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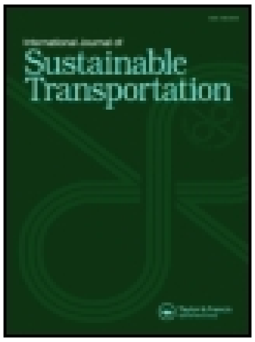

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Reducing the Ecological Footprint of Urban Cars

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Reducing the Ecological Footprint of Urban Cars

Abstract

This study develops the policy making capabilities of the Ecological Footprint. The new capabilities we introduce in our Ecological Footprint model allow us to clarify policy options in the face of the increasing management complexity due to a more interconnected and uncertain world. We investigate the effectiveness of three illustrative policy options for reducing the Ecological Footprint of urban car transport: 1) improvements in efficiency/technology, 2) substitution with alternate fuel mixes and 3) the reduction in demand by altering urban form. We investigate the success of policy options for a sub-national case study jurisdiction in Australia, but in the uncertain global context. We use a resilience framework which considers critical social, economic and environmental variables, multiple scales and multiple possible futures. We find that delaying policy options to mitigate CO_2 emissions from the transport sector will increase the risks born by society as a result of future global uncertainty, the uncertain timing of globally coordinated action on climate change and the timing of peak oil. We also find that the success of local policy is affected by the global future which prevails. The use of the Ecological Footprint allows policy to be informed by the consequences of both CO_2 emissions and increasing demand for land. The study provides a decision making framework that allows local decision makers to make robust policy despite global uncertainty. This framework has wider applicability to other nations and/or sub-national jurisdictions worldwide.

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Keywords

Transport; Ecological Footprint; policy; sustainability; urban; car

1 Introduction

World-wide transport accounts for 26% of anthropogenic CO2 emissions (Chapman, 2007). Of these emissions, 81% comes from road transport. Automotive emissions are recognised as the source of more air pollution than any other single human activity (Cameron, Lyons, & Kenworthy, 2004). In order to reduce the environmental impact of the transport sector, policy makers need models and indicators which allow them to investigate the environmental consequences of urban transport under different transport policies (Cameron et al., 2004). These indicators need to reflect and inform the increasing complexity that is inherent in contemporary environmental management (Milman & Short, 2008; Norberg & Cummings, 2008). Without such sophistication, we will be unable to make sufficiently robust policy choices required to maintain the resilience of jurisdictions to the increasing environmental pressures from human populations.

Here we present an approach to investigate and inform urban car policy using the Ecological Footprint at the national and sub-national scale but, within the uncertain global policy context. The objectives of the study are to investigate transport scenarios relating to urban car use for a case-study state jurisdiction within Australia – Western Australia. This study investigates the effectiveness of three illustrative policies for reducing the Ecological Footprint of urban car transport 1) improvements in efficiency/technology, 2) substitution with alternate fuel mixes and 3) the reduction in demand by altering urban form.

Modelling Ecological Footprints at a global scale together with sub-global scales has had limited research and application. Van Vuuren and Bouwman (2005) investigate a range of possible futures by dynamically modelling Ecological Footprints for 17 world regions to 2050. Moore, Cranston, Reed, and Galli (2011) undertook static modelling to compare a range of possible future global Ecological Footprints up to 2050. Finally, Lenzen et al. (2013) analyse global Ecological Footprints disaggregated by country under one future scenario to 2050.

The findings of the modelling are analysed through a resilience framework. A resilience approach is one which is motivated by the desire to manage the functions and structure of a particular system so that it continues to produce certain desired values (goods and services) to those that live there. A resilience approach ensures that the system operates in a robust manner so that disturbances are less likely to compromise the ability of the system to provide these values.

Resilience frameworks to critique and develop policy are becoming increasingly common both in Australia (for example, Hunt, 2016; Torabi, Dedekorkut-Howes, & Howes, 2017) and globally (for example, Collier et al., 2013; Crowe, Foley, & Collier, 2016). Although the link between sustainability and resilience is commonly researched and discussed, to the authors' knowledge, prior Ecological Footprint policy analyses using a resilience framework is general rather than explicit. In fact, in its static form, the Ecological Footprint is not designed to measure such

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dynamic concepts (Folke & Kautsky, 2000). Rather its role (and strengths) lie in being able to communicate current and historical state with a clarity which transcends that of many other environmental indicators (Collins & Flynn, 2015).

Here we use the following aspects of resilience theory in order to determine holistic policy options for the urban car sector that are likely to maximise the resilience of the Australian urban transport sector and the economy, society that rely in it in the long term. We do this explicitly by considering the:

- critical underlying dynamics of the system in our modelling and analysis;
- economic, social and environmental drivers and consequences;
- the consequences for both greenhouse emissions and impacts on land resources together;
- multiple scales which affect the success of policy;
- multiple plausible futures which affect the success of policy; and
- options for adaptation and transformation (mitigation policies).

Previous research investigating policy development using the Ecological Footprint associated with the transport sector largely focuses on single policy drivers (for example fuel or urban density in isolation, De Oliveira, Vaughan, & Rykiel, 2005; Muniz & Galindo, 2005; Ren et al., 2013), have a futures focus but at a single scale (Chi & Stone Jr, 2005) or analyse the impact of transport as one component of a broader Ecological Footprint policy investigation (Peeters & Schouten, 2006). This is the first analysis of the Ecological Footprint as a decision making framework to investigate the resilience of the transport sector by comparing multiple policy

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drivers simultaneously, comparing alternative futures using dynamic modelling and accounting for multiple scales.

2 Methods

2.1 The Model

The modelling of the global urban car transport sector that we describe here is set in the context of a larger global Ecological Footprint model which is outlined in more detail in McBain et al. (unpublished) and (Lenzen et al., 2013). The key groups of variables which inform the Ecological Footprint and Biocapacity in the larger model are: land use (built, cropping, grazing, plantation, forest), agricultural productivity (in response to land degradation, technological change and climate change) and climate change (the net emissions produced from the stationary energy sector, the transport sector, agricultural emissions, land clearing and forest sequestration).

The modelling timeframe (2010 till 2070) was selected in the knowledge that complex systems often exhibit delays in responses to change and that the outcomes of policy decisions may have some inertia.

2.2 The regional context

The Australian transport sector as a whole is 97% reliant on oil-based fuels for transport of which Australia has declining domestic reserves (Graham, Reedman, & Poldy, 2008).

Australia is a net importer of liquid fuels including petrol (ABARE, 2004) and imports of petroleum products have doubled since the 1960s predominantly to support the increase of transport demand over this time period (ABARE, 2004). This, together with the fact that fuel consumption of vehicles is high (Graham et al., 2008), makes the transport sector highly vulnerable to global fluctuations in oil prices and future oil availability (peak oil). Furthermore, greenhouse gas emissions from the transport sector are increasing relative to other sources and stand at over 14% of all emission in Australia in 2006 (Australian Greenhouse Office, 2008).

Since World War II Australian cities have transformed from fairly tight knit 'core-and-spoke' configurations, to having low-density, sprawling suburban characteristics (ABS, 2005). This has resulted (or been enabled) by the rapid rise in car ownership. The number of cars in Australian continues to increase in number (ABS, 2005) and private road vehicles comprise 93% of all transport in cities. Since nearly all population growth over the next three decades will occur in urban areas (O'Neill, 2005), urban car use will be one of the most important drivers of future environmental impact in Australia.

2.3 The global context

The Intergovernmental Panel on Climate Change Special Report on Emissions Scenarios (IPCC SRES) were used in our model to describe global scale uncertainty which would affect policy direction at the national and sub-national scale. The IPCC SRES scenarios describe a plausible and equally probable range of global futures. The scenarios do not investigate the implementation of any specific climate change mitigation policies. Therefore, they provide the ideal framework for considering the future uncertainty in which policy makers must make robust, long term policy decisions.

Each SRES scenario makes assumptions about the future trajectory of population, affluence (GDP) and technological change[i]. Population and GDP data were used as exogenous data in our model. Technological change was modelled endogenously as described below in section 2.1.8. The social and economic assumptions behind these scenarios acknowledge that population, affluence and technology do not progress independently of one another but each scenario is, internally coherent to account for interrelationships between them.

Data availability meant we examined three future scenarios: A2 (revised), B1 and B2. Historical GDP data was sourced from UN data for all countries in our study (UN, 2013). Future population and GDP data were sourced from GGI Scenario database ((IIASA), 2007). Rural, urban and total population data from 1980 to 2000 was obtained from the HYDE GIS database developed by Klein et al. (2006).

2.4 Model Variables

Below we outline the individual variables within our model relating specifically to the urban car transport sector and justify our approach.

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2.4.1 Vehicle Ownership

Car ownership per capita is a significant driver of vehicle kilometres travelled and largely responds to the level of affluence (Dargay & Gately, 1997). Thus car ownership predominates in developed countries (where it is 80% of total vehicle fleet) and in less developed countries two-wheeled transportation is more significant Cameron (2004). The gap between car ownership in developed and developing countries, however, is closing.

We used the approach of (Dargay & Gately, 1999) to estimate vehicle ownership in the recognition that ownership levels are largely driven by levels of affluence (per capita GDP) but that car ownership begins to saturate at different income levels for different countries. Dargay and Gately (1999) used a Gompertz relationship to model car ownership in response to GDP per capita.

$$V_{it} = \gamma \; \theta e^{\alpha e \; \beta iGDPt} + (1\text{-}\theta)V_{t\text{-}1}$$

Where, V_{it} = vehicle ownership for country i at time t, GDP = per capita income, α and β are factors defining the shape of the Gompertz function, γ= is the saturation level, and θ = lags in the adjustment of vehicle ownership to per-capita income. The coefficients for estimating car ownership are presented in Table 1. We estimated country specific saturation (β) for those countries not listed in (Dargay & Gately, 1999) by regressing known beta values from (Dargay &

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Gately, 1999) against per capita GDP and applying this relationship to countries with missing data.

2.4.2 Vehicle Kilometres Travelled (VKT)

We analysed the effect of urban density and the number of cars on the total urban vehicle kilometres travelled (Mulley & Tanner, 2009). We analysed data from the Millennium Transport Database for Sustainable Mobility by the International Union of Public Transport to derive a relationship determining total car vehicle kilometres travelled (VKT) for cities. Our assumption is that this city relationship also applies to broader urban areas used in our Ecological Footprint model.

We regressed data for total urban car VKT for 69 cities (randomly selected out of a full data set of 93 cities) against urban population density and total urban vehicle ownership (without the interaction term which was not significant). These variables were found to explain 86% of the variation in urban VKT. As expected, VKT increases with increasing number of cars in an urban area and decreasing urban density. We validated the regression relationship using the remaining 24 cities and found an 86% agreement between predicted and actual VKT data. The finite difference coefficients for urban density and total number of cars are listed below in
Table 2.

2.4.3 Fuel Mix - Global Assumptions for SRES Uncertainty Scenarios

Fuel mix is an important determinant of greenhouse gas emissions and the Ecological Footprint of transport. Globally, carbon intensive oil based products (mainly petroleum and less so diesel) dominate transport fuel choice (64 and 36%, respectively) (IEA, 2015). The use of alternate fuel is currently insignificant – at the beginning of our modelling period, for instance, less than 0.00004% was contributed by ethanol, biodiesel and hybrid cars (IEA, 2015). There are also immature technologies such as hydrogen which offer future opportunities to reduce the environmental impact of the transport sector.

Fuel mix was incorporated into the SRES scenarios as an exogenous variable in our model. The future fuel mix for each respective SRES scenario was guided by the summary from (Uherek et al., 2010) who, in turn, cite (J. Borken-Kleefeld et al., in prep). The quantified assumptions behind each SRES scenario are documented in Table 3.

2.4.4 Emission Factors

Emission factors used for each particular fuel type are presented in Table 4. We calculated the electricity demand from electric and H2 vehicles using the following assumptions: 0.2 kWh/km for electric vehicles (CSIRO & BITRE, 2008) and 0.259 kWh H2/km for H2-Fuel Cells and 0.464 kWh H2/km for H2-Internal Combustion Engines (Schade & Wietschel, 2007). This was added to overall electricity demand in each jurisdiction. The CO2-e emissions from each respective transport fuel option were then calculated as a percentage of total GHG emissions from electricity consumption based on the initial proportion of demand. It is noted that we do not include the embodied emissions that result from the manufacture of the vehicles themselves

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in our analysis. It is noted that the embodied emissions included in biofuels depends significantly on whether forest is cleared to grow biofuel crops; however, land clearing for crops is accounted for in other components of the model and is not, therefore, accounted for in these emission factors.

2.4.5 Efficiency/Technology

The emissions factors relating to fuel mix (section 2.1.6) were adjusted to account for technological improvements in car transport efficiency other than those related to fuel mix and engine type. Such efficiency improvements could include factors such as body design and aerodynamics, lightweight materials, continuously variable transmission, advanced low rolling resistance tyres, improved exhaust treatment and improved combustion technology (H. Turton, 2006). Other factors affecting efficiency changes also include car size and power; however, as noted by Turton (2006) the response of these particular factors to increases in affluence tend to counteract improvements in vehicle efficiency. Therefore, overall vehicle efficiency improvements must account for both technological improvements and trends which counter them. A review of the literature by H. Turton (2006) with these considerations in mind, concluded that average fuel consumption rates under moderate long term technological gains (e.g. SRES B2) could conservatively reduce emissions at 2% per decade till 2100 (or a total of 20% reduced fuel use).

We assumed that all engine types and fuel mixes (including technologically immature engine types such as hydrogen and EV) benefit equally at this rate. Emission factors for corn ethanol were chosen for the beginning of the modelling period and technological improvements presume this is replaced by more advanced cellulose based production systems such as Fischer-Tropsch and Dimethyl ether (DME) using lignocellulosic feedstock such as wood waste and switchgrass (Larson, 2006).

Little quantified data is available for SRES scenario specific changes in emission factors for transport. Uherek et al. (2010) noted that, in general, fuel efficiency improvements are high to very high in scenario B1, moderate in scenario B2 and low in scenario A2. We, therefore applied the 20% technological improvement to 2100 in scenario B2 (as in Turton (2006)). We apply a more optimistic rate of 50% reduction in fuel use to 2100 as appropriate technological gains assumed for scenario B1. We apply a 5% gain in vehicle efficiency to scenario A2 where investment in technological progress is low. Technological improvements over time are assumed to be linear. Delay in technological uptake due to turnover in capital stock of cars not considered here are the life-time of a car is short. Average age of car is about 10 years in Australia (ABS, 2016). All emission factors are documented in Table 5.

2.4.6 Land

Larson (2006) present land intensity factors per VKT for a range of biofuels. For ethanol we assumed a global average land intensity specific to corn ethanol (25,000 VKT/ha or 0.4E-4 ha/VKT) for the beginning of the modelling period. For biodiesel we assume a starting land intensity derived from the average of Watson and Elsayed for rapeseed (32,500 VKT/ha or 0.307E-4 ha/VKT). Future land intensity is adjusted at the same rate of technological improvement as fuel efficiency i.e. 5, 20 and 50% reduction in land intensity for scenarios A2, B2 and B1 in 2100, respectively (Table 5). In addition to the land required for producing biofuels is energy land to produce electricity for H2 and EV vehicles. The land requirement of H2 and EV was calculated from the land intensity of electricity consumption (and is calculated endogenously within our Ecological Footprint model, McBain et al., unpublished). We used land area (rather than the traditional metric used to measure Ecological Footprints, the Global Hectare or GHA). Unlike its name suggests, GHA is actually a measure of resources produced by land, not a measure of the land area itself (Wackernagel, Lewan, & Borgström-Hansson, 1999). For the purposes of this study, we were interested in studying the implications of policy to reduce CO_2 emissions for demand on land area.

2.5 Mitigation priorities for Australian States

We developed a set of urban car mitigation options and priorities in collaboration with state policy makers. Critically, these priorities are informed by state policy but do not necessarily reflect state policy. Rather they represent just *one set of investigative* mitigation strategies for the urban car transport sector.

For Australian states we assumed a uniform national fuel mix based on data from BITRE (2009) which served as starting fuel mix data which was then adjusted with respect to future priorities defined by each jurisdiction, respectively. The consequences of alternative future fuel mixes were investigated by applying an assumed future share of transport fuel mix for each jurisdiction derived from consultation with a range of state policy makers (all of which were partners in the research project).

We used an initial list of mitigation options for the transport sector from Pacala and Socolow (2004). Importantly, this list included only mitigation options for the transport sector which used scientific, technical and industrial know how which exists currently i.e. it does not rely on some future development or technology which is, as yet, unforeseen. This means that these options are currently feasible and available for incorporation into appropriate mitigation policy. The mitigation options included: biomass fuel replacing petrol, H2 in fuel-cell car replaces petrol, hybrid cars, efficient vehicles, reduced car size and/or power, and urban form improvements which reduce the use of vehicles and encouraged greater active transport such as bicycle and walking.

We asked state policy makers to prioritise this list of options (high, medium, low, zero) based on their understanding of the following criteria:

- address the components of the EF that have the greatest magnitude;
- highlight the factors which the EF is most sensitive to (those that have the greatest influence and which can be highlighted to 'most effectively' reduce footprint);
- highlight the environmental problems with highest profile in jurisdiction (issues that might have the greatest political leverage to justify change);
- highlight the environmental problems that scientifically are the most important;
- highlight factors that are easiest/cheapest to change;
- highlight factors that are likely to have the least negative repercussions for triple bottom line environmental, economic and social indicators; and

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- highlight factors that are likely to have most benefit for triple bottom line environmental, economic and social indicators.

State partners were asked to outline mitigation priorities on a scale of high (3), medium (2), low (1) or zero. The future fuel mix of for the state specific mitigation scenarios was adjusted so that they reflected the proportions dictated by these priorities. These priorities were translated into an assumed future fuel mix to 2100 and a second more stringent future fuel mix (Table 6).

2.5.1 Mitigation Scenario for Urban Density

The growth in driving (VKT) is significantly influenced by urban form i.e. the type of urban development which encourages alternate forms of transport (such as walking, biking and public transport) over driving (Ewing, Bartholomew, Winkelman, Walters, & Chen, 2008; Leck, 2006) predominantly through increasing urban density. Although good urban form includes characteristics such as more compact development, many other considerations such as a suitable mixture of land use (Leck, 2006) are also required in order to make it successful. Since two thirds of the development on the ground in 2050 will be built between 2007 and 2050, improving urban form to reduce VKT can be considered a low cost environmental policy since these investments largely need to be made anyway (Nelson & Malizia, 2006) in (Ewing et al., 2008).

In our first mitigation scenario for urban density we assumed a moratorium on the expansion of urban land after 2020 to allow for 10 year inertia of present, deeply entrenched policy of urban expansion. The moratorium on the expansion of urban area meant that there must be an increase in urban density to accommodate increasing future urban populations. The actual density was determined endogenously within our Ecological Footprint model (McBain et al., unpublished).

Our second mitigation scenario for urban density was more stringent. We assumed a moratorium on total urban area at the beginning of the modelling period until 2020. After this date we decreased urban area at the same rate as urban expansion in the decade before the modelling period (1990-2000) until the urban density equalled 75 people/ha. This was found by (Newman & Kenworthy, 2006) to be an urban density 'sweet spot' which results in reduced transport energy use and emissions but having sufficient room for urban parks and gardens.

2.6 Risk Analysis to Inform the Timing of Mitigation

As noted by (Graham et al., 2008) Australia's transport sector has a greater vulnerability to changing markets that many other countries because of high vehicle use, the relatively high fuel consumption by vehicles in its fleet, a 97 per cent reliance on oil-based fuels for transport and declining domestic reserves of conventional oil.

Two of the key uncertainties associated with the transport sector are the timing of peak oil and the timing of a global carbon price. Mohr and Evans (2008) find that conventional oil production will peak somewhere between 2010 and 2025, however, they also note a high variability in the estimated timing of peak oil in the literature.

The timing of a global carbon price is also uncertain. At the time of writing, a global carbon price, or at least a globally coordinated strategy for reducing carbon emissions,

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does not seem imminent. However, we must assume the possibility of this eventuality if we are to consider the wellbeing and survival of humanity in the long term. The ‘lock in’ of carbon intensive capital stock within a country will have large consequences to the vulnerability of a country’s economy and society, should a global response to climate change occur. Countries like Australia, who have a high investment in carbon intensive infrastructure, are highly vulnerable to such an eventuality in comparison to countries which are already investing away from such infrastructure and are much more flexible.

To determine the most prudent timing for implementing mitigation options we undertook a risk analysis which investigated a range of consequences in response to the two key uncertainties above (timing of peak oil, and timing of global carbon price) and investigated these consequences under scenarios of early and late adoption of mitigation options. The consequences investigated include the likely for the cost of mitigation ($M: low, $$M: medium, $$$M: high), the ability to plan strategically (↑: high, ↔: medium and ↓: low), the cost of adaptation ($A: low, $$A: medium, $$$A: high) and human suffering (☹:low, ☹☹:medium, ☹☹☹:high).

3 Results

3.1 Comparisons with Literature

Turton (2006) indicates *total* global car VKT of around 9 trillion in 2000 which compares well with our estimates of *urban* car VKT (9.5 trillion). Our modelled estimate of *urban* car VKT of 7.3 X 10^{10} VKT for Australia compares well with the total urban car VKT calculated from (BTE, 1998) of 1.10 x 10^{11} VKT. Similarly, the Department of Climate Change and Energy Efficiency (2010) also find a total car VKT of 1.5 x 10^{11} in Australia in 2000.

At the state level our modelling showed a 98% correlation with state specific VKT data from BTE (BTE, 1998) although estimates for BTE were about 1.5 times higher. This is likely due to differing assumptions and definitions relating to urban area and density (i.e. the two studies measure slightly different things). State based comparisons between data from BTE and modelled data showed an R^2 of 0.98.

Turton (2006) estimate 2500 Mt CO2-e for partial well-to-wheels car travel in 2000. Our global result for *urban cars* is comparable at 2401 Mt CO2-e. Higgins (2007) and Parisot (2011) found total emissions from Australian cars and total domestic road transport to be approximately 43 Mt CO2-e and 50 Mt CO2-e, respectively. Our results for Australia are 46 Mt CO2-e.

3.2 Risk Analysis to Inform Timing of Mitigation

In Table 7 below we present a matrix which summarises the range of consequences that are likely under two key uncertainties (the timing of peak oil and a global carbon price) and under two scenarios (early and late adoption of mitigation options).

The vulnerabilities to society are minimised with early peak oil and early transition away from carbon intensive transport sector. There are likely to be significant cost associated with investment in transition away from a fossil fuel intensive transport sector just ahead of declines in oil availability. There will be intermediate ability for society to plan for this transition. There will be minimum costs for adaptation to climate change because all nations will be forced to transition to a less oil intensive transport sector due to resource limitations. The additional influence of an early carbon price will not have further significant effects because transition has already occurred.

Later peak oil and early transition away from a carbon intensive transport sector is likely to result in medium levels of vulnerabilities to society. There are likely to be significant cost associated with transition away from a fossil fuel intensive transport sector. However, these costs will be spread across a longer time frame and thus smaller investment occurs each year resulting in a smaller per annum financial imposition - this is especially true for the case where late implementation of a carbon price. Importantly, this transition can be planned for and as a result there is less likelihood that other budgetary items which affect the welfare of society will be indiscriminately and heavily compromised. Intermediate costs are expected to be required for adaptation to climate change because not all nations are likely to plan ahead.

Early peak oil and late transition to a less carbon intensive transport sector will likely result in intermediate vulnerability levels for society. An energy crisis is likely because a transition away from a fossil fuel intensive transport sector will be required at very short notice. Such rapid transition is likely to be associated with massive increases in financial (e.g. oil prices, new infrastructure costs) and non-financial costs (e.g. health consequences). Intermediate cost associated with adaptation to climate change is likely to be required. The additional influence of an early carbon price will not have further significant effects because transition has already forced due to restrictions in oil availability.

Later peak oil and later transition tends to maximise the vulnerability of society. Later peak oil and late transition from a carbon intensive transport sector in the absence of the carbon price is likely to entail massive financial and non-financial (life, well-being, oil prices etc.) costs associated with adaptation and defence against the consequences of climate change. In addition, massive cost will also be associated with the energy crisis and subsequent transition to non-oil based transport sector once peak oil occurs at this later time. An early carbon price results in medium to high levels of vulnerability.

3.3 Modelling outcomes

Without mitigation the total global car VKT continues to increase linearly irrespective of which global SRES future eventuates (Figure 1, top). Due to differences in technological investment and uptake there are, however, divergent future impacts of CO_2 emissions. Emissions continue to increase unabated under an A2 future. Under a B1 scenario emissions level off quickly and then taper off slowly after 2050. Under a B2 scenario there are immediate decreases in emissions which continue a downward trajectory until the end of modelling in 2070 (Figure 1, middle). Land requirements, however, of the B1 and B2 scenarios are much higher than A2 because of the greater contributions from land intensive fuel mixes such as biofuels, H2 and EV (Figure 1, bottom).

The demand for urban car transport in Western Australia also increases into the future (Figure 2, top). The consequences of such increases, in terms of carbon emissions, are highly variable. Without mitigation, emissions reflect global patterns which are greatest under an A2 scenario, followed by B1 and B2. Not surprisingly, mitigation of emissions becomes more effective as it becomes more stringent (i.e. from less stringent fuel mix to more stringent fuel mix and, finally, more stringent fuel mix AND change in urban form).

However the success of mitigation options is dependent on both how stringent it is and the global context (Figure 2, top). In Western Australia, for example it is not until very stringent mitigation options are implemented that demand plateaus under a B1 and A2 scenario and drops significantly under a B2 scenario. Although demand for petrol and diesel decrease, demand for LPG increases under and A2 trajectory, irrespective of mitigation options, making the Western Australia transport sector vulnerable to the eventuality of peak gas in an A2 future.

Even under no mitigation of CO_2 emissions in Western Australia, emissions eventually decrease in a B1 and B2 context, although this is only after 2020 and 2050, respectively (Figure 2, 2nd row). Under an A2 scenario no such decrease is evident. Less stringent mitigation of fuel mix and urban form, do not significantly alter the trajectory of CO_2 emissions for the B1 and B2 global context. Emissions in the A2 context are slowed somewhat but do not at any stage decrease in the future. It is only in response to the most stringent mitigation scenario of fuel mix and urban form together, that we see a decrease in emissions irrespective of the future global uncertainty.

Land requirements (Figure 2, 3rd row) in Western Australia increase as the fuel mix becomes less fossil fuel intensive with the exception of built land which decreases in extent (Figure 2, bottom row).

4 Discussion

Our findings describe a world where the demand for urban car transport continues to increase into the future. The contribution of this sector to climate change in the future is highly uncertain. Under a future described by the IPCC A2 scenario, CO_2 emissions from the sector continue increasing linearly i.e. a future where there is little global policy coordination, high population growth, medium to low growth in affluence and slow/fragmented adoption of new technologies. A slightly more positive future under scenario B1 shows a levelling off of CO_2 emissions from the urban car sector (a globally coordinated world policy context with medium-high global population, medium income growth and low-medium technological uptake). Finally, under a B2 future, emissions from the sector decrease continuously to be 25% lower by 2070 than they are at present. This future presumes locally disparate policy approaches, low future populations, medium income growth and medium technological investment.

The SRES scenarios used to describe this uncertain future do not presume the implementation of specific policies which mitigate climate change. Therefore, even the most positive outcome occurring under a B2 scenario are small (25% reduction in emissions) and will require specific policy to mitigate the CO_2 contributions from the urban car sector in order to moderate the impact of climate change overall.

The global scenarios are useful in three ways. Firstly, by looking at the assumptions made about the main drivers (population, affluence, technology, coordination of global governance etc) policy makers can be more informed about where policy effort could be directed now in order to move towards a desired future. For instance, if a future with low carbon emissions is desired then policy which encourages locally customised policy approaches, low future populations, medium income growth and medium technological investment (i.e. a B2 future) could contribute to such a future. If, in comparison, income growth is prioritised, then the underlying assumptions behind the B1 scenario are more likely to support such a future.

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Secondly, the scenarios allow an analysis of economic vulnerability to the implementation of a global carbon price. For example, little investment in technology (e.g. scenarios A2 and to some degree B1) locks in a certain CO_2 emissions trajectory for some time because the infrastructure for producing electricity and technological infrastructure associated with vehicle production can have a long lifetime. The implementation of a global carbon price would disadvantage those countries which have not strategically planned transitions away from carbon intensive fuels and technologies, making them more vulnerable.

Lastly, the global scenarios describe the uncertain context that local policy makers make decisions in. Global variations in population, affluence and technology impact what occurs at national and sub-national scales. For example, new technological development at a global scale will directly affect what technologies are available in Australia. In an increasingly globally connected world it is clear that Australia's economic success depends on the global context in which it is embedded.

However, this highly uncertain future is also influenced by a further policy context which may constrain the sector - the future availability of fossil fuels. Vulnerability as a result of future peaks in fuel availability is likely to be variable and also dependent on which future scenario eventuates. J Borken-Kleefeld et al. (2010); Uherek et al. (2010) for instance, presume that oil and gas availability is low for the A2 scenario, is low (peaks and declines) in B1 and is medium in B2. Local policy makers cannot ignore either of these influences on local policy.

It has been difficult, however, to justify the transformation required for a more sustainable transport sector in Australia (Graham et al., 2008). For example, in the absence of a globally coordinated climate change strategy, current Australian policy advocates a delay in the adoption of ambitious carbon emissions targets (Garnaut, 2011). However, our results show that the uncertainty in relation to the timing a global carbon price or global CO_2 emissions reduction targets, together with the risks of peak oil, mean that delaying a transition away from a carbon intensive transport sector cannot be justified.

Such a delay increases the vulnerability of Australia's economy, society and the environment. Increases in oil prices, for example, will have massive social and economic consequences which are only like to worsen in the future unless more appropriate and timely policy implementation occurs. Low-income Australians for whom transport accounts for a higher proportional share of household income, and who tend to live on the urban fringe or in regional areas (where average kilometres travelled per day is higher) are particularly vulnerable (Graham et al., 2008).

Our sub-national case studies do indeed show the influence of the highly variable global context they operate within - both demand for car travel and CO_2 emissions are highly variable depending on which global future scenario eventuates. Given that each of these global scenarios are regarded as equally likely and plausible, policy makers in Australia must make policy decisions which are likely to be successful despite this future uncertainty. Therefore, global uncertainty must inform domestic policy to ensure it is 'future-proofed'.

We learn from investigating three illustrative mitigation options that stringent measures must be put in place in order to 'future proof' policy in Western Australia against this global uncertainty. Our findings show that a massive transformation of the transport sector and urban form are both required if mitigation policies are to successfully ensure the Western Australian jurisdiction continues to function in a safe operating space. This is, of course, not easy given the significant changes in capital infrastructure and behaviour required for a transition to a more sustainable and resilient transport sector. However, unless the most stringent mitigation scenarios are applied, the risk of transport policy failure is significant.

In Australia, as for the world as a whole, there is an increase in demand for land as a consequence of implementing a more diverse fuel mix which transitions away from fossil fuels. This means that policy to mitigate CO_2 emissions brings very real challenges for other components of the Ecological Footprint. The demand for land needed to produce energy for transport, for instance, grows significantly with a transition to alternate fuel choices. Biofuels have greater embodied land compared to fossil fuels. The land embodied in EV and H2 technologies, (whose energy is supplied by the electricity sector) also increases as the electricity sector itself decarbonises. This is because renewable stationary energy such as solar, hydro and wind require greater areas of land than those required by the dominant coal and gas technologies of today (Lenzen et al., 2016)

This increasing future demand for land is especially serious given the simultaneous increase of other types of land such as cropping, grazing, plantation, and built land (McBain et al., unpublished). The reality of competing policy outcomes in a resource constrained world does not mean we abandon policy approaches to reduce carbon emissions but poses the need for greater sophistication of transport policy development.

If policy outcomes which reduce CO_2 emissions are seen as a priority, then complementary policy will be required to mitigate the need for more land. Policy to reduce the land requirement of a decarbonising electricity sector could include co-use of land (e.g. wind together with grazing, decentralised solar on existing built land), use of land whose provision of other goods and services would not be compromised (e.g. offshore wind, solar on less productive land) and heavy investment in technological efficiency (McBain et al., unpublished). Synergistic land use planning are an obvious starting point (agriculture and biofuel production together could give greater economic resilience to farmers, for instance). The large land area required to produce biofuels can also be mitigated by prioritising research investment in biofuel technologies which can use waste products or have lower land intensity (e.g. algal sources).

In contrast to other types of land, the area of built land decreases as more stringent transport sector policies are implemented (and urban density increases). A reduced demand for urban land may have benefits because many urban centres are located on highly productive alluvial lands which can then provide other ecosystem services.

Happily, there are many co-benefits that are also likely as a result of implementing the transport mitigation scenarios investigated in this research. Although the implementation of the most stringent mitigation options will be costly, financial savings are also likely to result.

First of all, automotive emissions are the source of more air pollution than any other single human activity (Cameron et al., 2004). Decreasing these levels of pollution is likely to have significant health benefits. For example, BTRE (2005) estimated that in 2000 motor vehicle-related ambient air pollution in Australia accounted for between 900 and 4500 morbidity cases (cardio-vascular disease, respiratory diseases and bronchitis) and between 900 and 2000 early deaths. The economic cost of morbidity is estimated at $0.4 to $1.2 billion, while that of mortality is $1.1 to $2.6 billion. A transition to improved urban form can also have improved consequences for health by increasing levels of physical activity as urban design become more convenient and friendly for biking and walking (Ewing et al., 2008); thus, also contributing to the reduction in preventable chronic diseases such as cardiovascular disease for which direct and indirect health costs in Australia totalled $7.6 and $6.6 billion dollars, respectively in 2004 (Access Economics, 2005).

A more compact urban design may also reduce infrastructure costs. Burchell, Lowenstein, and Dolphin (2002) for instance, found more compact urban form to be eleven percent less expensive to service. The economic savings associated with grid lock in increasingly congested cities could

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also be significant. BTRE (2007) estimate the cost of congestion from all transport in Australian capital cities to be valued at around $9.4 billion.

A reduction in urban sprawl and/or urban area will also reduce future competition with other land uses that provide goods and services to human populations or land uses that provide biodiversity benefits by avoiding the clearing of vegetation. Other likely environmental benefits include improvements in downstream river and estuarine water quality (Allen, 2006). These benefits may be especially important in the future where competition and contestation over land is likely to increase dramatically with increasing human demand of goods and services beyond the ability of nature to provide them (McBain et al., unpublished).

Finally, the policy conundrum between demands for land versus reductions in CO_2 emissions reveals the urgent need for indicators or combinations of indicators which can inform the growing complexity of contemporary environmental management (Milman & Short, 2008). We have demonstrated here the power of the Ecological Footprint to simultaneously consider human impacts on land and carbon emissions to inform robust policy. Similar, multi-component indictors such as the ReCiPe Life Cycle Analysis (Goedkoop et al., 2013) and the Genuine Progress Indicator (Cobb, Halstead, & Rowe, 1995) are not commonly used to inform policy but have potential to reveal critical information for the transition to sustainability.

5 Conclusion

The sub-national mitigation options presented here are an example of how the Ecological Footprint policy tool developed can be used to explore and inform policy options. It is a tool which can be used to start collaborative, cross-disciplinary policy conversations which are based around a shared desire of wanting to maintain a societal function (transport) which is valued and relied upon.

This is the first analysis of which we are aware that considers the combined consequences for both carbon emissions and land requirement for policy which mitigates the environmental impact of the urban car transport sector. We find that the implementation of ambitious policy mitigation options can significantly reduce the carbon footprint associated with the sector, however; this can compromise policies to limit future demand for land unless implementation is well managed.

We present an approach which can be used by policy makers to investigate risks associated with different transport policies. The results of this study give policy makers mitigation options which significantly reduce the vulnerability of the Australian society to future uncertainties. This is the first time that the consequences of an alternate future fuel mix, urban form and stationary energy sector have been analysed for a sub-national jurisdiction but in the global context. This approach to policy development provides justification for the urgency of early mitigation and the significant investment it would entail. It provides an example of how such complex decision making can be approached to build robust and defensible policy – an approach which also has relevance to other jurisdictions elsewhere in the world.

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Table 1. Caption: Coefficients for car ownership

Variable	Term	Coefficient
θ	Speed of adjustment	0.09
γ	Saturation level	0.62
α	alpha	-6.42

Table 2. Caption: Regression coefficients for urban car VKT

Term	Coefficient	SE	P
# urban cars	13462.22477	690.5232379	<.0001
Urban density	-34219810.46	15605102.8	0.0309

Table 3. Caption: Assumed fuel mix (%) for global SRES scenarios. First generation biofuels are assumed to predominate until 2030 with second generation established by 2050. Bold values are from (Uherek et al., 2010). The remaining percentages were spread across fossil fuels in the same relative proportion as for year 2000.

SRES	Yr	Petrol	Diesel	LPG	Ethanol	Biodiesel	H2	EV
All	2000	64	36	3.E-07	4.E-05	2.E-06	0	0
A2	2050	64	36	3.E-07	4.E-05	2.E-06	0	0
A2	2100	64	36	3.E-07	4.E-05	2.E-06	0	0
B1	2050	48	28	3.E-07	10	10	2	2
B1	2100	33	19	2.E-07	20	20	4	4
B2	2050	51	29	6	5	5	3	3
B2	2100	34	19	14	12	12	5	5

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Table 4. Caption: Emission factors for car/passenger transport

Region	Fuel Type	GHG emissions (g CO2-e/km) in 2000	Source/Notes
Default world	Petrol	237.50	WRI (2008)[a]
	Diesel	197.00	WRI (2008)[a]
	LPG bi-fuel	148.50	EU W2W[b]
	Biodiesel	142.80	EU W2W[b]
	Ethanol	161.30	EU W2W[b]
	H2	-	
	EV	-	

[a] The WRI data, in turn, is sourced from the UK Dept. for Environment, Food and Rural Affairs (DEFRA), the US Environmental Protection Agency (EPA) and the IPCC's 2006 Guidelines for National Greenhouse Inventories.

[b] Well to Wheel

Table 5. Caption: Global technological improvements in emission factors, electricity demand and technological improvements in land intensity for car/passenger transport by 2100. Note that H2 and EV vehicles are, once again, not assigned an emission factor as these are accounted for by country specific changes in emission intensity of the stationary energy sector.

Fuel Type	A2	B1	B2
	GHG emissions (g CO2-e/km)		
Petrol	225.63	190.00	118.75
Diesel	187.15	157.60	98.50
LPG bi-fuel	141.08	118.80	74.25
Biodiesel	135.66	114.24	71.40
Ethanol (neat)	153.24	129.04	80.65
	kWh/km		
EV	0.190	0.100	0.160
H2 fuel cell	0.246	0.130	0.207
	10^{-4} ha/km in 2100		
Ethanol	0.380	0.200	0.320
Biodiesel	0.246	0.130	0.207

Table 6. Caption: Western Australian priorities translated into fuel mix for mitigation scenarios (%) by 2050 and 2100

Priority	2050	2100
Less stringent		
Petrol	40	10
Diesel	20	5
LPG	3E-07	2E-07
Ethanol	5	11
Biodiesel	5	11
H2	15	32
EV	15	32
More stringent		
Petrol	15	0
Diesel	5	0
LPG	2.6E-07	0
Ethanol	10	13
Biodiesel	10	13
H2	30	38
EV	30	38

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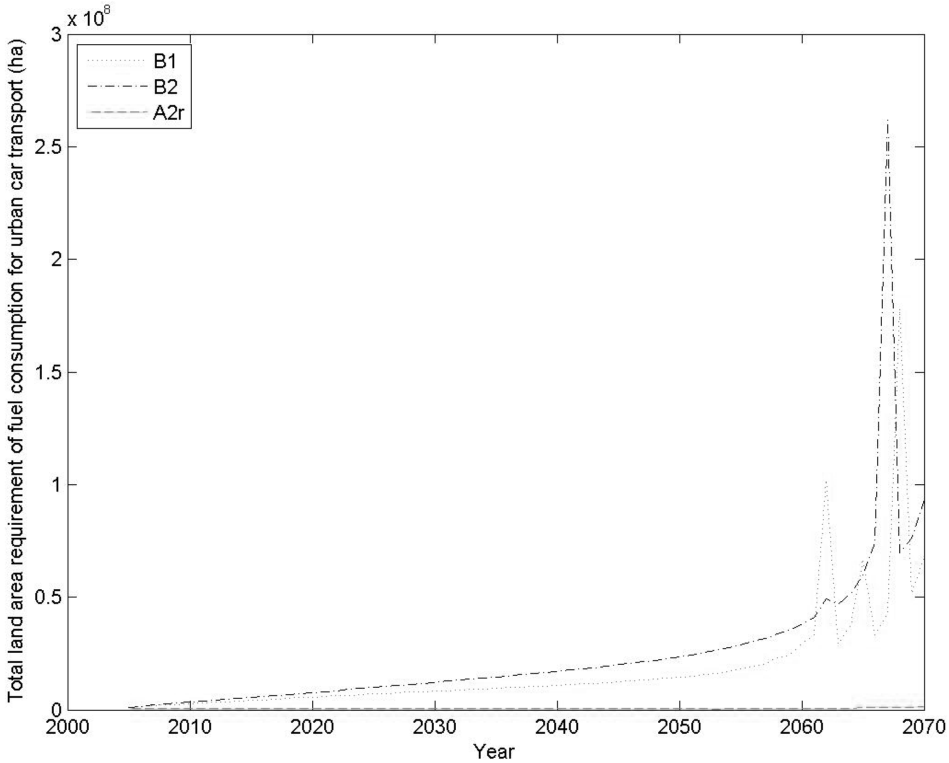
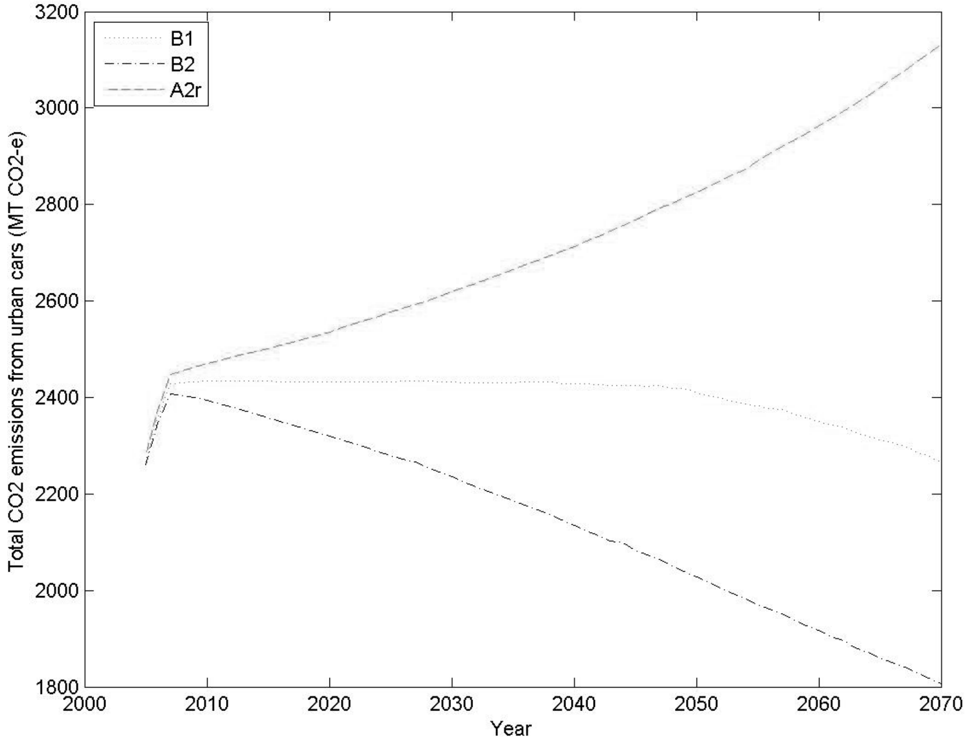
Table 7. Vulnerability assessment of the transport sector under global uncertainties of peak oil and the introduction of a global carbon price. The consequences investigated include the likely total long-term cost of mitigation ($M: low, $$M: medium, $$$M: high), the ability to plan strategically (?: high, ?: medium and ?: low), the cost of adaptation ($A: low, $$A: medium, $$$A: high) and human suffering (?:low, ??:medium, ???:high).

		Peak Oil			
		Early		Late	
Transition	Early	$$M ↔ $A ☹	$$M ↔ $A ☹	$$M ↔ $$A ☹☹	$$M ↑ $$A ☹☹
	Late	$$M ↔ $A ☹☹	$$M ↔ $A ☹☹	$$M ↔ $$A ☹☹	$$M ↔ $$$A ☹☹☹
		Early	Late	Early	Late
		Introduction Global Carbon Price			

Figure 1. Total global vehicle kilometres travelled (VKT, top) and CO_2 emissions (middle) and energy land requirement (bottom) from the urban car transport sector under three SRES scenarios


x 10^8
B1
B2
A2r
Total land area requirement of fuel consumption for urban car transport (ha)
Year
0
0.5
1
1.5
2
2.5
3
2000
2010
2020
2030
2040
2050
2060
2070



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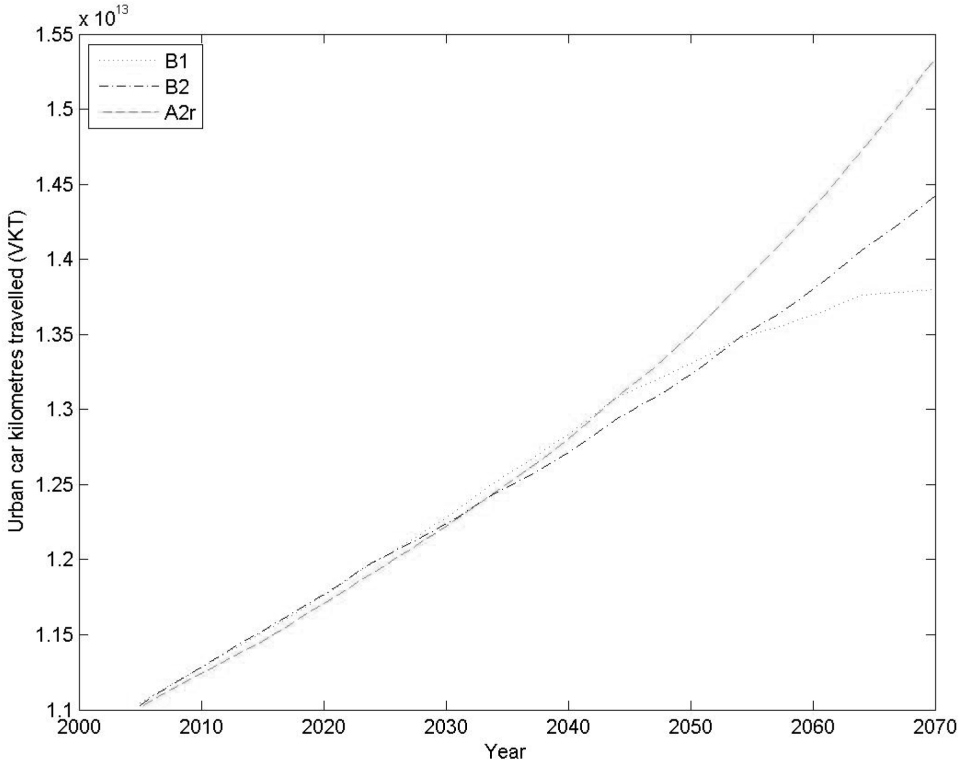

Figure 2. Total urban car VKT (top, vehicle kilometres travelled), CO2 emissions (2nd row, Mt CO2-e), stationary energy land area requirement (third row, ha) and built land area (bottom, ha) of the transport sector in Western Australia under four scenarios from left to right: a) no mitigation, b) mitigation of fuel mix c) mitigation of fuel mix and urban density and d) mitigation using more stringent fuel mix and urban density. Results are presented for three alternate global scenarios (B1, B2 and A2r).

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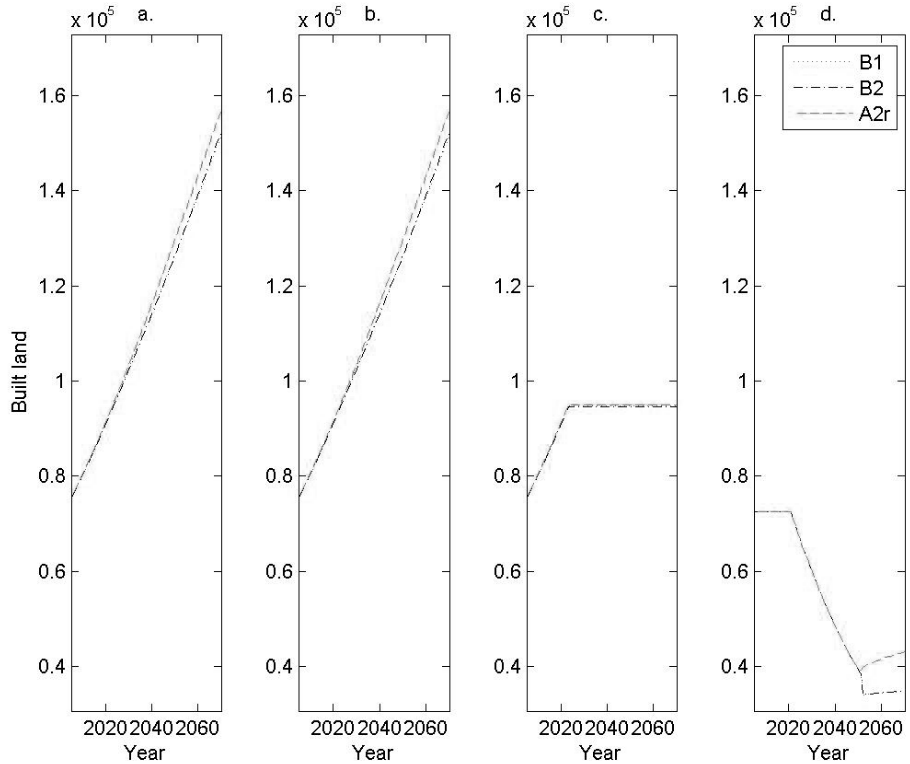
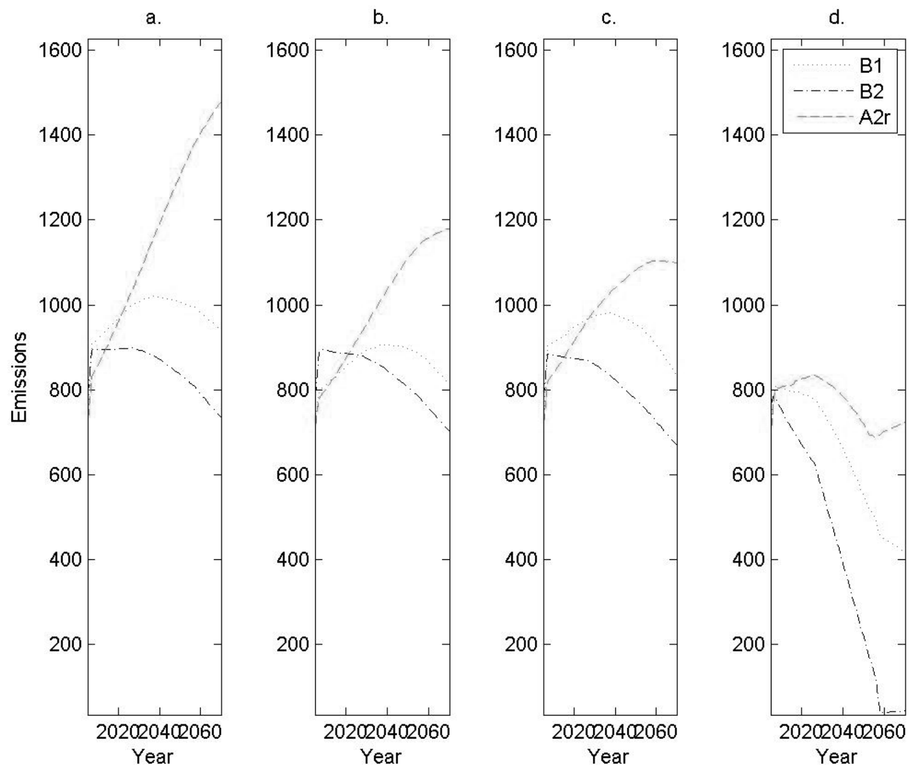
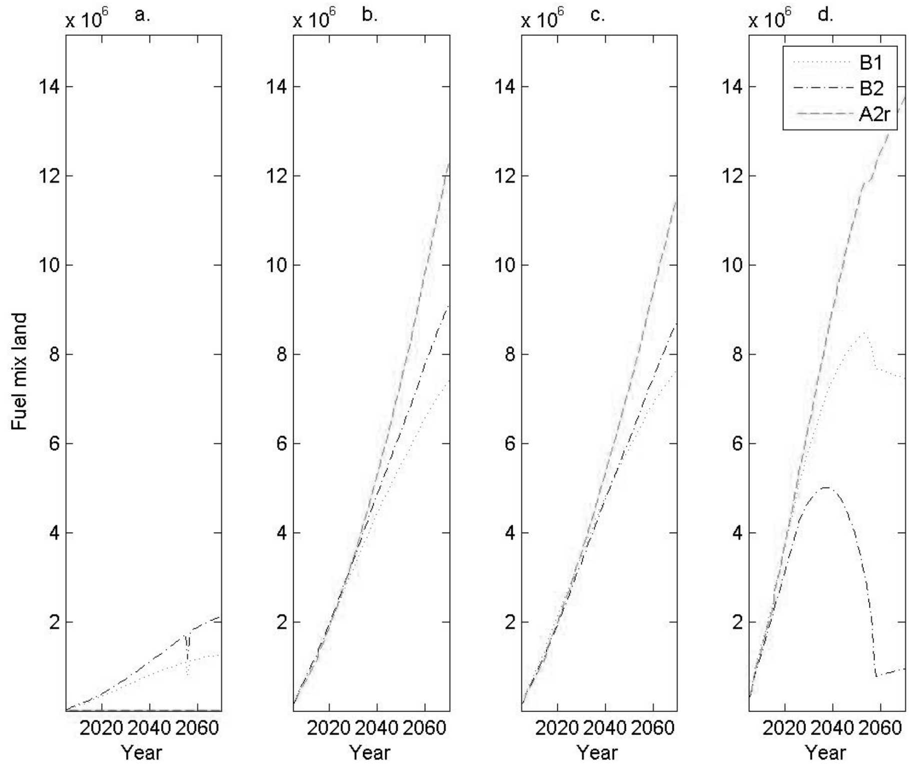
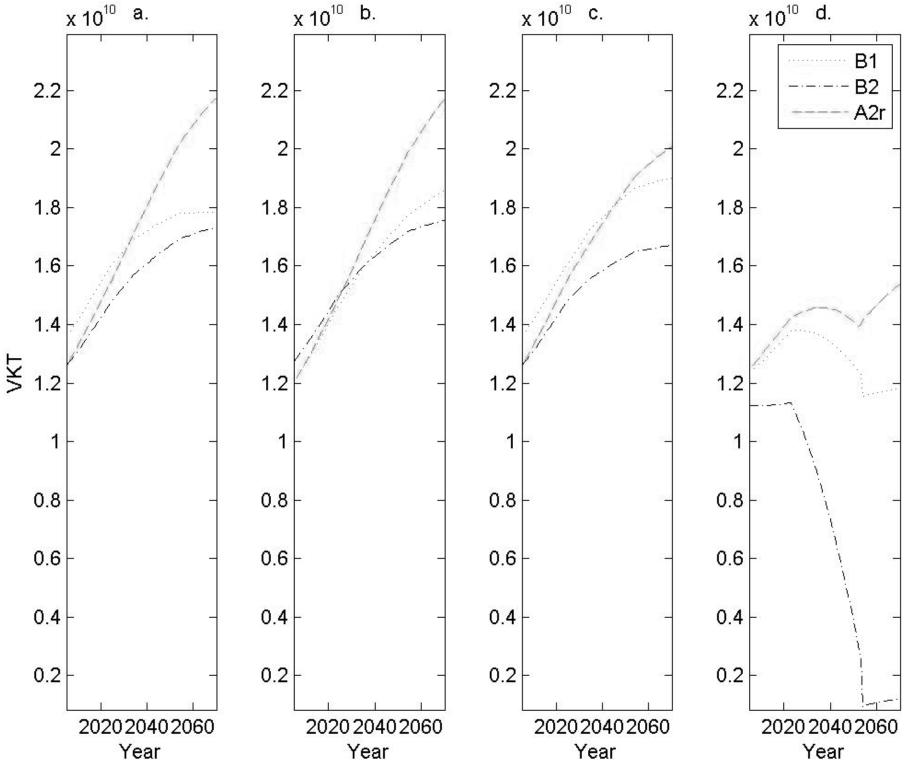

x 10^5 a.
x 10^5 b.
x 10^5 c.
x 10^5 d.
B1
B2
A2r
Built land
1.6
1.4
1.2
1
0.8
0.6
0.4
2020 2040 2060
Year


a.
b.
c.
d.
1600
1400
1200
1000
800
600
400
200
Emissions
2020 2040 2060
Year
B1
B2
A2r



a.
b.
c.
d.
x 10^6
Fuel mix land
Year
2020 2040 2060
2
4
6
8
10
12
14
B1
B2
A2r



x 10^10 a.
x 10^10 b.
x 10^10 c.
x 10^10 d.
B1
B2
A2r
2.2
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
VKT
2020 2040 2060
Year

[i] The A2 storyline is a very heterogeneous world. Population growth is high. Economic development is primarily regionally oriented and medium-low. Technological change is more fragmented and slower than in other storylines.

The B1 storyline describes a convergent world with a medium-high global population. It has rapid changes in economic structures and medium income growth. There is a globally coordinated emphasis is on global solutions to economic, social, and environmental sustainability.

The B2 storyline describes a world in which the emphasis is on local solutions to economic, social, and environmental sustainability. Global population size is low and income growth is medium. Technology growth is less rapid

