cent rate of improvement in fuel consumption will reduce, and that the optimum life will move back to higher years of in-service. In the market place, the resale price of the Toyota Prius has held up at least as well as the conventional C class cars, indicating that relatively less demanding use compared with a BEV may enable battery replacement free lives of the high teen years. This along with the prospects of significantly increased improvement possible in the internal combustion engine as found in Formula 1 racing cars for example make a strong case for the encouragement of mild hybrid uptake in the market.

7 CONCLUSIONS

It has been the province of automobile clubs to give advice to members on how long cars and vans might be used for life-time minimum per km travel cost; often slated as about 17 years. A similar approach has been applied to determine the optimum life of vehicles to minimise their life-time CO_2-e when their manufacturing and materials energy (including recycling) is added to their life-time fuel use emissions. If the life-time is short, there will be a need to enact legislation and incentives to terminate the life of a vehicle. 'Cash for clunkers' was a marketing ploy in the past. It is concluded:

1. The results here suggest for the European market, with the needed rapid improvement in vehicle fuel consumption to meet the EU 2020 target CO_2 emission regulation, that normal E and B class vehicles have an optimum life now of about 10 and 12 years, respectively. Mechanically many of these vehicles could continue to operate through to 15 to 20 years. However, as the rate of fuel consumption reduction reduces in the future, as it must, the optimum life will increase perhaps to 17 to 20 years.
2. It is recommended that some form of government policy be implemented to enable this process, of changing vehicle life-time, in the decades ahead in support of the most rapid achievement of greenhouse gas emissions reduction.
3. If battery electric vehicles (BEV) follow similar usage patterns to regular cars, their optimum life needs to be longer at the present time, at around 18 years, in a market with 5% improvement energy consumption per year. If their annual travel is less than that of the fleet average, as it is likely to be, the time in service should be even longer. This seems to be in conflict with early adopters and fleet buyers who are major purchasers of BEV cars, since the whole of car BEV image is important and the support for interior/infotainment systems etc in the very long term is unlikely. Therefore, it may be anticipated that owners are likely to be early rather than late scrapping their cars.
4. On the other hand, hybrids, even the simpler parallel hybrid used as the example here, looks to be the outstanding technology with an optimum life-time in the present market of 13 years and likely increasing to high teen years as technological improvements diminish.
5. These findings indicate that governments should subsidise hybrids, instead of the present support for all electrics i.e. BEVs.
6. Finally, it is obvious that these findings depend on the energy mixes in vehicle production and materials, and the proportion of CO_2-free electricity produced. Here, these values are based on the best available information. If vehicle production involved no CO_2-e

emission, these findings would be overturned. However, it is very unlikely that major components of the car such as steel, tyres etc will be made without carbon emissions.

ACKNOWLEDGEMENT

The author wishes to acknowledge support from the Centre for Automotive Research and Testing (ACART) and the co-operation of colleagues Profs Michael Brear and Chris Manzie.

REFERENCES

[1] ACIL Tasman and Watson H.C., *Setting the passenger car fuel consumption target for 2010,* Report prepared for FCAI and Australian Greenhouse Office, 1999.

[2] ACIL Tasman and Watson H.C., *National average carbon dioxide emissions by vehicles, possible target for new light duty vehicles in 2010,* Report prepared for FCAI and Australian Greenhouse Office, 2004.

[3] Watson, H.C., *Passenger car life cycle energy consumption.* S.A.E.-A. Paper No. 79313, pp. 1–10, 1979.

[4] Watson, H.C., *Summary of S.A.E.-Australia's Energy Policy.* S.A.E.-A. Paper No. 79310, pp. 1–10, 1979.

[5] Parikh Y. & Watson, H.C.*, Life cycle emissions manufacturing/ use/infrastructure.* In Transport Engine Emissions, Advanced Engineering Centre for Manufacturing, University of Melbourne, Victoria, 1997.

[6] Watson, H.C., Charters, W.W.S., Brey, S., Parikh, Y., Lamb, D.G. & Fewchuk, D., *Concept Car - Life Cycle Energy Analysis.* SAE paper 981154, 1998.

[7] Beer, T., Grant, T., Watson, H.C. & Olaru, D., *Life-Cycle Emissions Analysis of Fuels for Light Vehicles* Report (HA93A-C837/1/F5.2E) to the Australian Greenhouse Office , 2004.

[8] Schipper, L. *Automobile Fuel Economy and CO2 Emissions in Industrialized Countries: Troubling Trends through 2005/6* . EMBARQ, the World Resources Institute Center for Sustainable Transport, Washington, 2008.

[9] Available at: https://setis.ec.europa.eu/sites/default/files/reports/Driving_and_parking_patterns_of_European_car_drivers-a_mobility_survey.pdf

[10] ABS SMVU Australian Bureau of Statistics, Triennial Surveys of Motor Vehicle Usage , 1976.

[11] Sharma, R., Manzie, C., Breeside, M., Brear, M.J. & Crawford, R.H., Conventional, hybrid and electric vehicles in Australian driving conditions - Part 2 Life cycle CO2-e emissions. *Transportation Research Part C*, **28**, pp. 63–67, 2013.

[12] Available at: http://www.theicct.org/sites/default/files/publications/ICCTbriefing_EUCO2_201507.pdf. (accessed April 2017).