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RESEARCH ARTICLE

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Estimating mortality cost and social cost of CO_2 emitted by items, applied to passenger vehicles

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Abstract. Over 60% of carbon emissions are from residential consumption. People in developed nations need to reduce their carbon footprints six-fold to stabilize CO_2 levels in the atmosphere. This research develops a method of estimating and monetizing mortality costs of items. Mortality Cost of Carbon Rate (MCCR) is the fraction of a climate change related death that would probably occur over 80 yr with a specified temperature trajectory, from the emission of 1 tCO_2e. MCCRs are allocated to items on an exponential curve generated from two researched MCCRs corresponding to temperature trajectories. MCC of an item (MCCI) is its MCCR multiplied by its life cycle CO_2e emissions. The method was applied to the 2020 Australian passenger vehicle fleet and 6 vehicle types. MCCI was compared to mortalities from crashes and exhaust pollution. Total fleet mortality was estimated at around 62,000/ year. Mortality from 2020 CO_2 emissions will probably be around 56,000 - 75 times higher than crash deaths - with uncertainty range 28,000 to 106,000, compared to toxic exhaust emissions 5,600 and crashes 750. A Sustainable Personal CO_2 Footprint' of 1.5 t CO_2/ person/ year was set as a benchmark for sustainable consumption. Electric buses, E-bicycles/ scooters and micro-EVs are sustainable and if universally adopted, would reduce mortality by 96%. Social Cost of Carbon Mortality Rate (SCCMR) monetizes MCCR using a global Value of a Statistical Life Year. SCCM of items (SCCMI) is calculated as for MCCI. Research estimates of MCCR and SCCMR vary according to assumed causes of mortality, temperature trajectories and discount rates; many are underestimated as they exclude some mortality damage sectors. Toxic exhaust emission and crash mortalities were monetized using the Australian Value of a Statistical Life. Total social mortality cost of a large 4 wd ICE diesel SUV was approximately \$6300, current fleet average \$4800, and micro-EV \$400.

Keywords: Sustainable personal CO_2 footprint / Mortality Cost of Carbon Rate / Social Cost of Carbon Mortality Rate / crash mortality / exhaust pollution mortality / micro-EV / E-bicycle / E-bus

1 Background and introduction

Carbon emissions are generally analysed by industrial production sector and this has contributed to the common belief that the burden of reduction is on industries, rather than consumers. Many people in affluent countries have little if any awareness that the annual carbon emission 'footprint' from their own consumer choices averages about 12 tonnes of carbon dioxide equivalent (tCO_2e). This needs to be reduced more than six-fold to stop global greenhouse gas concentrations the atmosphere increasing and further to achieve 'net zero' carbon emission. Six consumption categories comprise 85–90% of typical carbon footprints in developed nations [1]. Private vehicle transport and food are by far the highest emitting categories, each accounting for about 25%. Electricity and air/ overseas travel each contribute 11–12%; waste and house contents/ clothing account for about 8% each. In all 6 consumption categories there are low carbon emission choices. Despite the significant carbon impacts of high emission items such as large cars [2], jet flights [3] and red meats [4], the consumption of them continues to increase. In countries with carbon taxes on industries [5], minor carbon costs are passed on by producers, but nowhere do consumers pay the social mortality cost of carbon, which remains externalized. The mortality costs of climate change are being passed on to today's children and future generations. A global study of the period 1991–2018 estimated about 100,000 warm-season heat-related deaths per year can already be attributed to anthropogenic climate change [6].

An estimation of sustainable personal CO_2 footprint (SPCF) is outlined as follows. Carbon dioxide accounts for about 75% of global greenhouse gas emissions [7]. In 2020,

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37 billion metric tons per year of human-sourced CO_2 emissions were added annually to the CO_2 accumulating in the Earth's atmosphere [7]. Dividing the 37 billion t CO_2 equally between the world population of 8 billion, per capita emissions are currently 4.6 tons/ person in 2022. About 52% of the CO_2 was taken up by the ocean and terrestrial biosphere [9,10]. To prevent emissions from rising further, human sourced emissions must be reduced to that amount i.e., to 52% of existing CO_2 emissions. That translates to 2.4 t CO_2 per capita. As an estimated 64% of carbon emissions are from household consumption [11,12], a global 'sustainable personal CO_2 footprint' (SPCF) is $0.64 \times 2.4 = 1.5$ t CO_2/ person/ year. A definition for SPCF is "tons of CO_2 each person on the planet can emit each year from their personal consumption of energy and goods if CO_2 concentrations in the atmosphere are to cease rising". Personal land transport accounts for about 0.24 tCO_2/ person/ year or 16% of the SPCF [13]. In this research, SPCF is used to benchmark the sustainability of consumer items, using the example of passenger transport modes. It is important to also define 'sustainable personal carbon footprint', which includes all other greenhouse gases, for example methane (CH4), nitrous oxides (NOx), in addition to CO_2. It is about 2 tCO_2e/ person/ year, 25% higher than SPCF. Other estimates of sustainable carbon footprint are 2t [14], 2.2 tCO_2e [15] and 4.8 t reducing to 0.8 tCO_2e in 2100 [16].

The world's >2.1 billion road vehicles account for about 16% of global fossil carbon dioxide (CO_2) emissions; passenger vehicles (cars, SUVs and 4 WD pickups/ wagons) account for about 9% [17]. When the embodied emission −20% of operational emissions − are added [1], passenger vehicles account for about 11% of global CO_2 emissions. While road safety and prevention of crashes is promoted by vehicle advertising and Government campaigns, the mortality cost of vehicle CO_2 emissions is not quantified or publicised. First year vehicle license and fuel taxes levied by nations varies more than 30-fold from several hundred dollars to >US$40,000 in Netherlands [18,19] The world's four highest per capita road transport CO_2 emitters − USA (4.5 t), Canada (4.1 t), Saudi Arabia (4 t) and Australia (3.3) [2] − all have fuel taxes within the lowest quartile of OECD rates [20]. While some countries have minor vehicle fuel and or registration tax components determined by CO_2 emissions, none have vehicle taxes based on mortality costs of air pollution and or CO_2 emissions.

The objective of this research is to develop a fair and equitable method of estimating the mortality and monetized social costs of CO_2 emitted by consumer items, demonstrate it by application to passenger transport modes and compare the results with mortality from vehicle exhaust emissions and crashes. The research introduces four novel concepts: Mortality Cost of Carbon Rate, Mortality Cost of Carbon of Items, Social Cost of Carbon Mortality Rate and Social Cost of Carbon Mortality of Items.

2 Methodology

Five processes were conducted to estimate annual mortality and monetized social costs incurred by CO_2 emitted by consumer items: 1/ Calculate the annualized CO_2 footprint of the items. 2/ Explain Mortality Cost of Carbon Rates (MCCR) and allocate them to vehicle modes. 3/ Explain a simple formula to estimate Mortality Cost of Carbon of Items (MCCI) and apply it to fleets of 7 passenger vehicle modes. 4/ Explain Social Cost of Carbon Mortality Rates (SCCMR) and allocate them to 7 vehicle modes. Explain Social Cost of Carbon Mortality of Items (SCCMI) and calculate them for each vehicle type. 5/ Finally, calculate mortalities and social costs incurred by vehicle exhaust emissions and crashes and compare them with those incurred by vehicle CO_2 emissions.

2.1 CO_2 emissions of items, applied to vehicle modes

To calculate annualized CO_2 emissions of a particular item, its lifetime and assumed amount of work done by it (if applicable) is defined and its embodied and operational emissions calculated:

Annualized lifetime CO_2 emissions = (Lifetime operational CO_2 emissions + embodied CO_2 emissions) / Lifetime of item.

Vehicle modes 1–6 were assumed to have an operational life of 15 yr and 225,000 km, E-buses an operational life of 1 million km carrying an average 20 passengers and e-bicycles an operational life of 30 yr and 30,000 km [1]. Operational CO_2 emissions were calculated using full cycle emission factors (EF) for the energy used. For ICE vehicles, the EF of fuel is the sum of scope 1, 2 and 3 emissions: gasoline is 2.5 and diesel 2.9 kg CO_2e/ L. Fuel EFs are comprised of 99% CO_2 [21]. Energy for electric vehicles (EVs) is assumed to be sourced from an electricity grid powered by 90% renewable energy, with an EF of 0.1 kg CO_2 / kWh. Embodied CO_2 (EC) from fossil fuels used to produce vehicles and replacement parts is generally proportional to the weight of the vehicle. Vehicle EC is >95% from materials. Iron and steels, aluminium, copper, plastics, rubber and lubricants comprise 70% of the materials used [1]. These were assumed to be virgin materials that were mined, refined and smelted using fossil fuels. Per ton vehicle mass, internal combustion engine (ICE) vehicles incur about 5.6 t CO_2 in their manufacture and 2.2 t CO_2 for lifetime maintenance (tyres, oils and replacement parts). Total EC is 7.8 t CO_2 / tonne [1,22]. Vehicle EC can potentially be reduced by up to 50% [23] by using recycled materials and 100% renewable electricity (error bars in Fig. 1). For EVs, EC is higher due to the batteries, which are modelled as being the most common type, Li-Ni-Co-Mg. EC is calculated in proportion to battery capacity, at 106 kg CO_2/ kWh [24], manufactured in Europe, with an electricity EF of about 0.3. The orange bar in Figure 1 is the low emissions estimate of 61 kg/kWh for the same batteries using renewable electricity and recycled materials [23]. Estimates can be as high as 187 kg CO_2/kWh in parts of China [25], with fossil fuel energy sources, high electricity EF and inefficient cathode production. Future solid state and sodium based battery chemistries may enable even lower EC and higher energy density.

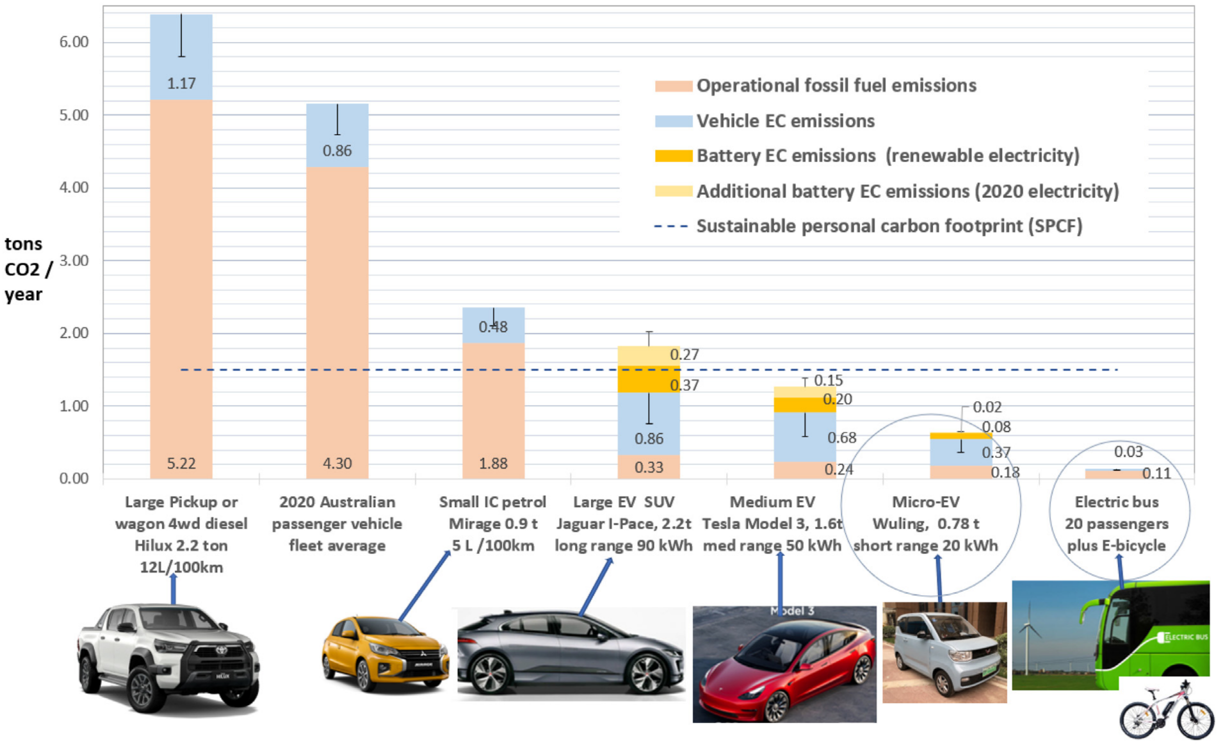

Fig. 1. CO_2 emissions for 7 vehicle modes travelling 15,000 km in one year (*assumed emission factor of electricity for EVs is 0.1 kg CO_2 / kWh*).

2.2 Mortality cost of CO_2 of items

CO_2 emissions are slowly removed from the atmosphere through biological uptake by plants and dissolution into the ocean. More than 20% of each ton of CO_2 (tCO_2) emitted now will still be in the atmosphere in 200 years' time [26]. Other more potent greenhouse gases such as methane, nitrogen oxides and ozone are removed more quickly by chemical reactions. For this reason and the massive quantities emitted, CO_2 accounts for about 75% of global warming. Mortality from CO_2 emissions alone is utilized in this research. Vehicle carbon emissions are 99% CO_2. Mortality functions can also be estimated for the other greenhouse gases (not in the scope of this study).

Mortality Cost of Carbon Rate (MCCR) is defined here as the fraction of a death from all climate change related causes that would probably occur over 80 yr with a specified temperature trajectory, from the emission of 1 t CO_2e. It is expressed as deaths/ tCO_2e emitted. Bressler, 2021 [27] estimated MCCs that included only excess temperature deaths, from 3 studies chosen from a review of 100 climate mortality papers [28–30]. He projected 83 million cumulative temperature related deaths globally by 2100, increasing exponentially after 2045 when temperatures exceed 2 °C. with most occurring between 2045 and 2100. The 'baseline scenario', where emissions continue at the existing rate resulting in 4.1 °C warming above preindustrial temperatures by 2100 resulted in 2.26×10^{-4} excess temperature related deaths/ tCO_2 emitted in 2020. The 'optimal scenario' where emissions fall to near zero by 2050, resulting in 2.4 °C warming by 2100 resulted in 1.07×10^{-4} excess temperature related deaths per tCO_2 emitted in 2020. However, estimates of MCCRs vary greatly depending on the assumptions and methods used. Bressler's rates do not represent total mortalities from global warming because there will be more deaths from climate related undernutrition, diseases, conflicts and extreme weather events in addition to temperature-related deaths. Also, some of each tonne of CO_2 emitted will remain in the atmosphere for longer than the 80 yr MCC assumption, incurring mortality out to 200 yr [31]. WHO, 2014 estimated 255,000 climate related deaths in 2050 under the SRES A1B scenario with 2.7 °C warming by 2100; 36% of deaths from undernutrition 26% from selected diseases and 38% from heat [30]. Climate Vulnerability Forum, 2022 [8] estimated that unabated climate change will probably cause about 3.4 million heat-related deaths globally per year by the 2100. The CVF3 Health Data Explorer tool [33,34] estimated temperature related mortality for people over 65. Under the 'SSP3–7' scenario where CO_2 emissions double and temperatures rise 3.6 °C by 2100 [35], deaths per 100,000 varied from −0.1 in Japan to 5.0 per 100,000 in Pakistan, with uncertainty of −40 to +70%. These three studies did not include mortalities from flooding, conflicts and wildfires. It is inferred from the cited studies that MCCRs, which include all climate change related excess mortalities, equate to 3 times Bressler's temperature related MCCs, with uncertainty of −50% to +90%.

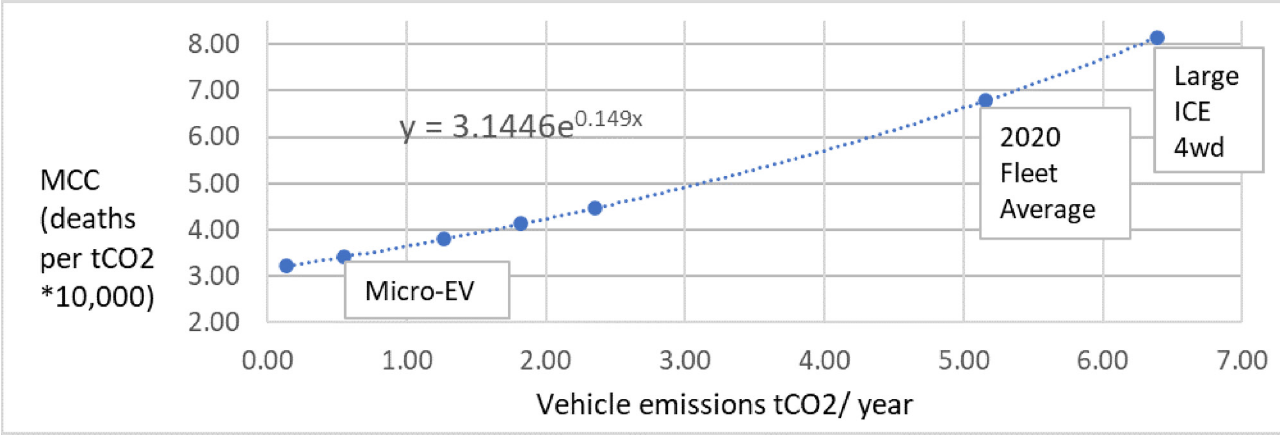

Fig. 2. Allocated MCCR vs vehicle annual CO_2 emissions.

This research postulates that MCCRs can be estimated for items according to the likely global temperature trajectory that would result if the global rate of consumption of that item were to continue unabated. Higher emitting items incur higher total MCCRs because continued consumption of them will result in higher temperature trajectories. Figure 2 shows an exponential scale of MCCRs for vehicle types. The current vehicle fleet incurs the 'baseline' total MCCR of 6.78×10^{-4} deaths/ tCO_2. The E-bus/ E-bike fleet option incurs the 'optimal' total MCC of 3.21 × 10-4 deaths/ tCO_2. The other fleet options are allocated rates according to their CO_2 emissions intensity, on an exponential trend line defined by the equation:

*MCCR = 3.144**e $^{0.149*x}$, where x = annual vehicle emissions (tCO_2/ year).

Mortality cost of carbon of an item (MCCI) is a product of the quantity of CO_2 emitted by it and its allocated MCCR. CO_2 mortality incurred by an item is estimated by:

MCCI = *(Full cycle operational plus embodied CO_2 emissions) * allocated MCCR.*

Annual Mortality Cost of CO_2 of hypothetical Australian vehicle fleet modes were estimated for the 16 million passenger vehicles that comprise 79.5% of 19 million vehicles in Australia [36]. The question asked was: 'What would be the CO_2 mortality cost of the passenger vehicle fleet if all drivers owned a particular type of vehicle?' The specific formula was:

*Annual MCCI of passenger fleet mode = (Annualized full cycle operational plus embodied CO_2 emissions of vehicle mode) * Allocated MCCR of vehicle mode * 16 million.*

2.3 Other mortality costs of items

Items may have mortality costs from other causes. These are generally incurred in the country and year in which the items are consumed. For example, tobacco causes deaths from cancers; vehicle exhausts cause deaths by respiratory and cardiovascular disease. Mortality from such causes is estimated by research. Other mortalities, such as vehicle crashes are caused by cars in the year they are used and can be quantified directly using annual statistics. In this study, mortality costs of vehicle exhaust emissions and crashes were estimated and compared with vehicle CO_2 mortality costs.

Vehicle exhaust pollution mortality is derived from two research papers with widely differing estimates. Swinburne University, 2022 estimated 1715 deaths/ year [37], based on a nation-wide study of particulate matter of less than 2.5 µm diameter (PM2.5) [38]. A much higher figure of 11,105 deaths/ year [39] was estimated based on a New Zealand study [40], which correlated regional premature deaths from cardiovascular and respiratory disease with NO_2 and PM2.5 levels in many regions. The base figure of 11,105 premature deaths was used because it includes NO_2 as well as PM2.5 pollutants. Air pollution mortalities are assumed to be proportional to the amount of fuel used, adjusted slightly for the fact that older diesel vehicles cause more deaths from (PM2.5) than gasoline. The passenger fleet uses 55% of national road vehicle fuel consumption and is mainly gasoline fuelled [36]. As gasoline fuelled vehicles emit less NO_2 and PM2.5 than diesel, it was assumed that it incurs 50% of 11,105 exhaust pollution deaths, i.e., 5,552 deaths. The lower estimate −50% of 1715 = 858 deaths − is indicated by error bars in Figure 3. The average fuel consumption of passenger vehicles was 11.1 L/100 km [36]. Exhaust pollution mortalities for the hypothetical fleet modes were calculated by:

*Passenger fleet mode exhaust pollution mortality = 5552 * (vehicle mode fuel consumption in l/100 km / 11.1).*

Vehicle crash mortality is an annual statistic. There were 1195 road crash deaths in Australia in 2019 [41]. Heavy trucks and light commercial vehicles were involved in 16% and 21% respectively. This study considers the remaining 63% of deaths that involved only passenger vehicles i.e., 753 deaths. Pedestrians (14%) and cyclists (4%) comprised a total 18% of Australian road deaths in 2020 [41]. Most fatalities are caused when larger vehicles collide with smaller vehicles. Risk of killing the driver of the other vehicle is substantially reduced in these 'hypothetical fleet' analyses because the passenger vehicles (80% of total)

Table 1. Calculated 2020 mortalities incurred by hypothetical Australian passenger fleets of 16 million vehicles, showing CO_2 emissions and allocated MCCRs for each vehicle type.

	Estimated climate change related deaths, 2021-2100, from CO2 emitted in 2020 *	Exhaust pollution deaths in 2020 (Uni Melb / EHINZ, 2023) **	Crash deaths in 2020	TOTAL DEATHS incurred by Australian passenger vehicle fleet in 2020	Annual CO2 emissions of vehicle type/ mode (metric tons)	Allocated MCCR (times 10,000)
Large diesel 4WD pickup/wagon, 2.2t	83,205	6,003	822	90,030	6.39	8.14
Current passenger vehicle mix	55,920	5,553	747	62,219	5.15	6.78
Small petrol hatch, 0.9t	16,800	2,501	710	20,011	2.35	4.46
Large 4WD EV SUV, 2.2t, 90 kWh	12,026	0	784	12,810	1.82	4.13
Medium EV, 1.6t, 50 kWh	7,714	0	747	8,461	1.27	3.80
Micro-EV, 0.78t, 20 kWh	3,518	0	672	4,190	0.64	3.41
E-bus/ E-bicycle (per passenger)	709	0	598	1,306	0.14	3.21

* Uncertainty: -50% to +90%. ** Uncertainty: -83%

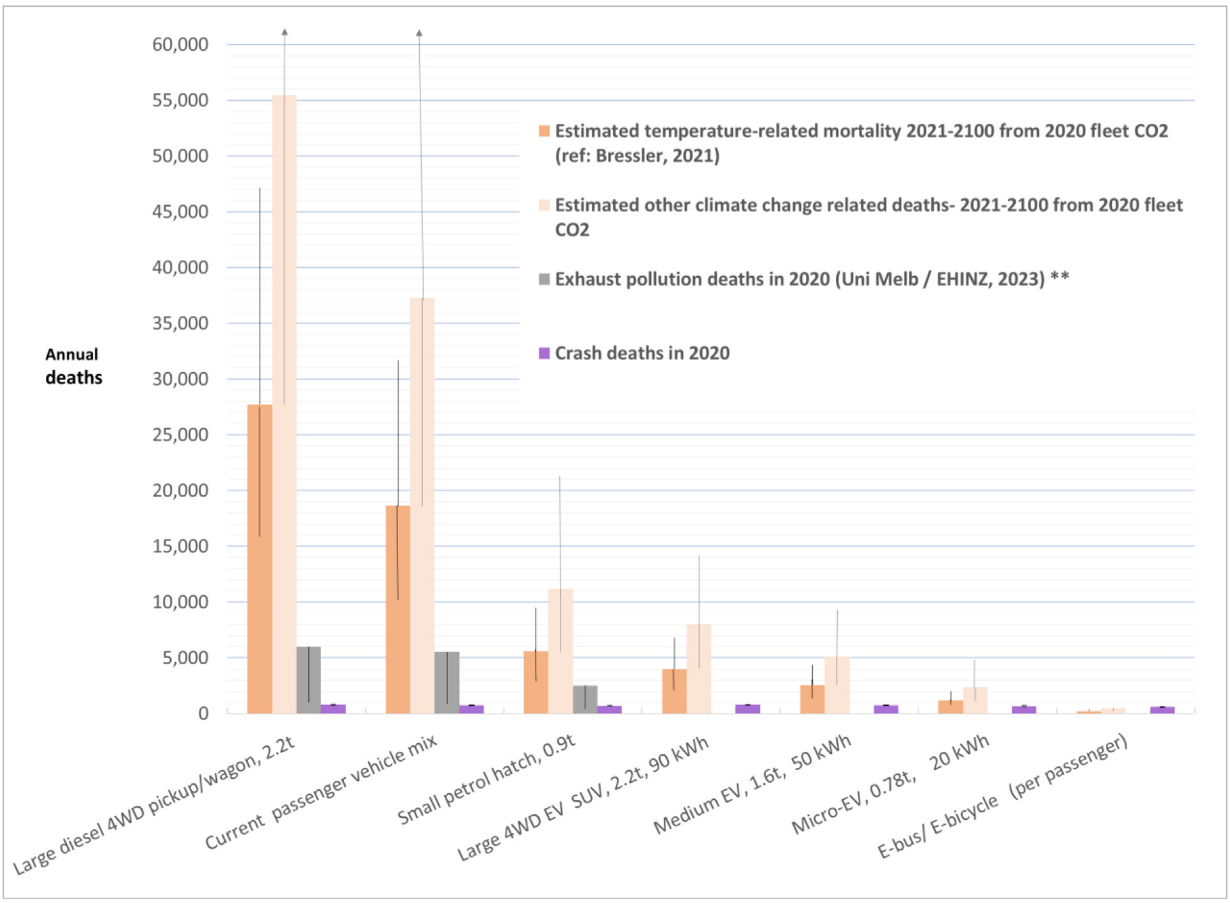

Fig. 3. Hypothetical Australian 2020 passenger fleet options: mortalities from CO_2 emissions (temperature and other climate related causes), toxic exhaust emissions and crashes.

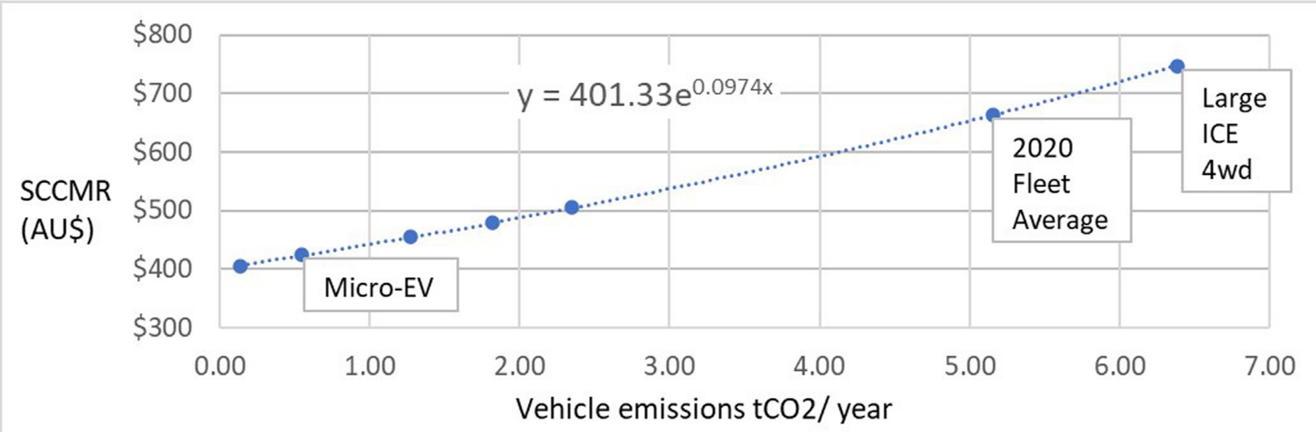

Fig. 4. Allocated SCCMR vs vehicle annual CO_2 emissions intensity.

are all the same size and type. However, large pickups/ wagons are more than twice as likely to kill pedestrians and cyclists, which are 18% of road crash deaths. A fleet collision death multiplier M was estimated for each fleet mode, indicating its relative likelihood of causing pedestrian and cyclist mortalities in a fleet of similar vehicles: large ICE 4 WD pickup/ wagon 1.1, large EV SUV 1.05, medium EV sedan 1.0, small ICE hatch 0.95, micro-EV 0.9, E-buses with E-bikes 0.8; uncertainty is +−10%.

The specific formula used was:

Passenger fleet mode crash mortality = *753* M.*

2.4 Social cost of carbon mortalities of an item (SCCMI)

Social Cost of Carbon (SCC) is a metric used by governments in formulating climate policy. SCC stochastically estimates US dollar costs of 1 metric ton of CO_2 emitted in a particular year due to climate change, usually over the following 80 yr, at a stated discount rate. SCC is estimated by summing partial SCC rates calculated by damage functions. Monetized mortality costs have only recently been included in SCC calculations [27]. Researched SCC rates vary widely [28,42], according to what damage sectors are included, the discount rate applied, the research data used and the assumed temperature trajectory. Rennert et al, 2022 [43,44] estimated a SCC rate of $185/ tCO_2 assuming a discount rate of 2%. It applied a global VSL estimated by adjusting the USA's VSL according to global incomes. The temperature trajectory was not explicit in the paper but was probably the 'Stated Policies' scenario with 2.6C rise by 2100 [45]. Of the four damage functions assessed, the partial SCC for mortality was highest at $90/ tCO_2 ($39–$165)/ tCO_2: 5%–95% range). Agriculture ($84) was also a large contributor and sea level rise and energy combined accounted for <$10/ tCO_2 [43].

Bressler, 2021 calculated partial SCC rates for excess temperature related mortality by applying a global value of a statistical life year (VSLY) to his MCC rates and discounting them over 80 yr at 2.5% discount rate. The VSLY used was "a multiple of 4 times global average consumption of just under $12,000 in 2020", equating to $48,000. This "gives equal weight to deaths no matter where they occur in the world. All lives are valued at the global average level." [27]. The SCC rate for the baseline scenario, which assumed a temperature rise of 4.1C by 2100, was US$258. The partial SCC for economic sectors was $37 and the partial SCC for temperature related excess mortality was $221. The SCC rate for an optimal emissions scenario where temperature rise was limited to 2.4C was US $158/ t CO_2 [27]. Assuming the same proportions, the economic SCC would be $23 and SCC for temperature related mortality would be $135. However, Bressler's SCC rates are underestimates, as other mortality damage functions such as diseases, under-nutrition, extreme weather events and sea level rise were not included. The social costs of all climate related mortalities over 80 yr caused by each ton of CO_2 emitted (denoted SCCMR) are inferred to be three times the partial SCC rates for excess temperature related mortality estimated by Bressler, with inferred uncertainty range of −50% +90%, as for MCCR (Sect. 2.2). SCCMRs for vehicle types were allocated along the exponential trend line shown in Figure 4, with baseline scenario estimate of $663 (3 times $221) allocated to the 2020 fleet average vehicle and the optimum scenario estimate of $405 (3 times $135) allocated to the E-bus/ E-bicycle mode. Other vehicle modes were allocated SCCMRs according to their rate of CO_2 emission, along the trendline defined by the exponential function:

$SCCMR = 401.33 * e^{0.097*x}$, where x = annual vehicle tCO_2 emitted.

The formula for SCCM of an item (SCCMI) is:

SCCMI of item = *(Embodied plus operational* tCO_2 *emitted by item) * allocated SCCMR.*

The formula for calculating the annual SCCMI for each vehicle type is:

Annualized SCCMI of vehicle = *(Annualized Embodied plus Operational* CO_2 *emissions of vehicle) * allocated SCCMR.*

2.5 Social mortality costs of other impacts of items

Some items incur Social Mortality Costs (SMC) from other impacts, such as toxicity or accidents. As most other mortality costs are incurred in the country where the item is consumed, the value of a statistical life (VSL) in that country is used to monetize them:

*Item's SMC of an Impact = VSL * Mortality Rate of the Impact.*

Social Mortality Cost (SMC) of exhaust pollution is incurred in the country and year specified (in this case Australia, 2020). The Value of a Statistical Life (VSL) for that country is applied. VSL is an estimate of the value society places on reducing the risk of dying. The Australian VSL is \$5 million [46] and is converted to US \$3.5 million. SMC of exhaust pollution for each vehicle type is calculated by ratioing the fuel consumption with the average for passenger vehicles in the Australian fleet, multiplying by passenger vehicle exhaust emissions mortality and dividing by number of vehicles in the fleet. A 2020 passenger fleet exhaust pollution mortality of 5,552 (Sect. 2.3) was assumed to be the base figure, with the lower research estimate [37] indicated by the uncertainty bar of −83% shown in Figure 4. The number of vehicles in the fleet is 16 million and fleet average fuel consumption is 11.1 L/100 km. The specific formula for a vehicle's social cost of exhaust pollution mortality in Australia, 2020 was:

*Vehicle SMC of exhaust pollution deaths = \$3.5 million * (5,552/ 16 million) * (vehicle fuel consumption L/100 km / 11.1).*

SMC of crashes for each vehicle mode is calculated by: Australian passenger fleet crash mortality statistic (753) multiplied by an estimated vehicle collision death multiplier (C) for each vehicle type multiplied by the VSL of US\$3.5 million divided by16 million vehicles in fleet. C reflects the relative likelihood of causing deaths in the 2020 national fleet mix of vehicles. C values are more variable than fleet crash death multiplier (M) values because the vehicle is operating in the current mix of vehicle sizes and types, not a hypothetical homogeneous fleet. Large 4 WD pickups and wagons are 100% more likely to kill other drivers and at least 130% more likely to kill pedestrians than sedans/ hatches [47,48]. Other SUVs are 30% and at least 70% respectively more likely to kill other drivers and pedestrians [49]. They are also more likely to be involved in collisions with pedestrians, due to driver blind spots greater width and height obscuring the view of other road users [50]. The C values estimated by the Author are: Pickup/ Wagon 4 WD 2.1; 2020 Fleet Average 1.0; Small ICE Hatchback 1.0; Large EV − SUV 1.5; Medium EV Sedan 1.0; Micro-EV 0.8; E-Bicycle and E-Bus 0.6. The specific formula for estimating monetized mortality cost of crash deaths in Australia was:

*Vehicle SMC of crash deaths = (753 * C * \$3.5 million) / 16 million.*

3 Results

3.1 CO_2 emissions from vehicle modes

Figure 1 shows the operational CO_2 emissions as pink bars, together with the embodied CO_2 emissions (EC) − blue bars − of each vehicle and where applicable its batteries (yellow bars). The dotted line is the SPCF of 1.5 t CO_2/ person/ year. Large ICE 4 WD pickups and wagons emit 6.4 t CO_2/ year whereas micro-EVs emit <0.6 tCO_2. EC accounts for about 18% of the total emissions for ICE vehicles, and up to 90% for EVs powered by RE. EC of EVs is higher than ICEVs due mainly to the high EC of batteries. The ICE vehicles incur 140% to 380% of SPCF and are not sustainable personal transport. Even a hypothetical 2 L/100 km micro-car would exceed 60% of the SPCF, although such vehicles using biofuels may be sustainable. The electric bus / bicycle option incurred 9% of SPCF and is sustainable. The micro-EV incurred 42% of the SPCF and would be sustainable if shared between 2 people. Due to their high embodied emissions, large and medium EVs incurred 75–110% of the SCF and would only be sustainable if shared between 5–7 people.

3.2 Australian vehicle fleet mortalities

The Australian passenger vehicle fleet incurred a total of about 62,000 deaths in 2020. (Tab. 1 row 2), Crashes accounted for around 750 deaths (1% of total). Vehicle exhaust PM2.5 and NO_2 pollutants accounted for 5500 deaths (9% of total). Total climate change related mortality during the period 2021–2100, from CO_2 emitted by the fleet in 2020 (MCCI of the fleet) will probably account for an estimated 56,000 deaths/ year with an uncertainty range of −50% to +90% (28,000 to 106,000 deaths). Temperature related mortality alone will probably account for about 18,500 deaths with uncertainty of −40 to +70%. Other climate change related mortality is assumed to be double temperature related mortality (sect. 2.4).

Total mortality would fall by 96% to about 2,500 if the fleet were all micro-EVs, E-bicycles/ scooters and E-buses, due mainly to a dramatic fall in future climate change related deaths from 2020 fleet CO_2 emissions. Exhaust pollution mortality would be reduced to zero and mortality from vehicle crashes reduced by about 15%. Total mortality would increase to about 90,000 if all vehicles were large diesel 4 wd pickups and wagons, 92% being future mortality from CO_2 emissions. Crash mortalities have minimal uncertainty as they are derived directly from statistics. Toxic pollution deaths are more uncertain as there are wide discrepancies in the research methods and data. Results are based on data from the most recent studies [14, 47] in which both PM 2.5 and NO2 pollution are accounted for and NO2 accounts for 90% of mortality. While statistics for cardiovascular and respiratory deaths are clear, more research is needed to more accurately

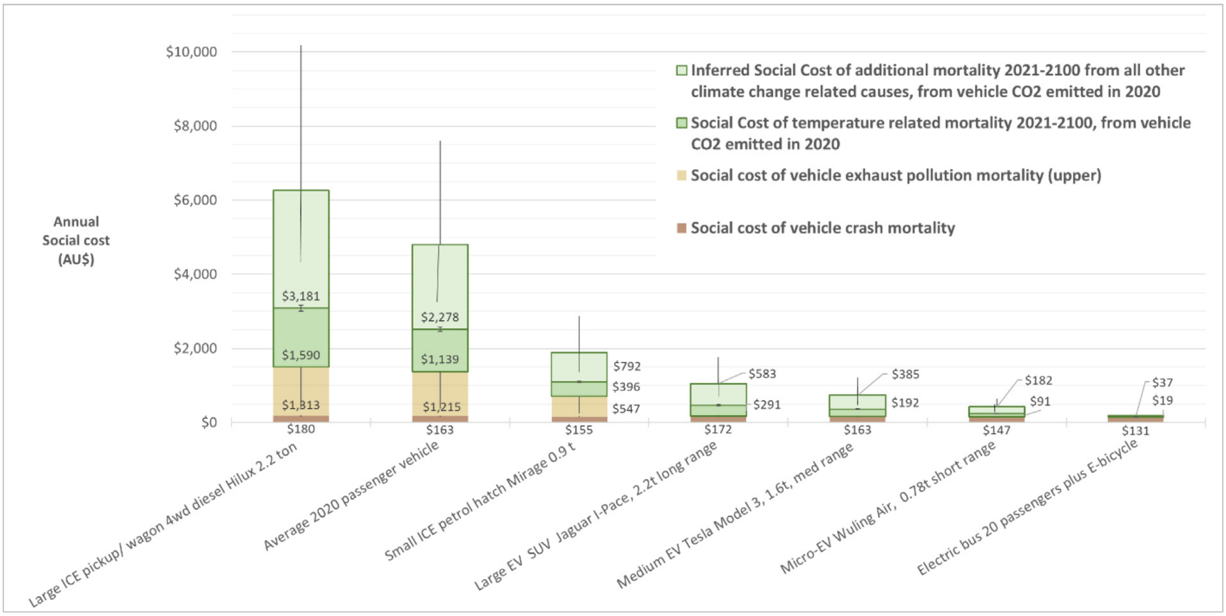

Fig. 5. Per vehicle monetized social mortality costs of 7 vehicle modes.

estimate what portions are caused by vehicle pollution sources. For example, by some estimates, particulate pollution from tyres and brakes comprise as much or more PM 2.5 pollution than exhausts.

3.3 Social Mortality Costs of 7 vehicle modes

The annual social costs of CO_2 mortalities (SCCMI), together with social mortality costs (SMC) of exhaust emissions and crashes are shown in Figure 5. For an average 2020 fleet passenger vehicle total social mortality costs are \$4796. SCCMI dominates at \$3418 or 71% of total SMCs. SMC of exhaust emissions of an average fleet vehicle are significant (\$1215 or 25% of total). Crash mortality costs are relatively low (\$163 or <4% of total). Micro-EVs and E-bus/E-bicycles incur total SMC of \$187 and micro-EVs \$420. Both incur zero SMC of exhaust emissions (as do all EVs), very low SCCMI and slightly lower SMC of crashes. SMC of crashes varies from \$131 for E-bus/ bicycle to \$180 for large 4 wd wagons/ pickups, the latter being more lethal to pedestrians. The total SMC of the global passenger fleet of 1.45 billion vehicles would amount to about US\$7 trillion. It could be reduced to <US\$0.6 trillion if all passenger vehicles were micro-EVs, E-buses and E-bicycles.

4 Discussion

Wide discrepancies in estimates of MCCRs and SCCMRs in the literature [42,51] are mainly due to inconsistent assumptions. Continuing research is recommended, to estimate holistic MCCRs and SCCMRs with more certainty and transparency, covering mortality from all climate related causes [52]. Assumed temperature trajectories, discount rate and period, VSLY and damage functions should be clearly stated. It is recommended that some assumptions be standardized, for example, long term discount rate set at 2.5% p.a., VSLY be used instead of VSL and measurement period be set at 80 yr, which approximates the lifetime of today's children. Estimating statistical life years lost would provide more meaningful data than premature deaths. It is hoped that MCCRs and SCCMRs will be continually revised with new research and updated data.

The concept of air pollution mortality taxes based on SMC of CO_2 (SCCMR) and SMC of toxic air pollution mortality is pertinent, along with regulation as means of reducing consumption of high emission consumer items [53]. For example, if applied to gasoline, a CO_2 mortality tax of \$663/ tCO_2 would increase the fuel price by 1.65/ L, whereas the current EU carbon price of about \$70/ tCO_2 would increase it by only 18 c/ L. Combined with air pollution labelling and awareness campaigns, phasing in domestic air pollution mortality taxes at point of sale would influence consumer behaviour. They could be levied nationally, like tobacco and alcohol taxes, thus minimizing 'carbon leakage' [55]. Tobacco taxes, which have increased to more than 65% of the retail price of cigarettes have been successful in halving rate of consumption [54,55]. As global warming from carbon emissions causes deaths across the entire planet, global VSLY is used to calculate SCCMRs, while toxic air pollution causes deaths in the country where it is emitted and the national VSLY is used to calculate SMCs for it. Some items incur emissions of other greenhouse gases, for example, production of red meats emits methane and nitrous oxides. Separate SCCMRs could be estimated and allocated for these items using the method outlined in Section 2.2.

5 Conclusions

This research has developed a methodology applicable in any country, which quantifies mortality costs of CO_2 incurred by consumer items (MCCI). Mortality over the next 80 yr from all climate change related causes (MCCR) is estimated to be three times Bressler's estimates for temperature related deaths only. The mortality cost of carbon (MCCI) of the Australian passenger vehicle fleet in 2020 will probably amount to about 75 times more deaths over the following 80 yr than 2020 vehicle crashes.

The study describes how Social Cost of Mortality Rates (SCCMRs) can be estimated and how they can be allocated to items according to the carbon intensity of each item. Unlike Bressler's partial SCC rates, SCCMRs include all climate change related mortality sectors. A SCCMR of \$663/ tCO_2 with uncertainty −50% to +90%. was estimated for average Australian fleet vehicles. The social cost of carbon mortality (SCCMI) of an item is the product its SMCCR and its life cycle carbon emissions. The annualized SMCCI of large 4 wd diesel wagons and pick-ups is \$4,762/ year and SMC of toxic exhaust emissions \$1,313/ year, equating to a total air pollution mortality cost of about \$6100/year. The social cost of CO_2 emissions from Micro-EVs was \$273/ year and SMC of toxic exhaust emissions was zero. Inefficient passenger vehicle modes carrying on average 1.5 occupants [49] are significant contributors to global carbon and toxic air emissions. Each type of vehicle should be taxed in proportion to the SMC of its CO_2 and air pollution emissions. Micro-EVs may be considered 'best practice' and might incur zero tax, while large diesel pickups might incur taxes of up to \$5800/ year. Popular micro-EVs sold in China and Japan can carry 2–4 passengers and travel at 100 kph with ranges of 150–200 km. This study also demonstrates that universal adoption of E-bicycles/ scooters, E-buses and micro-EVs, would reduce vehicle CO_2 and toxic exhaust pollution mortalities by 96%.

Glossary

tCO_2e	Metric tons of Carbon Dioxide equivalent.
MCCR	Mortality Cost of Carbon Rate, in units of deaths/ tCO_2e. The fraction of a death from all climate change related causes, that would probably occur over 80 yr with a specified temperature trajectory, from the emission of 1 tCO_2e.
MCCI	Mortality Cost of Carbon of an Item, in units of deaths/ item. The fraction of a death from all climate change related causes, that would probably occur over 80 yr with a specified temperature trajectory, from the CO_2e emitted by an item.
SC	Social Cost, in units of US\$
SCCMR	Social Cost of Carbon Mortalities Rate, in units of US\$/ tCO_2e. Monetized social cost of a MCCR, discounted over 80 yr
SCCMI	Social Cost of Carbon Mortalities of an Item, in units of \$US/ item. Monetized social cost of a MCCI, discounted over 80 yr.
SMC	Social Mortality Cost (of other impacts of an item), in units of US\$.
SPCF	Sustainable personal CO_2 footprint of 1.5 tCO_2/ person/ year.

Conflict of Interest

The author declares that he has no conflict of interest.

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